4
2002

LIBRARY
Michigan State
University

This is to certify that the
thesis entitled

A FRAMEWORK FOR PRODUCTION MANAGEMENT OF
RENOVATION PROJECTS

presented by

YASH PRATAP SINGH

has been accepted towards fulfillment
of the requirements for the

M.S. degree in CONSTRUCTION MANAGEMENT

Major Professor's Signature

10/1/07

Date

MSU is an affirmative-action, equal-opportunity employer

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.
MAY BE RECALLED with earlier due date if requested.

DATE DUE	DATE DUE	DATE DUE

6/07 p:/CIRC/DateDue.indd-p.1

A FRAMEWORK FOR PRODUCTION MANAGEMENT OF RENOVATION PROJECTS

By

Yash Pratap Singh

A THESIS

Submitted to:
Michigan State University
in the partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Construction Management

2007

ABSTRACT

A FRAMEWORK FOR PRODUCTION MANAGEMENT OF RENOVATION PROJECTS

By

Yash Pratap Singh

Renovation projects exhibit complex characteristics due to the presence of constraints that lead to their cost and schedule overruns. Numerous researchers have concluded that the performance of renovation projects is typically lower than that of new construction projects (Krizek et al. 1996, Mitropoulos et al. 2002, Attalla et al. 2003). The overall goal of this research was to develop a framework for production management of renovation projects that will be used by construction professionals for improving the schedule performance of renovation projects. The goal was achieved by conducting literature review and interviews of construction professionals. Literature of state-of-the-art construction performance measurement systems, renovation projects, and production management of construction projects was reviewed to identify essential attributes that a production management system should possess in renovation projects. Interviews of 6 contractors and 4 subcontractors were conducted for identifying state-of-the-art practices of production management in renovation projects. The research concluded that there is a lack of a formal process in practice for production management of renovation projects, and the state-of-the-art performance measurement systems find limited application in managing renovation projects. The developed framework proposed two major processes; production planning, and production performance assessment. This framework will assist contractors in renovation projects for improving their production planning techniques in the presence of constraints, and meeting the owners' requirements.

Dedicated to my father, Mr. B.P. Singh for his consistent support and having faith in me, my mother, Mrs. Shagun Singh for her unconditional love and sacrifice, and my loving brother, Chandra for giving me the courage to succeed at every step throughout my education.

ACKNOWLEDGEMENTS

I would like to express my up most gratitude and appreciation to Dr. Tariq Abdelhamid for not only furnishing his invaluable guidance, support, and insight throughout this research as the major advisor but also being an excellent mentor, inculcating in me the confidence and new knowledge during the hard stages of this thesis and masters program. I would also like to thank Professor Timothy Mrozowski for serving as the co-chair and providing his helpful inputs. I would also like to thank Dr. Nam-Kyu Park for serving as the external committee member and sharing her views for renovation projects.

I would particularly like to extend my respect and warm regards to Dr. Matt Syal for his special advices on different aspects of masters program. I express sincere thanks to other faculty members, staff, and colleagues at the Construction Management Program at MSU which supported me during my degree fulfillment.

I would also like to thank Don Schafer and Surabhi Rao for being outstanding coworkers in this research since the beginning. I would like to thank my colleague, Shilpi Mago, who provided the enormous support and encouragement during this long journey. I am also thankful to my old friends, Samarth Jain and Amanjeet Singh, who stood by me and shared some unforgettable moments during the final phases of this research.

Finally, I would like to express my deepest respect, gratitude, and appreciation to my family for their constant motivation, support, and sacrifices, without which this research would not have been possible.

TABLE OF CONTENTS

CHAPTER 4
DATA COLLECTION AND FRAMEWORK DEVELOPMENT, DEMONSTRATION AND VERIFICATION

CHAPTER 5
SUMMARY AND CONCLUSIONS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER-1

INTRODUCTION

1.1 Introduction

A renovation project is defined as a process of restoring or improving a built structure that includes modifications, conversion or phased complete replacement (Attalla et al. 2003). Being a large part of the construction industry, renovation projects characterize about one third of the total expenditure spent on construction projects (Mitropoulos et al. 2002). In the late 90's, a study conducted in the United States concluded that renovation projects including remodeling, reutilization and rehabilitation constituted up to 50% of the total construction budget expended (McKim et al. 2000). In commercial and institutional sectors, the annual expenditure on renovation projects has increased from close to $20 billion in 1992 to approximately $80 billion in 2002 (U.S. Census Bureau 1992, 1997, 2002).

Figure 1.1 shows a graph of the marked increase in annual expenditure on renovation projects during the 10 years from 1992 to 2002. This increasing investment in renovation projects has been attributed to the growing needs of public owners and governmental institutions, which represent a major clientele for renovation projects, in order to maintain and upgrade their infrastructure and built facilities (Attalla et al. 2003). Moreover, renovation projects mostly offer an economically viable alternative for public owners in comparison to new construction, as multiphase renovation projects tend to eliminate the need to close owner's operations during construction (McKim et al. 2000).

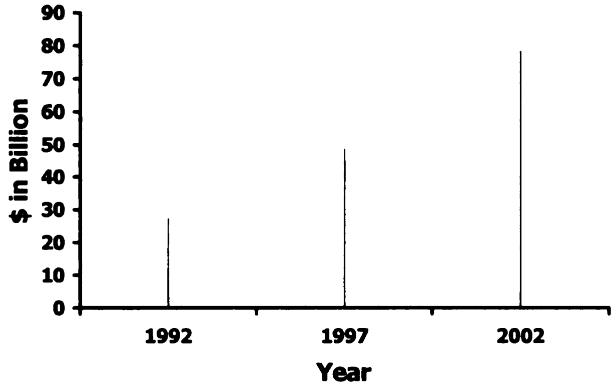

Figure 1.1 Growth in Expenditure on Renovation Projects (Commercial & Institutional)
(U.S. Census Bureau. 1992, 1997, 2002)

In spite of being a growing sector of the construction industry, it has been observed that the performance of renovation projects is typically lower than that of new construction projects in terms of time, cost and quality (McKim et al. 2000, Attalla et.al. 2003). Previous research has concluded that renovation projects, unlike new construction projects, involve considerable risks and uncertainty in existing conditions that adversely impact the project performance (Krizek et al. 1996, Mitropoulos et al. 2002, Attalla et al. 2003). Renovation of an operational facility imposes additional constraints on its construction process, which if not considered during project planning and controlling processes, could lead to project underperformance (Mitropoulos et al. 2002).

This issue of underperformance that plagues renovation projects is extensively investigated for new construction, as illustrated by the Sixth Annual Owner Survey conducted by the Construction Management Association of America (CMAA 2005). According to this survey, building trust and integrity in construction processes was the prime concern of the survey owners. The owners stated that trust and integrity are

necessary for procuring successful projects that meet the desired performance levels of cost, time and quality. In addition, one of the greatest challenges for delivering successful projects lies in controlling the inefficiency in construction processes and not the cost of labor, materials, and equipment (CMAA 2005). To address these concerns, CMAA identified the need for a change in traditional development of contract documents between owner and contractor that would clearly state the desired project outcomes and goals so that contractors could achieve required performance levels (CMAA 2005).

However, changes in contract documents would partially achieve the desired performance and a greater effort needs to be extended at the operational level to strengthen trust and integrity, and reduce construction process inefficiencies. Various researchers and practitioners in the field of Lean Construction view traditional construction project management to be narrowly focused on managing transactions and contracts, ignoring the production aspect of construction operations (Ballard 2000, Ballard et al. 1998, Koskela 1999). According to these researchers and practitioners, the performance improvement in construction projects is a function of the way contractors manage construction processes on daily basis and cause the work to flow between trades for generating desired value to owners (Ballard 2000, Mitropoulos 2003).

In addition, controlling the cost of inefficiencies requires determination of their causes, which is facilitated by production measurement at the operational level that measures how efficiently and effectively the contractor is performing (Cain 2004). Production performance assessment discloses the true inefficiencies inherent in construction processes by identifying the value and non-value adding activities (Ballard 2000, Koskela et al. 2001).

In 1998, as a vital contribution to the U.K. Construction Best Practice Program, the Egan Report titled "Rethinking Construction" emphasized that contractors need to reduce high levels of inefficiency and waste in construction processes. According to the Egan Report, this was the principal concern that owners had about the U.K. construction industry. This report underscored the need for development of performance measurement of both the quality and efficiency of construction processes for building strong relationships between owners and contractors (Cain 2004, Beatham et al. 2003).

Both, CMAA's owner survey and the Egan Report bring forward the significance of performance measurement in current construction practices to control the cost of inefficiencies and successfully deliver projects to owners that would reinforce the trust and integrity between owners and contractors. However, Lean Construction supplements this view by emphasizing performance measurement at the production level to minimize waste in construction processes and maximize the value for project owners (Ballard 2000).

Adoption of performance measurement in current construction practices has also been driven by the dissemination of Total Quality Management Principles (TQM) and ISO9001: 2000 standards, as potential solutions to increasing complexities of construction processes, competitiveness, and wasted efforts in reworks (Costa et al 2000). Consequently, construction firms have begun to investigate on "what is to be measured" and "how is it to be measured" so that the desired results are achieved (Samson et al 2001). Therefore, performance measurement has been recognized as a vital aspect of project controls for providing the basis for monitoring and controlling construction activities by bringing to surface their inefficiencies (Costa et al. 2000, Alarcon et al 2000).

A performance measurement system, whether in construction or any other industry, begins with the identification of a balanced set of indicators through which performance can be measured (Alarcon et al. 2000). Numerous studies have investigated adequate set of performance indicators for measuring the financial and non-financial aspects of construction processes that define their true performance. These studies have also focused on reviewing some of the state-of-the-art performance measurement systems being developed by collaborative benchmarking initiatives among construction companies across the globe. These state-of-the-art performance measurement systems were developed for the purpose of providing guidance in performance measurement of construction projects and establishing benchmarks for identifying best practices. Some of these state-of-the-art systems are: Key Performance Indicators (U.K.), National Benchmarking System (NBS-Chile), Construction Industry Institute Benchmarking and Metrics (CII BM&M, USA) and, Performance Measurement System for Benchmarking in the Brazilian Construction Industry (SISIND) (Costa et al. 2006).

One of the major outcomes of the studies that investigated these state-of-the-art performance measurement systems is their limited implementation in construction firms due to their incompatibility with the organizational capabilities. This has also been attributed to the complexity of construction projects comprising of different participants in a temporary organization (Lantelme et al. 2000). Some of the systems still focus on financial and contractual measures, ignoring those which are important to competitive success (Beatham et al. 2003). In addition, past research efforts have not reached a consensus on the most appropriate set of performance indicators suggested by different state-of-the-art systems (Korde et al. 2004). Therefore, it has been observed that these state-of-the-art performance measurement systems still find limited application in the construction projects which are more Complex, Uncertain and Quick (CUQ) (Costa et al. 2006, Beatham et al. 2000, Ballard 2000).

The CUQ level increases in case of renovation projects due to the presence of various constraints and consequently, the investigation of "what is to be measured" becomes extremely difficult (Mitropoulos et al.2002, Attalla et al. 2003, Krizek et al. 1996). Moreover, previous studies have concluded that these constraints make traditional project planning and monitoring techniques inappropriate for measuring and controlling performance in renovation projects (Mitropoulos et al. 2002, McKim et al. 2002). Therefore, in order to assess the impact of constraints on production level and measure the performance, it is essential to identify an appropriate set of performance indicators for improving the construction throughput in renovation projects. Measuring performance at the production level of renovation projects also requires an understanding of the complex nature of unforeseen conditions, which is one of the biggest constraints contributing to the uncertainty in construction planning processes (Krizek et al. 1996).

The challenges of renovation projects have driven previous researchers to focus on identifying and analyzing various constraints encountered in renovation projects, and to propose planning techniques for coping with these constraints. However, there is a need to develop assessment methods for ascertaining the impacts of these constraints on production level performance of renovation projects. Hence, this research focuses on constructing a framework for production planning, execution and performance assessment of construction operations in renovation projects under the impact of constraints identified in these projects.

1.2 Need Statement

Traditionally, renovation projects are evaluated by assessing achievements against the project objectives of budget and schedule, through measurement of Cost Variance (CV) and Schedule Variance (SV) as success indicators through the technique of Earned Value (EV) analysis (Beatham et al. 2003). The traditional method of EV analysis is shown in Figure 1.2, which measures the CV and SV based on the Budgeted Cost of Work Scheduled (BCWS), Budgeted Cost of Work Performed (BCWP) and Actual Cost of Work Performed (ACWP) (Nassar 2005). The equations for assessing CV and SV are:

$$CV = BCWP - ACWP \qquad \text{equation 1.1}$$

$$SV = BCWP - BCWS \qquad \text{equation 1.2}$$

In the traditional project management approach, a corrective action is taken only when the CV and/or SV trigger a negative value, which would mean that the project is over-budget and/or behind schedule respectively (Ballard 2000). Thus, the traditional project control model is based on a reactive approach, which has been concluded to be a deficient approach of controlling projects rather than controlling production (Ballard 2000, Koskela et al. 2001).

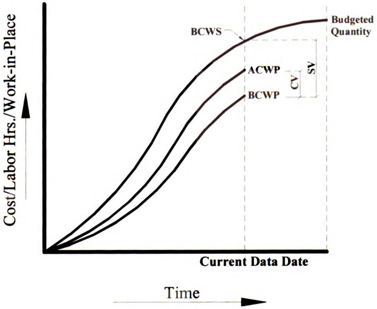

Figure 1.2 Earned Value Analysis (Nassar 2005)

The traditional performance indicators of CV and SV being focused only on cost and time have been extensively criticized for their inability to identify the real causes of results and predict the performance during construction process (Beatham et al. 2003). Being outcomes of the projects, these customary performance indicators of cost and time provide information about the results of a process and not the process itself. In other words, these performance indicators are incapable of establishing the cause-effect relationships between the results and their sources (Alarcon et al. 2000). Moreover, these indicators do not support rapid decision-making necessary for corrective actions, as the information retrieval usually gets delayed (Lantelme et al. 2000). In general, these indicators are the focus of construction performance measurement systems currently in practice. Therefore, the new move in current research in performance measurement is on identifying process-oriented indicators that provide relevant information for improving the on-going processes to achieve desired performance levels (Beatham et al. 2003).

Additionally, renovation projects are characterized by a number of constraints that make the establishment of cause-effect relationships even more difficult. As shown in Figure 1.3, it becomes an extremely complex task of investigating the negative deviations of CV and SV for a renovation project, as their source could be a single constraint or multiple constraints (Krizek et al. 1996). One of the major constraints identified is the uncertainty of unforeseen conditions, which is an inevitable aspect of renovation projects (McKim et al. 2002). This uncertainty relates to unknowns in pre-existing conditions, which can adversely impact the performance of construction activities, if not accounted for in their production planning. There are other constraints in renovation projects that add to this difficulty including space limitations, design coordination with existing conditions, traffic limitations, owner's operations limitations, pollution control, safety constraint, and limited capacity of existing utilities (Krizek et al. 1996, McKim et al. 2002).

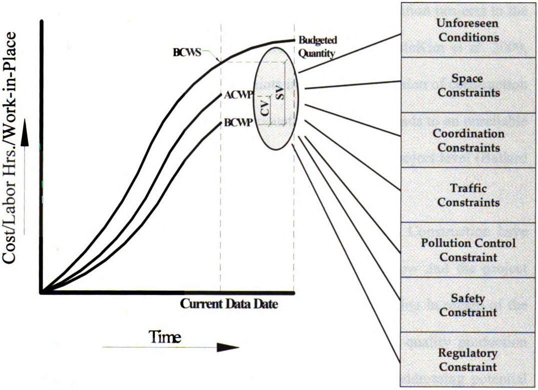

Figure 1.3 Earned Value Analysis in Renovation Projects (Modified from Nassar 2005)

Past studies have concluded that compared to new construction, renovation projects have been delivering lower performance levels of cost, time, and quality. Below are the excerpts from some of the studies of renovation projects that investigated the performance levels between new construction and renovation projects.

"Comparing several new and reconstruction projects, the latter showed significantly higher time and cost overruns." (Krug 1997)

"New construction projects perform much better than reconstruction projects that exhibited higher schedule and cost overruns." (McKim et al. 2000)

"Typically, the performance of renovation projects is much lower than new construction, in terms of their cost, schedule, and quality performance." (Attalla et al. 2003)

These studies attribute the lower performance levels of renovation projects to the presence of various constraints, as mentioned above (Krug 1997, McKim et al. 2000, Attalla et al. 2003). Operationally, these constraints impact the production of construction activities and increase the variability in their production rates. This leads to an unreliable workflow between trades decreasing the overall performance at the project level (Ballard 2000, Koskela 1999).

Numerous researchers and practitioners in the field of Lean Construction have investigated different methods to improve the reliability of workflow and the project throughput. They have reached on a consensus that production planning in regard of the constraints causes the events to conform to the plan by planning quality production assignments through communication with construction crews and addressing potential constraints upfront (Mitropoulos 2003, Ballard 2000, Koskela 1999). By identifying and analyzing the potential constraints of the upcoming work, a realistic production is planned than 'can' be achieved by the crew instead of what 'should' be achieved according to the original project plan. The constraint analysis makes the planned production ready by pulling required resources rather than pushing them on to the original plan (Koskela et al. 2001). Once the production is planned and executed, the application of performance measurement at the production level provides quantitative information that could be utilized to reduce production variability between different tasks and to identify the actual causes of poor performance (Ballard 2000). Therefore, by studying the constraints of renovation projects, it is possible to better plan for these constraints and to minimize their impacts on the production of construction activities and overall performance of the project.

Although the reviewed state-of-the-art construction performance measurement systems focused on identifying key performance indicators for general construction, there is a need to investigate their application to production management in renovation projects. This could result in either revising the current methods to plan and assess production performance in renovation projects or developing new methods. In addition, as past researches have not collectively concluded the adequate set of performance indicators for general construction (Korde et al. 2004), it becomes essential to investigate the feasibility of additional performance indicators for assessing the impacts of constraints on the production cost, time, and quality in renovation projects. This would lead to better production planning, execution and assessment methods for renovation projects in the presence of constraints.

From a systems perspective, this investigation necessitates development of a framework for production management that integrates various constraints with current production planning and performance assessment methods, and defines appropriate performance indicators to be measured at the production level of renovation projects. Reviewing state-of-the-art construction performance measurement systems in the context of renovation projects will provide a thorough understanding of current measurement methods and the basis for developing the intended framework.

Therefore, the unique nature of renovation projects, an expanding division of the entire construction industry, and their increasing underperformance in cost, time and quality (Krizek et al. 1996, Mitropoulos et al. 2002, Attalla et al. 2003) reinforce the need to investigate ways to make production planning in renovation projects more adept and reliable.

1.3 Research Questions

The research need underscores the importance of examining state-of-the-art construction performance measurement systems for their application to production management in renovation projects As the complex nature of renovation projects is defined by the presence of various constraints which lead to cost and schedule overruns, it becomes imperative to investigate these constraints, and develop assessment methods for their impacts on the cost and schedule of the production in renovation projects. This research primarily addresses the following three questions:

1) What are the limitations of state-of-the-art construction performance measurement systems for managing production in renovation projects?

2) What are the complexities of renovation projects that lead to underperformance in cost, time and quality?
   a) What constraints are prevalent in renovation projects that impact the production of construction activities?
   b) What activities are critical in renovation projects with greatest contribution in budget, schedule, and quality performance?
3) What methods plan the impact of constraints on the production of critical activities in renovation projects and assess their production performance accordingly?

1.4 Research Goals and Objectives

The overall goal of this research is to develop a framework for production management of renovation projects to improve schedule development and execution. The goal is achieved by fulfilling the following objectives:

1. Document state-of-the-art construction performance measurement systems and production management practices for renovation projects.

   Objective-1 is fulfilled by performing the following steps:

   a. Conduct literature review of state-of-the-art construction performance measurement systems, complexities of renovation projects, and production management of construction operations.
   b. Identify essential attributes of a production management system for renovation projects from literature review.

   c. Draft interview question and conduct interviews of contractors and subcontractors regarding their production management systems for renovation projects.

2. Develop a framework for production planning, execution and performance assessment of construction operations in renovation projects.

   Objective-2 is fulfilled by performing the following steps:

   a. Based on the interview responses, prepare modifications and/or additions to the essential attributes identified from literature review. This includes modifying the critical activities, constraints, performance indicators, and their measurement methods.
   b. Develop the intended framework.
   c. Demonstrate the developed framework with a hypothetical example of renovation projects.
   d. Verify the developed framework with second round of interviews on the production planning and assessment method suggested by the framework.

1.5 "Production Performance" Definition for this Research

In general, performance is defined as the ability to implement actions and achieve desired results. A major driver for this ability is continuous measurement and improvement of processes (Salminen 2004). Thus, performance measurement is a method of quantifying what has happened in the processes and identifying the scope for improvement in future actions (Hao et al. 2005).

In the construction industry, performance at the project level has been extensively discussed as the ability to finish projects on time, within budget and that meet the desired quality levels. Therefore, construction performance measurement typically entails assessing the actual project cost and schedule performance against what was estimated for identifying negative Cost Variance (CV) and Schedule Variances, and applying corrective actions. This assessment is typically performed through Earned Value (EV) analysis and Critical Path Method (CPM) techniques (Alarcon et al. 2000, Samson et al. 2004).

However, various researchers in the field of construction production management disagree with the conventional approach of construction project management towards performance measurement. The disagreement lies in the fact that traditional performance measurement techniques using EV analysis and CPM schedules are based on a 'reactive' model that triggers only when negative deviations are identified (Ballard 2000, Koskela et al. 2001). Project controls track the completion of each activity by determining whether the activity and project are within the cost and schedule limits. These traditional techniques fail to address possible constraints, resource capacities, pre-requisite work, and the quality of the state of the system upfront for the production of an activity. Thus, traditional performance measurement techniques do not assure a reliable work-flow between trades (Ballard et al. 1998, Koskela et al. 2001). The focus has been on managing contracts and CPM schedules by pushing more and more resources to speed the completion, which consequently adds more waste, the non-value adding activities at the production level (Ballard 2000, Koskela 1999).

Therefore, at the production level, performance has been defined as the ability to complete production assignments that are scheduled on weekly basis per the existing state of the system (Mitropoulos et al. 2003). These production assignments are established based on the analysis of constraints prevailing in prerequisite work, site conditions, and resource availability that could impact the production of construction activity. Production assignments signify what "can" be performed under the impact of existing constraints rather than what "should" be performed, as planned in the CPM schedule. The intention of planning and assessing production in the presence of constraints is to make the workflow more reliable between trades that minimizes waste in construction activities and reduces the variability in their production rates (Ballard 2000, Chitla 2000).

Management of production in renovation projects poses a question of 'what constitutes production performance in a renovation project'. Several studies have concluded that the constraints of renovation projects by their complex nature negatively impact the production of construction activities leading to schedule and cost overruns (McKim et al. 2000, Mitropoulos et al. 2002, Attalla et al. 2003). Being an inherent part of renovation projects, these constraints are generated due to numerous project conditions. Failure to address these constraints before planning production of each activity could result in cost and schedule deviations (Mitropoulos et al. 2002).

This research posits that the ability to define production assignments by proactively identifying and assessing the impact of constraints in the production of critical activities, as well as completing the production assignments within budget, on schedule, and at desired quality defines the "production performance" of contractors in renovation projects. This definition of production performance is considered in the development of the intended framework throughout this research.

1.6 Research Scope

The scope of this research is governed by the following factors:

1. The research focused on production management of renovation projects of institutional buildings that involves interior remodeling of occupied built facilities.
2. The research investigated production evaluation of construction activities and not the employees and craft labor of the firm. This research has not attempted to assess the performance of socio-economic factors of construction firms.
3. Production planning and assessment of construction activities of renovation projects forms the extent of this research. Design performance evaluation and the life-cycle performance evaluation do not form a part of this research.
4. The developed framework for production management of renovation projects focuses on planning and assessing only the production schedules of construction activities. Due to the complexities involved, the framework does not suggest any methods to assess the impacts of constraints on the production cost and quality of construction activities.
5. In order to obtain pertinent data from construction professionals, this research conducted interviews of six contractors and four subcontractors, based in Michigan due to geographical constraints.

1.7 Chapter Summary

This chapter provided an overview of the scope of this research by outlining its goals and objectives. It explained the need for a framework for production management of renovation projects in the construction industry. The chapter also discussed the contribution of this research in terms of its expected benefits to the project owners and contractors involved in renovation projects.

CHAPTER-2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the literature in three categories of; state-of-the-art construction performance measurement systems, renovation projects, and production management in construction. The literature was obtained in the form of theses, dissertations, journals and articles from University library sources and the web. Each category of literature was reviewed to bring forward its emphasis areas for achieving the research objectives.

The purpose of reviewing state-of-the-art construction performance measurement systems was to obtain an understanding of their objectives for development, performance indicators, performance measurement processes, and implementation strategies. The literature of renovation projects was reviewed to understand its complex nature and scope of additional requirements for managing construction operations. This included review of various constraints that act as the primary sources of cost and schedule overruns in renovation projects. Construction production management literature provided an overview of performance assessment processes at the production level of construction operations. It also brought insights into how inefficiencies of construction process operations at the production level were previously addressed. The following sections discuss each category of literature in detail.

2.2 Concept of Performance Measurement

The performance of any process is the result of the abilities of its sub processes and individuals to implement desired actions. Measurement is the process of ascertaining this ability and comparing it with the standards or planned targets. Measurement of performance, both quantitatively and qualitatively, reveals the inefficiency and scope for improvement in the process. Therefore, performance measurement is the process of quantifying what has happened in the processes and identifying the scope for improvement in future actions (Hao et al. 2005). As a starting point for upgrading any process, performance measurement provides essential information about the status quo of the process and improvement opportunities in that process (Beatham et al. 2003).

In management sciences, a central objective of measuring performance is to improve the competitive ability of a company in reducing operational costs and increasing the profits. This forms the prime reason for increasing interests of companies in every sector in performance measurement (Salminen 2004). Prior to measuring performance, it is essential to determine what to measure, how to measure, and the data collection and analysis methods. The decision about what to measure depends on what to improve in a process. The question of how to measure determines what methods will be used to take the measurement. The data collection and analysis methods define the team responsible for collecting the measured data and analyzing it appropriately to compute the performance (DOE 1996).

2.3 Performance Measurement in the Construction Industry

The construction industry is characterized by its dynamic nature, complexity of processes, and involvement of several stakeholders in different processes that need to be kept in control for achieving project success. The competitive ability to control construction processes under desired performance levels has been identified as one of the most significant factors in defining a company's growth (Beatham et al. 2003). Consequently, performance measurement has been a major issue of concern in the construction industry over past 15 years (Bassioni et al. 2004). This has also been driven by increasing demands of owners for measuring construction performance due to tremendous increase in reworks and wasted efforts in construction processes that lead to projects being over-budgets, behind schedule and poor in quality (Beatham et al. 2003).

In spite of growing significance of performance measurement systems in the construction industry, it has been widely recognized that traditional performance measurement practices that focus only on cost and schedule deviations, do not provide an accurate assessment of construction projects (Costa et al. 2006). The traditional performance measurement systems have been extensively criticized by numerous researchers for their multitude of limitations in the context of current construction practices. The following section provides an overview of these limitations of traditional measurement systems.

2.3.1 Limitations of Traditional Performance Measurement Systems

Previous studies indicate that there is a growing dissatisfaction with the traditional performance measurement systems focusing only on financial indicators. Samson et al. (2002) stated that financial indicators are unable to explain the status of a continuing process and therefore, do not form the basis for future actions. These indicators have been referred to as being "lagging" measures because they only explain the outcomes of any action after its occurrence and do not offer the opportunity to change or improve performance during the process. Therefore, these indicators do not support continuous improvement due to their inability to define the cause-effect relationships between the results and causes (Beatham et al. 2003).

The traditional performance measurement systems have also been criticized for being based on easily quantifiable measures such as cost, productivity, and schedule deviation. Measuring factors that contribute to competitive success has been neglected (Beatham et al. 2003). Instead, measurement of performance at process level, and even, operational level, has been observed to give a better indication of current and future performance (Alarcon et al. 2000). Samson et al. (2002) stated that the essential characteristics of performance indicators that an effective measurement system should possess are; i) the ability to identify causes of results and ii) the ability to identify improvement opportunities based on the result analysis.

As the financial measures are not linked with the value-adding activities, they cannot fully explain the causes of inefficiencies in the process. It restricts the process transparency where the non-value-adding activities become invisible, as the traditional indicators are focused on conversion activities, ignoring the flow activities (Alarcon et al. 2000). In addition, these indicators have a short-term focus of making profit instead of a long-term strategic focus, as they are not linked with the strategies and objectives of construction companies (Beatham et al. 2003).

In addition to the indicators being used, there are some limitations of the measurement process of traditional performance measurement systems (Costa et al. 2000, Samson et al. 2002):

- There is a use of too many measures focused internally on the administrative issues and few measures focused externally on the actual construction processes.
- The cycle time to generate information from the measurement data is usually too long to make decisions.

- The indicators are not related to the critical processes that contribute to the overall performance.
- The measurement methods for the indicators are not clearly defined.
- The performance does not relate to the operational costs and the system tends to be backward focused.
- There is a tendency to blame individuals for underperformance instead of identifying the right process to improve.

The limitations of traditional performance measurement systems have driven previous researchers to make recommendations for the essential characteristics of performance indicators. The authors have suggested that the indicators should be (Costa et al. 2000, Samson et al. 2002, Beatham et al. 2003):

- Able to realize company's goals and objectives.
- Able to identify causes of results.
- Able to identify improvement opportunities in the processes for better performance.
- Easy to measure and simple to understand.
- Related to the key business processes that impact the performance.
- Able to generate information that support expedited decision-making.

2.3.2 State-of-the-art Construction Performance Measurement Systems

The limitations of traditional performance measurement systems led numerous researchers to focus on developing what have been termed as state-of-the-art performance measurement systems for the construction industry. As per a study conducted from 1994

to 1996, it was concluded that the rate of appearing each new article pertaining to performance measurement was five hours of every working day (Beatham et al. 2003). Although, not all of these systems were related to construction, but they illustrated that performance measurement has been an issue of concern in all the industries.

These state-of-the-art performance measurement systems have investigated different models for measuring and analyzing construction performance but the overall focus was on identifying appropriate indicators that could measure the performance of construction processes. Some of these systems also developed the measurement methods of performance indicators at the project level, trade level, and activity level (Korde et al. 2004).

2.3.3 Performance Indicators of State-of-the-art Construction Performance Measurement Systems

A performance indicator represents a quantitative or qualitative assessment of any data that is used to evaluate performance of business operations against the desired targets (Hao et al. 2005). In the construction industry, the performance indicators have been extensively recognized as Key Performance Indicators (KPI), as most of the state-of-the-art performance measurement systems employ this terminology (Robert et al. 2003).

The key performance indicators for construction operations have been extensively studied and analyzed by numerous researchers in order to achieve at the most favorable subset that collectively measures the efficiency and effectiveness of construction processes. Some of the studied indicators measure the success of results, i.e., construction projects while others measure the construction processes to achieve successful results.

The former are called "lagging" indicators and the latter are termed as "leading" indicators (Beatham et al. 2003). In numerous studies, these KPIs have been used synonymously with Critical Success Factors (CSF), although the purpose of both KPI and CSF is to assess the performance of construction projects or operations. The following section provides an overview of various studies that focused on identifying the performance indicators or success factors for construction projects.

Chan et al. (2004) developed a framework for assessing construction success that involved identification of KPIs for assessing project success. The identified KPIs were time, cost, value and profit, health and safety, environmental performance, quality, functionality, user expectation and satisfaction and, participants' satisfaction.

In 2004, *Salminen* developed a performance measurement system for construction site operations, which was divided into three parts; preconditions, the operation processes, and the results. The author investigated the essential elements of construction site performance and their measurement methods. Further, the relationships between performance elements were analyzed and most important performance elements were identified. Each of the three parts of the developed performance measurement system consisted of performance factors as:

1. Preconditions-This part relates to the preconditions of the site created by the owner, designer, and consultants.
2. Operation Process- Management system, work behavior, and leadership formed the main factors that contribute to operation performance.
3. Results- Cost, schedule deviation, quality, and safety were the main factors for measuring results of any construction project.

The research conducted forty-seven case studies of four construction firms that generated three hundred performance variables. The author reduced this number by combining similar variables through discriminant analysis. It was concluded that cost, schedule deviation, quality, and safety were the main factors that contribute to project success.

Attala et al. (2003) identified thirty six CSFs of reconstruction projects, under broad categories of cost, schedule, quality, scope, communication, safety and site for developing a performance prediction model. For investigating the factors in fifty-four case studies, they were further reduced to seventeen through statistical application for making the research manageable and controllable. The authors categorized these seventeen indicators under project phases of scope definition and planning, tendering stage, schedule control, cost control, quality control, communication, safety control and project completion. It was concluded that the most critical phases for performance in reconstruction projects are management and control of planning, tendering and scheduling.

Beatham et al. (2003) analyzed KPIs developed by seven organizations in the U.K. construction industry, with the objective of developing an integrated business improvement system. Among the investigated KPIs, the Construction Best Practice Program (CBPP) was considered one of the foremost systems that included ten headline KPIs during its initial launch in 1998; client satisfaction-product & service, profitability, productivity, defects, safety, predictability-time & cost, construction time and construction cost. In 2000, CBPP KPIs were increased to 38, to be measured in seven criteria of time, cost, quality, client satisfaction, change orders, business performance and health and safety, and they were further organized in a hierarchical model of headline, operational and diagnostic level measurement (Beatham et al., 2003).

After analyzing the KPIs of all organizations, the authors concluded that most of the systems had employed post result lagging indicators and they do not offer an opportunity to change the performance during process. Some of the examples of lagging KPIs were defects, client satisfaction, time, cost, profitability, productivity, risk, reuse of design etc. It was found that some of the KPIs could be employed as leading indicators if used during the process such as defects, client satisfaction, time, cost etc. The authors suggested European Foundation of Quality Management (EFQM) categorization for the investigated KPIs in three broad categories of Key performance indicators, key performance outcomes and perception measure. This categorization would facilitate appropriate application of KPIs for measuring both process performance and project performance (Beatham et al., 2003).

Chua et al. (1999) identified CSFs of a construction project for different objectives of budget, schedule and quality. As per the authors, the need to assign resources appropriately for each objective necessitated this categorization of success factors. The authors compiled sixty seven CSFs from literature review that involved previous studies dealing with identification of CSFs for different aspects of construction projects such as project execution strategies, project performance, project management, project partnering, contracting methods and contract disputes.

The identified CSFs were investigated for their relative contribution to different project objectives of cost, time and quality. In order to understand this relative importance of CSFs, the authors organized them under different levels of focus where a comparative analysis could be performed at each level. This was achieved by developing a hierarchical model for construction project success that categorized the CSFs in four main project aspects of i) project characteristics, ii) contractual arrangements, iii) project participants and, iv) interactive processes. Under each project aspect, the CSFs were analyzed for their relative importance in contributing to different project objectives.

The authors conducted survey of twenty construction experts having approximately fifteen years of industry experience and they were requested to perform a pair-wise comparison of sixty-seven CSFs for achieving the project objectives of budget, schedule and quality. This pair-wise comparison was based on Analytical Hierarchy Process (AHP) importance scales and the collected data was analyzed through Expert system software that could perform the AHP calculations. As per the analysis results, it was concluded that each project objective had different set of top ten CSFs, however, 'adequacy of plans and specifications' and, 'constructability' figured out as the leading success factors for all the three objectives. The other common CSFs for cost, time and quality, each having different importance levels, were PM competency and, PM commitment and involvement.

Further, these top ten CSFs for each project objective were reviewed for their hierarchy under four main project aspects, as stated above. For instance, under the 'external project characteristics' project aspect, the top most CSFs for budget performance, schedule performance and quality performance are economic risks, technical approval authorities and, site limitations and location respectively. This analysis helped the authors to understand the nature of CSFs under different project aspects and their contribution to different project objectives. This would also make the resource allocation to each project objective appropriate for each project aspect.

In 2001, *Samson et al.* emphasized the importance of effective performance indicators to make the traditional performance measurement systems more adapt to the emerging trends in the construction industry. These trends refer to high costumer's requirements, environmental awareness, high competition and continuous improvement of construction business processes. The authors discussed some of the essential characteristics of performance indicators that an effective measurement system should possess, which are; i) ability to identify causes of results and ii) the ability to identify improvement opportunities based on the result analysis.

At a conceptual level, the authors developed a performance measurement framework based on five essential dimensions, each representing a different perspective of construction business. These perspectives were innovation and learning, processes, projects, stakeholders, and financial. Performance measurement from each of these perspectives has been suggested and explained, to obtain an integrated and holistic performance where each perspective has its designated role in measuring and improving the performance of different aspects of construction business. For instance, performance from learning and innovation perspective contributes in expanding the knowledge base of a company, while from project perspective, performance is the ability to deliver projects on time, within budget, and of right quality that satisfies client needs.

In addition, in order to measure the performance from each perspective, the authors have identified performance indicators based on these five perspectives. These indicators have been further grouped into process indicators, performance driver indicators and result indicators. This categorization helped the authors to clearly define the scope and function of each performance indicator.

In 2000, *Alarcon et al.* presented a classification system of construction performance indicators based on the results, processes and variables that support decision-making for taking corrective actions. Through this categorization, the decision maker gets equipped with the ability to identify the root causes of the problems. On the other hand, the authors have criticized current selection of traditional indicators, i.e., cost and schedule, for measuring performance and, have emphasized the significance of incorporating process oriented indicators for their ability to identify non-value adding activities in the processes.

Through an extensive literature review, followed by a thorough investigation by different participating companies, the research formulated a list of twenty performance indicators that would achieve the research main objective by supporting management decisions, encouraging continuous improvement and benchmarking. However, while implementation in case studies, it was identified that the application of proposed indicators would be limited to the capacity of the existing control systems used by different companies and it was suggested to commence with few and easily measurable indicators. Further, the authors extended the need to incorporate the measurement of operational level indicators (e.g. rework, transportation, waste, cycle time) that would support waste identification at the task level of construction processes. As a part of benchmarking initiative, the research developed a baseline from the results of five recent projects, each from seven construction companies, which helped in understanding the variability in the distribution of various indicators within companies.

Nassar (2005) developed an integrated project performance hierarchical structure that provided a basic framework for defining the success factors from the perspectives of project team, construction organization and client organization. The amalgamation of different perspectives in a single framework facilitated a balanced performance measurement approach, comprising of eight performance indices; safety performance index, client satisfaction index, quality performance index, schedule performance index, cost performance index, billing performance index, project team satisfaction index and, profitability performance index. The author assigned relative importance to each index in contributing to the overall project performance index, through application of Analytical Hierarchy Process (AHP). Based on the relative weights of performance indices, overall performance index can be ascertained, representing the performance at management level and operational level. However, the author stated that the importance levels of performance indices are functions of the type and status of the project. For instance, in the project closeout stage, the relative importance of cost performance index would be lower than schedule performance index as major fraction of the estimated budget has been spent by that time and, finishing the project on schedule becomes more essential.

For measuring each success index, the author identified its respective essential attributes as performance indicators, which were identified on the basis of the author's fifteen years of industry experience, but due to the uniqueness of construction projects, the author suggested formulating these indicators by contractors themselves.

2.

Pe

M

fo

th

re

or

pr

eff

co

per

un

qua

En

sub

that

diff

fina

emp

satis

depe

2.3.4 Performance Measurement Methods of State-of-the-art Construction Performance Measurement Systems

Measurement of any performance indicator, quantitatively or qualitatively, brings forward the efficiency and effectiveness of a certain aspect of the products, services and the processes that produce them (DEO 1996, Hao et al. 2005). Quantitative measurement results in a number and a unit of measure, which represent the magnitude and the nature or meaning of performance indicator respectively. For instance, construction productivity, being measured in $/hour or units/hour provides the magnitude of labor efficiency on construction sites. Being in a project-oriented industry, construction companies have been struggling in defining the appropriate methods for assessing the performance of various aspects of construction. This has been attributed to the uniqueness and complexity of construction projects (Costa et al. 2004).

On the theoretical front, conflicting views for measuring performance under qualitative and quantitative aspects of construction can be found. The Department of Energy (DOE) suggests quantitative measures rather than qualitative due to their subjectivity and unclear interpretations (DOE 1996). However, in 1998, Williams stated that performance is not a result of common views, rather it holds different meanings to different stakeholders and therefore, performance measurement involves both hard financial and non-financial measures and, soft measures such as client satisfaction, employees attitudes etc. In addition, Kast et al. (1985) incorporated 'participant satisfaction' as one of the measures in performance because the success of any process depends on the satisfaction of its enablers (Salminen 2004).

Despite the importance of performance measurement method in construction, a very few authors have discussed the appropriate methods for measuring performance indicators both objectively and subjectively. The major emphasis has been on identification of performance indicators and the implementation methods of the proposed performance measurement systems and not on the performance measurement methods (Attalla et al. 2003). Although, some authors have investigated the hierarchy or relative importance of performance indicators for measuring overall performance of construction projects, but it is essential to understand the methods for measuring the indicators for their appropriate application.

Attalla et al. (2003) suggested calculating Process Performance Factor (PPF), as a quantifiable and objective indicator of overall performance of reconstruction projects. The main three components of PPF were change order cost, rework cost and schedule delay and each component was assigned a relative weight in contributing to the overall performance as shown in the equation below.

$$\begin{aligned} PPF = {} & X \times [1\text{-Change orders cost/original contract value}] \times 100 \\ & + Y \times [1\text{-Cost of rework/original contract value}] \times 100 \\ & + Z \times [1\text{-Schedule delay/original schedule}] \times 100 \end{aligned}$$

Chua et al. (1999) assigned relative weights to project objectives of budget, schedule, and quality in achieving construction project success through Analytical Hierarchy Process (AHP) among which schedule performance was found to be a major contributory factor as compared to other two objectives. For each project objective, top ten CSFs were analyzed for their relative importance but the measurement methods for the CSFs were not investigated.

Chan et al. (2004) categorized the identified KPIs under objective and subjective measures and presented their quantitative and qualitative methods of measurements. The application of identified KPIs and their measurement methods were also investigated on three hospital projects where the authors concluded that the time and cost performance get impacted by the adopted project procurement method, traditional and design build.

Alarcon et al. (2000) suggested measurement methods for the identified performance indicators of project results, processes, and variables. The authors stated the objective of measuring each indicator as benchmarking, continuous improvement, waste identification, variability reduction, process improvement, and reduce cycle time. In addition, performance measurement at operational level was also emphasized with the identification of Lean based performance indicators to be measured at task level with their appropriate measurement methods.

McKim et al. (2000) developed quantitative methods of Cost Performance Factor (CPF) and Schedule Performance Factor (SPF) for controlling cost and time performance in reconstruction projects. The equations of CPF and SPF are:

CPF (%) = [Total value of change order/original contract value].100

SPF (%) = [Total project delay/original project duration].100

In addition, the authors also suggested three quantitative measures for the Quality Performance Factor (QPF) as i) estimated cost of rework and repair, ii) number of rework/or repair requests and iii) number of users' complaints related to noise, dust, smoke etc.

Nassar (2005) adopted the earned value method for measuring the performance indicators of eight success indices. For instance, measurement of cost performance index entailed measuring its lower level performance indices such as indirect cost performance index (CPII), engineering cost performance index (CPIE), labor cost performance index (CPIL), material cost performance index (CPIM), construction equipment cost performance index (CPIC), subcontractor cost performance index (CPIS) and, tools/consumable cost performance index (CPIT). Each indicator has been suggested to be measured by dividing its earned value by its actual value.

Nassar (2005) also suggested a qualitative rating system based on the calculated value of each index. For measuring the qualitative success index such as client satisfaction or project team satisfaction, earned value of each lower level performance index is the product of its priority weight and its achieved value on a qualitative scale of 1-10. This quantitative method for qualitative aspects would eliminate any biases in the reviewer's opinions. The overall performance is the algebraic sum of the weighted contribution of each performance index (Nassar 2005).

Russell et al. (1997) suggested the s-curve method of time dependent variables for predicting performance of construction projects. The authors developed s-curves of continuous project variables such as contractor construction efforts hours expended, invoices paid by the contractor, total commitment for materials and equipment, cost of owner project commitments and cost of contractor project commitments, and designer project cost. These variables are time dependent as their values change during the course of the project. Through case studies of 54 projects, s-curves of these variables were plotted for both 'successful' and 'less than successful' projects. Depending on the status of the project, project managers could identify the applicable variables and ascertain their actual value and compare them with the developed s-curve of 'successful' projects for predicting the performance of those variables.

2.3.5 Role of Performance Measurement in Realizing Strategies

"In order to control a strategy, it has to be measured".

(Bassioni et.al., 2004)

There has been a consensus among researchers and industry experts that performance measurement is an integral aspect of strategic planning and controlling process. For an organization, performance is the ability to implement desired strategies (Salminen 2004). Therefore, a performance measurement system should be developed on the basis of company's strategies and objectives. There should a clear link between the measures adopted and strategic objectives, which establishes a cost-benefit analysis of the chosen strategies and assesses the appropriateness of selected measures for realizing the strategies (Lantelme et al. 2000). Several authors view performance measurement as an effective manner of supporting and implementing strategies.

Beatham et al. (2003) brings forward the significance of strategic control system in construction performance measurement. A strategy outlines the important dimensions of any performance measurement system by clarifying: what are the reasons for measuring performance, what is a good performance, what are the priorities, what is the trade-off between performance measure, and when to take actions on underperformance. The authors developed an Integrated Business Improvement System (IBIS) that defined the critical success factors and their respective performance measures based on the business objectives and the overall vision of the company. Therefore, the fulfillment of business strategies is governed by achieving desired performance in critical success factors.

Costa et al. (2002) having conducted a literature review of current performance measurement systems such as Balanced Scorecard, Performance Pyramid etc. and, case studies of five medium and small sized construction firms, identified the need to develop a construction based performance measurement system that should be linked to companies' competitive strategies. During case studies, the authors analyzed the companies' strategies through a strategy map that clearly linked different functional strategies to achieve companies' objectives. The case studies were critically investigated against well-defined constructs of; measure definition, alignment of measures to strategies, insertion of measures into company routine, and learning achievement through measurement.

These constructs provided a comprehensive structure for identifying some of the best practices in performance measurement, and improvement opportunities in those practices. The key best practices identified were: development of a quality management system, employee rewards program, alignment of measures to company strategies and critical processes, and decentralization of decision-making. These practices not only revealed the companies' competitive abilities to measure the performance but also provided the authors with a foundation for formulating the guidelines. The proposed guidelines primarily centered on defining the company's competitive strategies, objectives and, developing performance measures to support those strategies. In addition, appropriate use of information systems for supporting decision-making and taking corrective actions, was another concluding concern.

Being a part of business improvement system, performance measurement supports the implementation of business strategies. In 2000, *Lantelme et al.* conducted nine case studies of construction firms with the objective of developing implementation guidelines for performance measurement systems. The authors concluded that strategic planning provided a framework for the development of performance measurement system where the measures were structured hierarchically in the organizational structure and there existed a clear link between higher-level measures and company's goals and objectives.

However, *Price et al.* (2003) stated that the use of strategic planning is not widespread in the construction industry for being focused only on operational cost effectiveness, ignoring the strategic positioning of the company and consequently, performance measurement would not be used as a strategic deployment tool.

2.3.6 Implementation Methods of State-of-the-art Construction Performance Measurement Systems

The construction industry has been deprived of successful implementation of developed performance measurement systems (Beatham et al. 2003, Costa et al. 2002). A number of studies have investigated the nature of barriers inherent in construction companies that confine this implementation and have come across two types of problems. The first is associated with the design of performance measurement system and the second relates to the organizational capabilities to handle the developed systems. The limitations in traditional design of performance measurement systems involve inappropriate selection of performance indicators and associated measurement methods. The organizational capabilities relate to managers' disinclined attitude towards systematic performance measurement, employees' lack of training for understanding the system, and lack of an appropriate data management system (Costa et al. 2002). Researchers have concluded that successful implementation of a performance measurement system requires creating a continuous measurement culture through the engagement of users in understanding and appreciating the system (Beatham et al. 2003).

In 2000, *Lantelme et al.* conducted research on the implementation phase of performance measurement systems, being used by the construction companies in Brazil. The research need followed from the implementation problems associated with the SISIND (System of Quality & Productivity Indicators for the Construction Industry) Project in Brazilian construction companies, which was developed as a performance measurement system by the Building Research Group (NORIE) of the Federal University of Rio Grande, do Sul (UFRGS). The main objective centered on developing implementation guidelines of performance measurement system in construction firms. To achieve this, the authors first identified prevailing problems associated with the implementation process of performance measurement by conducting interviews with managers of nine firms (six construction and three manufacturing firms) and then proposed the implementation guidelines based on literature review of lean production principles and organizational learning.

The literature review provided a basic understanding of those management approaches that sustain the implementation of performance measurement through application of Lean Construction principles. These principles emphasized the importance of measuring performance of production systems at the operational level, which facilitates process transparency, and decentralization of decision-making. In addition, the concepts of organizational learning helped in understanding the cyclic mechanism of self-assessment process and implementation of corrective actions based on performance evaluation.

Since the sample size of interview process consisted of diverse companies that varied by size and trade type, the data analysis gave an insight into those barriers that restricted successful implementation of performance measurement and, those practices that made the implementation process successful. Lack of organizational capability for handling the data pertinent to performance measurement and, managers' behavioral aspects of short-term focus and reluctance to use appropriate tools and techniques for data analysis were identified as the main barriers among interviewed companies.

From the barriers, the authors formulated implementation guidelines for performance measurement that also incorporated successful practices identified in interviewed companies. The guidelines mainly emphasized on improving the process transparency by information sharing, establishing a system thinking for identifying causes of under-performance, reducing cycle time in information retrieval and making the corrective action, use of simple and easy to understand measures, and use of benchmarking for continuously improving the processes by evaluation against best practices.

Similarly, *Costa et al.* (2000) suggested guidelines for implementing performance measurement systems in construction companies which involved strategy communication at all levels, creation of a measurement environment, systematic performance measurement at designated intervals referred to as 'formal moments', employees' empowerment including their training and decision making authorities and, managers' participation in systematic data collection and analysis processes.

Samson et al. (2001) developed a framework for performance measurement system to be applied in Tanzanian Construction Industry which was based on five essential dimensions, each representing a different perspective of construction business. These perspectives were innovation and learning, processes, projects, stakeholders and financial. Performance measurement from each of these perspectives has been suggested and explained to obtain an integrated and holistic view of performance where each perspective has its designated role in measuring and improving the performance of different aspects of construction business.

The authors discussed organizational strategies required for the implementation of the proposed framework of performance measurement in construction firms. These strategies are i) leadership commitment that involve self involvement and motivation, ii) employee involvement and empowerment for decision-making at the operational level, and iii) information management that maintains a continuous learning cycle based on the results. The suggested strategies would drive the functional nature of the framework for its intended purpose and enable the performance drivers to implement the system and produce desired results in processes.

Beatham et al. (2003) having identified the implementation barriers of political, infrastructure, and focus nature, suggested a four step methodology for successfully implementing the proposed Integrated Business Improvement System (IBIS) in construction companies. Communication of IBIS structure and its measurement process to employees is the first step, and mutual agreement of business objectives and measurement areas among all managers by empowering them is the next step. Bringing transparency and consistency in performance measures, and employing senior managers for encouraging the measurement process among lower level employees by using it as a key management tool define the last two steps.

2.4 Discussion of State-of-the-art Construction Performance Measurement Systems' Literature

State-of-the-art practices in construction performance measurement systems facilitated the understanding of current performance measurement processes, their performance indicators, measurement methods and implementation strategies for successfully integrating the measurement systems with current construction practices. Although each system had some limitations, but collectively they provided some of the essential attributes of a production management system required for renovation projects.

The study by *Chua et al.* (1999) presents a comprehensive approach of understanding the nature of CSFs for different project objectives. The categorization of CSFs in four main project aspects facilitated i) the development of hierarchical model for project success and ii) application of mathematical tools such as AHP in assigning the relative importance to CSFs, which figures out as a vital approach for achieving the research intent. The research proved the common misconception that for each project objective the critical success factors and even their hierarchy remain the same.

Samson et al. (2001) research brings forth the significance of performance indicators' attributes in the effectiveness of a construction performance measurement system. The authors' approach of first identifying the limitations in current practices and then addressing them through development of the framework, illustrates an effective contribution to the Tanzanian construction industry. However, the authors did not discuss the measurement effectiveness and performance forecast abilities of the proposed performance indicators, which could also have provided some insight to their measurement methods.

The research conducted by *Alarcon et al.* (2000) underscores the use of those indicators that facilitate establishment of cause- effect relationships and support decision-making for taking corrective actions. However, the authors failed to present any theoretical and analytical explanation for selection of proposed indicators from the literature. Moreover, the research could have investigated development of relationships between the performance indicators and, assigning priorities in achieving overall performance. This could have delivered an improved understanding of managing the performance amongst project participants through sharing the impact of performance indicators on overall project throughput. Although the research focused on identifying new performance indicators, it could have been oriented towards the identification process from system thinking perspective.

Costa et al. (2002) research presented a comprehensive approach of analyzing the companies' performance measurement systems from their strategic standpoint. It underlined the need to develop strategic objectives as a basis for setting the desired performance levels and measuring the processes. The authors' illustration of a company's strategic map, through literature review, helped in understanding the scope of each functional strategy type, and the implicit link between performance measures and

cor
ind
pro
ov
ev
rig
its
inv
me
cur
prac

na
aut
cons
exp
indu
effec
used
supp
addi
equi
made

competitive strategies. Moreover, it created a framework to categorize performance indicators, as measures of processes to support strategies. Identification of critical processes through this framework can be an effective way of mapping the performance in overall process. The adopted method for selecting case studies based on the criteria of existing performance measurement systems was a thoughtful approach of examining the right processes for achieving the research objectives. Although the research is ongoing, its intermediate results and even the adopted methodology can be a useful tool for other investigations focusing on identifying the current best practices in performance measurement for construction industry. It would assist in assessing the inefficiencies in current construction practices and, bridging the gap between theoretical awareness and practical applications.

The research conducted by *Lantelme et al.* (2000) is helpful in understanding the nature of barriers prevalent in construction industry for measuring the performance. The authors' approach of comparing performance measurement systems implemented in the construction companies with those in the manufacturing companies presents an exploratory way of identifying the best practices outside the realm of construction industry. The proposed guidelines can be viewed as a starting point for assessing the effectiveness and identifying the inefficiencies of performance measurement systems used by any construction firm. However, there is a lack of facts and figures, which could support the validation of successful practices identified in the manufacturing industry. In addition, for implementing the guidelines in construction companies, further research is required for identifying the organizational and production management changes to be made in construction industry.

Overall, the reviewed performance measurement systems underscore the identification of key performance indicators of critical activities of construction projects that majorly contribute in project performance. The performance indicators suggested by the reviewed performance measurement systems need to be analyzed for their effective application in renovation projects. Moreover, the major performance categories of the reviewed performance measurement systems figure out as cost, time, quality, and safety. The literature also suggested possible quantitative methods such as Analytical Hierarchy Process (AHP) that was applied by this research to the essential attributes for developing the intended framework for production management of renovation projects.

2.5 Literature Review of Renovation Projects

Renovation projects have been distinguished from new construction projects due to their unique nature and complexity of construction processes (Jimenez 1999). These projects are characterized by constantly changing environment, which is attributed to unforeseen events in the preexisting conditions that have prominent impact on the project success. Apart from the unforeseen conditions, the renovation projects become much more unpredictable due to the presence of constraints which define their dynamic environment and complex nature. These constraints are those factors, which are typically outside the project scope, but still cause frequent changes in the planned scope of work and impact the estimated budget, schedule and quality of the project (Krizek et al. 1996, Mitropoulos et al. 2002).

For instance, if a contractor encounters asbestos while demolition of any sort, that was not foreseeable, it would have to stop the demolition activity or any other work near that area. This would not only impact the next trades' scheduled work but also the overall schedule of demolition activities, which was coordinated with owner's operations for minimizing the disruption (Rush 2002).

In addition, if the contractor had ordered the materials for installation right after demolition, it would have to arrange for a temporary storage area for stacking the materials until the asbestos is removed and demolition is completed. In an operational building, where the occupants have taken over rest of the building area, it becomes extremely difficult for the contractor to find adequate material storage space for such a short notice (Jimenez 1999). The contractor would have to transport the materials back to the suppliers and get them redelivered, and reschedule all the work as per the owner's operations. This would probably delay the overall project, which could also have adverse repercussions on the owner's estimated budget. The owner's money spent on leasing the swing space for the period of asbestos removal would be wasted, as the owner could have started to occupy the swing space once the demolition starts after the asbestos removal. Therefore the actual leasing period would exceed its estimated schedule and cost more to the owner (U.S. GAO 2003). This is an outcome of uncertainty constraint in the preexisting conditions of renovation projects. These circumstances could also emerge due to utility constraints if, during demolition, the contractor breaks any utility pipes such as mechanical, plumbing or electrical, that was serving the building occupants (Krizek et al. 1996).

In this environment of constant changes and uncertainty in the scope of renovation projects, where the external constraints have negative impacts on the project outcomes, traditional project planning and controlling techniques that only consider "what is inside the project" prove to be inadequate for delivering successful results (Wayne et al. 1988, Jimenez 1999). Numerous studies have investigated the complex nature of renovation projects and concluded that their increasing overruns in cost and schedule are due to the presence of these external constraints. These studies have shown that the external constraints impose additional challenges for managing a renovation project, which require extensive pre-construction planning for encountering and coping with the constraints (Attalla et al. 2002, Mitropoulos et al. 2002).

In a multiphase renovation project, where the construction is carried out in an operational facility, the impact of external constraints on project scope gets accentuated due to the development of process friction between owner's operations and construction activities (Attalla et.al 2002, McKim et al. 2000). In the absence of any swing space, this friction generates more external constraints that are required to be managed for project success. This friction makes multiphase renovation projects most difficult in achieving successful completion. The constraints not only impact the construction process but also the design process leading to reworks and design iterations (Mitropoulos et al.2002). The following section provides an overview of previous studies that dealt with the constraints of renovation projects and their scheduling techniques.

2.5.1 Constraints of Renovation Projects

Various researchers have explored the challenging nature of renovation projects and they have concluded that it is essential to plan ahead for these challenges in order to minimize their impacts on the project success and plan the production of an activity based on the existing constraints. These constraints of renovation projects have been investigated for both institutional and commercial buildings where the ongoing academic and office operations are of critical nature and require extensive construction pre-planning efforts (Rush 2002, Mitropoulos et al. 2002).

In 1996, *Krizek et al.* investigated the project teams' experiences gained through the first five phases of multiphase reconstruction of an intuitional building, with the purpose of accumulating and transferring their learning to further phases. This study was carried out by analyzing the contract documents and conducting interviews of owners, designers, and contractors involved in the project, and the authors identified those external constraints that impacted the performance of the reconstruction project. These constraints were physical, coordination, utility, pollution, and uncertainty.

Physical constraint constituted height limitations, site access limitations and inadequate load conditions at the work area for performing construction activities. It also included space limitations for installing any new services in the existing structure and, storing materials near the work area. Coordination constraint referred to the additional efforts for scheduling or sequencing the construction activities for minimizing the disturbance to owner's operations. This constraint also involved monitoring and controlling those activities that generate pollution during their execution and disturb the health and safety of building occupants. Demolition activities that generate dust, debris, noise, vibration, and odor, were among the top most disturbing activities that were required to be taken care of by the contractors.

Utility constraints involve those efforts on the part of contractors required for avoiding disruption to the existing services of the building such as electrical and mechanical. Consideration of utility constraint was of particular importance in case of demolition activities as they might break any hidden services to the building occupants. In addition, shutting down of any service for a new equipment installation required additional coordination with the existing building operations for avoiding disturbance to occupants.

Uncertainty is one of the major constraints in renovation projects that greatly impact the project scope and cause schedule and cost overruns. The unforeseen conditions encountered by contractors while demolition or uncovering activities could reveal major disparities between plans and specifications, and actual site conditions. Sometimes, the actual conditions could only be ascertained after the demolition activities. Therefore, the conditions, which were not foreseeable by the contractors, were the main factors that contribute to the unpredictability of renovation projects.

After analyzing these constraints in a case study, the authors suggested a graphical simulation of construction operations that could simulate appropriate sequences of construction activities with possible conflicts or constraints discussed above. Therefore, the simulation would produce the adjusted schedule of the construction project that incorporates most of the physical, utility and coordination conflicts with the construction activities' schedule for minimizing disruption to owner's operations.

The authors also concluded that from a contractual standpoint, it is imperative for the contractors to be fully aware of these constraints prior to commencing the work on site. For handling uncertainties, the contractors should anticipate possible events that might be encountered and then prepare the bid accordingly and submit a detailed price breakdown of the same.

The study conducted by *Rush* in 2002 on renovation of school projects, is another major example of institutional buildings' renovation projects that focused on identifying external constraints. The author stated that in a renovation project that also involves additions to the existing building, the decision to first construct the addition or renovate the existing building depends on the availability of the swing space and financial constraint of the owner. One of the cost saving alternatives could be to construct the addition first and use it as the swing space, and then renovate the existing building once the occupants have moved to swing space. In such case, maintaining a safe circulation of construction workers and building occupants between construction zone and swing space becomes the key constraint.

In a renovation project, the uncertainty constraint increases as the function of the building age. For an aged building, the absence of original construction documents presents considerable risks of encountering unforeseen conditions that would impact the estimated budget and schedule. The presence of preexisting hidden services and/or asbestos is a prime example of these circumstances. This requires extensive effort for examining the existing conditions before proceeding to design and construct its renovation. Even in the presence of as-built drawings, it becomes imperative to check the adequacy of plans and specifications with the current building conditions that might have been deteriorated and/or require additional specifications as per prevailing regulatory codes (Rush 2002).

In this study, the author identified important issues that need to be considered while planning the construction operations of a multiphase renovation project for an institutional building. These issues were utility services, preparation for construction, salvage, air quality, disposal, schedule and sequence, and the age and maturity of building's current occupants.

Utility services refer to non-disruption of existing services and arrangement of temporary services for construction operations. Preparation for construction and salvage require on-site temporary arrangements for weather protection, traffic control, storage of unsafe materials and equipment, and recyclable material management including its identification, deconstruction, storage and removal. The issue of air quality imposes pollution constraint on the contractor for maintaining control measures for minimizing dust and debris being generated due to construction operations, specifically during demolition process. Disposal of hazardous materials, such as asbestos, requires considerable coordination with owner's operations for safe material movement, space designation for disposal, and disposal methods. Schedule and sequence of construction activities need to be coordinated with the occupants' current operations. The age and maturity of building occupants impose constraint for installing additional construction signs for maintaining students' safety and safeguarding stored materials against vandalism.

It has been stated that these external constraints not only impact the construction processes but also affect the design process leading to number of design changes and rework. In an extensive study of an office renovation project, *Mitropoulos et al.* (2002) analyzed the causes of design iterations and reworks. The authors examined problems encountered during construction phase and identified two major constraints that potentially impacted the design process: i) preexisting and hidden conditions that were not predicted, and ii) the incapacity of the downstream utility system, which was not accounted in the design process to support new services proposed in the renovation work.

It was identified that the project characteristics imposed these constraints that caused design changes and impacted the estimated project budget and schedule. In the absence of any as-built drawings of the building, the uncertainty constraint was the prime factor that gave rise to unforeseen conditions. In addition, limitation of adequate space above the ceiling for installing new mechanical, electrical and plumbing services imposed physical constraints that caused design modifications in the proposed architectural ceiling layout for accommodating the mechanical and electrical fixtures.

In this study, *Mitropoulos et al.* (2002) developed a graphical representation of chronological events actually occurred in the design and construction phase of the renovation project. Through this chain, the authors identified those events that caused major design iterations and impacted the estimated budget and schedule. Most of these events were encountered in the demolition phase where unfavorable and unforeseeable conditions necessitated frequent design changes. One of the prime examples was encountering of the vertical pipes after uncovering the columns that were not expected. Since the proposed design required all columns to be exposed, the presence of these vertical pipes initiated a design change for covering all columns with wood veneer and increased the estimated cost. Another example was associated with the incapacity of existing utilities to support new services. The mechanical system design was changed tremendously, as the existing capacity of the system was insufficient and caused the redesign of the overall mechanical system to be a stand-alone. This change caused major increase in the estimated mechanical system cost and schedule.

Another major impact on the overall project schedule was caused by the regulatory constraint that required the existing concrete ceiling to be fireproofed and approved by the city authority. This process caused a delay of two months in the overall schedule. Similarly, the authors exemplified numerous events that were caused by different constraints and impacted the project cost and schedule. In order to cope with these constraints, the authors suggested some preventive strategies among which accelerated discovery of existing constraints was of prime importance. Discovering the constraints by investigating the existing building conditions that could impact the proposed project cost and schedule, prior to design, could avoid the rework and design iterations. For this purpose, it was suggested that exploratory demolition should be initiated before the design process commences.

This study brings forward factual examples of renovation project's problems that could be anticipated in any reconstruction project. The events, as explained by the authors, could develop into generic constraints for renovation projects that need to be incorporated in their project planning and controlling techniques. The authors' approach of creating a chain of events was a comprehensive method of analyzing the causes and effect of each constraint on the project schedule and budget.

2.5.2 Scheduling Techniques for Renovation Projects under Constraints

Due to the schedule and coordination constraints of renovation projects, the traditional Critical Path Method schedules have been criticized to be incomplete for managing the production of multiphase renovation projects (Jimenez 1999). Various researchers have developed different scheduling techniques for incorporating external constraints and making the schedule much more adaptable to the changing conditions of renovation projects.

In 1988, *Wayne et al.* developed Disturbance Scheduling Technique for managing renovation projects that integrated the production planning of renovation projects with the ongoing building operations. This technique dealt with incorporating three constraints typically encountered in renovation projects (coordination, physical and disturbance) with the traditional construction logic and network analysis models. These constraints have been stated to be unique for renovation projects, which require scheduling considerations in production planning for obtaining a better flow of the tasks without any disruptions.

Coordination constraint requires consideration of owner's operations during renovation, while preparing construction schedules. Physical constraint deals with space limitations for accessing the site, loading and storing the materials and equipment, installing any new services, and movement of materials, both vertical and horizontal, through designated passageways in the absence of service elevators. Disturbance constraint refers to those activities' considerations that might cause disruptions to owners operations. Installing any new services that might require temporary shut down of existing utilities or demolition activities that might require temporary enclosures around construction zones to prevent dust, debris and odor, are the prime examples of disruption activities that have cumulative impacts on owners' operations.

Focusing on these constraints, the author developed disturbance scheduling technique that attempts to eliminate the constraints in four phases in their decreasing order of intensity. Phase-1 involved traditional schedule development based on CPM logic that assumes the building to be unoccupied. Phase-2 primarily dealt with establishing constraints' category and their hierarchy for the specific project. Phase-3 involved modifications of the initial schedule based on constraints' hierarchies and their categories for developing a plan that allows minimum operations of the existing building throughout renovation. In the final phase, the constraint of resource limitations available per day was applied to the modified schedule for developing it into a workable plan.

Similarly, in 1999, *Jimenez* suggested a soft-logic approach in construction scheduling, when operating in the uncertain and dynamic environment of renovation projects. The soft-logic introduces flexibility in construction schedule to absorb the dynamic nature of renovation projects so that any unforeseen condition could be incorporated in the schedule without major changes. The author stated that traditional project planning techniques, being rigid in nature, do not provide the opportunity to adjust the project plans with the changing conditions and therefore, are not suitable for renovation projects. The author identified those characteristics of renovation projects that have major project impacts and need to be considered in project planning. These characteristics included sequencing of project activities, unforeseen conditions, scheduling issues, space confinement, and operations reach.

Sequencing of project activities refers to organizing and restructuring the construction operations depending on the technical requirements of a building's normal operations, in case of a multiphase renovation project. Due to unforeseen conditions expected in renovation projects, it becomes imperative to develop multiple project plans based on the assumptions of different possible scenarios, and for incorporating expected major changes, the project contingencies are usually high.

Scheduling issues involved the assignment of appropriate durations to each construction activity according to the building constraints and expected unforeseen conditions. This assignment, being extremely crucial, requires expert judgments and considerable experience of project teams in managing renovation projects. Space confinement refers to the limitation of physical space for performing construction activities for causing minimum disruption to the existing structure. Operations reach applies to simultaneous construction of several renovation projects at multiple locations of a single building. In an uncertain environment, where situations change dynamically, operations reach involves managing resources such as labor and/or equipment between different locations and according to the coordinated construction schedule with owner's operations.

These characteristics of renovation projects impose additional constraints on traditional project planning techniques that require thorough investigation of these constraints in the existing conditions for establishing reliable and accurate budgets and schedule. Therefore, the author suggested a soft logic approach, as an alternate to hard logics of traditional Critical Path Method so that frequent changes in renovation projects can be accommodated.

In 2003, *Horman et al.* discussed the adoption of a Short Interval Production Schedule (SIPS) to manage the production of the Pentagon renovation project. The overall sequence of the Pentagon renovation was governed by the movement of occupants to an off-site swing space from wedge-2 to wedge-5. Since the off-site swing space had the capacity of accommodating only one wedge's occupants, only single wedge was available, at one time, for renovation with rest of the wedges being operational. Once the wedge was renovated, the contractor would hand it over to its occupants who were in the swing space, and move to the next wedge from where the occupants have moved out to the available swing space. This cyclic arrangement imposed two major project constraints on the contractor for managing the project: i) non-disruption to building operations in other wedges, and ii) efficient handover of renovated wedge to the occupants and moving to the next wedge.

To manage the project under these constraints, SIPS were developed both at the project level with a broader perspective, and trade contractor level with production perspective. The main purpose of SIPS was to handle construction operations, usually one at a time, at the production level by breaking them down into smaller activities, identify their durations, and assign appropriate crew sizes as per the estimated quantity of the work. In a typical SIPS development, the authors suggested to plan appropriate buffers to absorb the variability between trades' production rates that might be generated due to the constraints of renovation project. Two types of buffers were discussed for Pentagon renovation project; time, and resources. All project weekends were suggested to be used as time buffer to finish any disrupted work as per the planned schedule. The intent of resource buffer was to offer flexible resource capacities to accommodate any variability in the workflow. Therefore, the authors suggested planning the production with under utilization of resources so that in case of any conflicts generated from the constraints, high levels of utilization could be employed without major disruption in the schedule.

2.6 Discussion of Renovation Projects' Literature

The overall literature review of renovation projects and construction performance measurement systems underscores the significance of managing construction processes under the constraints of renovation projects. In the literature of renovation projects, the importance of external constraints has been emphasized because of their major impacts on the project success (Krizek et al. 1996). This requires considerable pre-construction planning effort for minimizing the impacts of constraints on the estimated cost and time (Mitropoulos et al. 2002).

In addition, the literature also explains the conditions or factors that generate these constraints and contribute to project cost and time overruns. In other words, the constraints are composed of various conditions or factors, which may or may not be the part of a project's scope but are present in the project location. Successful assessment of these conditions or factors would lead to a better constraint assessment and therefore, a better production management of renovation projects. These conditions or factors are required to be assessed for coping with the constraints. Therefore, these conditions or factors could define the performance indicators for assessing the impact of constraints of renovation projects.

As stated before, the major performance categories of the reviewed state-of-the-art performance measurement systems were cost, time, quality, and safety. Therefore, in the context of renovation projects, it becomes essential to investigate the impacts of identified constraints on the cost, time, quality, and safety of renovation projects.

2.6.1 Reiteration of Constraints

This research incorporates the constraints identified from various literary sources of renovation projects as a prime essential attribute of production performance management system. A brief overview of all the identified constraints and their conditions or factors from the literature review has been presented below:

1. Physical constraint- The physical constraint refers to limitation of physical space, such as limited height and/or limited area, for performing construction activities (Krizek et al. 1996). This constraint could be generated by various conditions at any location:

   a. Space limitations for construction

   b. Space limitations for material storage

   c. Space limitation for installing new equipment/material

2. Utility constraint- This constraint is generated by the limited capacity of the existing services for their use in construction activities and/or to support the load of proposed systems in renovation project. The incapacity of existing services could impact the design of proposed systems and delay the project, if not accounted in the project planning. In addition, during construction, there could be disruption limitations over the existing services, imposed by the owner (Krizek et al. 1996, Mitropoulos et al. 2002). Therefore the conditions that give rise to utility constraint are:

   a. Limited capacity of downstream systems

   b. Non-disruption to existing utilities

   c. Impact of existing utilities and/or structural systems on the design of new systems

3. Pollution Constraint- The constraint of pollution control could be generated by various infection control procedures, imposed by the owner, that are required during construction

operations (Rush 2002). The infection control procedures may require the contractor to perform temporary construction activities before commencing the actual work. Installation of temporary drywall around the construction zone before starting any demolition activity to prevent any dust, debris and/or odor, is an example of temporary construction. The control factors that generate pollution control constraint are:

a. Noise control
b. Dust control
c. Debris control
d. Odor control
e. Vibration control

4. Uncertainty constraint- The uncertainty in preexisting hidden conditions has been stated as one of the major constraints that impacts the performance of renovation projects. This constraint could be generated by the non-availability of as-built drawings of the renovation area and/or presence of any unforeseen conditions in the preexisting structure that do not conform to the design drawings and specifications of the renovation area (Krizek et al. 1996). Other type of unforeseen conditions is those, which cannot be anticipated while design and can only be ascertained during construction. A prime example of this type of unforeseen conditions is the presence of asbestos in hidden structures that can only be ascertained after the demolition (Rush 2002). Therefore, the conditions that generate uncertainty constraint are:

a. Non-availability of as-built drawings
b. Presence of unforeseen conditions
c. Presence of any hazardous materials

5. Coordination constraint- Coordination constraint primarily arises in an operational building where the construction activities need to be coordinated with owner's operations. This coordination creates a process friction that needs to be managed by the contractor in creating minimum disruption to owner's operations. An example of a condition that generates coordination constraint is the restriction and/or additional monitoring of demolition or noise generating construction activities during owner's operation timings (Krizek et al. 1996, Wayne et al. 1988). Similarly contractor's mobilization and demobilization according to the owner's relocation from the renovation area to swing space and then from swing space to the renovated area, defines other condition. In a renovation project, since the end-users of renovated space are always available at the owner's end, there could be multiple inspections by end-users for approving the final ergonomics and finishes, which may disrupt construction operations' planned schedule and/or even change the scope of work at the last moment. Therefore, broadly, the conditions that generate coordination constraint are:

a. Timing limitations due to owner operations
b. Relocation of owner operations to and from swing space
c. Owner furnished equipments
d. Removal & reinstallation of owner's furniture
e. Multiple inspections by end-users and owner's representatives

6. Regulatory constraint- Regulatory constraint arises when the specifications of the existing materials in or around the renovated area do not conform to the current building codes. This situation is most often encountered in old-aged buildings being renovated after the demolition or uncovering of hidden conditions (Mitropoulos et al. 2002, Rush

2002). An example of such condition is non-conformance of structural concrete insulation with the current fire codes, which only gets ascertained once the concrete is uncovered. In such situation, the contractor would have to replace the existing insulation with the one conforming to the current codes and obtain the permit from the city authority before covering the concrete. This would probably delay the project and increase the estimated project cost. The same situation could arise if the loading capacity of the structural frame has been deteriorated over time and does not conform to the loading requirements of the current building codes. Therefore, the condition that generates regulatory constraint is:

a. Non-conformance of existing materials and/or conditions with the current codes.

7. Schedule constraint- Scheduling issues in a renovation of an operational building has been discussed by most of the researchers. The owner's restrictions on certain types of construction activities of disruption nature for specific times may compel the contractor to reschedule or re-sequence those activities for the time when owner's operations are not going on. This could change the construction logic, initially planned by the contractor or impact the material deliveries being ordered or impact the next trades' scheduled work (Wayne et al. 1988).

Sometimes, restrictions are imposed during construction when the occupants feel too disrupted with the construction going on in an adjoining area. This could be a result of non-involvement of existing occupants around the renovated area in the pre-construction planning process (Jimenez 1999). Since the occupants were not involved in the planning process, their disruption becomes unpredictable which only gets ascertained during construction. Therefore, for a contractor, it becomes imperative to involve the end-users or occupants of the area around renovation in construction planning processes to avoid future changes in construction logic.

In some situations, the scheduling constraint is also generated by the uncertainty constraint of renovation projects. Since the existing conditions of hidden structure cannot be completely foreseeable, the contractor may have to include some buffer activities in the construction schedule to absorb any schedule disruption from the unforeseen conditions. These buffers could be in the form of overtime shifts during nights and/or weekends, which will allow the completion of disrupted work as per the schedule (Horman et al. 2003). Similarly, schedule constraint may also be generated by the coordination constraint where the owner's operations timings could impose schedule limitations of certain construction activities (Krizek et al. 1996). Therefore, the schedule constraint in a renovation project is generated by the following conditions:

a. Additional duration due to work restructuring
b. Impact on crew productivities

8. Safety constraint- In a renovation project of an occupied building, the contractor is responsible for the safety of not only his/her employees and labor but also for the users and visitors of the building (Rush 2002). Even if the regular users are provided with clear instructions for any safety hazard from the construction, safety monitoring of the public users will still be required as they are unaware of the construction activity. Unlike a new construction project, the contractor may be unable to completely enclose the construction zone in a renovation project due to the presence of physical constraints and may have to employ a permanent safety engineer during that particular construction activity. If the

cost of the safety engineer was not accounted for in the project estimate, this would probably increase the overall project cost. In case of any public injury or fatality due to the construction activities, the contractor would have to bear the cost of public litigations. Therefore, the safety constraint in a renovation project arises from:

a. Safety restrictions for users and public

9. Traffic constraint – The movement of labor, materials, and equipment is of critical nature in a renovation project. The owner may provide designated corridors and elevators to the contractor for moving materials both horizontally and vertically, from the storage area to construction zone. However, in the absence of any designated corridors, the contractor bears the risk of disrupting owner's operations, building's existing conditions and affecting the safety of building users and visitors through movement of materials and equipment (Jimenez 1999). An example of such condition could be the absence of service elevators in an operational building undergoing renovation on upper floors. In such case, the contractor would have to use the public elevators for carrying materials and equipment which imposes tremendous risk of disrupting user's circulation, safety, and building's existing finishes. To avoid this, the other option could be to use an external crane for lifting the materials to the upper floors. This condition, if not accounted in the project planning stage, would probably increase the estimated budget because of the cost of external crane. In addition, in order to properly use the external crane, the weather conditions should be adequate and appropriate physical space should be available outside the building. the conditions that generate traffic constraint in a renovation project are:

a. Limitation of materials and equipment movement
b. Limitation of labor movement

2.6.2 Critical Activities in Renovation Projects

The constraints identified from the literature primarily impact specific activities of renovation projects where the occurrence frequency of constraints' conditions becomes highest. For this research, these specific activities that involve maximum frequency of the constraints' conditions are termed as critical activities. These activities become critical in nature, as their execution requires additional planning and control of constraints to finish the project on time, within budget, and of desired quality. Therefore, consideration of constraints in the critical activities' planning could provide a possible solution for minimizing their impacts.

The researcher has identified these critical activities from the analysis of renovation projects' literature that explains the complexities of specific processes due to the presence of constraints. For instance, demolition process has been discussed by various authors in that it requires considerable attention due to pollution constraint, uncertainty constraint, and physical constraint. Therefore, selective demolition becomes one of the critical activities in renovation projects that impact the performance. Similarly, other critical activities in a renovation project are:

1. Preparation of plans and specifications
2. Site investigation by contractor
3. Preparation of site logistics plan
4. Mobilize and demobilize
5. Temporary construction
6. Selective demolition
7. Material and equipment procurement

8. Demolition waste management
9. MEP rough-inns

The critical activities were assimilated from the literature review of renovation projects' processes that are mostly impacted by the external constraints, and therefore are likely to have major contribution to the overall performance of renovation projects. These above mentioned critical activities do not form an exhaustive list and could be modified or added with the nature of renovation projects.

2.7 Literature Review of Production Management in Construction

In industrial engineering, the term production had been used synonymously with manufacturing or making things. Since the beginning of 20th Century, the automotive industry in America and Europe primarily viewed production as manufacturing, and began the movement of mass production, which involved producing as many parts as possible and as cheaply as possible (Liker 2004, Ballard 2000). Mass production focused on the efficiency of individual processes and ignored the aspects of flexibility and customer choice in manufactured products. However, various influential production management theorists such as Taiichi Ohno and W. Edward Deming criticized mass production for generating waste (non value adding activities) and not being focused on the flow and value aspects of production (Koskela 1999).

With the advent of lean production about six decades ago, the term production began to be viewed as designing and making things with an integrated view of transformation, flow and value. Lean production has also been termed as the Toyota Production System, as it was developed on the foundational principles of the Toyota

Way, reflecting the production culture of Toyota of eliminating waste and generating customer value. Therefore, a production process began to be conceived from three perspectives; i) conversion of inputs to outputs, ii) flow of materials and information through time and space, and iii) generation of value for the customer (Koskela et al. 2001, Ballard 2000).

Consequently, in the construction industry, the movement of Lean Construction emerged in the early 90s as a response to increasing waste and rework in construction processes. Lean Construction theorists support the integrated view of transformation, flow, and value for managing construction processes that tend to eliminate waste and improve their efficiency and effectiveness. These theorists have criticized the traditional project management practices of the construction industry for being narrowly focused on transformation, transactional contracts and activities while ignoring the flow and value aspects of operations (Koskela et al. 2001, Ballard et al. 1998).

Ballard (2000), one of founders of Lean Construction, stated that project control in the construction industry functions on a reactive model being focused on detecting cost and schedule variances rather than proactively dealing with the management of production at the site level. The emphasis has been on only the transformation aspect of construction processes assuming the workflow and value generation as inherent parts. Mitropoulos (2003) stated that traditional project control methods in the construction industry are based on the thermostat model that identifies negative deviations from target levels and applies corrective actions to bring the project back on track.

Howell and Ballard (1998) differentiated the traditional project control prevalent in construction industry from production control being followed in lean manufacturing industries. A project control system works on the thermostat model as stated above by pushing resources (labor, material and equipments) according to the original plan developed, and then monitoring cost and time deviations. On the other hand, a production control system functions on pull principle that releases the resources into a system based on the current state of the system. The current state is analyzed for the amount of work in progress, potential constraints in site conditions and quality of available assignments, and accordingly establishes production assignments for the resources.

In support of this view, in 1999, Koskela proposed the following five principles for establishing production assignments:

- The assignment should not start until its pre-requisite conditions are fulfilled.
- The realization of the assignment should be measured in terms of its Percent Plan Complete (PPC), which is the number of planned activities completed divided by the total number of activities planned, expressed as a percentage.
- If the PPC of an assignment is low, its causes should be identified and removed.
- An activity buffer (work backlog) should be created so the crew can be utilized when an assigned activity is not possible to begin.
- Apply a pull system in scheduling by looking ahead to assess whether upcoming tasks can be started.

Koskela (1999) stated that a production control system in construction should function on these five principles for managing day to day production at the construction site level. Numerous other researchers in the Lean Construction arena have been focusing on developing appropriate production control systems that would conform to the integrated transformation, flow and value aspect for improving performance and reducing waste.

A major milestone was established by the introduction of the Last Planner System (LPS) ™ of production control, designed by Glen Ballard in 2000. This system stressed the importance of formation of production assignments through communication with construction crews or those individuals or groups that implement the assignments. The person or group who prepares the production assignments is termed as the last planner.

As shown in Figure 2.1, the main objective of this system is to act as a filtering criterion for selecting only those activities from the plan that 'can' be done based on the site conditions rather than what 'should' be done according to the master plan. In deciding what 'can' be done, the analysis of constraints prevailing in site conditions plays a major role for establishing production assignments. Two key functions of LPS are production unit control and work flow control. Production unit control establishes the production assignments, directs the crew in completing them, measures the percentage of assignments completed in terms of PPC and identifies the causes of failures. Work flow control maintains and coordinates the flow of work between trades.

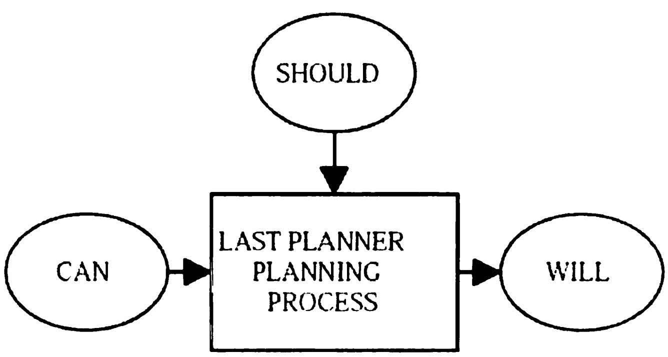

Figure 2.1 Objective of Last Planner System ™ (Ballard 2000)

Both these key functions are facilitated by the lookahead process which is the backbone of the Last Planner System ™. A lookahead process typically retrieves from the master schedule the upcoming activities for next 3 to 12 weeks, which are further subjected to constraint analysis, activity definition, and load and capacity matching for establishing weekly production assignments.

The constraint analysis screens the assignments for the upcoming 1 or 2 weeks under possible constraints and makes the work ready by pulling necessary resources. The constraint analysis ensures that the production assignments are released for execution only when all the applicable constraints have been satisfied or removed. This ensures that the potential problems or constraints have been addressed and resolved upfront to avoid their impacts on the production level later on. The possible constraints to be encountered are analyzed through an activity definition model (ADM) that categorizes the constraints under; directives, prerequisite work, and resources. The directives are defined by the instructions or guided procedure provided to the labor for executing any work. Prerequisite work, as the name suggests, is the work performed by other trades or any information that provides an input for the planned work. The term "resource" includes those sources that have production capacities and associated cost such as labor, tools, equipment, and even space. This process of identifying possible constrains through ADM is termed as explosion as it provides a greater detail for executing each activity (Ballard 2000, Ballard et al. 1998, Koskela et al. 2001).

Another important aspect of ADM is the assessment of "output" of any activity after its execution, and comparing it with the required criteria. If after the comparison, the output meets the required criteria, the work is released to the next trade; otherwise, it should be redone to meet the required criteria (Ballard et al. 1998). A typical ADM is shown in Figure 2.2.

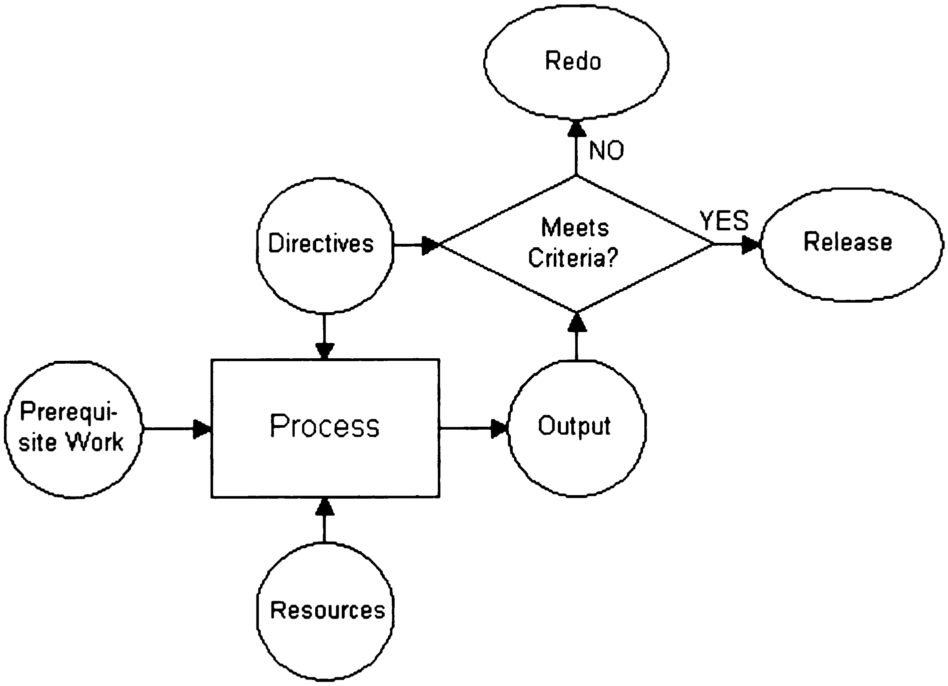

Figure 2.2 Activity Definition Model (Lean Construction Institute 2004)

Constraint analysis represents a proactive approach of planning production assignments which is in contrast with the traditional throw-it-over-the-wall approach of assuming everything and then reacting to the deviations. Overall, the Last Planner System ™ causes the events to conform to the plan by planning quality production assignments through communication with construction crews and addressing potential constraints upfront. This system makes the planned production ready by pulling required resources rather than pushing them on to the original plan (Ballard 2000, Koskela et al. 2001).

In 2003, Mitropoulos presented a detailed explanation of making the 'planned work ready' by proposing project metrics to evaluate the status of upcoming work and the quality of lookahead process. Building on the work of previous Lean Construction theorists, this research criticized the traditional schedule controls using Critical Path Method (CPM) and Earned Value (EV) analysis techniques for being narrowly focused on correcting negative deviations from project goals rather than controlling and stabilizing the workflow between trades. The term 'control' in traditional project management is used synonymously with controlling contracts rather than production at the construction site level. Mitropoulos (2003) stated that traditional project control methods do not employ any mechanism for assessing the status of upcoming works, which limits the abilities of project teams to proactively identify and address potential problems before they are encountered. Therefore, in the traditional system, any corrective action implemented based on the analysis of only past actions without assessing the status of upcoming work might result in wasted efforts.

This research emphasized the importance of a "make-ready" process in the assessment of upcoming work by identifying and removing possible constraints. The analysis of constraint enables the make-ready process to produce sound assignments that 'can' be completed by crews, and stabilize the flow of work between trades. In addition, the assignment of resources to the upcoming work would be balanced by matching required capacities. The make-ready metric proposed by Mitropoulos is an extension to the make-ready process proposed by Ballard in 1997. Ballard (1997) proposed five steps of a make-ready process which are:

1. Develop a lookahead schedule
    - This retrieves the activities for upcoming 3 to 12 weeks.
2. Analyze constraints

- This involves identifying and analyzing potential constraints to evaluate the upcoming work in the lookahead schedule for deciding whether to make it ready for implementation.

3. Develop action items
    - Action items are the outcome of constraint analysis which is targeted to remove the identified constraints.
4. Develop Weekly-Work Plans (WWP)
    - The activities in the upcoming work for following week, for which the constraints have been removed, are selected to develop their weekly work plans.
5. Track PPC and analyze plan failures
    - After every WWP execution, the PPC should be measured to identify the effectiveness of the weekly planning process and a lower level of PPC should be reason out to identify causes of plan failures.

From the analysis of five steps mentioned above, Mitropoulos identified three additional purposes that a make-ready process should fulfill for the assessment of upcoming work, which are: i) assessment of how much work will be ready to perform out of the planned work, ii) assessment of the accuracy of forecast of expected amount of work, and iii) assessment and improvement of organization's ability to make work ready. In order to fulfill these additional purposes, Mitropoulos (2003) proposed to introduce three metrics in the make-ready process proposed by Ballard.

The first metric is the planned work ready (PWR) that indicates the percentage of planned activities which according to the project teams are ready and could be performed for each week in the lookahead window. This also facilitated in calculating and planning for the earnable man-hours in the lookahead window as per the available labor capacity. The second metric assesses the accuracy of forecasting the planned work ready by comparing the work expected to be performed with the work actually performed. The third metric assesses the organization's ability to remove identified constraints through the measurement of three deltas which deal with measuring the number of constraints identified vs. expected to be removed vs. actually removed, and number of constraints identified vs. actual constraints found. A lower value of these ratios suggests a lower organizational capacity to identify and remove constraints. Figure 2.3 shows these three metrics proposed by Mitropoulos in the make- ready model of Ballard.

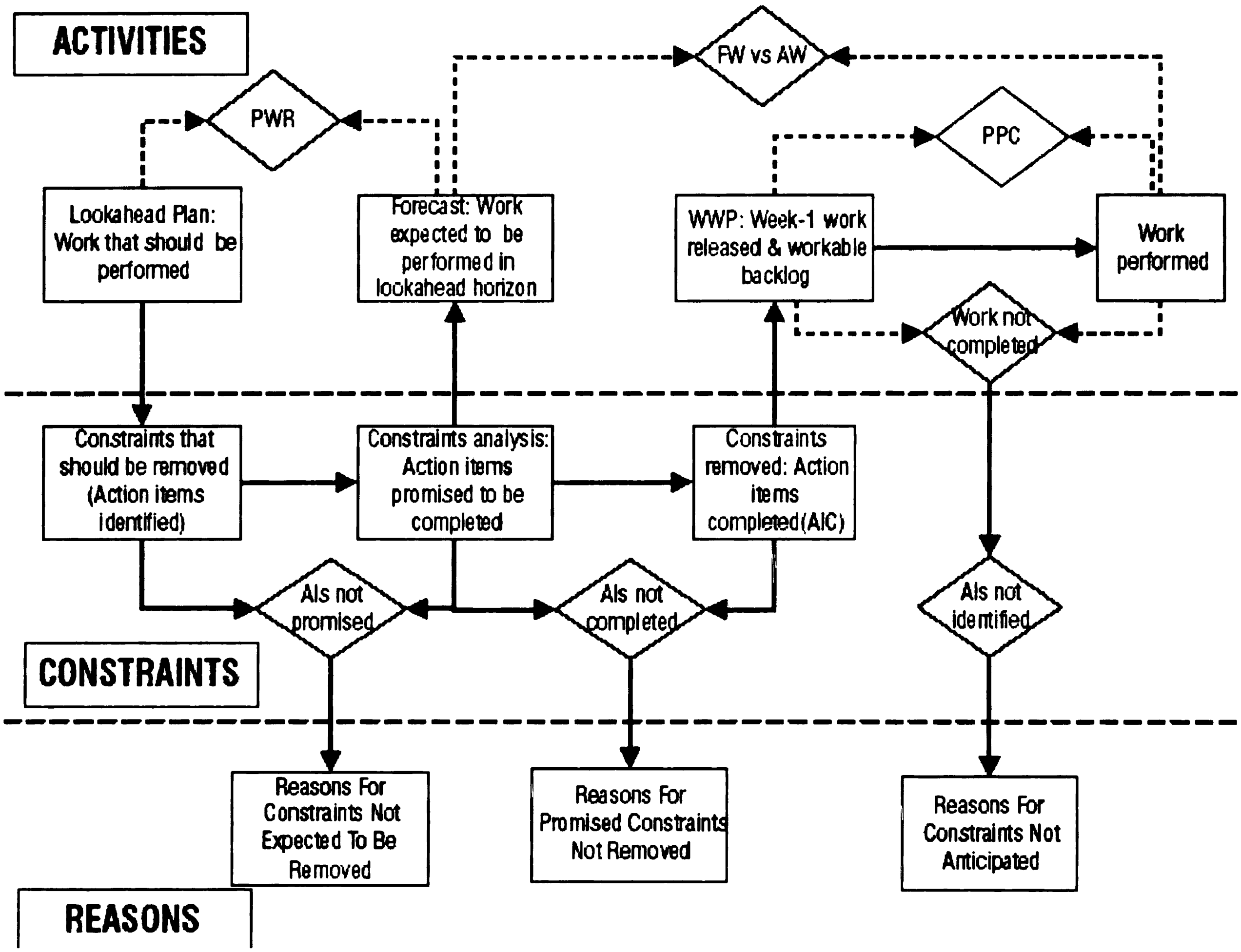

Figure 2.3 Metrics Introduced by Mitropoulos in Make-ready Process (Mitropoulos 2003)

2.8 Essential Attributes of a Production Management System in Renovation Projects

The literature review of state-of-the-art performance measurement systems, renovation projects, and production management provided an overview of some of the essential attributes that a production management system should posses in renovation projects. For instance, the "constraints" of renovation projects to be analyzed in production planning forms one of the essential attributes of a production management system. Similarly, "critical activities" of renovation projects that are mostly impacted by the constraints presents another essential attribute. Other essential attributes include; project conditions that generate constraints, performance indicators and their measurement methods, broad performance categories, planned production, and production failure analysis. The essential attributes identified from the literature review are discussed in detail in Chapter 4.

2.9 Chapter Summary

This chapter provided an overview of previous research that focused on state-of-the-art performance measurement systems, renovation projects and construction production management. Each category of literature is extensively discussed to explain its contribution in the fulfillment of research goal and objectives. The performance indicators, performance measurement methods, and implementation strategies suggested by state-of-the-art performance measurement systems are discussed. The complex nature of renovation projects is explained through the discussion of various constraints that are prevalent in these special projects. Production management techniques for construction activities are presented to apply them in renovation projects. Overall, the literature review brings forth the essential attributes such as constraints, critical activities, and performance indicators that were addressed in developing the intended framework for production management of renovation projects.

CHAPTER - 3

RESEARCH METHODOLOGY

3.1 Introduction

The research goal is to develop a framework for production management of renovation projects. To accomplish this goal, a five-phased methodology was adopted as a basis for achieving the research objectives. The research is based on a rationalistic approach in which the existing literature facilitated creating a conceptual framework, which is further verified against actual practices (Salminen 2004). Figure 3.1 shows the adopted phased methodology in which each phase produces a deliverable, which becomes the input for the next phase.

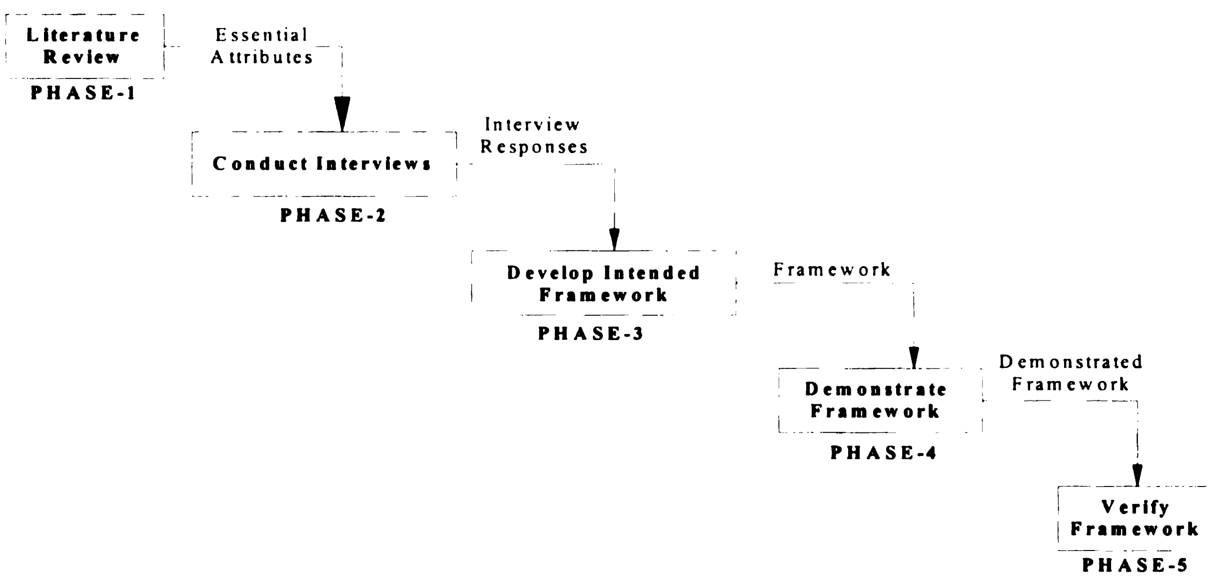

Figure 3.1 Phased Research Methodology

The first two phases were instrumental in achieving the first objective and the last three phases formed the basis for achieving the second objective. The five phases are defined as:

1. Literature review
2. Conduct interviews

3. Framework development
4. Framework demonstration
5. Framework verification

The next section provides a brief overview of all the five phases which is followed by a detailed discussion of the contribution of each phase in achieving research objectives.

In order to develop a framework for production management of renovation projects, it becomes essential to investigate the literature of all the three facets of research goal namely, i) state-of-the-art construction performance measurement systems, ii) the complexities of renovation projects that affect production performance and iii) production management of construction processes. The literature review was conducted in phase-1.

Figure 3.2 shows the detailed methodology adopted for this research where the phases are broken down further explaining their lower level tasks. The literature review is broadly divided under the three categories mentioned above and the background study of each category helped in understanding its emphasis areas for achieving the research objectives. The overall literature review contributed in identifying the essential attributes that a production management system should posses for its effective application in renovation projects. Essential attributes, as a deliverable from Phase-1, became the input for the next phase.

Phase-2, as shown in Figure 3.2, involved conducting interviews of contractors and subcontractors regarding their production performance management systems for renovation projects. The essential attributes obtained from the literature review assisted in drafting the interview questions.

In Phase-3, the intended framework for production management of renovation projects was developed on the basis of literature review and per the interviews of contractors and subcontractors.

Phase-4 involved demonstration of the developed framework through a hypothetical case example of a construction activity in an institutional renovation project. Phase-5, the concluding phase of the research, involved verification of the framework through a second round of interviews.

3.2 Existing Knowledge, Research Drivers, and Research Contribution

This research entailed reviewing the existing knowledge through Phase-1 of literature review from which, the main drivers for conducting the research from Phase-2 through Phase-5 were determined. The research drivers provided clear directions for investigating the performance measurement systems of interviewed contractors, and assisted in developing the intended framework. The research drivers were comprised of essential attributes of a production management system for renovation projects, which helped in formulating the questions for conducting interviews with contractors and subcontractors. As the essential attributes have not been explicitly discussed in a specific literature, this research has assimilated them from the overall available literary sources of renovation projects, state-of-the-art performance measurement systems, and production management.

Figure 3.2 shows a clear distinction of existing knowledge, research drivers, and research contribution in the adopted research methodology. The main contribution of this research begins from Phase-2 where a sample of current performance measurement practices were documented in the form of the interview responses. In Phase-3, the intended framework for production performance management of renovation projects was developed driven by the essential attributes and interview responses. Phase-4 demonstrated the framework and in the last phase of the research, the developed framework was verified with the help of suggestions from the interviewed contractor.

The following sections present a detailed discussion of each phase with its contribution towards achieving the research objectives.

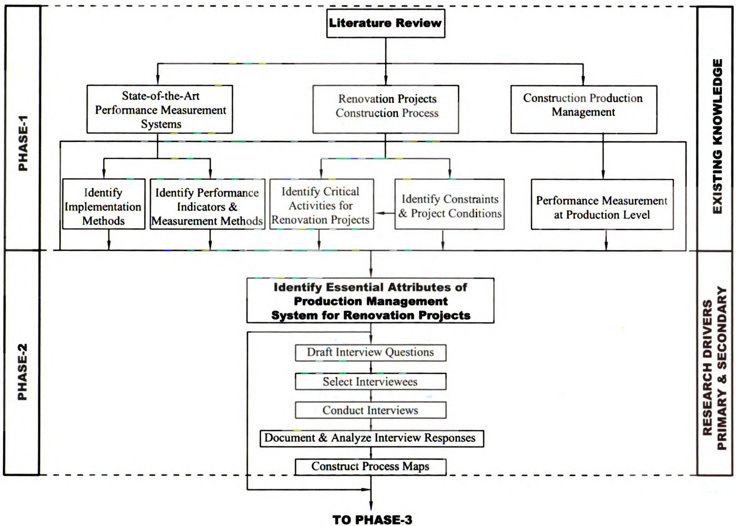

Figure 3.2 Detailed Research Methodology

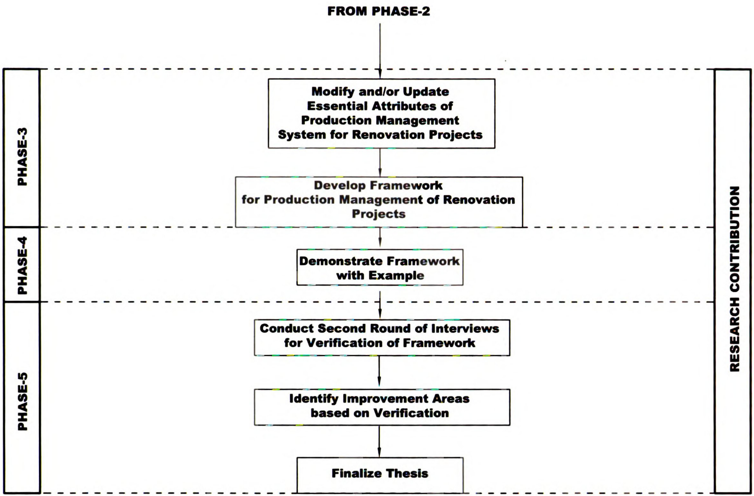

Figure 3.2 (Cont'd)

3.3 Phase-1 Literature Review- Detailed Discussion of Contribution to Objective-1

Objective-1 Document state-of-the-art construction performance measurement systems and production management practices for renovation projects.

The research reviewed an extensive amount of literature in the three categories discussed above, in the form of published theses, journals and articles available in various libraries and on the web. Each category of the reviewed literature is discussed next with an explanation of why the literature in that category was reviewed.

3.3.1 State-of-the-art Construction Performance Measurement Systems

As per Lean Construction, the production of any construction operation should be conceived from an integrated view of transformation, flow, and value (Ballard 2000, Koskela 1999). Therefore, production planning and control processes should incorporate the assessment of construction operations based on these three perspectives, in order to eliminate wasted efforts and rework.

Assessment of construction operations based on only the "transformation" (cost, time, and quality) perspective has been the focus of traditional performance measurement systems practiced in the construction industry, as a result of which the level of inefficiency in construction projects increased tremendously (Ballard 2000, Koskela 1999). In order to address these inefficiencies through appropriate performance assessment methods of construction projects, numerous researchers focused on developing what have been termed as state-of-the-art performance measurement systems that investigated different models for measuring construction performance (Korde et al. 2004).

As the research goal is to develop a framework for production management of renovation projects, it became imperative to understand how the state-of-the-art performance measurement systems that primarily focus on measuring cost, time and quality performance i.e. "transformation" focus only, address production management, and what are the shortcomings in their application to renovation projects. In addition, the literature of state-of-the-art construction performance measurement systems was reviewed to identify those attributes that need to be emphasized for developing the intended framework.

As shown in Figure 3.3, these systems were reviewed to form an understanding of their objectives, performance criteria, performance measurement processes and implementation methods. The performance criterion of each system represents the scope of its metrics, as defined through performance indicators (PI) under qualitative and quantitative aspects of construction. The categorization of PIs under 'process orientated' and 'result orientated' provides the purpose for measuring each PI (Alarcon et al. 2000). The measurement methods of these performance indicators were also reviewed to understand their application to production management in renovation projects.

The review of performance measurement processes suggested by state-of-the-art systems facilitated understanding the process links between essential attributes of a performance measurement system such as critical processes, performance indicators, and measurement methods. The implementation strategies for the performance measurement systems suggested by these systems identified the implementation barriers prevalent in the construction industry and the important aspects of performance measurement systems that make the implementation successful.

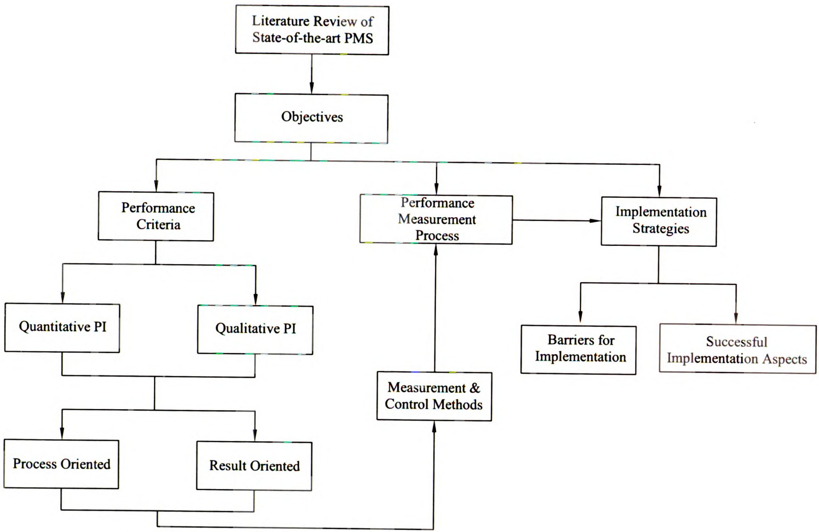

Figure 3.3 Emphasis Areas of State-of-the-art Performance Measurement Systems

3.3.2 Renovation Projects

The literature of renovation projects was reviewed to understand their complex nature and scope of additional requirements for managing their construction process. The literature review identified those external constraints that affect the production in renovation projects and lead to schedule and cost overruns. These constraints are generated from those conditions in which typical renovation projects are undertaken and are not controllable by the contractor for the majority of cases (Mitropoulos et al. 2002, Krizek et al. 1996).

For instance, a physical constraint defines the space limitation for construction operations and material storage at the job location for any activity such as 'erect scaffold' (Krizek et al. 1996). These limitations cannot be overcome by increasing the available space. However, the contractor can get around this constraint by effectively planning the production of this construction activity on day-to-day basis. If the constraint is not taken into account while planning different tasks of this activity, it may adversely impact the performance of any task, which could be related to cost, time and/or quality. Some other examples of these constraints are utility constraint, safety constraint, pollution control constraint, traffic constraints, etc (Mitropoulos et al. 2002, Krizek et al. 1996, Attalla et al. 2003)

Through the identified constraints, this research captured some critical activities that have significant contribution in performance of renovation projects. These activities are critical in nature as they involve constraints during their execution and, if their production is not planned appropriately with the nature of constraints, they could result in underperformance in time, cost, quality, and/or safety.

For the purpose of production planning, each constraint was analyzed to identify the project conditions which generate that constraint and lead to cost and schedule overruns in renovation projects. For instance, a physical constraint for any construction activity is generated due to; i) Space limitations for construction, ii) Space limitations for material storage, iii) Space limitations for newly designed equipment, and iv) Space limitations on site access (Krizek et al. 1996). A thorough assessment of these conditions will dictate the production that could be achieved in the presence of a physical constraint. Therefore, these project conditions can be regarded as the performance indicators for getting around physical constraint for a construction activity. For example, measuring the performance for an activity such as 'erecting scaffold' that is under a physical constraint will involve measuring its actual production against what was planned based on the project conditions.

Table 3.1 lists some of the constraints applicable in renovation projects and their appropriate project conditions identified from the literature that discusses the complexities of renovation projects. Table 3.1 does not present an exhaustive list, as the constraints and project conditions would change from project to project.

As this research is focused on assessing the schedule impacts of constraints, assessment methods of their project conditions to estimate the additional duration of an activity were investigated. This investigation was facilitated by the literature review of state-of-the-art construction performance measurement systems. The assessment methods of project conditions are further explained in Chapter-4.

Table 3.1 Constraints and Project Conditions for Renovation Projects

Constraints	Project Conditions
Utility Constraint	Limited capacity of downstream system
	Non-disruption to existing utilities
	Impact of existing utilities and/or structural systems on the design of new systems
Physical Constraint	Space limitations for construction
	Space limitations for material storage
	Space limitation for installing new equipment/material
Pollution Constraint	Noise Control
	Dust Control
	Debris Control
	Vibration Control
	Odor Control
Uncertainty Constraint	Non-availability of As-built Drawings
	Presence of unforeseen conditions
	Presence of hazardous material
Coordination Constraint	Timing limitations due to owner operations
	Relocation of owner operations to and from swing space
	Owner furnished equipments
	Removal & reinstallation of owner's furniture
	Multiple inspections by end-users and owner's representatives
Regulatory Constraint	Non conformance of existing materials or project conditions with current codes
Traffic Constraint	Limitations of materials and equipment movement
Schedule Constraint	Additional duration due to work restructuring
	Impact on crew productivities
Safety Constraint	Users & public safety

3.3.3 Production Management in Construction

Review of construction production management literature provided insights into how inefficiencies of construction process operations at the production level were previously addressed. Production management practices such as Last Planner System ™ provided an understanding of operational shielding from various constraints of renovation projects by effective planning and assessment of performance at production level. In addition, studies that focused on the impact of variability on crew production rates and reliability of hand-offs were reviewed due to the importance of stabilizing the workflow against the impact of constraints in a renovation project.

3.3.4 Essential Attributes Identified from Phase-1

Phase-1 was instrumental in identifying the following essential attributes of production management systems for renovation projects:

1) Critical activities to be managed
2) Constraints to be identified for each critical activity
3) Weighted impacts of constraints in impacting the production of critical activities
4) Project conditions that result in each constraint
5) Broad performance categories (Cost, Time, Quality & Safety)
6) Performance indicators of State-of-the-art performance measurement systems as applicable to renovation projects
7) Measurement methods of performance indicators
8) Interrelationships between constraints as they impact production
9) Planned production from constraint analysis

10) Production failure analysis

These essential attributes formulated the basic construct of the framework in Phase-3.

3.4 Phase-2 Conduct Interviews- Detailed Discussion of Contribution to Objective-1

Phase-2 involved two sequential tasks; i) conducting interviews of contractors and subcontractors, and ii) constructing a comprehensive process map of production management systems employed by the interviewees in renovation projects.

For conducting interviews, 6 contractors and 4 subcontractors were selected from a sample set, which formed a part of another research project entitled "Vendors' Performance Assessment" (VPA) underway at the School of Planning, Design & Construction, MSU. The sample set comprised of approximately 10 to 15 contractors and subcontractors, which were suggested by the Physical Plant division of MSU for conducting the VPA project mentioned above (Mrozowski et al. 2007).

From the results of Phase-1, the interview questions were drafted with the goal of understanding the process of planning and assessing the production performance of construction activities and not any employee's job performance. These questions mainly addressed; i) the constraints encountered in renovation projects, ii) the project conditions that generate these constraints, iii) the critical activities that contribute to schedule performance, and iv) production planning techniques in the presence of constraints.

In addition to the developed questions, this research also incorporated data obtained from the responses of contractors to some of the questions developed for the VPA project. This was conducted because the VPA project involved some of the common attributes for both new construction and renovation projects as applicable to this research, such as the critical success factors for a construction project, their measurement methods etc (Mrozowski et al. 2007). The responses of contractors and subcontractors on these common questions provided insight into how they perceived differences between new construction and renovation projects with respect to performance measurement. The developed interview questions along with the responses are presented in Appendix-1 of this thesis.

The target group of interviewees comprised of construction managers, site superintendents, project engineers and field engineers. The interviews were conducted in a one-on-one basis to eliminate any group favoritism in opinions and arrive at a clearer understanding of the production management systems adopted.

Based on the interview responses, the research intended to document the implemented production management systems by constructing a comprehensive process map. The purpose of constructing this process map was to depict the interaction between essential attributes of performance measurement systems being adopted by contractors by illustrating the sequence of activities involved in the processes of planning, measuring and evaluating the production in renovation projects. Therefore, for identifying the scope for improvement in current practices, this process map's intent was to form the basis for documentation and analysis of current performance measurement systems being employed. However, the research could not construct this process map, as any relevant data was not obtained from the interviews of contractors and subcontractors. It was concluded after the interviews that the interviewees did not have a formalized process of production management in renovation projects. Further explanation is provided in Chapter-4.

3.5 Phase-3 Framework Development - Detailed Discussion of Contribution to Objective-2

Objective-2 Develop a framework for production planning, execution and performance assessment of construction operations in renovation projects.

This phase involved developing the intended framework for production management of renovation projects. The framework established links between essential attributes for their application in a suggested process of production planning and assessment of renovation projects. This process is based on defining the dependency interrelationships within different constraints, their importance levels in impacting the production schedule of critical activities, and the assessment of project conditions of each constraint for quantifying the additional duration of critical activities. The framework incorporated quantitative techniques such as correlation analysis and Analytical Hierarchy Process (AHP) for production planning.

The framework incorporated any additional essential attributes obtained from the interview responses. This addition involved some critical activities, additional constraints, and project conditions of constraints. The developed framework for production management of renovation projects is demonstrated in the next phase.

3.6 Phase-4 Framework Demonstration - Detailed Discussion of Contribution to Objective-2

In Phase-4, the developed framework is demonstrated with a case example of a construction activity in an institutional renovation project. The example is completely hypothetical and its intent is to illustrate the application of the developed framework for production planning and assessment in renovation projects.

The demonstration presented a production management system that not only assesses the production performance for the demonstrated activity but also plans its production schedule in the presence of constraints. This involved application of quantitative tools such as AHP and correlation analysis to the constraints of renovation project, which represent the primary essential attributes that impact the schedule performance of construction activities. All quantitative information as required by the framework was assumed for the demonstration example.

3.7 Phase-5 Framework Verification- Detailed Discussion of Contribution to Objective-2

In the final phase of this research, the developed framework was verified as to whether it can be employed in renovation projects. This was done through a second round of interviews of contractors. The interviewees were presented with the demonstration example and asked to provide feedback on the appropriateness and limitations of the essential attributes identified. The interviewees also responded on the production planning and assessment methods proposed in the framework. The responses from this round also helped in formulating recommendations for future areas of research in production management of renovation projects.

3.8 Chapter Summary

This chapter provided an overview of a systematic approach that this research adopted for achieving the research goal and objectives. The research methodology outlined how the research utilized state-of-the-art construction performance measurement systems, complexities of renovation projects, and the principles of construction production management. The literature review and interview procedure are discussed in detail to bring forward the significance of each step in arriving to an understanding of the theoretical knowledge and actual practice of production management of renovation projects. The chapter mentioned where the quantitative tools such as AHP and correlation analysis for analyzing the essential attributes of production management system were used in this research. In addition, the framework development process, and how it was demonstrated and verified are briefly discussed.

CHAPTER - 4

DATA COLLECTION AND FRAMEWORK DEVELOPMENT, DEMONSTRATION AND VERIFICATION

4.1 Introduction

As the main research contribution, this chapter provides a detailed account to Phase-2 through Phase-4 of the research that includes interview process, data collected, and development and demonstration of the intended framework for production management of renovation projects. The interviews are documented based on the common themes observed in the responses of 6 contractors and 4 subcontractors. A consolidated process map was intended to be constructed from the interview data that could illustrate a general production management process of renovation projects currently in practice.

Concurrently, the intended framework was primarily developed from essential attributes of production management systems identified in literature review, and subsequently incorporating any additional essential attributes identified in the interviews. The framework development encompassed constructing a comprehensive process of production planning, execution, and control of renovation projects, by capturing their essential attributes identified above. In the last section of this chapter, in order to provide a better understanding of the developed framework to the reader, its application has been demonstrated with an example of a construction activity of a renovation project. This framework is finalized in Phase-5 as the main research product, after its verification in the second round of interviews.

4.2 Interview Procedure

As stated in chapter 3, the contractors and subcontractors to be interviewed were selected from a sample set of another research project entitled "Vendors' Performance Assessment" (VPA), underway at the School of Planning, Design & Construction, Michigan State University (MSU). Initially, the Physical Plant of MSU suggested 10 to 15 contractors and subcontractors, each to be interviewed for the VPA research project. From this sample set, 6 contractors and 4 subcontractors were interviewed after making initial contacts based on their availability and participatory interests (Abdelhamid et al. 2007).

The interviewed contractors varied in terms of their company sizes and project types. One of them was a large sized contractor; the other was a mid-size contractor, while all others were small sized contractors. The value of projects that the interviewed contractors typically undertake ranges from $15 Million to $500 Million for large sized, $5 Million to $100 Million for mid sized, and $10,000 to $23 Million for small sized contractors. The collective project portfolio of these contractors included institutional, commercial, hospitals, utilities, infrastructure, waste water treatment plants, hospitality, manufacturing plants, restoration, municipal projects, and conservation projects. The interviewed contractors primarily work as general contractor or construction manager on these project types for both new construction and renovation works.

At the production level of renovation projects, the subcontractors are directly involved in addressing project conditions and constraints. While identifying the interviewees, the researcher selected subcontractors, as they would provide better feedback on production management in renovation projects. The interviewed subcontractors involved two plumbing, one electrical, and one HVAC subcontractor that undertake different project types. Different trade contractors were interviewed, as they could provide an insight to different types of critical activities in renovation projects with their encountered constraints and project conditions. The project types of the interviewed subcontractors include institutional, commercial, hospitals, auto plants, underground, and industrial work.

The interviews were conducted on one to one basis for avoiding any group favoritism, and the research team conducting the interviews typically involved 2 to 3 members for precise data collection.

4.2.1 Interview Questions

As the VPA project involved some of the attributes for new construction projects' performance assessment systems, which were useful for this research in context of renovation projects also, the interview questions to be asked for this thesis were combined with the interview questions of the VPA project. As a result, common interviews were conducted for both the project and this research, which also reduced the interview time (Abdelhamid et al. 2007).

Some of the common attributes between the VPA project and this research were; critical success factors, their measurement methods, and their hierarchies in terms project success. Therefore, some of the questions for VPA project that dealt with these attributes also included an additional question for obtaining answers in context of renovation projects. For instance, one of the questions for the VPA project is:

Define in your own terms project success (critical success factors), i.e. what is a successful project to you?

In order to orient this question towards renovation projects, the typical additional question added after this was:

Is this the same for renovation?

The purpose of inserting this additional question in some of the VPA questions was to obtain data concerning the interviewed contractors' and subcontractors' views of differences in the performance assessment systems between new construction and renovation projects.

In addition to the common questions of VPA project, 5 additional questions were short listed from a list of 10 questions drafted in this research specifically for renovation projects. These questions were based on the essential attributes identified from the literature review. The short listing was done to reduce the interview time and obtain objective data which was not specific to any renovation project. For instance, the question drafted to obtain the "hierarchies of constraints impacting project schedule" was not selected from the list, as it could generate subjective responses specific to any renovation project. Instead, the question drafted to obtain "project conditions in renovation projects that impact the estimated budget, schedule, and quality the most" was selected, as it was more generic in nature and lesser time consuming to respond.

These 5 questions were placed in a separate section of "Renovation projects" in the main interview questions of the VPA project. These questions mainly dealt with the contractor's and subcontractor's process for planning daily crew assignments in renovation projects, the encountered constraints or project conditions that impact the cost, time and quality of renovation projects, and their critical activities that impact the schedule performance. The interview questions were common for contractors and subcontractors.

4.2.2 Data Collection

The data collected from each interview was documented in two consolidated spreadsheets, each for 6 contractors and 4 subcontractors, which involved all the responses for each question. This facilitated the data synthesis and analysis in identifying any commonalities and differences in the responses for all questions. Snapshots of consolidated spreadsheets are shown in Figure 4.1 and 4.2. The completed spreadsheets of all interview questions and the common questions from the VPA project and this research are included in Appendix – 1.

No.	Questions	Responses
	Vendor Performance Assessment Questions	
VP2	**Define in your own terms project success (critical success factors), i.e. what is a successful project to you?** **Is this same for renovation projects?**	1. Profitable project 2. On time 3. Owner satisfaction 4. Vendor satisfaction Yes
		When it meets and exceeds all of client's expectations. Profit is not the main aim of the firm Yes, both are client driven.
		When the end user is happy, the company makes profit and no one gets hurt. Yes (it is more invasive when owner is occupying the premises)
		For a successful project we consider following factors fulfilled: A Happy Owner, future work, On schedule, Good relationships, Make profit, Good quality product, Add value to the life of entity, negotiate more work. Yes
		A successful project is which is done on time, its on budget (which makes owner happy), should have a good profit margin Yes.
		Schedule completion, Within Budget, Owner completely satisfied with process and product. Yes

Figure 4.1 Snapshot of Consolidated Spreadsheet of Contractors' Responses (Abdelhamid et al. 2007)

No.	Questions	Responses
Vendor Performance Assessment Questions		
VP2	**Define in your own terms project success (critical success factors), i.e. what is a successful project to you? Is this same for renovation projects?**	1.Finishing Projects on time 2. Within budget and 3.Happy owners Yes
		That the owner should be happy, project completed in time, make profit Yes
		customer satisfaction, profit, learning from project, better relationship. Yes
		The critical success factors for any job would be a good Profit margin, high level of owner satisfaction, no repair calls, lack of warranty issues. Yes

Figure 4.2 Snapshot of Consolidated Spreadsheet of Subcontractors' Responses (Abdelhamid et al. 2007)

4.2.3 Synthesis and Analysis of Data Collected

This section presents the data synthesis and its analysis based on the consolidated spreadsheets for contractors and subcontractors. This is done first for the common questions of VPA project followed by the renovation project questions, as discussed below.

4.2.3.1 Interview Responses to VPA Questions

In response to the common interview questions for the VPA project and this research, none of the respondents differentiated in the performance assessment systems for renovation and new construction projects. Both contractors and subcontractors reported that the critical success factors, their consistencies, hierarchies, and measurement methods were same for new construction and renovation projects. The most commonly stated critical success factors were; on time, on budget, customer satisfaction, and quality.

Three of the interviewed contractors had employed a formal vendor performance evaluation system for their construction projects. These contractors included one large, one mid size, and one small contractor and stated that they use the same evaluation form for renovation projects also. In addition, these contractors stated that the frequency of filling out the performance evaluation form remains the same for both new construction and renovation projects. The other three small sized contractors who did not have a formal vendor performance evaluation system in place stated that if they would develop a vendor performance evaluation form, all the factors they would look to evaluate vendors on will remain same for both new construction and renovation projects. Some of these stated factors include: change order rate, RFI rate, working style of personnel, safety, quality, timeliness, responsiveness, and interaction with the owner. This data was obtained as responses to questions VP 14, VP 17, and VP 32 of Vendor Performance Assessment section.

These responses reflect that currently, there are no perceived differences in practice regarding project success between renovation and new construction projects. However, the literature states that the nature of renovation projects is more complex than new construction projects, as the former involve a number of additional constraints, not encountered in new construction. These constraints may adversely impact the project success of renovation projects and lead to schedule and cost overruns. Numerous researchers have investigated methods for coping with the constraints of renovation projects for improving their performance (Krizek et al. 1996, Mitropoulos 2002, Wayne et al. 1988). None of the respondents in the interviews reported that coping with these constraints was a critical success factor of renovation projects.

Moreover, the literature of state-of-the-art construction performance measurement system states that the definition of critical success factors and their hierarchy should be a function of project type, objectives and company's strategies for achieving project success (Costa et al. 2006, Beatham et al. 2003). For instance, in a renovation project of an occupied building, "safety of the occupants" becomes an important factor that defines the project success. Moreover, "non-disturbance to owner's operations" also becomes an important factor that should be considered by the contractor, when performing construction in an operational building. Both these factors do not directly relate to cost, time, or quality of a project, and were not reported by any respondent, as being a critical success factor for renovation projects.

Overall, the similarity of critical success factors between new construction and renovation projects, as reported by the interviewed contractors and subcontractors reflects that the project objectives, and contractors' and subcontractor' strategies for managing construction remain constant when moving from new construction to renovation projects. Under budget, on-time, and desired quality were stated as critical success factors whether a new construction or a renovation project is being undertaken.

4.2.3.2 Interview Responses to Renovation Project Questions

In response to the "renovation project" questions, only one of the respondents, a mid-size contractor, had a formal documented process of planning daily crew assignments, based on the project conditions of renovation projects. However, detailed information could not be obtained due to proprietary reasons. Four other interviewed contractors stated that their superintendent or foreman is responsible for planning crew assignments. One of these contractors' consented with the literature stating that forecasting crew assignments is difficult due to the uncertain and dynamic nature of renovation projects. Another contractor stated that any formal process has not been employed for establishing crew assignments. The reader is directed to Appendix - 1 for reviewing the responses to "renovation project" questions.

From the interviewed subcontractors, the plumbing subcontractor stated that daily crew assignments are established based on the evaluation of self work area and the other trades' work areas to avoid any potential conflicts. These evaluations are based on the type and size of the renovated work. The electrical subcontractor reported that they used daily log reports for documenting crew assignments but a formal documented process of arriving at and establishing crew assignments was still absent. The HVAC and other plumbing subcontractor stated that crew assignments are established by their foreman and/or superintendents, but on an informal basis.

In response to the question 2 of renovation projects (RP2 in Appendix-1), the project conditions stated by all the respondents that impact the estimated budget, time, and quality were similar to what were identified in the literature of renovation projects. The stated project conditions involve; inadequate design, concealed conditions, poor as-built drawings, unforeseen conditions, presence of hazardous materials, suitability of infrastructure or accommodate project requirements, aesthetic maintenance, inaccessible project location, and undoing of old installation (demolition). These project conditions stated by respondents were also found in the literature of renovation projects that generate various constraints for construction and lead to cost and schedule overruns.

As renovation projects are characterized by constantly changing project conditions, it became imperative to understand the contractors'/subcontractors' frequency of addressing project conditions of renovation projects with regard to establishing crew assignments and their associated processes involved, which was the focus of question 4 (RP4 in Appendix-1). Different answers were obtained for this question. Three contractors including the large and mid-sized stated that the project conditions are addressed as soon as they are identified while one other contractor stated a daily frequency. The other two contractors did not give any frequency and stated that they address the project conditions as it becomes necessary.

From the interviewed subcontractors, only plumbing and electrical subcontractor mentioned that the project conditions are addressed on a daily basis or as the changes occur. The other two subcontractors did not state any frequency. Overall, none of the respondents had a standardized process of addressing project conditions in renovation projects.

As this research is focused on analyzing the schedule impacts of constraints on renovation projects, one of the renovation project questions (RP5 in Appendix-1) was directed towards identifying the critical processes/activities that impact the schedule performance of renovation projects the most. Similar to the responses obtained for project conditions in question RP2, most of the critical processes stated by the respondents were also identified by this research in the literature review. The stated critical processes/activities involve; hazardous material abatement, demolition, mobilization, ductwork, flooring, finishes, and taking care of the existing structure.

4.2.4 Process Maps of Interviewed Contractors and Subcontractors

This research initially contemplated on constructing a comprehensive process map currently in practice for production management of renovation projects. This process map would have depicted the sequence of activities of contractor or subcontractor for planning, measuring, and evaluating the production assignments in renovation projects based on the project conditions and constraint analysis. In addition, the linkages between essential attributes of a production management system would have also been reviewed in the process map by the researcher.

For constructing this process map, the researcher intended to obtain relevant documented data from Question 1 of renovation projects category (RP 1) of interview questions. However, based on the analysis of the interview data, the researcher concluded that any pertinent data could not be obtained to accomplish this step. This was attributed to the informal processes of production planning being undertaken by the interviewees.

As discussed in the previous section, the researcher did not obtain, from the responses of contractors and subcontractors, any formal documented procedure of establishing daily crew assignments in renovation projects. Most of the respondents stated that either they did not have a standardized documented process or the process was informally communicated between their superintendents and crew foremen.

Half of the interviewed contractors stated that they did not have any formal process of establishing daily crew assignments, as their superintendents and foremen take care of this issue through informal communication and any standardized procedure is not practiced. Two contractors stated that either the superintendent or the foreman plans the crew assignments based on the project conditions, and for this purpose, one of the contractors referred to their daily logs. Nonetheless, the process of how the crew assignments in daily logs are planned and arrived at, and the process of analyzing project conditions and the constraints of renovation projects prior to planning crew assignments were not documented in a standard format by any interviewed contractor. Similar responses were obtained from all the interviewed subcontractors stating that the crew assignments are established by their foremen and superintendents without following any documented standard procedure.

From the interview responses, the researcher concluded that the procedure of establishing crew assignments was an understood fact in the form implicit knowledge possessed by the foremen and the superintendents of the interviewed contractors and subcontractors. However, this knowledge of arriving at suitable crew assignments has not been documented which could restrict developing a standardized procedure of addressing project conditions of renovation projects. In addition, none of the respondents stated any sequence of activities for planning daily production of construction crews in renovation projects. Therefore, in the absence of any formal documented process of production planning obtained from the interviewees, the researcher did not construct any process map, as intended, for its application to the framework development.

4.2.5 Interview Conclusions

From the interviews of contractors and subcontractors, it could be observed that the state-of-the-art performance assessment systems in practice do not involve major changes from new construction to renovation projects. This is exemplified by the critical success factors, measurement methods and their hierarchies mostly reported as same for new construction and renovation projects.

However, numerous researchers have concluded that the performance of renovation projects is typically lower than that of new construction projects, as the former involve much more risks, uncertainty, and dynamism in their project conditions not encountered in new construction. This has also been attributed to various constraints generated by the project conditions of renovation projects (Krizek et al. 1996, Mitropoulos 2002, Wayne et al. 1988). Planning and controlling the impact of these constraints and project conditions on the critical success factors stated by the interviewed contractors and subcontractors would result in better performance. In other words, if the impact of constraints on the cost, time, quality, and customer satisfaction is planned and controlled, the performance of renovation projects can be improved.

In addition, the critical success factors reported by the interviewees were on a broad level of a project such as quality, repeat business, and client satisfaction. There was no success factor reported that dealt with the production level of construction activities such as percentage of plan completed (PPC), and quality work delivered to the next trade. The literature of production management supports the use of these production level indicators for managing projects which are complex, uncertain, and quick (CUQ). As the CUQ level increases in renovation projects due to the presence of constraints, use of production level indicators becomes imperative for managing construction on daily basis and assessing the production performance of a construction crew.

As observed in the responses to renovation project questions, most of the project conditions and constraints stated in literature were also reported in the interviews to be encountered in actual practice. These constraints involve; uncertainty, dynamic nature, irregularity in plans and specifications, coordination with owner's operations, and traffic conditions. These stated constraints adversely impact the time, cost and quality performance of renovation projects.

Although the interviewees agreed on the complexities of renovation projects and the constraints involved, but it could also be concluded that on a major scale, there was a lack of a formalized documented procedure of assessing project conditions and constraints of renovation projects for establishing crew assignments. An implicit process between the superintendents and foremen for establishing crew assignments was mostly stated in the interviews, which reinforces the need for developing a formal process that could be used by contractors or subcontractors for managing production in the presence of constraints.

Overall, the interviews of contractors and subcontractors suggest that there is a lack of a formal system for production planning, execution and assessment in renovation projects. This is exemplified by informal processes of production planning in practice and the similarities in performance assessment systems for renovation and new construction projects, as reported by most of the respondents. As renovation projects experience lower performance levels in terms of cost, time and quality, the interview data underscores the need to develop a production management system for renovation projects that could be employed to deliver better performance level.

In addition, production management of renovation projects should be viewed from a perspective that involves thorough analysis of constraints during production planning of crew assignments. This would deliver quality production assignments for the crews which could be attainable in the presence of constraints. This would also reinforce the performance assessment of construction crews with regard to their ability of coping with the constraints. Thus, a production management system for renovation projects should involve constraints' identification and assessment for planning production assignments and assessing performance of construction crews accordingly.

The following section presents some of the essential attributes of a production management system for renovation projects that this research has captured from the interviews and literature review.

4.3 Essential Attributes of a Production Management System for Renovation Projects

Although in the literature, the essential attributes of a production management system have not been explicitly stated in context of renovation projects, this research has assimilated them from the principles of state-of-the-art performance measurement systems, complexities of renovation projects that impact the production of construction activities, and practices of production level planning of construction processes. These essential attributes are:

1) Critical activities to be managed
2) Constraints to be identified for each critical activity
3) Weighted impacts of constraints in impacting the production of critical activities
4) Project conditions generating each constraint
5) Broad performance categories (Cost, Time, Quality & Safety)
6) Performance indicators of State-of-the-art performance measurement systems as applicable to renovation projects
7) Measurement methods of performance indicators
8) Interrelationships between constraints in impacting production
9) Planned production from constraint analysis
10) Production failure analysis

As stated before, this research has not attempted to retrieve all of the above stated essential attributes from the interviews due to the subjectivity involved in the nature of some attributes and a limited sample size of 10 contractors and subcontractors. For instance, a limited number of interviews with contractors cannot provide a definitive hierarchy of constraints in impacting production, as it could change from contractor to contractor and project to project.

In support of this view, the developed framework has defined possible interactions between essential attributes by incorporating hypothetical figures to their subjective assessment. In addition, the main purpose of developing this framework lies in presenting a comprehensive process of production planning, execution and assessment by linking these essential attributes in a systematic approach, which could be adopted by contractors in renovation projects for improving their schedule performance.

4.4 Interface between Renovation Projects & State-of-the-art Construction Performance Measurement Systems

Renovation projects are characterized by their complex nature due to the presence of external constraints and unforeseen conditions that impact the production of various construction activities. This impact could be on the cost, time, quality and/or safety of the activity's production (Krizek et al. 1996, Mitropoulos 2002, Wayne et al. 1988).

Based on the understanding assimilated from the interviews and literature review, this research has developed a graphical illustration, shown in Figure 4.3, of the complex state of renovation projects interfacing with the reviewed state-of-the-art construction performance assessment systems.

Overall, Figure 4.3 demonstrates the intricacies involved in production assessment of a construction activity in renovation projects. Figure 4.3 shows some of the essential attributes of production management systems for renovation projects, as mentioned in section 4.3. These essential attributes are: the constraints, their project conditions, critical activities, broad performance categories of state-of-the-art construction performance measurement systems and their performance indicators.

Through Figure 4.3, this research attempts to illustrate that in renovation projects, the production of a construction activity as it relates to the estimated time, cost, quality, and safety, could be impacted by multiple constraints and their various project conditions, and not merely labor, material and equipment availability, which are traditionally considered for project planning and controlling processes. Those construction activities, which are typically impacted by these constraints, collectively define critical activities. For instance, all activities pertaining to demolition process in renovation projects such as concrete drilling and sawing, drywall cutting, ceiling uncovering, and dismantling of mechanical ducts, would fall under the "Selective Demolition" critical activity.

The literature and interviews state that there are numerous project conditions that generate constraints in a renovation project (Krizek et al. 1996, Mitropoulos 2002, Wayne et al. 1988). A thorough investigation of these project conditions would lead to better identification and assessment of constraints and therefore, a better production management of renovation projects. In addition, these project conditions need to be investigated in order to assess the impact of constraints on the production of critical activities. Therefore, this research assumes that these project conditions could define the performance indicators for production management of renovation projects because these project conditions would identify the ability of a construction crew for completing a production assignment within budget, on time and at desired quality. Thus, in Figure 4.3 shows these project conditions as performance indicators for each constraint.

Figure 4.3 clearly shows that a performance indicator of any constraint could have multiple impacts on the production of various critical activities with respect to their estimated cost, time, quality, and safety performance. In other words, any critical activity's production could be impacted by multiple performance indicators of numerous constraints. This impact can only be quantified and planned when all these essential attributes are linked in a systematic process of production planning, execution, and performance assessment.

On the contrary, from the interviews of contractors and subcontractors and the literature review of state-of-the-art construction performance measurement systems, this research concluded that these systems do not incorporate the constraints, project conditions, and critical activities of renovation projects in their performance measurement processes. Past researchers have also concluded that state-of-the-art performance measurement systems have not been able to identify a definitive set of performance indicators which assess the true performance of construction projects (Krizek et.al. 1996, Costa 2006).

Therefore, state-of-the-art performance measurement systems could prove to be incomplete in their effective application to production management in renovation projects. This research has also observed this ineffectiveness of state-of-the-art performance measurement systems in the performance indicators proposed by these systems, which do not account for the constraints of renovation projects as shown in Figure 4.3. In addition, the interviews of contractors and subcontractors revealed that current practice do not consider coping with the constraints as a critical success factor for performance assessment of renovation projects.

For a renovation project, the lack of identification of constraints and their assessment in production planning and assessment processes could lead to budget and schedule failures, and could incapacitate project teams in identifying real causes of underperformance. If a project were running over budget or behind schedule, it would become extremely difficult to ascertain which constraints have caused these impacts in which critical activities.

Although the performance indicators of state-of-the-art performance measurement systems are incomplete for renovation projects, but this research has analyzed the feasibility of using their measurement methods for the performance indicators of renovation projects in planning and assessing the production. This analysis has further lead to the development of both objective and subjective measurement methods for performance indicators of constraints of renovation projects. For instance, performance indicator of "cycle time", as suggested by *Alarcon et al.* (2000), could assess the schedule impact of project condition of "limited site access" that generates "physical constraint", as it involves limited movement of crews, labor and equipment. Similarly, other performance indicators of state-of-the-art performance measurement systems have been analyzed for their appropriate application to assess the constraints' schedule impacts on production of renovation projects.

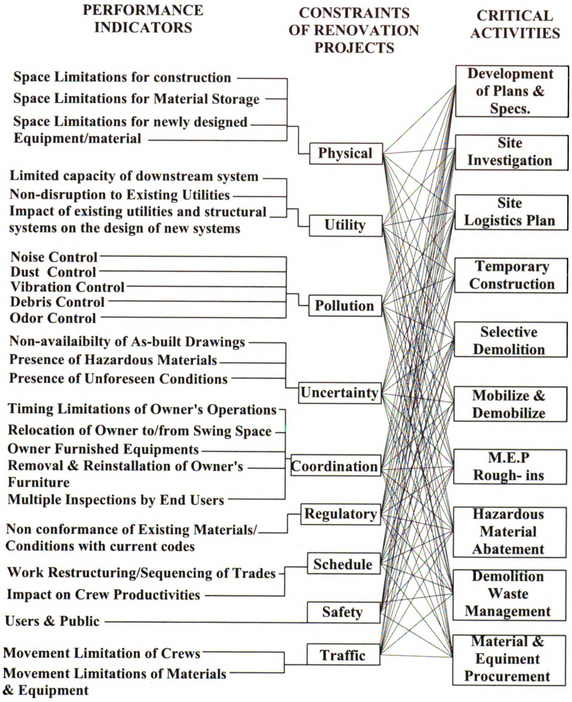

Figure 4.3 Interface between Renovation Projects and State-of-the-art Performance Measurement Systems

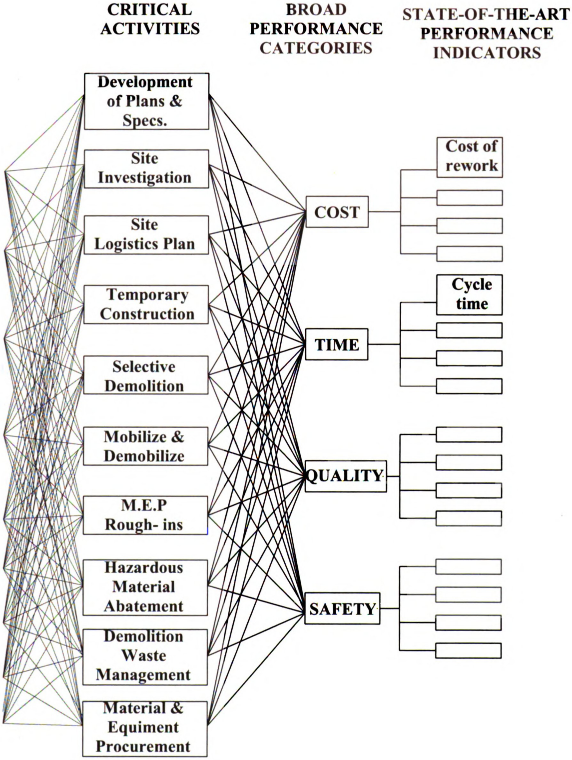

Figure 4.3 (Cont'd)

The complexities of renovation projects contribute to the need for developing a simplified and methodical process of production planning and assessment that takes into consideration the essential attributes, discussed above. In order to fulfill this need, this research has developed a framework for production management of renovation projects. This framework establishes appropriate links between essential attributes for their effective application in production planning, execution, and assessment process of renovation projects. The framework provides a template to contractors for incorporating their subjective assessment of essential attributes as they relate to specific project conditions.

4.5 Introduction to the Production Management Framework for Renovation Projects

Prior to discussing the framework for production management of renovation projects, there is a need to reiterate the definition of "production management" for renovation projects as stated in this research. In industrial engineering, production management refers to planning , executing, and controlling the production assignments on day-to-day basis that are established based on the analysis of constraints prevailing in site conditions, prerequisite work, and resource availability (Ballard 2000). Numerous studies have concluded that the constraints in renovation projects by their complex nature, negatively impact the production of construction activities leading to schedule and cost overruns ((Mitropoulos et al.2002, McKim et al. 2000, Krizek et al. 1996). Those construction activities that frequently encounter these constraints during their execution contribute most to the production performance and, hence, are termed critical activities.

Therefore, this research posits that the process of planning, executing, and controlling the production of critical activities based on the analysis of constraints for the purpose of completing the production assignments within budget, on schedule and of desired quality, defines production management in renovation projects.

Hence, a framework for production management of renovation projects should primarily originate from those essential attributes, which characterize the complexities of renovation projects. Constraints and critical activities represent the leading essential attributes that should drive the framework development and identify other essential attributes such as performance factors of each constraint, their measurement methods, etc.

At a broad level, this framework proposes two major processes: production planning, and production performance assessment. Both these processes are linked in a cyclic process to obtain the feedback from production performance assessment and apply it in future production planning processes for continuously improving the schedule performance of renovation projects.

By linking the essential attributes stated in section 4.3, this framework presents a high level process of planning and assessing the production performance at the construction activity level of renovation projects based on the analysis of prevailing constraints. This high level process, at a micro level suggests a number of steps required to be performed by the contractors for production planning and assessment. These suggested steps also represent the development stages of framework, as they correspond to the chronological sequence of how this research developed the framework from essential attributes identified in literature and interviews. The following section briefly states these development stages of this framework.

4.6 Stages in Framework Development

Section 4.4 emphasized that it is imperative to identify relationships between essential attributes and link them in a methodical process for their effective application in production management of renovation projects. In the previous section, the process of production management for renovation projects was defined, which underscored the importance of constraints and critical processes in building this process. This section states the chronological stages in development of the framework undertaken by this research for defining possible interactions between essential attributes and developing production planning and performance assessment methods for renovation projects. These stages are:

1. Identification of constraints and critical activities
2. Mapping the interdependency relationships between constraints and reduce the number of constraints- optional step
3. Mapping the impact levels of constraints on the estimated production schedule of critical activities
4. Identification of weighted impacts of constraints on the production schedule of critical activities
5. Quantification of additional production duration of critical activities based on project conditions
6. Prepare lookahead schedule of production assignments
7. Match production assignments and resource capacities
8. Preparation of execution plan for each critical activity
9. Production performance assessment

10. Production failure analysis

Figure 4.4 shows the developed framework that involves all of the above mentioned stages. As stated before, the stages shown in Figure 4.4 represent the steps proposed by the framework that should be performed in production management of renovation projects. These steps have been synthesized from the analysis of the literature of renovation projects and production management, which provided the basis for developing the framework. Before proceeding to define how each step should be performed, an explanation of why each step is required would provide the reader with the significance of each step in the overall framework for production management of renovation projects.

The first step in production planning is to identify possible constraints and critical activities in the scope of work by reviewing the project conditions. The constraints prevailing in renovation projects and the critical activities that are impacted by these constraints form the primary essential attributes that impact the production performance of renovation projects.

While impacting the production of critical activities, the constraints of renovation projects may exhibit varying degree of dependency levels within themselves. Any constraint may be weakly dependent on one constraint, strongly dependent on two constraints while absolutely dependent on all others. Therefore, for the second step, a correlation analysis is required to be performed among the constraints. This would help in understanding the contribution of each constraint towards other constraints. This analysis would eventually help in accurately planning the production of construction activities in the presence of absolutely dependent or strongly dependent constraints.

Step-2 has been specified as optional because its main purpose in the framework is to limit the number of constraints and simplify the procedures in steps 3, 4 and 5. Skipping this step might have a slight impact on the estimation of production in step-5, which is explained further in the demonstration of framework. Therefore, after identification of constraints and critical activities in step-1, a decision node is placed, as shown in Figure 4.4 to either proceed through step-2 or go directly to step-3.

Similar to the previous step, in step 3, a correlation analysis is required between constraints and their impacts on different critical activities. These relationships would help in understanding the impact levels of each constraint on the increase or decrease of the estimated production performance in all critical activities. It is important to analyze this impact on the production of each critical activity as it relates to estimated cost, time, quality, and safety performance. This analysis would enable project teams to understand the dynamic nature of how each constraint changes with each critical activity so that they would be better able to plan the production accordingly.

The purpose of step-3 is to map the impact levels of constraints on the production of critical activities while the purpose of step-4 is to establish hierarchy of constraints based on the mapped impact levels. As explained in step-3, each constraint has different impact levels on the production of different critical activities, it becomes imperative to obtain the relative importance of constraints for each critical activity. The hierarchy would be established through Analytical Hierarchy Process (AHP) in step-4.

The production planning of any critical activity would entail estimating the impacts of constraints on its estimated budget, schedule and quality. For quantifying these impacts of constraints, assessment of project conditions that generate these constraints should be done. Therefore, defining the assessment methods of project conditions of each constraint, through step-5, is one of the major stages in this framework because these assessment methods would facilitate production planning.

Step-5 represents a major milestone in production planning as it has a dual function in the overall framework. The first function entails the assessment of project conditions of each constraint and estimating their impact on production schedule of critical activities. The second function is to normalize this impact by capturing the data from previous steps (correlation analysis and AHP) and use it in estimating the production duration of a critical activity.

Step-6 entails entering the production assignments of critical activities in a lookahead schedule for the upcoming 3 to 6 weeks. Only those assignments are to be entered in the lookahead schedule for which all the constraints have been addressed or removed.

Step-7 involves balancing the production duration and scope of work with the available resources based on the analysis of broad external constraints, which are maximum buffer, pre-requisite work and given directives. The revised production duration would represent the performance that any activity 'can' achieve under the impacts of the constraints. Communication of this production estimate to the construction crew prior to activity execution becomes an important step. However, simply communicating the production estimate would not enable the crew in achieving it. Therefore, step-8 involves preparing an activity execution plan, which in addition to production estimate, includes preparing a daily production schedule that lays out the production assignments of crews based on the analysis of constraints and associated project conditions.

Step-9 is required to determine the production efficiency of the crew, which captures how well the crew performed under the presence of the constraints. Therefore, assessment of production performance should be done after activity execution in the presence of constraints and comparing it with the estimated production. Based on production performance assessment, if the actual production does not meet the estimated production, a production failure analysis is required in the last step (step-10) to understand the cause of underperformance and apply the learning to future constraints analysis.

Overall, this framework is developed per the literature review and interview responses of contractors and subcontractors. Steps 1 through 10 of the developed framework are shown in Figure 4.4. While performing some of these steps, the framework suggests incorporating query nodes (Query node-1, 2 &3) which are explained in the detailed discussion of those steps. The following section discusses in detail steps 1 through 10 of the framework.

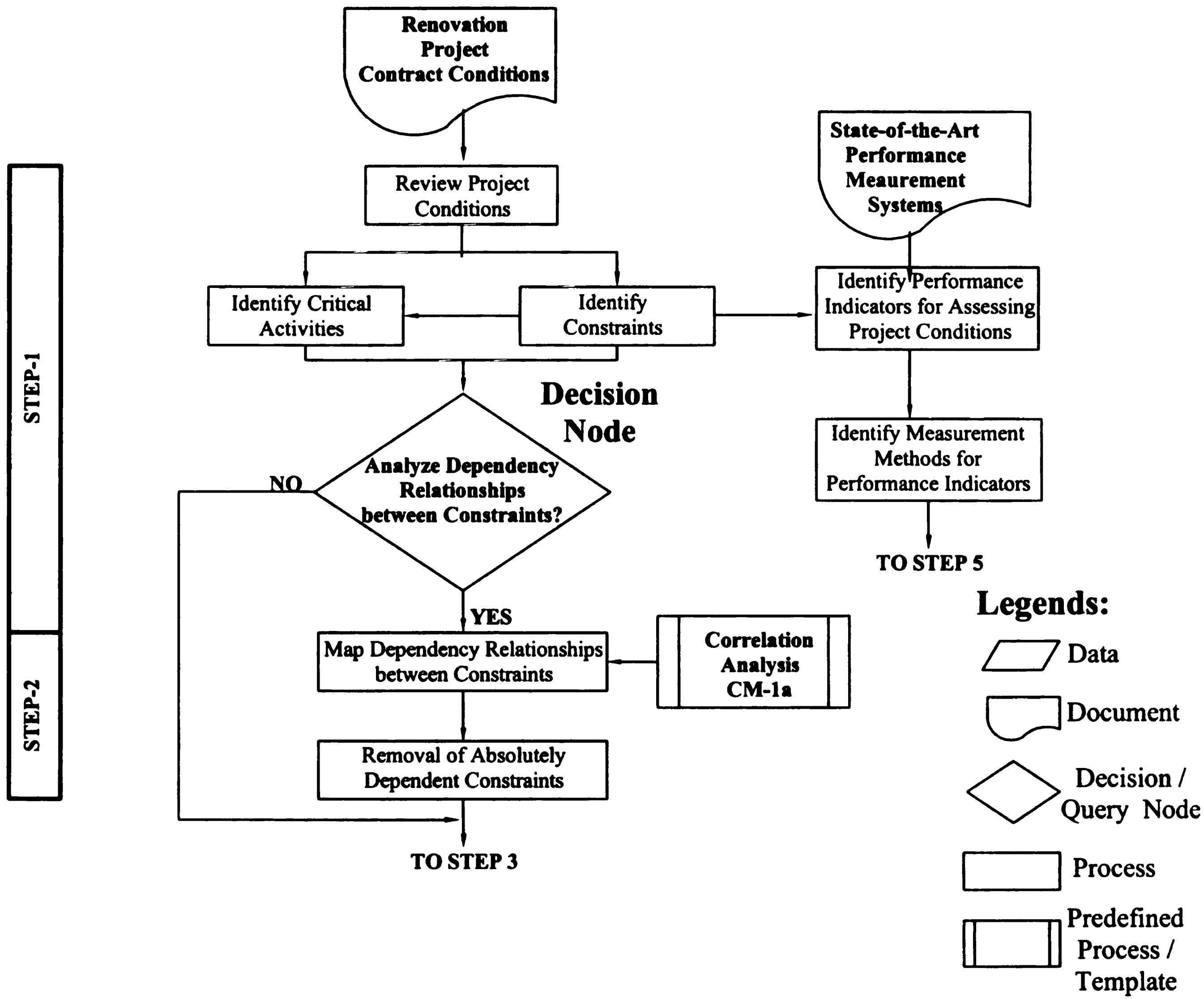

Figure 4.4 Developed Framework for Production Management of Renovation Projects

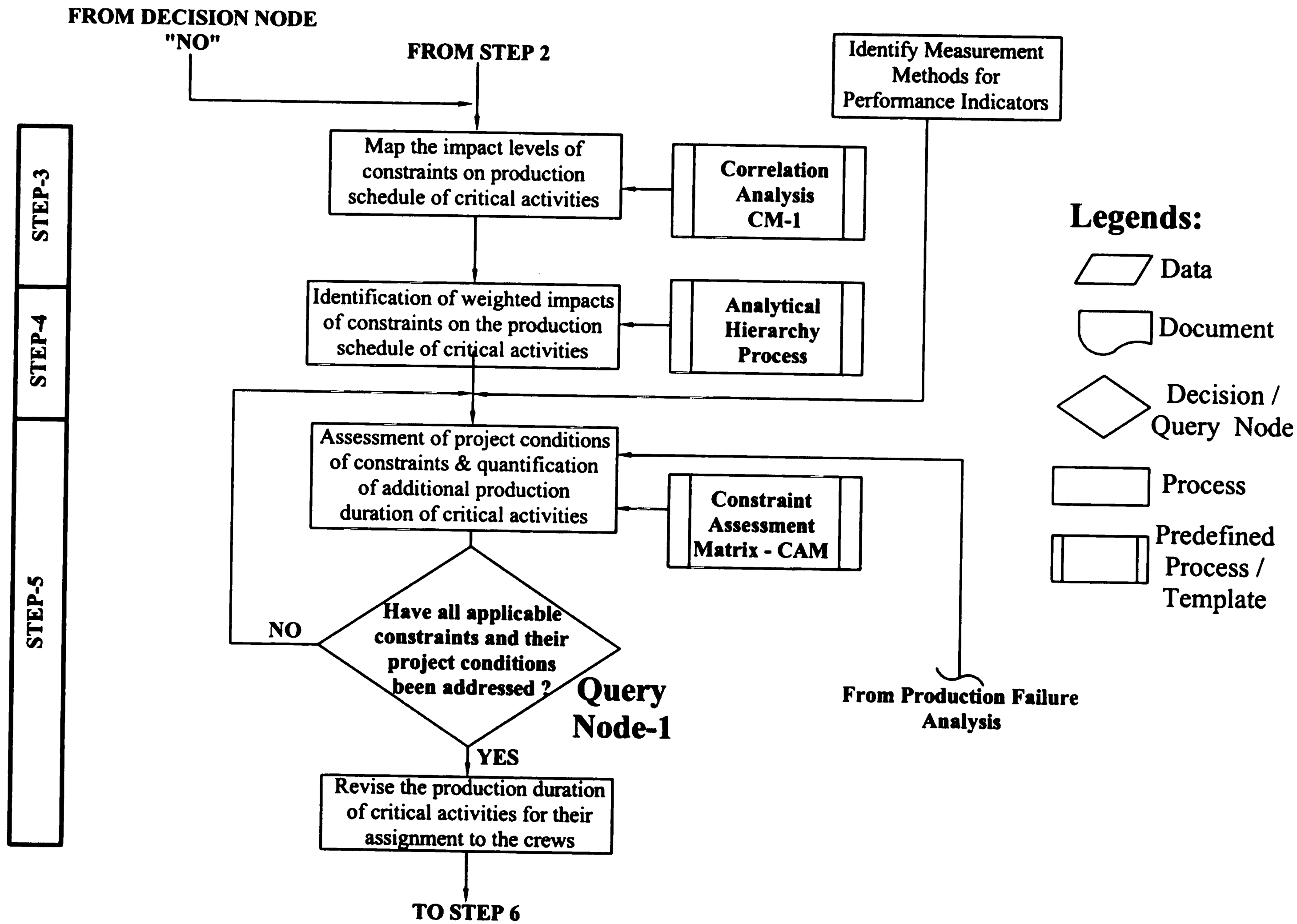

Figure 4.4 (Cont'd)

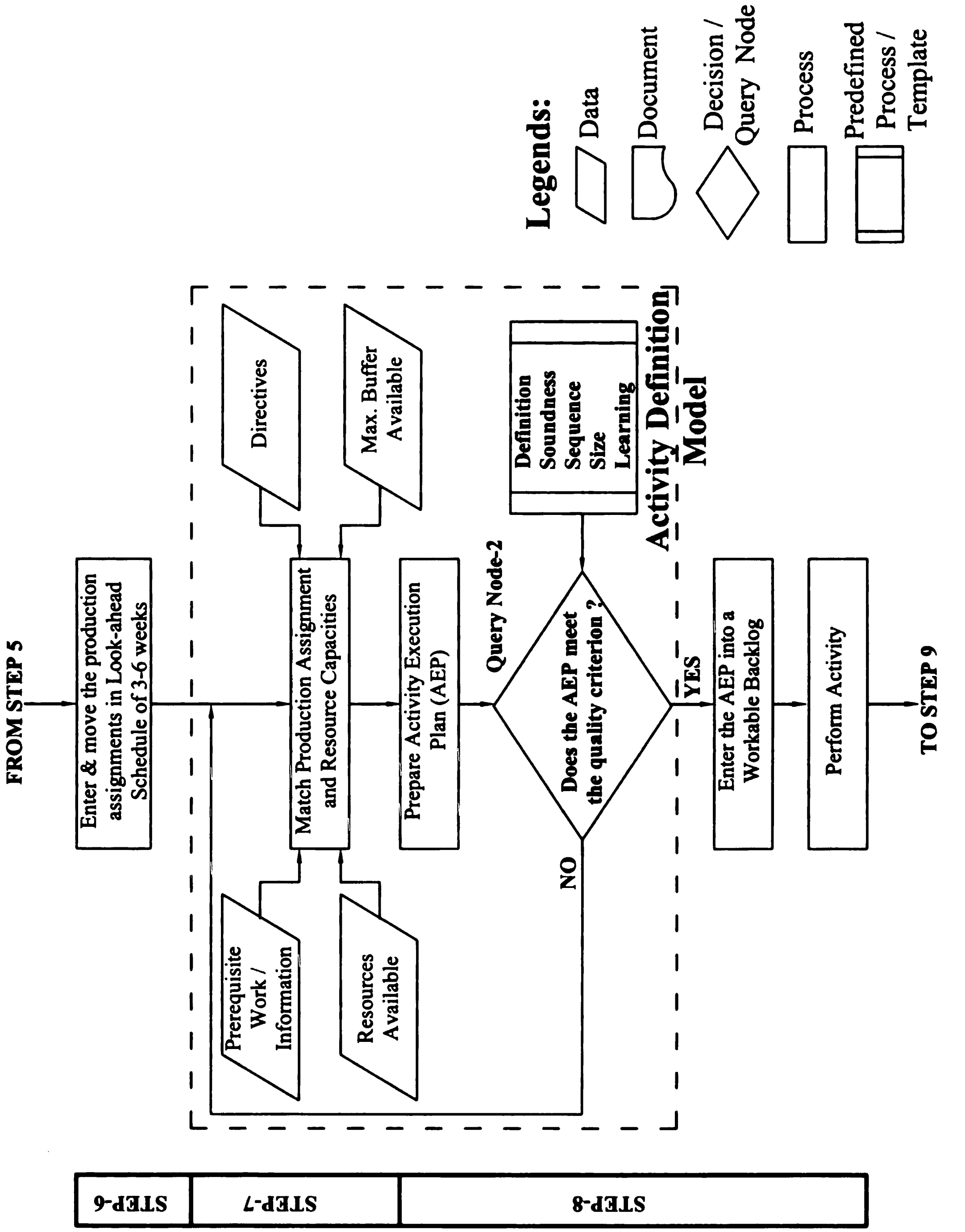

Figure 4.4 (Cont'd)

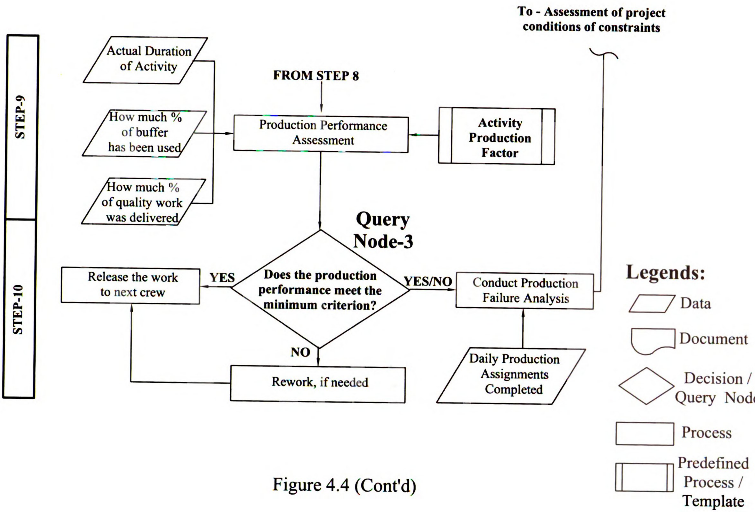

Figure 4.4 (Cont'd)

4.6.1 Step-1 Identify Constraints and Critical Activities

The first step in planning the production of any activity should be to review all pertinent project conditions that might impact the production of various construction activities. These project conditions could be specified in the contract between owner and contractor and/or could be informally communicated to the contractor prior to start the work. As stated by the literature of renovation projects, these project conditions generate various constraints that adversely impact the construction activities. Therefore, as an outcome of the project conditions review, all the constraints should be identified that could be encountered during construction.

Having identified the constraints, all construction activities should be reviewed to identify those the production of which will be impacted by the constraints. These activities are termed critical activities, as their production planning requires a thorough consideration of potential constraints upfront, in order to avoid the cost and schedule overruns. Although, the constraints and critical activities are very project specific, but for the explanation of the framework from steps 2 through 10, the constraints and critical activities have been assumed based on the literature review.

4.6.2 Step-2 Interdependency Relationships between Constraints- Correlation Matrix 1a (CM-1a)

The correlation analysis in step-3 and AHP calculations in step-4 for all constraints could prove to be complex and time consuming. In such case, the synergies between constraints should be explored which might reduce the number of constraints in steps 3 and 4. For example, if there are 20 constraints present for any construction activity, it would be wise to limit this number prior to conducting their correlation analysis with critical processes and AHP calculations by identifying interdependency relationships between these 20 constraints.

Therefore, prior to mapping production impacts of each constraint in different critical activities in step-3, this framework recommends investigating the interdependency levels between all constraints impacting the production. This analysis helps in understanding the contribution of each constraint towards generating other constraints. For instance, if physical constraint is absolutely dependent on coordination constraint, then the impact due to coordination constraint on the production of critical activities would not be solely an outcome of its associated project conditions, but an indirect impact of project conditions of physical constraints also. Therefore, each constraint exhibits a specific dependency level on the existence of other constraints. These dependency levels could be absolute, strong, moderate, slight or none.

Correlation analysis has been adopted as a tool in the form of a matrix to check the interdependency levels between constraints. This matrix is termed as Correlation Matrix-1a (CM-1a). As stated before, performing this analysis has been specified as an optional step in the framework, which would be guided by a decision node, as shown in Figure 4.2, of whether to go through step-2.

Table 4.1 shows an example of CM-1a for a selective demolition activity where each constraint is mapped against all other constraints. In this matrix, each cell (a_{ij}) is referred by its relative row number (i) and column number (j). In the assignment of column and row numbers, the left most column and the top most row are ignored, as they list all the constraints from top to down and left to right respectively.

In this matrix, each cell (a_{ij}) represents the dependency level of "column" constraint on the "row" constraint. For instance, in Table 4.1, cell a_{12} represents that utility constraint is slightly dependent on physical constraint. In another example, the cell a_{36} represents that schedule constraint is absolutely dependent on pollution constraint. As can be seen from Table 4.1, a typical correlation matrix-1a uses five dependency levels, which are; absolute (A), strong (S), moderate (M), slight (SL), and none (N).

Therefore, in order to complete and read this matrix, one should follow each column constraint at one time moving from left to rights, and analyze its dependency level on all row constraints. For instance, in Table 4.1, the user would start filling this matrix from the first column constraint at the left i.e. physical constraint and analyze its dependency on all row constraints moving down from physical to regulatory constraint. It should be noted that in each cell (a_{ij}), the dependency level is to be assigned with the assumption that only ith row constraint and jth constraint are present.

The dependency levels in this matrix have been assigned numerical figures from 1 to 9, which represent the percentage of a column constraint being dependent on row constraint, in the presence of only these two constraints. These numbers would not be employed for performing any quantitative assessment, but they would facilitate in making qualitative judgments of the level of dependencies between constraints. For instance, if physical and coordination are the only constraints present, it would be simple to identify whether one constraint is 30%, 50%, 70%, 90% or 0% dependent on the other constraint as compared to whether the dependency is slight, moderate, strong, absolute or negligible.

A negative sign prior to the dependency level indicates a reverse dependency of row constraint on column constraint. For instance, for cell $_{(13)}$, the negative sign before 'M' indicates that instead of pollution constraint (column) being moderately dependent on physical constraint (row), physical constraint (row) is moderately dependent on pollution constraint (column).

Therefore, relating the numerical figures and dependency signs to Table 4.1, it could be seen that the first column constraint i.e. physical depends 50% on pollution, 90% on coordination, and 0% on regulatory constraint. The negative signs before dependency levels on other row constraints depict that these row constraints are dependent on physical constraint. Thus, utility constraint depends 30%, uncertainty constraint depends 50%, schedule constraint depends 70%, safety constraint depends 70%, and traffic constraint depends 50% on the physical constraint. Similarly, other dependency levels can be interpreted by observing their signs and numerical assessment.

Table 4.1 Correlation Matrix-1a for an Example Selective Demolition Activity

Constraints	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	--	SL	-M	M	-A	S	S	M	N
Utility	-SL	--	SL	S	S	M	A	SL	N
Pollution	M	-SL	--	SL	-A	A	M	SL	SL
Uncertainty	-M	-S	-SL	--	SL	S	-SL	-SL	A
Coordination	A	-S	A	-SL	--	-S	M	M	N
Schedule	-S	-M	-A	-S	S	--	SL	SL	N
Safety	-S	-A	-M	SL	-M	-SL	--	M	N
Traffic	-M	-SL	-SL	SL	-M	-SL	-M	--	N
Regulatory	N	N	N	-A	N	N	N	N	--

Legend

A	Absolute Dependency = 9	S	Strong Dependency = 7	M	Moderate Dependency = 5
SL	Slight Dependency = 3	N	No Dependency = 0		

Note: The relationships in Table 4.1 are only for illustration.

4.6.2.1 Constraint Reduction Process

As stated above, the purpose of identifying dependency relationships between constraints is to limit the complexities involved in correlation analysis in step-3 and AHP calculations in step-4, by reducing the number of constraints. If a column constraint is absolutely dependent on the row constraint, this means that only column constraint could be considered in step-3 and 4, as the column constraint would represent the row constraint. Based on the project conditions, the absolute interdependency relationships could also extend beyond two constraints, which would significantly decrease the number of constraints in subsequent phases.

Based on CM-1a exemplified above, Table 4.2 shows that 5 constraints could be eliminated from further steps due to their absolute dependencies on 3 other constraints. Therefore, for performing further steps of the framework, only 4 constraints could be considered instead of 9.

Table 4.2 Constraint Reduction using CM-1a

Constraint to be Removed	**Representative Constraint**
Physical	Coordination
Pollution	Coordination
Schedule	Pollution
Safety	Utility
Regulatory	Uncertainty

4.6.3 Step-3 Impact levels of Constraints on Estimated Production Schedule of Critical Activities- Correlation Matrix 1 (CM-1)

After obtaining the interdependency levels between constraints, dependencies between the constraints and the estimated production of critical activities would be mapped. This analysis would help in understanding the level of impact that any constraint could have on the estimated production of a critical activity. Similar to CM-1a, a correlation matrix (CM-1) would be prepared between constraints and critical activities to map the impact levels. It is important to map the impacts of constraints on the cost, time and quality of the production critical activities. Therefore, the estimated production of critical activities would be categorized under budgetary, schedule and quality performance and for each category, a separate correlation matrix would be developed against the constraints.

However, this research focuses on identifying only the schedule impacts on the production of critical activities. Therefore, only one type of correlation analysis regarding the schedule impacts would be discussed for the remainder of this thesis.

Table 4.3 shows an example of Correlation Matrix 1 (CM-1) between constraints and critical activities with respect to the impact levels of constraints on production schedule of critical activities. This matrix is constructed on a structure similar to CM-1a except in this case, each constraint is mapped against all critical activities in a matrix form. Each cell (a_{ij}) represents the level of impact that the constraint in ith row has on the production schedule of critical activity in jth column. The impact levels have been categorized under 5 types; absolute (A), strong (S), medium (M), slight (SL), and none (N). These impact levels represent the contribution of constraints in increasing the production schedule of critical activities. For instance, in Table 4.3, cell a_{35} represents that pollution constraint has a strong impact on the production schedule of the selective demolition critical activity. This means that assuming only pollution constraint being present for a selective demolition activity, 70% of its additional duration will be due to the pollution constraint. In another case, cell a_{37} represents that pollution constraint has a moderate impact on the production schedule of MEP rough-in critical activity.

Similar to CM-1a, this matrix should also be completed and read from left to right, considering each critical activity in jth column at one time. While considering a critical activity in jth column, the impact levels of all row constraints on its production schedule should be mapped, moving from top to down. For instance, in Table 4.3, the completion of the correlation matrix should begin from the left most critical activity in the first column i.e. development of plans and specifications. While considering this critical activity, the impact levels of all constraints, from physical to regulatory, on its production schedule should be mapped. Once all the constraints' impact levels have been mapped, the next column should be considered in the same manner. As the impact levels in this case cannot be reversed, only positive sign should be assigned to all the impact levels mapped.

Table 4.3 shows the first approach of constructing a correlation matrix-1 for all the 9 constraints being considered independently. These 9 constraints could have been reduced to 4 based on the constraint reduction process discussed above. Mapping the impact levels of only 4 constraints as representatives of 5 other constraints would become much simpler compared to the process presented in Table 4.3.

This alternative approach of mapping the impacts of only representative constraints, in correlation matrix (CM-1) is presented in Table 4.4. The matrix structure of alternative approach is similar to that of first approach shown in Table 4.3, except that in this case, only representative constraints along with those which are not absolutely dependent on any other constraints are to be mapped against each critical activity.

In this case, it can be seen that the impact levels of representative constraints have been increased as compared to their individual impact levels as mapped in the previous CM-1, as was shown in Table 4.3. This is due to the fact that a representative constraint now characterizes the impact of its dependent constraint also, which should be more than its individual impact.

The correlation matrix-1 between constraints and critical processes is followed by Analytical Hierarchy Process (AHP) to establish the hierarchy of constraints in impacting production of critical processes. Thus, knowing the information in CM-1, either through approach 1 or 2, would facilitate conducting AHP as explained in the next section.

Table 4.3 Correlation Matrix-1 (Approach-1)

Critical Processes	Development of Plans and Specifications	Site Investigation	Preparation of Site Logistics Plan	Temporary Construction	Selective Demolition	Mobilize and Demobilize	M.E.P Rough-ins	Hazardous Material Abatement	Demolition Waste Management	Material & Equiment Procurement
Constraints										
Physical	5	5	9	9	7	7	9	5	5	9
Utility	7	9	3	5	9	5	9	3	1	1
Pollution	3	3	7	7	7	9	5	7	5	5
Uncertainty	9	9	5	5	9	9	9	9	3	3
Coordination	7	5	7	5	5	9	7	3	7	9
Schedule	5	3	5	7	7	5	7	5	5	7
Safety	3	3	5	5	5	7	5	5	5	7
Traffic	3	5	9	9	3	7	3	5	5	9
Regulatory	9	9	3	5	3	3	5	3	5	1

Legend

A	Absolute Impact = 9	S	Strong Impact = 7	M	Moderate Impact = 5
SL	Slight Impact = 3	N	No Impact = 1		

Note: The impact levels in Table 4.3 are only for illustration.

Table 4.4 Correlation Matrix-1 (Approach-2 for Reduced Number of Constraints)

Critical Processes	Development of Plans and Specifications	Site Investigation	Preparation of Site Logistics Plan	Temporary Construction	Selective Demolition	Mobilize and Demobilize	M.E.P Rough-ins	Hazardous Material Abatement	Demolition Waste Management	Material & Equiment Procurement
Constraints										
Utility	7	9	7	7	9	7	9	7	5	5
Uncertainty	9	9	5	5	9	9	9	9	5	5
Coordination	9	7	9	7	7	9	9	5	9	9
Traffic	3	5	9	9	3	7	3	5	5	9

Legend

A	Absolute Impact = 9	S	Strong Impact = 7	M	Moderate Impact = 5
SL	Slight Impact = 3	N	No Impact = 1		

Note: The impact levels in Table 4.4 are only for illustration.

4.6.4 Step-4 Identification of Weighted Impacts of Constraints on the Production Schedule of Critical Activities- Using AHP

In order to better estimate the production schedule of a critical activity in the presence of various constraints, it becomes essential to identify the relative weight at which each constraint impacts the production schedule of critical activities. Assigning suitable weights to each constraint through the quantitative technique of Analytical Hierarchy Process (AHP) was selected to establish the hierarchy amongst constraints.

In order to conduct AHP, a pair-wise comparison matrix is prepared with all constraints being individually placed in rows and columns. Each cell (a_{ij}) represents the importance of its relative row constraint (i^{th} row) over its column constraint (j^{th} column) in impacting the production schedule of a critical activity. The AHP uses a scale of 1 to 9 to reflect the importance level that an i^{th} row constraint has over the j^{th} column constraint. The 9 importance levels are shown in Table 4.5.

Table 4.5 Scale of Importance Levels in AHP (Saaty 1980)

Scale	Definition{Importance of row constraint over column constraint}
1	Equal Importance
3	Weakly more
5	Moderately more
7	Strongly more
9	Absolutely more
1/3	Weakly less
1/5	Moderately less
1/7	Strongly less
1/9	Absolutely less

In each cell of the pair-wise comparison matrix of AHP for all constraints, the assignment of importance level should be referenced to Table 4.5. In addition, this assignment should also be facilitated by the impact levels of constraints mapped in CM-1, as was shown in Table 4.3 and 4.4. For this purpose, this research has mapped the AHP importance levels to the corresponding impact levels of CM-1, as shown in Table 4.6.

Table 4.6 has two major columns. The left column shows the impact levels of CM-1 for any two constraints with all the possibilities of different combinations. Constraint 1 of CM-1, in the left column, represents the ith row constraint being compared to jth column constraint in AHP, which is Constraint 2 of CM-1. The comparison between any two constraints in the pair-wise comparison matrix of AHP should first refer their impact levels on the production schedule of critical activities in CM-1, and then assign the corresponding importance scale of AHP, shown in the right column of Table 4.6. Therefore, the overall purpose of using CM-1 is to facilitate the assignment of importance levels in AHP's pair-wise comparison matrix and to avoid any subjectivity in evaluator's judgments by providing additional data in the form of correlation matrix.

An example of the pair-wise comparison matrix of AHP for all constraints is shown in Table 4.7 that has assigned the importance level of ith row constraint over the jth column constraint in impacting the production schedule of a selective demolition activity. In order to provide the reader a clearer understanding of how to use Table 4.6 for completing Table 4.7, two example cases are illustrated. In the first case, if physical and pollution constraints are being compared in the pair-wise comparison matrix, their impact levels on the production schedule of selective demolition activity should be first referred.

With reference to the impact levels of constraints mapped in CM-1, shown in Table 4.4, it could be seen that both physical and pollution constraints have a 'strong' impact on the production schedule of selective demolition activity. Therefore, in the left column of Table 4.6, if physical constraint represents Constraint 1 and pollution constraint represents Constraint 2, then the pair wise comparison between these two constraints will result in equal importance (a "1" in this case). This "1" should be placed in cell a_{13} of the pair-wise comparison matrix shown in Table 4.7. It should be noted that the numbering of rows and columns does not include the left most column and the top most row as they only list all the constraints.

In the second case example, if physical constraint and safety constraint are being compared in AHP, then with reference to CM-1, shown in Table 4.4, it could be seen that physical constraint strongly impacts the production schedule of selective demolition activity but safety constraint has a moderate impact. Therefore, according to Table 4.6, the pair-wise comparison between physical (Constraint 1) and safety constraint (Constraint 2) should assign a weakly favored scale to physical constraint over safety constraint (a "3" in this case). This "3" should be placed in cell a_{17} of the pair-wise comparison matrix shown in Table 4.7. Similarly, all other cells of the pair-wise comparison matrix, shown in Table 4.7, could be filled.

Using AHP method and Table 4.6, Table 4.8 is produced for the example, which shows the relative weights of constraints in impacting the production schedule for any task belonging to the 'selective demolition' critical activity.

Table 4.6 Mapping of AHP and Correlation Matrix-1 Scales (Modified from Saaty 1980)

Correlation Matrix Scale (CM 1)		AHP	
Constraint 1	Constraint 2	Definition {Importance of row constraint (1) over column constraint (2)}	Scale
N SL M S A	N SL M S A	Equal Importance	1
SL M S A	N SL M S	Weakly more	3
M S A	N SL M	Moderately more	5
S A	N SL	Strongly more	7
A	N	Absolutely more	9
N SL M S	SL M S A	Weakly less	1/3
N SL M	M S A	Moderately less	1/5
N SL	S A	Strongly less	1/7
N	A	Absolutely less	1/9

As per Table 4.8, utility and uncertainty constraints have the most impact on production schedule of selective demolition activity. This means that while planning the duration for any activity of selective demolition, all project conditions related to utility and uncertainty constraints must be identified, assessed, and given the highest priority for their additional duration, otherwise, the actual duration would exceed than what is planned. This is not to say that project conditions of all other constraints should be ignored, they are still required to be considered for additional duration but it will be normalized with lesser priority scale. The assessment of project conditions is explained later in detail in Section 4.6.4.

In order to provide the reader an understanding of how to conduct AHP and calculate relative weights through it, a typical process is discussed in the appendix section (Appendix-2). Therefore, the reader is directed to Appendix-2 for further explanation of AHP.

The AHP process should be repeated for obtaining the hierarchy of constraints in impacting the production schedule of each critical activity. In addition, for obtaining the hierarchy of constraints in impacting the cost and quality of production of critical activities, AHP process should be conducted separately for cost and quality, based on their respective CM-1 matrices. However, this research focuses only on the schedule impacts that constraints have on the production of critical activities.

As stated before, the constraints interdependency relationships would facilitate in limiting the calculations of AHP. If the optional matrix of CM-1 based on the reduced number of constraints, shown in Table 4.4, is used then, as an alternative to conducting

AHP calculations of 9 constraints, only 4 constraints could be considered, as representatives of the 5 other constraints. Table 4.9 and 4.10 show the pair-wise comparison matrix of these 4 constraints and their final weights, respectively. As expected, it could be observed that the weightage of representative constraints in Table 4.10 have increased from that calculated in Table 4.8.

Table 4.7 Pair-wise Comparison Matrix for All Constraints for Appraoch-1

A =

	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	--	1/3	1	1/3	3	1	3	5	5
Utility	3	--	3	1	5	3	5	7	7
Pollution	1	1/3	--	1/3	3	1	3	5	5
Uncertainty	3	1	3	--	5	3	5	7	7
Coordination	1/3	1/5	1/3	1/5	--	1/3	1	3	3
Schedule	1	1/3	1	1/3	3	--	3	5	5
Safety	1/3	1/5	1/3	1/5	1	1/1	--	3	3
Traffic	1/5	1/7	1/5	1/7	1/3	1/5	1/3	--	1
Regulatory	1/5	1/7	1/5	1/7	1/3	1/5	1/3	1	1

Table 4.8 Final Weights for All Constraints through Approach-1

W =

Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
0.114	0.253	0.114	0.253	0.051	0.114	0.051	0.024	0.024

Table 4.9 Pair-wise Comparison Matrix for Approach-2 (Reduced Number of Constraints)

A =

	Utility	Uncertainty	Coordination	Traffic
Utility	--	1	3	7
Uncertainty	1	--	3	7
Coordinatic	1/3	1/3	--	5
Traffic	1/7	1/7	1/5	--

Table 4.10 Final Weights for Limited Number of Constraints

W =

Utility	Uncertainty	Coordination	Traffic
0.394	0.394	0.164	0.048

4.6.5 Step-5 Quantification of Additional Production Duration of Critical Activities based on Project Conditions- Constraint Assessment Matrix (CAM)

The objective of obtaining relative weight of constraints is to better assess the impact of constraints and estimate the production duration of critical activities. After ascertaining the relative weights of all constraints in impacting the production schedule of each critical activity, the production time can be planned through a process of constraint assessment.

Constraint assessment process primarily involves planning the additional duration of critical activities after assessing project conditions, and applying the established hierarchy of constraints to their relevant project conditions. Therefore, for planning the additional duration of critical activities, the following two factors should be considered:

1. Hierarchy of constraints in impacting estimated duration of critical processes
2. Assessment of project conditions of all constraints for estimating the required additional duration of critical activities

Constraint assessment process should be conducted separately for each critical activity involved in the scope of work. This process of planning additional duration of each critical activity is to be conducted through Constraint Assessment Matrix (CAM). For any critical activity, CAM incorporates all constraints, their project conditions as performance indicators, assessment methods of project conditions, additional duration required due to each project condition, and the normalized additional duration based on constraint weight.

An example of CAM for a construction activity of 'selective demolition' is shown in Table 4.11. The assessment of project conditions in Table 4.11 are for illustrations only and do not relate to any real renovation project.

It should be noted that in Table 4.11, CAM lists all project conditions and constraints, irrespective of the type of critical activity being considered. This has been done to avoid project team's unawareness of the impact of any project condition while planning the additional duration of a critical activity. Therefore, even if the assessment of a project condition reveals a 0 day impact, it should be documented for ascertaining the quantified impact of each constraint, and analyzing delay causes after activity execution.

This research has identified the project conditions, shown in Table 4.11, from the literature review and interview data. Therefore, the list of project conditions shown in Table 4.11 is not exhaustive.

For each identified project condition, this research has developed assessment methods to estimate the additional duration from the literature review of state-of-the-art performance measurement systems and construction production management. The assessment of each project condition requires project team's knowledge and previous experience of performing construction activities in similar project condition. In addition, the assignment of quantitative scale values to qualitative project conditions necessitates project teams' expert judgment based on the site conditions and nature of project conditions.

The additional duration due to any project condition of a constraint is estimated based on its developed quantitative or qualitative assessment method depending on the nature of project condition. For instance in the example shown in Table 4.11, the additional duration required due to the project condition of "off-site storage space" can be quantitatively assessed as:

Additional duration = Cycle time to install the material on site / cycle time to deliver the material from off-site storage space to construction site (time lapse between material procurement and material installation

or

1- wait time of crew for receiving the material on site/ cycle time to install the material on site

In this example, the additional duration results in a 0 day duration based on the assumption that off site storage space is not required.

In another case example of quantitative assessment, shown in Table 4.11, the additional duration due to project condition of "noise, dust, debris, vibration, and odor control" can be assessed as:

Additional duration = (Time for enclosing construction zone + time for installing peripheral sound & vibration insulation + time for installing negative air machines + any other time for pollution control activities+ non-work period specified by owner due to pollution problems)

The qualitative assessment applies to those project conditions which are subjected to evaluator's judgment and prior experience. For instance, for the example shown in Table

4.11, the additional duration due to the project condition of "space limitation of on-site storage space" can be qualitatively assessed with a reference quantitative scale as:

Available space	Additional duration (% of original duration)
• More than required	0
• Required	0 to 10
• Limited	10 to 20
• Very limited	more than 20

Based on the assumption that the on-site storage space is bit less than what is required, the additional duration will be increased by 5 % of the original duration. Therefore, as shown in Table 4.11, 0.5 day comes out as the additional duration, as the original duration was 10 days.

After estimating the additional duration due to all project conditions, the total additional duration due to all project conditions of each constraint should be added, and then normalized by multiplying it with the constraint's relative weight obtained through AHP. The normalization process gives the minimum impact that a constraint will have on the production duration. Therefore, the normalized additional duration represents the quantified contribution of a particular constraint at a minimum level, in impacting the production schedule of a critical activity.

For instance, in the example shown in Table 4.11, the total additional duration due to utility constraint is 4 days, which represents the maximum impact of utility constraint on the schedule of selective demolition activity. Based on the relative weight of 0.253 for utility constraint, which is obtained from AHP (Table 4.9), in impacting the schedule, the total additional duration should be normalized to ascertain the least additional duration due to utility constraint, which must be included in the production schedule of selective demolition. The normalized additional duration due to utility constraint is:

Normalized additional duration due to utility constraint = 4 x 0.253 = 1.012 days

Therefore, the additional duration due to the project conditions of each constraint should be normalized according to the relative importance of that constraint in impacting production schedule, obtained from AHP.

The summation of normalized additional duration gives the minimum additional duration (AD_{min}) required for any critical activity. However, the summation of additional duration due to project conditions of all constraints without their normalization, gives a maximum additional duration (AD_{max}) required for any critical activity.

$$AD_{min} = \sum_{i=1}^{N}(\text{additional duration due to project conditions of each constraint}) \times W$$

$$AD_{max} = \sum_{i=1}^{N}(\text{additional duration due to project conditions of each constraint})$$

Where,

N= Number of constraints

W = Relative weights of constraints for impacting production schedule of critical process

With reference to the example in Table 4.11,

AD_{min} = (4 x 0.253) + (1 x 0.114) + (1.25 x 0.142) + (4 x 0.253) + (0.5 x 0.051) + (0 x 0.024) + (0.5 x 0.024) + (0.67 x 0.114) + (0 x 0.051) = 2.393

= 3 days (approx.)

AD_{max} = 4 + 1 + 1.25 + 4 + 0.5 + 0 + 0.5 + 0.67 + 0 = 11.92 = 12 days (approx.)

Therefore, the constraint assessment process results into a range of additional duration, having a minimum and maximum value. An estimated additional duration (EAD) is a middle value of its range, as shown in equation.

$$EAD = \{(AD_{min}) + (AD_{max})\} / 2$$

The Revised Production Duration (RPD) for any critical activity, based on the assessment of constraints would be:

RPD = Original duration (without consideration of constraints) + EAD

For the example shown in Table 4.11, the EAD and RPD are:

EAD = 3 + 12 / 2 = 7.5 = 8 days (approx.)

RPD = 10 + 8 = 18 days

The RPD will serve as a benchmark for critical activities against which the production performance will be evaluated after the execution.

Table 4.11 Constraint Assessment Matrix for an Example Selective Demolition Activity (Approach-1)

Constraints	Project Conditions or Performance Indicators (PI)	Assessment Method	Additional Duration based on assessment	Constraint Weightage from AHP	Normalized Additional Duration based on Constraint weightage [additional duration due to constraint x relative weight of constraint]	Explanation of Assessment
Utility Constraint	1Capacity of downstream system	If the available capacity of the utilities and/or the load bearing capacity of the structure is less than the required capacity for construction activities (loading capacity, electrical loading etc.), then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20		0.253		
	2.Non-disruption to existing utilities	Non work period due to non-disruption to existing utilities	2 days			

Table 4.11 (cont'd)

	3.Impact of existing utilities and/or structural systems on the design of new systems	If the existing capacity of utilities and/or the structural system is less than the required capacities for supporting new and/or upgraded systems, then how much additional duration is required to complete the activity Available capacity . Additional duration (in % of original duration) • More than required 0 • Required 0 to 10 • Limited 10 to 20 • Very limited more than 20	0.2 x 10 = 2 days			
	Total additional duration due to utility constraint		4 days		**4 x 0.253 = 1.012 day**	
Physical constraint	1. Space limitations for construction	Available space . Additional duration (in % of original duration) • More than required 0 • Required 0 to 10 • Limited 10 to 20 • Very limited more than 20	0.05 x 10 = 0.5 day			
	2. Space limitations for material storage	For on-site storage: Available space . Additional duration (in % of original duration) • More than required 0 • Required 0 to 10 • Limited 10 to 20 • Very limited more than 20	0.05 x 10 = 0.5 days			

Table 4.11 (cont'd)

		For off-site storage: Cycle time to install the material on site / cycle time to deliver the material from off-site storage space to construction site (time lapse between material procurement and material installation) or 1- wait time of crew for receiving the material on site/ cycle time to install the material on site	0	0.114		
	3. Space limitation for installing new equipment/material	If the available space is less than the space required to install equipment or material, then how much percentage of activity duration would be increased Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	Total additional duration due to physical constraint		1 day		1 x 0.114 = 0.114 day	
Pollution control	1. Noise, dust, debris, vibration and odor control	(Time for enclosing construction zone + time for installing peripheral sound & vibration insulation + time for installing negative air machines + any other time for pollution control activities+ non-work period specified by owner due to pollution problems)	1.25 days	0.114		
	Total additional duration due to pollution constraint		1.25 days		day	
Uncertainty constraint	1. Non-availability of As-built Drawings	Time required/expended for site investigation	1 day			

Table 4.11 (cont'd)

	2. Presence of unforeseen conditions	Planned time buffer based on site investigation	0	0.253		
	3. Presence of hazardous material	Abatement period for hazardous material	3 days			
	Total additional duration due to uncertainty constraint		4 days		4 x 0.253 = 1.012 day	
Coordination constraint	1. Timing limitations due to owner operations	Non-work period	0.5 day			
	2. Relocation of owner operations to and from swing space	(Minimum time for relocating owner operations to swing space for starting construction + non-work period due to owner relocation from swing space to the renovated space)	0			
	3. Owner furnished equipments	If the work is dependent on installation of owner furnished equipment/material, then value of PI= (Lead time + installation time)	0			
	4. Removal & reinstallation of owner's furniture	Expected removal time for floor mounted furniture in the lobby	0			
	5. Multiple inspections by end-users, owner's representatives and hazardous material inspection team	Expected inspection time	0			
	Total additional duration due to coordination constraint		0.5 day	0.051	0.5 x 0.051 = 0.025 day	

Table 4.11 (cont'd)

Regulatory constraint	1. Non conformance of existing materials or project conditions with current codes	If the existing materials or project conditions do not conform to the current building codes then how much additional duration is required to complete the activity Additional duration (% of original duration) • 0 • 0 to 10 • 10 to 20 • more than 20	0	0.024	0 x 0.024 = 0 day	
	Total additional duration due to regulatory constraint		0			
Traffic constraint	1. Limitations of materials and equipment movement	(Wait time + time lapse b/w material handling from storage space and delivery on site) and/or (Time required for moving or maneuvering equipment/scaffold from one construction location to another) and/or (Labor movement restriction period)	0.5 day	0.024	0.5 x 0.024 = 0.012 day	
	Total additional duration due to traffic constraint		0.5 day			
Schedule constraint	1. Work Restructuring and/or Sequencing of Trades	Additional duration due to work restructuring	0	0.114	0.67 x 0.114 = 0.076 day	
	2. Impact on crew productivities	Decrease in productivity/estimated productivity x original duration	20/300x10 = 0.67 day			
	Total additional duration due to schedule constraint		0.67 day			

Table 4.11 (cont'd)

Safety constraint	1. Users & public	Time to be expended in special safety consideration	0	0.051	0 x 0.051 = 0 day	
	Total additional duration due to safety constraint		0			
Range of Additional Duration			**Maximum 11.92 = 12**		**Minimum 2.393 = 3**	
Estimated Additional Duration (EAD)			**7.5 = 8 days**			
Revised Production Duration of selective demolition of ceiling system = Original Duration + Estimated Additional duration			**10 + 8 = 18 days**			

Note: The assessment of Project Conditions are for illustration only.

The constraint assessment matrix shown in Table 4.11 is based on the independent impacts of constraints mapped in CM-1 (Table 4.3) and their relative weights calculated in AHP for all 9 constraints. For the alternative approach in which the number of constraints was reduced to 4 due to their interdependencies a different method for constraint assessment should be followed.

Table 4.12 shows the alternative CAM which is based on the same structure of the previous CAM in Table 4.11, but due to the interdependencies, the framework recommends two major deviations which are:

1. Normalizing the estimated additional duration due to each constraint should be based on their relative weights obtained from the constraint reduction process (CM-1a, Table 4.1), and the AHP using the reduced number of constraints (Table 4.10).
2. The constraints which were observed to be absolutely dependent on others will have the total additional duration due to their project conditions, added to the additional duration due to their representative constraints.

The purpose of including these deviations during the constraint assessment process is to preserve the consideration of those constraints which were removed from AHP and CM-1. For instance, in Table 4.1, physical constraint was observed to be absolutely dependent on the coordination constraint for the example activity of selective demolition and therefore, was removed from CM-1 (Table 4.4) and AHP calculations (Table 4.10). The removal of physical constraint from AHP makes its relative weight to be 0 for the constraint assessment process. However, 0 relative weight does not imply that the additional duration due to project conditions of physical constraints would also be 0.

As shown in Table 4.12, the additional duration due to physical constraint is 1 day for the selective demolition activity. Normalizing this duration based on 0 relative weight will again result in 0 additional days and the impact of physical constraint will not be considered in planning the additional duration of selective demolition activity. Therefore, in order to reflect the impact of physical constraint and maintain its consideration, this 1 day should be added to the additional duration due its representative constraint i.e. coordination.

Based on the above mentioned deviations, Table 4.12 shows an example of constraint assessment process for a selective demolition activity, in which the dependent constraints have been assigned a relative weight of 0, while all other constraints' weightage have been obtained from AHP conducted in Table 4.10.

In this case, the assessment methods for project conditions are similar to those in the first approach. The alternative CAM incorporates an additional section after each constraint's assessment for identifying if the constraint is a representative one or being represented by other constraint. In the first case, the additional duration due to represented constraints should be added to its additional duration while in the latter case, the additional duration due to its project conditions should be added to its representative constraint. For instance, in Table 4.12, as schedule constraint is represented by the pollution constraint, the total additional duration due to schedule constraint (0.67 day) has been added to the total additional duration due to the pollution constraint. In other case, as physical constraint is represented by coordination constraint, the additional duration due to physical constraint (1 day) has been added to the additional duration due to coordination constraint. In order to avoid any repetition or error, once the additional duration of represented constraint has been added to its representative constraint, the additional duration due to the former should become 0. This can be seen with utility and physical constraint in Table 4.12.

After adding the total additional duration due to the project conditions of each constraint including its represented constraints, the overall method of normalization of additional duration also differs from what is discussed in the first approach. The normalization of all represented constraints results a 0 day additional duration due to their 0 relative weights which means that the additional duration due to the represented constraints would be normalized with the relative weight of its representative constraint, as are the cases with utility and physical constraints in Table 4.12.

Therefore, this approach of constraint assessment process also results into a range of additional duration, having a minimum and maximum value. An estimated additional duration (EAD) is a middle value of its range, as shown in equation.

$$EAD = \{(AD_{min}) + (AD_{max})\} / 2$$

The Revised Production Duration (RPD) for any critical activity, based on the alternative approach of constraint assessment would be:

$$RPD = \text{Original duration (without consideration of constraints)} + EAD$$

For the example shown in Table 4.12, the EAD and RPD are:

$$EAD = 4 + 12 / 2 = 8 \text{ days (approx.)}$$

$$RPD = 10 + 8 = 18 \text{ days}$$

It could be seen that the maximum value of additional duration (AD_{max}) is not changed from approach 1 to 2, as the assessment methods of project conditions are same in both approaches and AD_{max} is just the summation of additional duration without their normalization. The difference of 0.5 day is encountered in AD_{min} values due to the change in normalization method with the additional duration due to represented constraints being normalized according to the relative weights of their representative constraints. The differences between the results of both approaches have been discussed later in the demonstration section.

Similarly, Estimated Additional Cost (EAC) can be ascertained for a critical activity, where the assessment of project conditions would involve estimating the additional cost required. In such case, the relative weights of constraints would also change for impacting the production cost of critical activities.

Table 4.12 Constraint Assessment Matrix for an Example Selective Demolition Activity (Approach-2)

Constraints	Project Conditions or Performance Indicators (PI)	Assessment Method	Additional Duration based on assessment	Constraint Weightage from AHP	Normalized Additional Duration based on Constraint weightage [additional duration due to constraint x relative weight of constraint]	Explanation of Assessment
Utility Constraint	1Capacity of downstream system	If the available capacity of the utilities and/or the load bearing capacity of the structure is less than the required capacity for construction activities (loading capacity, electrical loading etc.), then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	2.Non-disruption to existing utilities	Non work period due to non-disruption to existing utilities	2 days			
	3.Impact of existing utilities and/or structural systems on the design of new systems	If the existing capacity of utilities and/or the structural system is less than the required capacities for supporting new and/or upgraded systems, then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0.2 x 10 = 2 days			
	Additional duration due to represented constraints (Safety)		0 day			
	Total additional duration due to utility constraint		**4 days**			

Table 4.12 (cont'd)

Is Utility constraint being represented by any other constraint	**If Yes, the additional duration due to utility constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to utility constraint should remain the same.**	**No**	**4 days**	0.394	4 x0.394 = 1.576 day	
Physical constraint	1. Space limitations for construction	Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0.05 x 10 = 0.5 day			
	2. Space limitations for material storage	For on-site storage: Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0.05 x 10 = 0.5 days			

Table 4.12 (cont'd)

		For off-site storage: Cycle time to install the material on site / cycle time to deliver the material from off-site storage space to construction site (time lapse between material procurement and material installation) or 1- wait time of crew for receiving the material on site/ cycle time to install the material on site	0			
	3. Space limitation for installing new equipment/material	If the available space is less than the space required to install equipment or material, then how much percentage of activity duration would be increased Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	Additional duration due to represented constraints		0			
	Total additional duration due to physical constraint		1 day			

Table 4.12 (cont'd)

Is Physical constraint being represented by any other constraint	**If Yes, the additional duration due to physical constraint should become 0 and carry over it's original additional duration to representative constraint. If No, the additional duration due to physical constraint should remain the same.**	**Yes- Coordination constraint**	**0 day**	0	0 x 0 = 0 day	
Pollution control	1. Noise, dust, debris, vibration and odor control	(Time for enclosing construction zone + time for installing peripheral sound & vibration insulation + time for installing negative air machines + any other time for pollution control activities+ non-work period specified by owner due to pollution problems)	1.25 days			
	Additional duration due to represented constraints (Schedule)		0.67 day			
	Total additional duration due to pollution constraint		1.92 days			

Table 4.12 (cont'd)

Is Pollution constraint being represented by any other constraint	**If Yes, the additional duration due to pollution constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to pollution constraint should remain the same.**	**Yes- Coordination constraint**	**0 day**	0	0 x 0 = 0 day	
Uncertainty constraint	1. Non-availability of As-built Drawings	Time required/expended for site investigation	1 day			
	2. Presence of unforeseen conditions	Planned time buffer based on site investigation	0			
	3. Presence of hazardous material	Abatement period for hazardous material	3 days			
	Additional duration due to represented constraints (Regulatory)		0			
	Total additional duration due to uncertainty constraint		4 days			

Table 4.12 (cont'd)

Is Uncertainty constraint being represented by any other constraint	**If Yes, the additional duration due to uncertainty constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to uncertainty constraint should remain the same.**	**No**	**4 days**	0.394	4 x 0.394 = 1.576 day	
Coordination constraint	1. Timing limitations due to owner operations	Non-work period	0.5 day			
	2. Relocation of owner operations to and from swing space	(Minimum time for relocating owner operations to swing space for starting construction + non-work period due to owner relocation from swing space to the renovated space)	0			
	3. Owner furnished equipments	If the work is dependent on installation of owner furnished equipment/material, then value of PI= (Lead time + installation time)	0			
	4. Removal & reinstallation of owner's furniture	Expected removal time for floor mounted furniture in the lobby	0			
	5. Multiple inspections by end-users, owner's representatives and hazardous material inspection team	expected inspection time (multiple no.)	0			

Table 4.12 (cont'd)

	Additional duration due to represented constraints (Physical and Pollution)		1 + 1.92 = 2.92 days			
	Total additional duration due to coordination constraint		3.42 days			
Is Coordination constraint being represented by any other constraint	**If Yes, the additional duration due to coordination constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to coordination constraint should remain the same.**	**No**	**3.42 days**	0.164	3.42 x 0.164 = 0.561 day	
Regulatory constraint	1. Non conformance of existing materials or project conditions with current codes	If the existing materials or project conditions do not conform to the current building codes then how much additional duration is required to complete the activity Additional duration (% of original duration) • 0 • 0 to 10 • 10 to 20 • more than 20	0			
	Additional duration due to represented constraints		0			
	Total additional duration due to regulatory constraint		0			

Table 4.12 (cont'd)

Is Regulatory constraint being represented by any other constraint	**If Yes, the additional duration due to regulatory constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to regulatory constraint should remain the same.**	**Yes- Uncertainty constraint**	**0 day**	0	0 x 0 = 0 day	
Traffic constraint	1. Limitations of materials and equipment movement	(Wait time + time lapse b/w material handling from storage space and delivery on site) and/or (Time required for moving or maneuvering equipment/scaffold from one construction location to another) and/or (Labor movement restriction period)	0.5 day			
	Additional duration due to represented constraints		0			
	Total additional duration due to traffic constraint		0.5 day			

Table 4.12 (cont'd)

Is Traffic constraint being represented by any other constraint	**If Yes, the additional duration due to traffic constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to traffic constraint should remain the same.**	**No**	**0.5 day**	0.048	0.5 x 0.048 = 0.024 day	
Schedule constraint	1. Work Restructuring and/or Sequencing of Trades	Additional duration due to work restructuring	0			

Table 4.12 (cont'd)

	2. Impact on crew productivities	Decrease in productivity/estimated productivity x original duration	20/300x10 = 0.67 day			
	Additional duration due to represented constraints		0			
	Total additional duration due to schedule constraint		0.67 day			
Is Schedule constraint being represented by any other constraint	**If Yes, the additional duration due to schedule constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to schedule constraint should remain the same.**	**Yes- Pollution constraint**	**0 day**	0	0 x 0 = 0 day	

Table 4.12 (cont'd)

Safety constraint	1. Users & public	Time to be expended in special safety consideration	0			
	Additional duration due to represented constraints		0			
	Total additional duration due to safety constraint		0			
Is Safety constraint being represented by any other constraint	**If Yes, the additional duration due to safety constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to safety constraint should remain the same.**	**Yes- Utility constraint**	**0 day**	0	0 x 0 = 0 day	
Range of Additional Duration			**Maximum 11.92 = 12**		**Minimum 3.737 = 4**	
Estimated Additional Duration (EAD)			**8 days**			
Revised Production Duration of selective demolition of ceiling system = Original			**10 + 8 = 18 days**			

Note: The assessment of Project Conditions are for illustration only.

4.6.6 Step-6 Enter and Move Production Assignments in Lookahead Schedule

As a part of the lookahead process, the Last Planner System ™ (LPS) of production control suggests preparing a lookahead schedule of the upcoming work for the next 3 to 12 weeks for the purpose of controlling the flow of work between trades (Ballard 2000). The appropriate size of lookahead window is the function of project characteristics and lead times for material, information, labor and equipments (Ballard 2000, Howell et al. 2002).

Having reviewed the complexities of renovation projects from both literature and interviews, this research recommends incorporating a lookahead schedule as an integral part of the production management framework. This framework employs the lookahead schedule for its intended objective as suggested by Ballard (2000), of producing a "phase" schedule of those activities that "can" be performed based on the state of the system (constraint analysis) rather than what "should" be performed as per the CPM. The lookahead schedule would assure a reliable workflow between trades and reinforce the constraint assessment before executing any activity. Therefore, while preparing the lookahead schedule, a general rule is that only those activities or assignments for which the constraints have been removed or addressed, through CAM, should be allowed to enter and move in a lookahead schedule.

The fulfillment of this rule would be facilitated by a query node (Query Node-1) in the framework. Prior to revising the production duration of critical activities based on the Constraint Assessment Matrix (CAM), query node-1 assures that in the CAM, all the pertinent constraints are addressed with the assessment of their project conditions to identify additional duration. Figure 4.5 shows the location of query node-1 in the framework. If the answer to the query is "no", the framework suggests to go backward to conduct CAM again considering all constraints and their project conditions. In case of a "yes" answer, one should follow the next step of revising the production duration of critical activities and entering them into the lookahead schedule. Therefore, query node-1 reinforces the consideration of all constraints upfront rather than reacting to them later on which could adversely affect the production schedule.

In the lookahead schedule, the activities would begin to advance forward week by week as their preceding activities are selected for further steps of the framework. During this time, if any activity for which a new constraint is generated, would not be allowed to move forward but would be directed to go backward to the CAM for assessing the impact of constraints and revising its production duration.

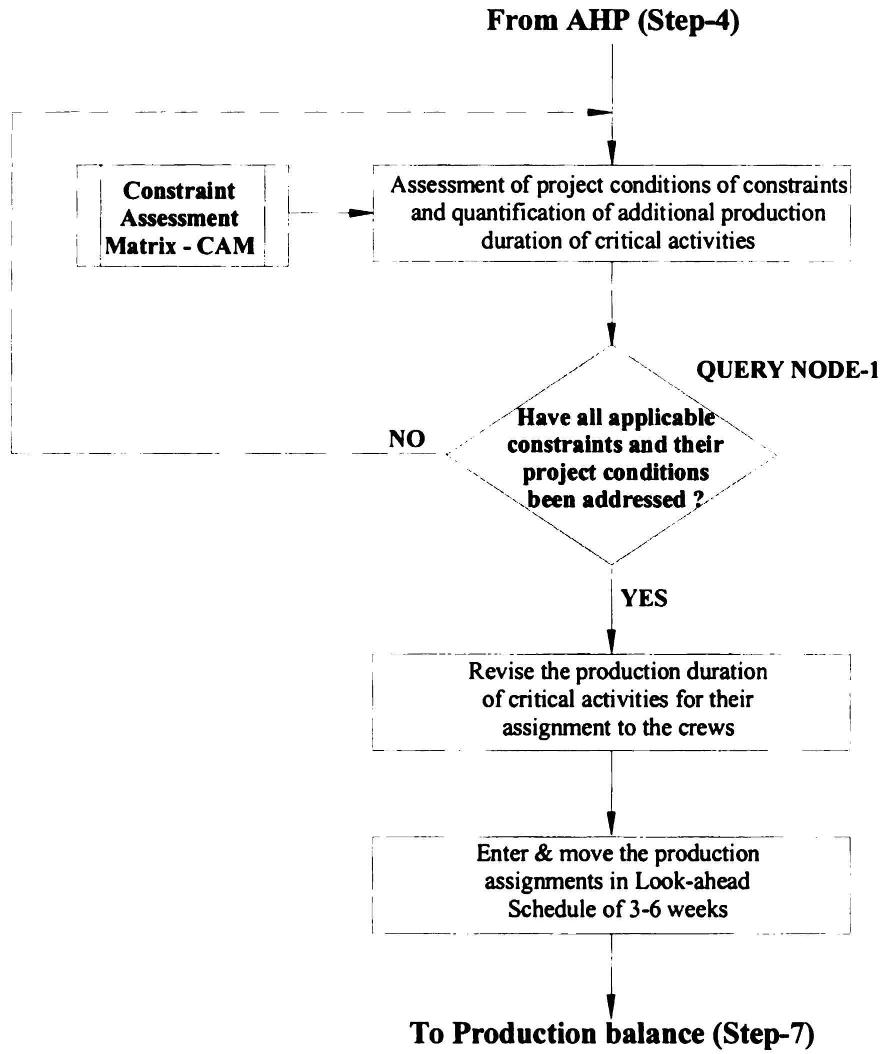

Figure 4.5 Function of Query Node-1 in the Framework

4.6.7 Step-7 Match Production Assignments and Resource Capacities

As discussed in Chapter 2, the Activity Definition Model (ADM) of the Last Planner System ™ explodes each activity to analyze the three broad constraints for its execution which are; perquisite work, required resources, and directives. As the name suggests, prerequisite work represents the base or structure which should be in place before executing the activity. Resources could be labor, tools, equipment and/or space while directives dictate the production of activity against which its performance is assessed (Ballard 2000).

As the framework covers the assessment of internal constraints generated from project conditions of renovation projects, it also becomes essential to investigate the external constraints which are required to execute the production assignments critical activities within their estimated duration. Having only considered the internal constraints in production planning could have adverse impacts on production performance. Therefore, this research adopts the ADM for analyzing production assignments of renovation projects from the perspectives of four broad external constraints, including the three stated above and the fourth one is maximum time buffer available for executing the activity. The maximum time buffer for any activity is the difference between its maximum additional duration and estimated additional duration, as calculated from the constraint assessment matrix.

Maximum Time buffer = AD_{max} - EAD

For instance, the maximum time buffer for the example selective demolition activity, as calculated from its CAM, shown in Table 4.12, is:

Maximum time buffer = 12 – 8 = 4 days

The amount of duration over and above the additional duration, estimated on the basis of constraint assessment, during which any activity should be completed represents the maximum time buffer for that activity. As the amount and availability of time buffer for any activity could affect the assignment of resources, it represents one of the four major constraints in ADM for renovation projects.

Figure 4.6 shows the ADM in the developed framework, which suggests that once an activity is selected for its execution from the lookahead schedule, it should be exploded to analyze the four broad constraints based on which, the production capacities of the available resources should be compared with the scope of work required to be completed in its revised production duration. This means either adjusting the resources according to the production duration or production duration according to the available resources or both. This balance between production duration and available resources, based on the analysis of external constraints would result in a workable production assignment.

4.6.8 Step-8 Activity Execution Plan

After estimating the revised production duration of critical activities and balancing it with the available resources, their execution plan would be developed by using the constraint assessment matrix that would provide guidance for their execution. Table 4.13 shows an example of an Activity Execution Plan (AEP) for a selective demolition activity that stipulates the planned resources, revised production duration, estimated work quantity, planned buffer, and prerequisite work.

Development of this plan before activity execution represents a proactive approach of planning the production in the presence of constraints, both internal and external. This plan would also involve the daily production schedule that will direct the contractor in executing daily construction activities based on the revised production duration estimated from constraint assessment process. The daily production schedule would drive the contractor for establishing daily production assignments for crews, keeping in mind the constraints, so that the activity could be finished within its revised production duration. Therefore, a major significance to the contractor for creating this plan is to prepare for all possible constraints, and release only those assignments for production for which the line of attack of each constraint has been worked out and could be finished within their revised duration, even if the resources to perform the task and its prerequisite work are available.

Although, AEP shows a maximum time buffer available for an activity, but its end date is still constrained by the start date of next immediate activity. Thus, the use of buffer is discouraged, unless any deviations in production assignments are encountered due to unforeseen conditions because employing the time buffer would effect the start date of next immediate activity.

Table 4.13 Activity Execution Plan

Activity	**Selective Demolition of Interior walls**
Prerequisite Work	Stripping of Floor carpet
Planned Resources	1 Foreman, 3 Labors, 2 Carpenters
Estimated Quantity	300 sqft (3 Phases)
Critical Activity	Selective Demolition
Optimum Schedule	10-01-07 to 10-19-07
Optimum Production Duratior	18 Days
Maximum Buffer	4 Days (till 10-23-07)
Next Activity	Installation of carpet flooring scheduled to be started on 10-20-07
Production Schedule	
Days	**Production Assignment**
10-01-07 - Monday	The crew forman will conduct a thorough site investigation and an inspection might be conducted by the Hazardous material abatement team.
. . . . .	. . . . .
10-19-07 - Friday	Finish installation of all fixtures and uninstall temporary wall around Phase-3 and clean up.

4.6.8.1 Quality Criteria for Activity Execution Plan – Query Node 2

During the initial application of the last planner system, Ballard and Howell (1997) found that approximately 50% of the planned assignments were completed by the crews. It was concluded that this was an outcome of an inadequate work selection from the lookahead schedule, which also gets affected by the dynamics and uncertainties of the production systems. The lack of consideration of the quality of work being selected adversely affected the reliability of the work flow. It became apparent that the quality of production assignments should be assessed before selecting for execution. Therefore, as a possible solution, quality criteria were proposed for assessing the assignments. The quality criteria has five dimensions; definition, soundness, sequence, size, and learning.

"Definition" means whether the assignment explains in detail the type and amount of materials to be collected, required coordination with other trades so that it can be made ready, and it is possible to verify and conclude the completion of the assignment. "Soundness" determines the feasibility of the assignment in terms of its pre-requisite work and available resources. "Sequence" assesses the internal logic of the work from the standpoints of constructability, customer requirements and overall project goals. "Size" reviews whether the right amount of work is selected as per the productive capability of crews and could be completed within the planned time frame. The last criterion, "learning", focuses on assessing whether the incomplete assignments are being tracked with their causes.

This research has captured from the literature review of renovation projects that uncertainty and dynamism form their primary characteristics that affect production

(Krizek et al. 1996, Mitropoulos 2002, Wayne et al. 1988). These projects constantly exhibit changing conditions, which could affect the reliability of workflow in their production systems, even if the internal and external constraints have been assessed prior to entering the assignments in lookahead schedule, and their execution plans have been developed. As a result, in renovation projects, it becomes imperative for the last planner to assess the quality of each Activity Execution Plan (AEP) developed in the previous step of the framework, and to verify that the performance of AEP meets the required quality criteria. The framework suggests employing the quality criteria of Last Planner System ™ including five dimensions, as proposed by Ballard and Howell. As all the five dimensions of quality criteria are subjective in nature, their assessment could be done on qualitative basis.

Therefore, as shown in Figure 4.6, for the purpose of improving the reliability of workflow in renovation projects, this framework proposes a query node (Query Node-2) after preparing the AEP that checks whether the plan meets the required quality criteria. Being a qualitative assessment, the decision at this query node is a function of evaluator's/last planner's past experience and knowledge in managing production of renovation projects. If the answer to the query node is "no", it means that either one or more quality dimensions of the AEP i.e. definition, soundness, sequence, size, and learning, does not satisfy the minimum requirements and the plan will not be released for execution. In such case, as the Figure 4.4 depicts, the AEP should be sent backwards to revisit its activity definition model for adequately matching the production assignment and resource capacities. In the other case, the AEP should be forwarded to the backlog of workable plans.

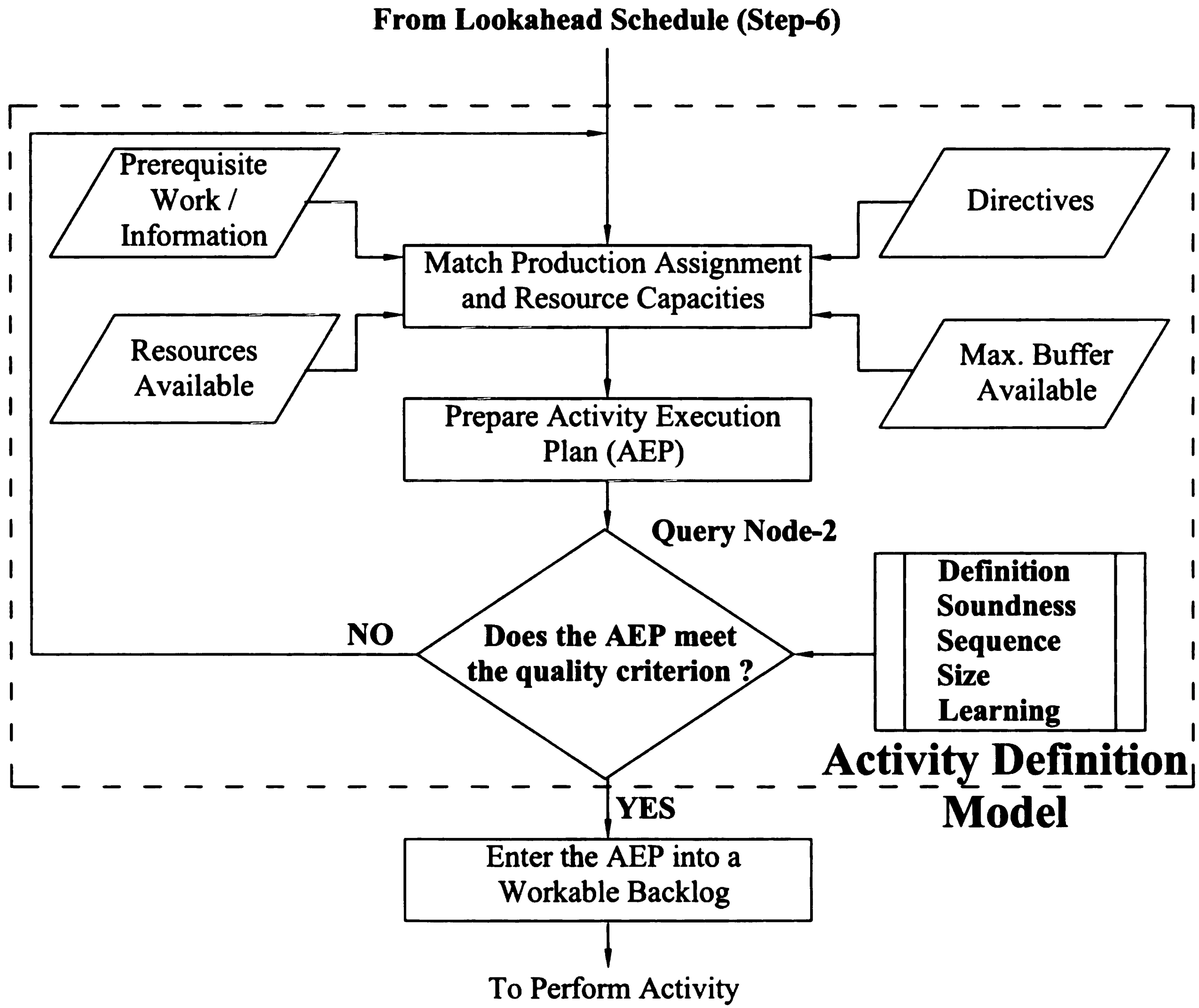

Figure 4.6 Activity Definition Model adopted in the Framework

4.6.8.2 Enter Activity Execution Plan in Workable Backlog

The workable backlog forms a part of the last planner system, as suggested by Ballard and Howell (1997), where its objective is to maintain a backlog of sound assignments that can be made ready for execution. Having assessed the quality of assignments, the workable backlog assures that the assignments in workable backlog are realistic and workable. The workable backlog is usually made for the upcoming assignments of 2 weeks (Ballard 2000, Howell et al. 2002).

Therefore, once the quality of the Activity Execution Plan (AEP) is verified in the previous step of the framework (if the answer is "yes" in query node-2), it should be placed in a backlog of assignments, which the crew knows can be done in their estimated production duration. Figure 4.6 shows the location of workable backlog in the framework. This framework suggests that the size of workable backlog could be a function of project characteristics and duration, as renovation projects could have short durations also. Any AEP that forms a part of workable backlog provides assurance that all the potential constraints, both internal and external, have been addressed and the quality performance of the plan has been assessed from the five dimensions mentioned above. Thus, any critical activity whose AEP is in the workable backlog can be made ready to be performed by the crew.

4.6.9 Step-9 Production Performance Evaluation

After the activity execution, its production performance would be evaluated by comparing the actual duration and revised production duration, as shown in Figure 4.7.

At the production level, the performance evaluation includes measuring the consistency of work-flow between hand-offs. In this context, flow and quality of work delivered between the trades are required to be measured after activity execution. Therefore, the percentage of quality work delivered to the next trade and the percentage of planned buffer used should also be measured. The production performance of any critical activity, say selective demolition, would be expressed by the Activity Production Factor (APF), explained as follows:

Activity Production Factor $(APF)_{\text{Selective demolition}}$ =

(Revised production duration/ Actual duration) + (% of quality work delivered to the next trade/100) + (1- % of buffer) } / 3 equation 4.1

The three components of APF are shown in Figure 4.7. A desired value of APF for any activity would always remain 1. As per the equation 4.1, an APF value of 1 means that the activity finished within the revised production duration delivering 100% of quality work to the next trade, and without using any percentage of time buffer initially planned. In a renovation project, although, achieving an APF value of 1 could be a utopian situation, but comparing APF with its desired value of 1 could determine the level of underperformance in the production efficiency of a crew and apply the learning in further activities. Therefore, the comparison between desired and actual values of APF would provide a stretch goal to work towards continuous performance improvement.

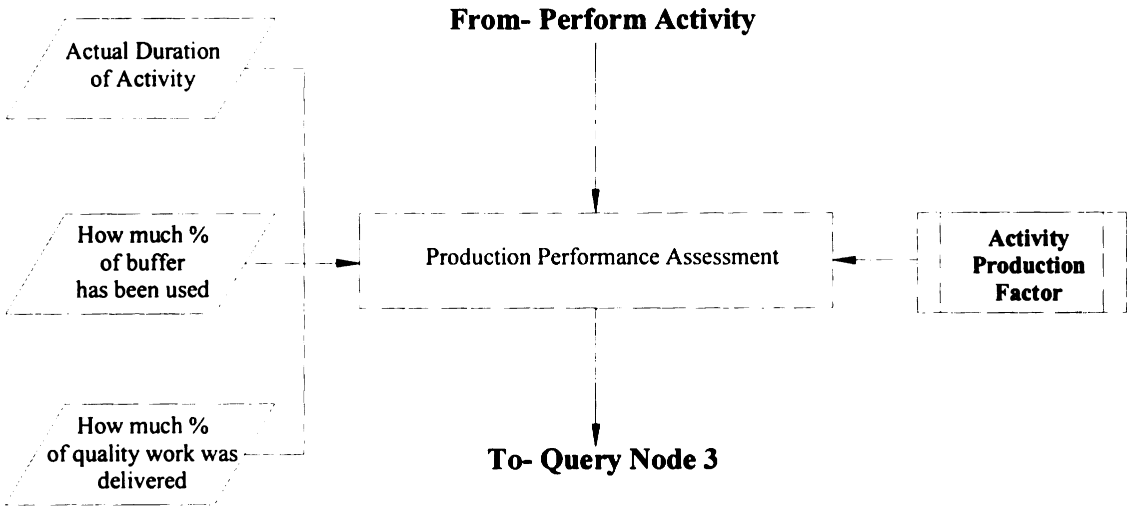

Figure 4.7 Components of Production Performance

In order to release any work to the next trade, it is essential to verify that the production performance of the completed work at least meets the minimum criterion in regard to its APF value. Otherwise, the quality defects of the delivered work could get unnoticed by the next crew and the delivered work would also affect the production of the next activity, as it might first required to be reworked before the next crew begins to work. This would impact the reliability of the work flow and generate more waste in the production of next activities. Therefore, instead of delivering a defected work between trades, it should be corrected at its source and then moving it further.

The framework suggests a query node (Query Node-3) after the production performance assessment to verify whether it meets the minimum criterion before releasing it to the next trade. As shown in Figure 4.8, if the answer to the query node is "no", production failure analysis should be conducted and simultaneously, the work should be redone, if needed. If the answer is "yes", the work would be released to the next trade, but the production failure analysis still needs to be conducted to improve the production efficiency further. The process of how to conduct production failure analysis is explained in the next section.

4.6.10 Step-10 Production Failure Analysis

A comparative analysis of Activity Production Factor (APF) of a critical activity with its desired value of 1 could estimate the underperformance level of the activity and identify those constraints that impacted the activity's production. This process of ascertaining the production underperformance levels along with their causes has been termed as production failure analysis for this research. For instance, if APF of a critical activity comes out as 0.7, this means that the crew fell approximately 30% short of completing their production assignments within the estimated production duration, and of desired quality. The 30% production failure could be attributed to either single or multiple constraints.

In order to ascertain which constraints have resulted in production failure or poor quality, the actual crew production should be documented on a daily basis against the production schedule of Activity Execution Plan (AEP). Table 4.14 shows an example of actual daily production of a demolition crew against the production schedule of its AEP. The documentation of actual daily production would lead to a better understanding of which project conditions have affected the production that were not accounted for in the constraint assessment matrix.

For instance, in the example shown in Table 4.14, the comparison between planned production and actual production documented for date "10-19-07" illustrates that the temporary walls could not be uninstalled because of public traffic near construction zone. This means that "traffic" constraint was either not properly assessed or ignored during the constraint assessment process of production planning. It could also be concluded that the weighted impact of traffic constraint on the production schedule of the exemplified activity of "selective demolition of interior walls" was not established through AHP of constraints and/or correlation matrix.

Therefore, the overall objective of conducting production failure analysis is to direct better judgments for the assessment of constraints in future production planning for similar activities. Thus, in Figure 4.6, the production failure analysis is preceded by a feedback loop to the constraint assessment matrix that maintains a continuous learning after each activity execution from its failure analysis, by improving the identification and assessment of constraints.

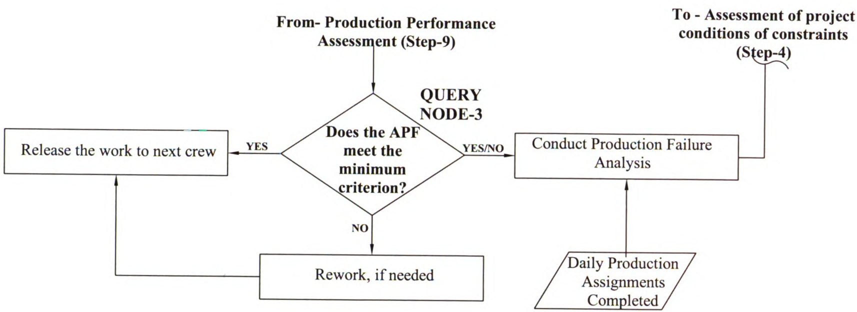

Figure 4.8 Function of Query Node-3 in the Framework

Table 4.14 Actual Daily Production Documentation for Production Failure Analysis

Activity	Selective Demolition of Interior walls	
Prerequisite Work	Stripping of Floor carpet	
Planned Resources	1 Foreman, 3 Labors, 2 Carpenters	
Estimated Quantity	300 sqft (3 Phases)	
Critical Activity	Selective Demolition	
Optimum Schedule	10-01-07 to 10-19-07	
Optimum Production Duration	18 Days	
Maximum Buffer	4 Days (till 10-23-07)	
Next Activity	Installation of carpet flooring scheduled to be started on 10-20-07	
Production Schedule		**Daily Production Documentation**
Days	**Production Assignment Planned**	**Production Assignment Completed (Yes/No)**
09-03-07 - Monday	The crew forman will conduct a thorough site investigation and an inspection might be conducted by the Hazardous material abatement team.	Site investigation and Inspection completed
. . . . .	. . . . .	. . . . .
10-19-07 - Friday	Finish installation of all fixtures and uninstall temporary wall around Phase-3 and clean up.	Installation of fixtures completed but temporary walls could not be uninstalled due to public traffic near construction zone.
10-20-07- Saturday	None	Temporary walls uninstalled

4.6.11 Summary of Developed Framework for Renovation Projects

The production management framework is developed from the literature review of state-of-the-art performance measurement systems, renovation projects' complexities, and production management of construction processes. By linking the essential attributes of production performance management in renovation projects, this framework presents a detailed process of planning and assessing the production performance at the activity level of renovation projects.

In addition to the literature review, the production management framework incorporates the inputs for the essential attributes from the interview responses. For instance, the interviewees were asked to identify project conditions of renovation projects and critical construction activities. This response has facilitated in identifying any additional constraint, project condition, and critical activities to be incorporated in the essential attributes of the framework that could be applied to steps 1 through 5.

The production management process suggested by the framework is broadly divided in two phases: production planning and production performance assessment. Production planning of any construction activity involves constraint assessment based on the hierarchy of constraints for that activity, while production performance assessment involves assessing the production factor of critical activity based on its actual duration, percentage of quality work delivered, and percentage of buffer used.

The following section presents a detailed demonstration of the developed framework with an example of a construction activity in a renovation project.

4.7 Demonstration of the Framework

This demonstration example is hypothetical and has been assumed to be a part of interior remodeling of an institutional building. The scope of work involves replacing 3500 sqft suspended ceiling assembly for an elevator lobby of an institutional building per a new design. Under a negotiated contract, the contractor is required to replace existing ceiling panels, cross tees, wire hangers, and wall moldings with newly designed ceiling suspension system. If the existing structure does not have enough capacity to support new design, the contractor would be required to work on its structural improvement.

The work is located in the elevator lobby of the building's fourth floor. A hypothetical plan of the lobby is shown in Figure 4.9. The lobby opens up into an auditorium, opposite to the elevators. The fire exit stair is located on one side of the elevator while on other side, faculty offices are located.

Prior to starting the work, the contractor has been asked to notify the owner of an appropriate duration of the work as per the project conditions (stated in the contract) and a list of special measures, furnished by the facilities management department.

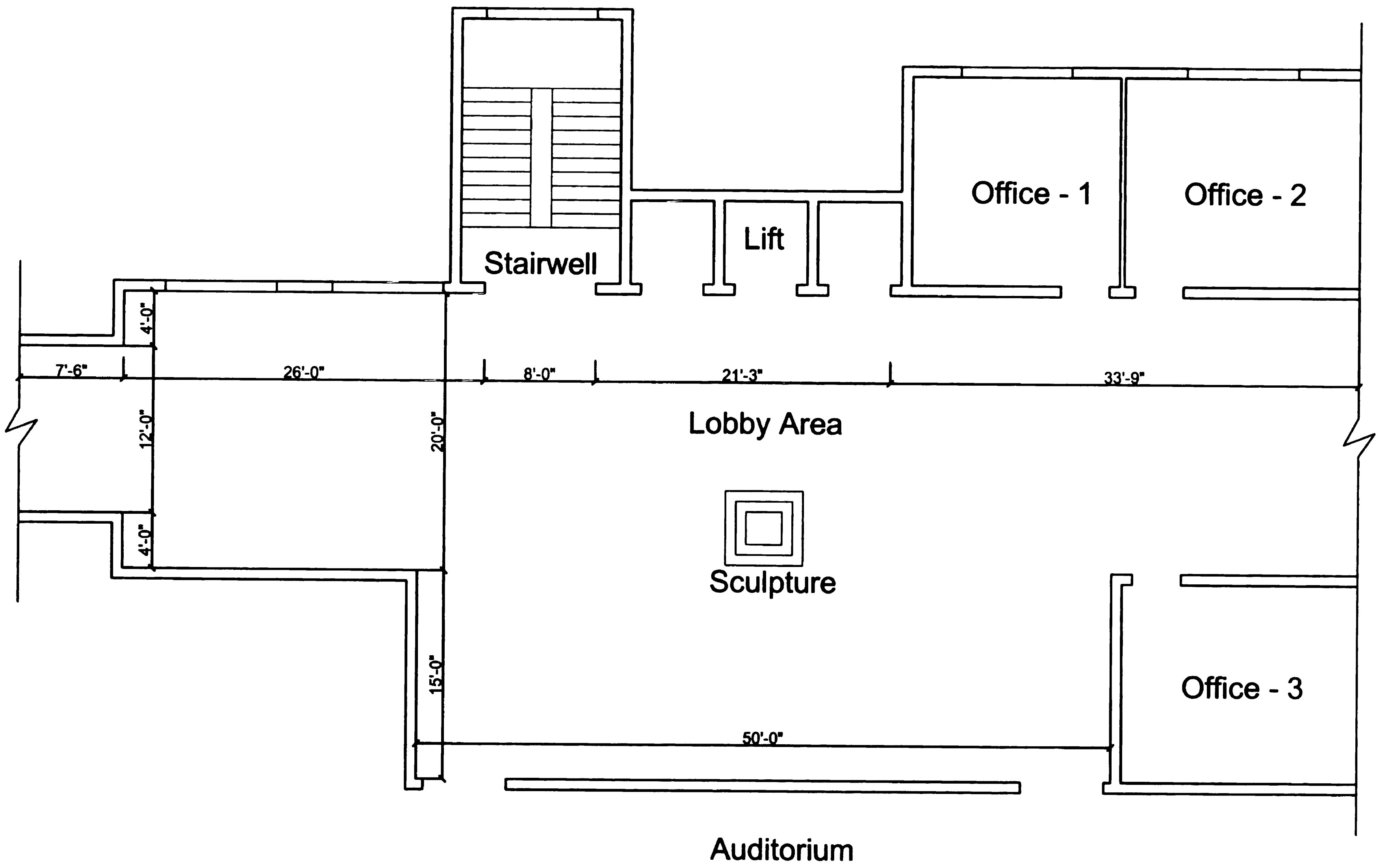

Figure 4.9 Plan of Elevator Lobby to be Renovated

4.7.1 Scope of work and required Resources

Table 4.15 summarizes the major portions of work along with the required crew sizes and their daily output. The contractor has referred to the Means Building Construction Cost Data 2005 for obtaining the standard crew sizes and their daily outputs.

Table 4.15 Scope of Work and Required Resources

Scope of Work	Crew	Daily Output
1. Selective demolition of ceiling panels on suspension system, including system	2 laborers	720 sqft
2. Installation of new ceiling suspension system		
a. Hanging wire, 12 ga., 4' long	1 carpenter	6500 sqft
b. Carrier channels for ceilings with recessed lighting fixtures	1 carpenter	460 sqft
c. Install 2'x2' grid panels, 9/16" T bar	1 carpenter	650 sqft
3. In case of asbestos presence, demolition of ceiling suspension system in asbestos contaminated area	1 asbestos foreman 7 asbestos workers	3500 sqft

4.7.2 Estimated Duration of Work

Initially, assuming that there are no constraints present, the contractor would calculate the total duration of ceiling replacement activity based on the crew sizes and their daily outputs mentioned above. The total duration of work would include:

1. Duration of selective demolition

Total quantity of work/720sqft = 3500/720 sqft = 5 days

2. Installation duration of new suspended ceiling system:

The contractor would use two carpenters for installing the new system, except for hanging wires. For a crew of two carpenters, assuming that the crew productivity will be decreased by 10%, the duration of installation activity will be:

Hanging wires- 3500/6500 sqft =	1 day
Carrier channels for ceilings- 3500 / (460x 2 – 10% of 460 x2) sqft =	5 days
2'x2' grid panels, 9/16" T bar- 3500 / (650x 2 – 10% of 650 x2) sqft =	3 days
The total duration for installation of new ceiling suspension system =	9 days

In case the contractor encounters asbestos during ceiling demolition, asbestos abatement crew would be used instead of two laborers and the duration of selective demolition of ceiling suspension system will be 7 days (5 + 3500sqft/2100sqft per day). So the total duration of work including demolition and installing new ceiling will be 16 days.

4.7.3 Assessment of Project Conditions & Identification of constraints

Before notifying the owner of the duration of this work as estimated above, the contractor, on a project level, should assess the project conditions and special measures for identifying potential constraints to be encountered during the replacement of the ceiling system. Table 4.16 briefly summarizes project conditions and states the constraints generated due to those conditions.

Table 4.16 Example Project Conditions and Constraints Generated

Project Conditions	Constraints
The work cannot take place from Noon to 8 on Monday through Wednesday due to continuous class schedule conflicts in the auditorium. For other weekdays, the contractor would have to take extra care during class times.	-Coordination -Schedule - Physical - Pollution
The contractor should coordinate the ceiling replacement activity with an owner furnished sculpture to be installed in the middle of the lobby.	- Coordination - Physical
The faculty offices located next to the lifts imposes additional risk of disrupting construction operations, and being disrupted due to construction operations from 9am to 5pm during weekdays. The contractor should take adequate measures for minimizing both.	-Coordination
The contractor cannot take over the entire lobby at one time, for maintaining the students and faculty movement. The work should be done in incremental phases and the contractor must always leave a 6 ft. wide continuous passageway to allow for the movement of physically challenged individuals.	- Physical
There are no service elevators in the building and the contractor cannot use public elevators for carrying materials and equipment.	-Traffic
For maintaining the continuous operations of the building, the contractor cannot remove the suspended fixtures that include lights, diffusers, and fire sprinklers during weekdays from 7am to 8pm. During nights and weekends, when the diffuser is removed, open ducts should be covered securely for preventing any dust or debris in the air flow system.	-Utility - Coordination

Table 4.16 (cont'd)

As the work is located in a lift lobby of an operational building, storage space is not available for material or equipment.	-Physical -Traffic
The original building was constructed in 1960, so the contractor might encounter asbestos after uncovering the ceiling.	-Uncertainty
After removing the ceiling, the contractor would check the structural specifications of the joists with current building standards.	-Regulatory
The contractor should conduct a thorough site investigation before starting the work for developing an appropriate logistics plan.	-Schedule -Coordination
The flooring needs to be covered temporarily to avoid any possible damages due to erecting of scaffolds.	-Coordination
The contractor should incrementally remove the floor-mounted furniture and reinstall them once the work is complete.	- Coordination
The contractor cannot block the fire exit and auditorium exits during building operational time.	- Physical - Traffic

4.8 Steps Suggested by the Framework

As suggested by the developed framework, the following section describes a step by step procedure for production planning and assessment for the demonstrated ceiling replacement work. The demonstration explains both approaches for production planning; one considering each constraint independently without considering dependency relationships between constraints, and the other considering the dependency relationships and limiting the number of constraints in further steps.

Figure 4.10 shows both approaches of demonstration in the framework. The decision of "no" at the decision node results in the first approach, while the "yes" decision resulted in the alternative approach of going through dependency relationships and constraints reduction process.

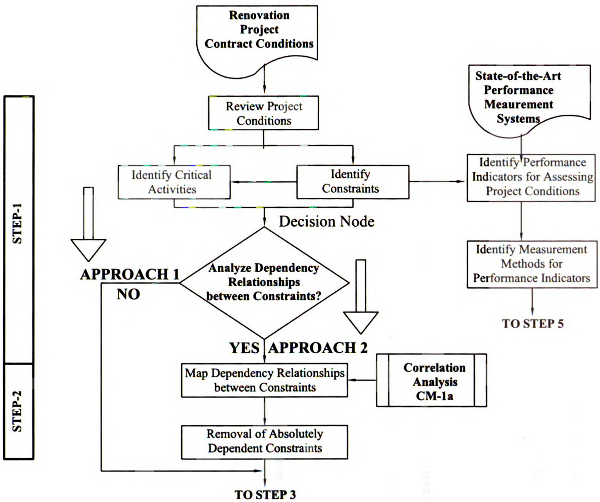

Figure 4.10 Approach 1 and 2 for Demonstration of Framework

4.8.1 Step-1 Identification of Constraints & Critical Activities

The project conditions listed in Table 4.16 will result in the following constraints; physical, utility, pollution, uncertainty, coordination, schedule, safety, traffic, and regulatory. These constraints will impact the estimated duration of the major portions of work, as the constraints will be encountered during their execution. These major portions are the following critical activities; selective demolition of existing ceiling system, and installation of ceiling suspension system.

4.8.2 Step-2 Mapping the Interdependency Relationships between Constraints

As step 2 is an optional step, the first approach does not consider this step and works directly from step 3.

4.8.3 Step-3 Mapping the Impact Levels of Constraints on Estimated Production Schedule of Critical Activities

The level of impact that each of these constraints will have on the estimated duration of critical processes will be different. These different impact levels are required to be mapped through correlation analysis. As stated before, this research considers five levels of impact that a constraint could have on the duration of critical process: absolute, strong, moderate, slight, and no impact. The correlation matrix (CM-1), shown in Table 4.17 maps the impact levels of each constraint on the estimated duration of each critical process as per the project conditions.

Table 4.17 Correlation Matrix-1

Critical Processes / Constraints	Demolition- Ceiling assembly removal	Ceiling suspension system Installation
Physical	M	A
Utility	S	A
Pollution	S	M
Uncertainty	M	N
Coordination	A	A
Schedule	M	S
Safety	SL	SL
Traffic	SL	SL
Regulatory	N	S
Legend		
Absolute impact =A		Strong impact = S
Moderate impact = M		Slight impact = SL
No impact = N		

4.8.4 Step-4 Identification of Weighted Impacts of Constraints on the Production Schedule of Critical Activities

After obtaining the impact levels of constraints, their relative weights would be established to understand their overall contribution to increased duration of the critical activities. As the framework suggests, the hierarchy will be established through the quantitative technique of Analytical Hierarchy Process (AHP). The AHP is required to be performed for each critical activity involved in the scope of work because as per the project conditions and correlation analysis, the contribution of constraints will change for each critical activity. For instance, per the correlation analysis, the physical constraint has a moderate and strong impact on the estimated duration of "selective demolition" and "installation of ceiling system" activities respectively. Consequently, the hierarchy of physical constraint for increasing the duration of "selective demolition" will be different in case of "suspended ceiling installation".

In the pair wise comparison of any two constraints in AHP, the assignment of relative importance will be guided by the correlation matrix-1, as shown in Table 4.18.

Table 4.18 Mapping of AHP and Correlation Matrix-1 Scales

Correlation Matrix Scale (CM 1)		AHP	
Constraint 1	Constraint 2	Definition {Importance of row constraint (1) over column constraint (2)}	Scale
N SL M S A	N SL M S A	Equal Importance	1
SL M S A	N SL M S	Weakly more	3
M S A	N SL M	Moderately more	5
S A	N SL	Strongly more	7
A	N	Absolutely more	9
N SL M S	SL M S A	Weakly less	1/3
N SL M	M S A	Moderately less	1/5
N SL	S A	Strongly less	1/7
N	A	Absolutely less	1/9

4.8.4.1 AHP for Selective Demolition of Ceiling System

Table 4.19 shows the AHP's pair-wise comparison matrix of constraints for impacting the estimated duration of selective demolition process. Each cell represents the importance of a row constraint over column constraint. The importance scale for each row constraint has been filled on the basis of the correlation matrix and Table 4.18. For instance, physical constraint moderately impacts the estimated duration of selective demolition while utility constraint strongly impacts its estimated duration. Therefore, while comparing the importance of physical constraint over utility constraint, as per Table 4.18, a scale of 1/3 (weakly less important) has been assigned to physical constraint. Similarly, all other pair-wise comparison cells have been completed.

Table 4.19 Pair-wise Comparison Matrix

[A] =

	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	1	1/3	1/3	1	1/5	1	3	3	5
Utility	3	1	1	3	1/3	3	5	5	7
Pollution	3	1	1	3	1/3	3	5	5	7
Uncertainty	1	1/3	1/3	1	1/5	1	3	3	5
Coordination	5	3	3	5	1	5	7	7	9
Schedule	1	1/3	1/3	1	1/5	1	3	3	5
Safety	1/3	1/5	1/5	1/3	1/7	1/3	1	1	3
Traffic	1/3	1/5	1/5	1/3	1/7	1/3	1	1	3
Regulatory	1/5	1/7	1/7	1/5	1/9	1/5	1/3	1/3	1

Table 4.20 Pair-wise Comparison Matrix (Decimal Form)

[A] =

	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	1	0.333	0.333	1	0.200	1	3	3	5
Utility	3	1	1	3	0.333	3	5	5	7
Pollution	3	1	1	3	0.333	3	5	5	7
Uncertainty	1	0.333	0.333	1	0.200	1	3	3	5
Coordination	5	3	3	5	1	5	7	7	9
Schedule	1	0.333	0.333	1	0.200	1	3	3	5
Safety	0.333	0.200	0.200	0.333	0.142	0.333	1	1	3
Traffic	0.333	0.200	0.200	0.333	0.142	0.333	1	1	3
Regulatory	0.200	0.142	0.142	0.200	0.111	0.200	0.333	0.333	1

Table 4.21 Normalization Matrix

[A] =

	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	0.067	0.051	0.051	0.067	0.075	0.067	0.106	0.106	0.111
Utility	0.201	0.152	0.152	0.202	0.125	0.202	0.176	0.176	0.155
Pollution	0.201	0.152	0.152	0.202	0.125	0.202	0.176	0.176	0.155
Uncertainty	0.067	0.051	0.051	0.067	0.075	0.067	0.106	0.106	0.111
Coordination	0.336	0.458	0.458	0.336	0.375	0.336	0.247	0.247	0.200
Schedule	0.067	0.051	0.051	0.067	0.075	0.067	0.106	0.106	0.111
Safety	0.022	0.030	0.030	0.022	0.053	0.022	0.035	0.035	0.067
Traffic	0.022	0.030	0.030	0.022	0.053	0.022	0.035	0.035	0.067
Regulatory	0.013	0.022	0.022	0.013	0.042	0.013	0.012	0.012	0.022

Table 4.22 Final Weights

[W] =

Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
0.078	0.172	0.172	0.078	0.333	0.078	0.035	0.035	0.019

Table 4.22 shows the final relative weights of constraints in impacting the duration of selective demolition activity. However, there is a need to check the degree of consistency in contractor's judgments of pair-wise comparison. Saaty (1980) stated that perfect consistency is impossible to achieve, but, a low consistency will result in inconsistent results and therefore, all pair-wise judgments should be re-evaluated. Therefore, Saaty (1980) proposed Consistency Ratio (CR) as a measure of consistency used in AHP. If the value of consistency ratio exceeds 0.1, it signifies inconsistent judgments of the decision-maker (contractor) in pair-wise comparison, which need to be revised (Nassar 2005). The value of CR depends on the value of Consistency Index (CI) which is defined as:

$CI = \lambda_{max} - n / (n-1)$

n = number of items being compared

λ_{max} = maximum eigenvalue of the normalized comparison matrix

There are 3 steps to calculate λ_{max}:

1. In the pair-wise comparison matrix, multiply each column with the corresponding final weight.
2. Divide the sum of rows with the corresponding final weights.
3. Compute the average of values from step 2 and denote it by λ_{max}.

The value of CR = Consistency Index (CI) / Random Index (RI)

Random index is the value of consistency index of a randomly generated pair-wise comparison matrix for 'n' number of items. Based on the "n" value, the value of random index should be obtained from Table 4.23 (Nassar 2005).

Table 4.23 Random Index Values (Nassar 2005)

N	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

4.8.4.2 Consistency Measurement for AHP of Selective Demolition

Table 4.24 shows how to calculate the maximum eigenvalue of the normalized comparison matrix (λ_{max}) for selective demolition activity.

Table 4.24 Multiplication of Pair-wise Comparison Matrix with Final Weights

λ_{max} =		Physical	. . . . .	Regulatory	X	
	Physical	1	. . . . . .	5		0.078
	Utility	3	. . . . . .	7		0.172
	Pollution	3	. . . . . .	7		0.172
	Uncertainty	1	. . . . . .	5		0.078
	Coordination	5	. . . . . .	9		0.333
	Schedule	1	. . . . . .	5		0.078
	Safety	1/3	. . . . . .	3		0.035
	Traffic	1/3	. . . . . .	3		0.035
	Regulatory	1/5	. . . . . .	1		0.019

From Table 4.24, $\lambda_{max} = 9.321$

CI = 9.321 – 9 / (9 -1) = 0.0401

Value of RI is = 1.45 (for n= 9, from Table 4.23)

CR = 0.0401 / 1.45 = 0.028

The CR value of 0.028 (less than 0.1) signifies that the consistency in the pair-wise comparison of constraints for the selective demolition activity was high and therefore, there is no need to re-evaluate pair-wise judgments.

4.8.4.3 AHP for Installation of Ceiling Suspension System

Similar to the AHP of selective demolition, the pair-wise comparison matrix for installation of ceiling suspension system, shown in Table 4.25, has been completed up on the basis of Table 4.18 and the correlation analysis.

Table 4.28 shows the final weights of constraints in impacting the duration of ceiling suspension system installation.

Table 4.25 Pair-wise Comparison Matrix

[A] =

	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	1	1	5	9	1	3	7	7	3
Utility	1	1	5	9	1	3	7	7	3
Pollution	1/5	1/5	1	5	1/5	1/3	3	3	1/3
Uncertainty	1/9	1/9	1/5	1	1/9	1/7	1/3	1/3	1/7
Coordination	1	1	5	9	1	3	7	7	3
Schedule	1/3	1/3	3	7	1/3	1	5	5	1
Safety	1/7	1/7	1/3	3	1/7	1/5	1	1	1/5
Traffic	1/7	1/7	1/3	3	1/7	1/5	1	1	1/5
Regulatory	1/3	1/3	3	7	1/3	1	5	5	1

Table 4.26 Pair-wise Comparison Matrix (Decimal Form)

[A] =

	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	1	1	5	9	1	3	7	7	3
Utility	1	1	5	9	1	3	7	7	3
Pollution	0.200	0.200	1	5	0.200	0.333	3	3	0.333
Uncertainty	0.111	0.111	0.200	1	0.111	0.143	0.333	0.333	0.143
Coordination	1	1	5	9	1	3	7	7	3
Schedule	0.333	0.333	3	7	0.333	1	5	5	1
Safety	0.143	0.143	0.333	3	0.143	0.200	1	1	0.200
Traffic	0.143	0.143	0.333	3	0.143	0.200	1	1	0.200
Regulatory	0.333	0.333	3	7	0.333	1	5	5	1

Table 4.27 Normalization Matrix

[A] =

	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	0.235	0.235	0.219	0.169	0.235	0.253	0.193	0.193	0.253
Utility	0.235	0.235	0.219	0.169	0.235	0.253	0.193	0.193	0.253
Pollution	0.047	0.047	0.044	0.094	0.047	0.028	0.082	0.082	0.028
Uncertainty	0.026	0.026	0.008	0.018	0.026	0.012	0.009	0.009	0.012
Coordination	0.235	0.235	0.219	0.169	0.235	0.253	0.193	0.193	0.253
Schedule	0.078	0.078	0.131	0.132	0.078	0.084	0.137	0.137	0.084
Safety	0.034	0.034	0.014	0.057	0.034	0.017	0.027	0.027	0.017
Traffic	0.034	0.034	0.014	0.057	0.034	0.017	0.027	0.027	0.017
Regulatory	0.078	0.078	0.131	0.132	0.078	0.084	0.137	0.137	0.084

Table 4.28 Final Weights

[w] =

Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
0.221	0.221	0.055	0.016	0.221	0.104	0.029	0.029	0.104

4.8.4.4 Consistency Measurement for AHP of Installation of Ceiling Suspension System

Table 4.29 shows how to calculate the maximum eigenvalue of the normalized comparison matrix (λ_{max}) for the activity of installation of ceiling suspension system.

Table 4.29 Multiplication of Pair-wise Comparison Matrix with Final Weights

λ_{max} =

	Physical	. . . . . .	Regulatory
Physical	1	. . . . . .	3
Utility	1	. . . . . .	3
Pollution	1/5	. . . . . .	1/3
Uncertainty	1/9	. . . . . .	1/7
Coordination	1	. . . . . .	3
Schedule	1/3	. . . . . .	1
Safety	1/7	. . . . . .	1/5
Traffic	1/7	. . . . . .	1/5
Regulatory	1/3	. . . . . .	1

X

0.221
0.221
0.055
0.016
0.221
0.104
0.029
0.029
0.104

From Table 4.29, λ_{max} = 9.370

CI = 9.370 – 9 / (9 -1) = 0.0462

Value of RI is = 1.45 (for n= 9, from Table 4.23)

CR = 0.0462 / 1.45 = 0.032

The CR value of 0.032 (less than 0.1) signifies that the consistency in the pair-wise comparison of constraints for the activity of installation of ceiling suspension system was high and therefore, there is no need to re-evaluate pair-wise judgments.

4.8.5 Step-5 Quantification of Additional Production Duration of Critical Activities based on Project Conditions- Constraint Assessment Matrix (CAM)

As stated before, constraint assessment process primarily involves planning the additional duration of critical activities after assessing project conditions, and applying the established hierarchy of constraints to the additional duration based on assessment of project conditions. The major factors that should be considered for planning the additional duration of selective demolition activity, and installation of ceiling suspension system activity, are:

1. Weighted impacts of constraints on the production duration of critical activities
2. Assessment of project conditions of all constraints for estimating the required additional duration of critical activity

Table 4.30 shows the constraint assessment matrix (CAM) for selective demolition activity. The assessment of each project condition for the selective demolition activity has resulted in greater than or equal to 0 day additional duration. As suggested by the framework, the total additional duration due to project conditions of each constraint is added, and then multiplied by the constraint's relative weight obtained through AHP. Therefore, the additional duration due to the project conditions of each constraint is normalized according to the relative importance of that constraint in impacting production duration of selective demolition activity.

For each project condition whose assessment resulted in additional duration of greater than 0 day, an explanation of assessment is provided in the right most column, which provides information about the data relating to that condition. For the given demonstration example, these explanations can be seen in Table 4.30 & 4.31, which have been assumed for each critical activity. For obtaining a better understanding of the assessment method of project conditions and the additional duration based on the assessment, the reader of this thesis is suggested to go through their explanations of assessment. This framework suggests completing this column of assessment explanation, in order to document and employ them further in production planning of construction activities under similar project conditions.

It could be seen in Table 4.30 that amongst all the constraints, coordination constraint results in the highest value of additional duration of 2.5 days without its normalization. This is in complement with the weighted impacts of constraints established from AHP, as coordination constraint has the highest weighted impact of 0.333 on the production duration of selective demolition activity. Similarly, regulatory constraint results in the least additional duration of 0 day without its normalization, and it has the least weighted impact of 0.019 on the production duration of selective demolition activity. Therefore, the weighted impacts of constraints, as established through AHP, are the functions of the amount of additional duration resulted due to the assessment of their project conditions.

4.8.5.1 Query Node-1

Assuming that all the constraints have been addressed for both critical activities, the answer to the query node-1 will be "yes" and the production duration of critical activities will be revised as follows.

The summation of normalized additional duration due to all constraints gives the minimum additional duration (AD_{min}) required for selective demolition activity.

However, the summation of additional duration due to project conditions of all constraints without their normalization, gives the maximum additional duration (AD_{max}) required for this activity, as shown below.

$$AD_{min} = \sum_{i=1}^{N}(\text{additional duration due to project conditions of each constraint}) \times W$$

$$AD_{max} = \sum_{i=1}^{N}(\text{additional duration due to project conditions of each constraint})$$

Where,

N= Number of constraints

W = Relative weights of constraints for impacting production schedule of critical process

From Table 4.30,

AD_{min} (selective demolition) = (1 x 0.172) + (0.5 x 0.078) + (1.25 x 0.172) + (0.5 x 0.078) + (2.5 x 0.333) + (0 x 0.019) + (0.625 x 0.035) + (0.5 x 0.078) + (0 x 0.035) = 1.358

= 2 days (approx.)

AD_{max} (selective demolition) = 1 + 0.5 + 1.25 + 0.5 + 2.5 + 0 + 0.625 + 0.5 + 0 = 6.875

= 7 days (approx.)

Therefore, the constraint assessment matrix shown in Table 4.30 has resulted into a range of additional duration having a minimum and maximum value. The estimated additional duration (EAD) would be a middle value of its range.

$$EAD = \{(AD_{min}) + (AD_{max})\} / 2 = (2 + 7) /2 = 4.5 \text{ or } 5 \text{ days}$$

The Revised Production Duration (RPD) for selective demolition activity, based on the assessment of constraints would be:

RPD = Estimated duration (without consideration of constraints) + EAD

= 5 + 5 = 10 days

Similarly, for the installation of ceiling suspension system activity, Table 4.31 shows the CAM that lists the same project conditions and constraints, but the additional duration resulted due to each project condition and the weighted impacts of constraints have changed per the nature of critical activity.

For instance, the additional duration due to utility constraint for the activity of selective demolition per Table 4.30 is 1 day and its weighted impact is 0.172. But, for the installation of ceiling suspension system activity per Table 4.31, the additional duration due to utility constraint is 2.9 days and its weighted impact is 0.221. The change in additional duration and hierarchies are direct outcome of the nature of project conditions and the critical activity itself, as the constraints' impacts differ for each critical activity.

From Table 4.31,

AD_{min} (installation) = (2.9 x 0.221) + (2.85 x 0.221) + (1.25 x 0.055) + (0 x 0.016) + (3 x 0.221) + (2 x 0.104) + (0.625 x 0.029) + (1.9 x 0.104) + (0 x 0.029)

= 2.424

= 3 days (approx.)

AD_{max} (selective demolition) = 2.9 + 2.85 + 1.25 + 0 + 3 + 2 + 0.625 + 1.9 + 0 = 14.525

= 15 days (approx.)

The estimated additional duration (EAD) would be a middle value of its range.

EAD = {(AD_{min}) + (AD_{max})} / 2 = (3 + 15) /2 = 9 days

The Revised Production Duration (RPD) for installation of ceiling suspension system, based on the assessment of constraints would be:

RPD = Estimated duration (without consideration of constraints) + OAD

= 9 + 9 = 18 days

For the reader's better understanding of the demonstration, the framework is reproduced in Figure 4.9 which shows steps 1 through 10 of the demonstration including the query nodes.

Table 4.30 Constraint Assessment Matrix for Selective Demolition of Ceiling Suspension System

Constraints	Project Conditions or Performance Indicators (PI)	Assessment Method	Additional Duration based on assessment	Constraint Weightage from AHP	Normalized Additional Duration based on Constraint weightage [additional duration due to constraint x relative weight of constraint]	Explanation of Assessment
Utility Constraint	1Capacity of downstream system	If the available capacity of the utilities and/or the load bearing capacity of the structure is less than the required capacity for construction activities (loading capacity, electrical loading etc.), then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0	0.172		The required capacities for ceiling demolition activity is with in the existing capacity of the building.
	2.Non-disruption to existing utilities	Non work period due to non-disruption to existing utilities	1 day			Due to the project condition of not shutting down any services between 7am to 8pm during weekdays, it has been assumed that one extra day during weekend will be required to remove ceiling mounted fixtures.

Table 4.30 (cont'd)

	3.Impact of existing utilities and/or structural systems on the design of new systems	If the existing capacity of utilities and/or the structural system is less than the required capacities for supporting new and/or upgraded systems, then how much additional duration is required to complete the activity Available capacity . — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	Total additional duration due to utility constraint		1 day		1x 0.172 = 0.172 day	
Physical constraint	1. Space limitations for construction	Available space . — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0.1x5 = 0.5 day			Given that the construction is to be executed in a temporary enclosure during all 5 phases, the estimated duration will be increased by 10% for not disturbing the existing structure outside the enclosure, and due to multiple mobilization and demobilization in limited space.
	2. Space limitations for material storage	For on-site storage: Available space . — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			

Table 4.30 (cont'd)

		For off-site storage: Cycle time to install the material on site / cycle time to deliver the material from off-site storage space to construction site (time lapse between material procurement and material installation) or 1- wait time of crew for receiving the material on site/ cycle time to install the material on site	0	0.078		
	3. Space limitation for installing new equipment/material	If the available space is less than the space required to install equipment or material, then how much percentage of activity duration would be increased Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	Total additional duration due to physical constraint		0.5 day		0.5 x 0.078 = 0.039 day	
Pollution control	1. Noise, dust, debris, vibration and odor control	(Time for enclosing construction zone + time for installing peripheral sound & vibration insulation + time for installing negative air machines + any other time for pollution control activities+ non-work period specified by owner due to pollution problems)	1.25 days	0.172		The contractor has assumed that approx. 2 hrs./phase (for 5 phases, each of 700 sqft) will be expended for erecting temporary enclosure that comprises of drywalls taped to the floor.
	Total additional duration due to pollution constraint		1.25 days		day	

Table 4.30 (cont'd)

Uncertainty constraint	1. Non-availability of As-built Drawings	Time required/expended for site investigation	0.5 day	0.078		Due to the non-availability of as-built drawings of lift lobby, prior to start the work, the contractor will conduct a thorough site investigation to identify any inconsistencies between new design and existing conditions. The site investigation will take about 4 hrs.
	2. Presence of unforeseen conditions	Planned time buffer based on site investigation	0			
	3. Presence of hazardous material	Abatement period for hazardous material	0			
	Total additional duration due to uncertainty constraint		0.5 day		0.5 x 0.078 = 0.039 day	
Coordination constraint	1. Timing limitations due to owner operations	Non-work period	1.5 days			Given that the work cannot take place Monday through Wednesday, from Noon to 8 pm, an additional 1.5 days (12 hrs.) will be required to complete the demolition.
	2. Relocation of owner operations to and from swing space	(Minimum time for relocating owner operations to swing space for starting construction + non-work period due to owner relocation from swing space to the renovated space)	0			

Table 4.30 (cont'd)

	3. Owner furnished equipments	If the work is dependent on installation of owner furnished equipment/material, then value of PI= (Lead time + installation time)	0	0.333		
	4. Removal & reinstallation of owner's furniture	Expected removal time for floor mounted furniture in the lobby	0.5 day			Floor mounted furniture comprises of wooden seats, tables and display boards. After removal, the furniture has to be moved to the storage room located on ground floor.
	5. Multiple inspections by end-users, owner's representatives and hazardous material inspection team	Expected inspection time	0.5 day			An inspection might be conducted by the Hazardous material abatement team, if, during demolition, the existing conditions pose any risk of asbestos presence.
	Total additional duration due to coordination constraint		2.5 days		2.5 x 0.333 = 0.832 day	
Regulatory constraint	1. Non conformance of existing materials or project conditions with current codes	If the existing materials or project conditions do not conform to the current building codes then how much additional duration is required to complete the activity Additional duration (% of original duration) • 0 • 0 to 10 • 10 to 20 • more than 20	0	0.019	0 x 0.019 = 0 day	
	Total additional duration due to regulatory constraint		0			

Table 4.30 (cont'd)

Traffic constraint	1. Limitations of materials and equipment movement	(Wait time + time lapse b/w material handling from storage space and delivery on site) and/or (Time required for moving or maneuvering equipment/scaffold from one construction location to another) and/or (Labor movement restriction period)	0.625 day	0.035		An additional 1 hr. will be required per phase for moving and maneuvering scaffold from one phase location to another, due to owner traffic and limited space.
	Total additional duration due to traffic constraint		0.625 day		0.625 x 0.035 = 0.022 day	
Schedule constraint	1. Work Restructuring and/or Sequencing of Trades	Additional duration due to work restructuring	0			
	2. Impact on crew productivities	Decrease in productivity/estimated productivity x original duration	72/720x5 = 0.5 day	0.078		The contractor has assumed that the crew productivity will get decreased by 10% due crowding conditions and limited space.
	Total additional duration due to schedule constraint		0.5 day		0.5 x 0.078 = 0.039 day	
Safety constraint	1. Users & public	Time to be expended in special safety consideration	0	0.035		
	Total additional duration due to safety constraint		0		0 x 0.035 = 0 day	
Range of Additional Duration			**Maximum 6.875 = 7**		**Minimum 1.358 = 2**	
Estimated Additional Duration (EAD)			**4.5 = 5 days**			
Revised Production Duration of selective demolition of ceiling system = Original Duration + Estimated Additional duration			**5 + 5 = 10 days**			

Table 4.31 Constraint Assessment Matrix for Installation of Ceiling Suspension System

Constraints	Project Conditions or Performance Indicators (PI)	Assessment Method	Additional Duration based on assessment	Constraint Weightage from AHP	Normalized Additional Duration based on Constraint weightage [additional duration due to constraint x relative weight of constraint]	Explanation of Assessment
Utility Constraint	1Capacity of downstream system	If the available capacity of the utilities and/or the load bearing capacity of the structure is less than the required capacity for construction activities (loading capacity, electrical loading etc.), then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0	0.221		
	2.Non-disruption to existing utilities	Non work period due to non-disruption to existing utilities	2 days			As the installation of fixtures can only be done during weekend and night, an additional 2 days will be required.

Table 4.31 (cont'd)

	3.Impact of existing utilities and/or structural systems on the design of new systems	If the existing capacity of utilities and/or the structural system is less than the required capacities for supporting new and/or upgraded systems, then how much additional duration is required to complete the activity Available capacity . — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0.1 x 9 = **0.9 day**			The contractor might expect some joists that need structural bracing for supporting new ceiling.
	Total additional duration due to utility constraint		2.9 days		2.9x 0.221 = 0.641 day	
Physical constraint	1. Space limitations for construction	Available space . — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0.15x9 = **1.35 day**			Given that the construction is to be executed in a temporary enclosure during all 5 phases, the estimated duration will be increased by 10% for not disturbing the existing structure outside the enclosure, and due to multiple mobilization and demobilization in limited space. In addition, there will be a 5% increase in the estimated duration as the space will also be limited by inclusion of all tools and materials within the enclosure.
	2. Space limitations for material storage	For on-site storage: Available space . — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20 and/or	0			

Table 4.31 (cont'd)

		For off-site storage: Cycle time to install the material on site / cycle time to deliver the material from off-site storage space to construction site (time lapse between material procurement and material installation) or 1- wait time of crew for receiving the material on site/ cycle time to install the material on site	3500/ (4 sqft x 75 panels/hr. x 8 hr./day) = 1.5 day	0.221		Given that the storage space is not availbale in the lift lobby, the contractor would have to store the material on ground floor parking area. Assuming the cycle time of 1 labor for delivering ceiling panels to the lift lobby is 75 panels/hr.
	3. Space limitation for installing new equipment/material	If the available space is less than the space required to install equipment or material, then how much percentage of activity duration would be increased Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	Total additional duration due to physical constraint		2.85 days		2.85 x0.221 = 0.629 day	
Pollution control	1. Noise, dust, debris, vibration and odor control	(Time for enclosing construction zone + time for installing peripheral sound & vibration insulation + time for installing negative air machines + any other time for pollution control activities+ non-work period specified by owner due to pollution problems)	1.25 days	0.055		The contractor has assumed that approx. 2 hrs./phase (for 5 phases, each of 700 sqft) will be expended for erecting temporary enclosure that comprises of drywalls taped to the floor.
	Total additional duration due to pollution constraint		1.25 days		1.25 x 0.055 = 0.068 day	
Uncertainty constraint	1. Non-availability of As-built Drawings	Time required/expended for site investigation	0			
	2. Presence of unforeseen conditions	Planned time buffer based on site investigation	0			
	3. Presence of hazardous material	Abatement period for hazardous material	0			

Table 4.31 (cont'd)

	Total additional duration due to uncertainty constraint		0 day	0.016	0 x 0.016 = 0 day	
Coordination constraint	1. Timing limitations due to owner operations	Non-work period	1.5 days			**Given that the work cannot take place Monday through Wednesday, from Noon to 8 pm, an additional 1.5 days (12 hrs.) will be required to complete the demolition.**
	2. Relocation of owner operations to and from swing space	(Minimum time for relocating owner operations to swing space for starting construction + non-work period due to owner relocation from swing space to the renovated space)	0			
	3. Owner furnished equipments	If the work is dependent on installation of owner furnished equipment/material, then value of PI= (Lead time + installation time)	0.5	0.221		The floor mounted sculpture is to be onstalled bt owner's self-performed crew and its estimated duration will be approx. 4 hrs. During installation, due to limited space, the contractor cannot work on ceiling installation activity.
	4. Removal & reinstallation of owner's furniture	Expected installation time for floor mounted furniture in the lobby	0.5 day			Floor mounted furniture comprises of wooden seats, tables and display boards. After removal, the furniture has to be moved to the storage room located on ground floor.
	5. Multiple inspections by end-users, owner's representatives and hazardous material inspection team	expected inspection time (multiple no.)	0.5 day			The contractor would expect multiple inspections from facilities management, and building users which will approx. consume 4 hrs.
	Total additional duration due to coordination constraint		**3 days**		3 x 0.221 = 0.663 day	

Table 4.31 (cont'd)

Regulatory constraint	1. Non conformance of existing materials or project conditions with current codes	If the existing materials or project conditions do not conform to current building codes then how much additional duration is required to complete the activity Additional duration (% of original duration) • 0 • 0 to 10 • 10 to 20 • more than 20	2 days	0.104		After selective demolition of ceiling assembly, it was found that the existing batt insulation do not conform to the fire safety requirements of current building codes. The order and installation of new insulation will result in 2 additional days to the estimated duration.
	Total additional duration due to regulatory constraint		2 days		2 x 0.104 = 0.208 day	
Traffic constraint	1. Limitations of materials and equipment movement	(Wait time + time lapse b/w material handling from storage space and delivery on site) and/or (Time required for moving or maneuvering equipment/scaffold from one construction location to another) and/or (Labor movement restriction period)	0.625 day	0.029		An additional 1 hr. will be required per phase for moving and maneuvering scaffold from one phase location to another, due to owner traffic and limited space.
	Total additional duration due to traffic constraint		0.625 day		0.625 x 0.029 = 0.018 day	
Schedule constraint	1. Work Restructuring and/or Sequencing of Trades	Additional duration due to work restructuring	1 day			Assuming that the contractor has to change the sequence of reinstallation activities that includes first installing all the fixtures and then the panels. This change in logic has increased the installation duration by 1 day.
	2. Impact on crew productivities	[{Estimated productivity/(estimated - decrease in productivity) x original duration} - original duration	[{1170/(1170-117) x3} - 3] +[{828/(828-82.8)x 5} -5 = 0.9 day	0.104		The contractor has assumed that the crew productivity will get decreased by 10% due crowding conditions and limited space.
	Total additional duration due to schedule constraint		1.9 day		1.9 x 0.104 = 0.197 day	

Table 4.31 (cont'd)

Safety constraint	1. Users & public	Time to be expended in special safety consideration	0	0.029		
	Total additional duration due to safety constraint		0		0 x 0.029 = 0 day	
Range of Additional Duration			**Maximum 14.525 = 15**		**Minimum 2.242 = 3**	
Estimated Additional Duration (EAD)			**9 days**			
Revised Production Duration of installation of ceiling suspension system = Original Duration + Estimated Additional duration			**9 + 9 = 18 days**			

4.8.6 Alternate Approach to Production Planning using Dependency Relationships between Constraints- Approach 2

As the framework suggests, an alternate approach to limit AHP calculations can be used. This approach involves a correlation analysis carried out to ascertain the interdependency levels between constraints. This approach would lead to limited number of constraints which would simplify the correlation analysis of CM-1 and AHP calculations, as compared to previous approach. However, the accuracy of determining the additional duration based on a limited number of constraints may result in error. This is considered and explained in the current demonstration example.

The interdependency levels between constraints should be mapped for each critical activity of the demonstration example, i.e., selective demolition of ceiling suspension, and installation of new ceiling suspension system. The following section illustrates this alternate method of production planning from steps 2 through 5 of the framework. These 4 steps have been explained again but considering the dependency relationships between constraints, as in the first approach, these 4 steps did not consider dependency relationships between constraints. From steps 6 through 10, as the procedure suggested by the framework is same, therefore, steps 6 through 10 have been explained once, considering the dependency relationships between constraints. To reiterate, the first five steps suggested by the framework are:

1. Identification of constraints and critical activities
2. Mapping the interdependency relationships between constraints and reduce the number of constraints- optional step

3. Mapping the impact levels of constraints on estimated production schedule of critical activities
4. Identification of weighted impacts of constraints on the production schedule of critical activities
5. Quantification of additional production duration of critical activities based on project conditions

4.8.7 Step-1 Identification of Constraints and Critical Activities

As this step is common for both approaches, the constraints and critical processes would remain same, as identified in section 4.8.1

4.8.8 Step-2 Mapping the Interdependency Relationships between Constraints

For the selective demolition activity, Table 4.32 shows the correlation analysis through the correlation matrix-1a (CM-1a) for selective demolition activity, which maps the dependency level of each column constraint (jth.) on all row (ith.) constraints. The dependency levels, shown below, are absolute, strong, moderate, slight, and none. Each cell (a_{ij}) in this matrix represents the dependency level of the jth. column constraint on the ith. row constraint. For instance, cell a_{23} in the CM-1a shown in Table 4.32, shows that pollution constraint is moderately dependent on the utility constraint. A negative sign prior to the dependency level indicates a reverse dependency of row constraint on column constraint. For instance, for cell a_{12}, the negative sign before 'M' indicates that instead of utility constraint (column) being moderately dependent on physical constraint (row), physical constraint (row) is moderately dependent on utility constraint (column).

In order to provide the reader a clearer understanding of the correlation matrix (CM-1a) between constraints, as shown in Table 4.32, for the selective demolition activity, the following section discusses dependencies of first column constraint (physical) on all row constraints.

4.8.8.1 Dependency level of Physical constraint (first column) on all other constraints (rows) for Selective Demolition Activity

1. Utility constraint- Moderate dependency

Due to the presence of existing services above ceiling, the physical space required to remove existing hanging wires and channels, will not be adequate, and due to this limited space, the risk of disrupting utilities increases while replacing the ceiling assembly, even if the task does not require any shuts down of services. Therefore, physical constraint is moderately dependent on utility constraint.

2. Pollution control- Strong dependency

The ceiling demolition activity needs to be executed in a temporary enclosure to avoid the transmission of dust, debris, noise, and odor being generated, to other areas. Thus, given that the activity is to be done in incremental phases while not blocking any fire exits, auditorium entry, and maintaining at least 6' wide passageway implies that erection of temporary enclosure for controlling pollution would impose a strong physical constraint on the contractor.

3. Uncertainty constraint- Slight dependency

The limitation of physical space for construction does not necessarily mean that there are possibilities of encountering unforeseen conditions, but simultaneously it could have a slight relationship with the execution of construction in a limited space. For instance, the loading capacity per unit area of the floor might not allow all the trades to work at the same time, in the temporary enclosure.

4. Coordination constraint- Strong dependency

Due to the existing operations of the building, the contractor cannot take over the entire lobby at one time. This imposes a strong physical constraint for carrying out phased demolition.

5. Schedule constraint- No dependency

The time buffers, or any non-work period would not impact the physical space required for demolition activity. However, the productivity of crews might be strongly affected due to phased construction in limited space. Therefore, physical constraint is not dependent on schedule constraint but, due to the productivity loss, schedule constraint is moderately dependent on physical constraint.

6. Safety constraint – Moderate dependency

In this operational building, the contractor bears the risk of injuring any visitor, and the contractor would have to incorporate all tools, material, and equipment within the temporary enclosure. This further limits the available space for construction.

7. Traffic constraint- Strong dependency

Due to limited physical space, the maneuvering and shifting of scaffold from one location to another in conjunction with the building users' continuous movement in the lift lobby would require more time than estimated.

8. Regulatory constraint- No dependency

In the given case, the building codes do not seem to impact physical space required for construction, material storage or site access.

Similarly, for installation of ceiling suspension system activity, Table 4.33 shows the correlation analysis through CM-1a, which maps the dependency level of each column constraint on all row constraints. It could be seen that due to the change in the scope of work and project conditions, the dependency levels mapped in Table 4.32 for the selective demolition activity have been changed in Table 4.33 for the installation activity.

For instance, in Table 4.33, in the cell a_{16}, the dependency level of schedule constraint on the physical constraint has changed from "moderate" to "absolute". This is due to the fact that the installation activity requires transitory storage and handling of new materials in the temporary enclosures of all five phases, limiting the physical space available to crew which will eventually affect its productivity. In addition, due to the limited physical space for material storage in the elevator lobby, all material will be stored on the ground floor. In the absence of a service elevator, this will increase the cycle time to get the material to the fourth floor through the staircase, which might increase the wait time of the labor for installing new material.

Table 4.32 Interdependency Relationships between Constraints for Selective Demolition (Correlation Matrix-1a)

Constraints	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	--	-M	-S	-SL	-S	M	M	-S	N
Utility	M	--	M	S	-A	M	S	N	M
Pollution	S	-M	--	S	M	S	A	N	S
Uncertainty	SL	-S	-S	--	S	S	SL	SL	A
Coordination	S	A	-M	-S	--	A	-SL	S	N
Schedule	-M	-M	N	-S	-A	--	-SL	-M	-M
Safety	M	-S	-A	-SL	SL	SL	--	S	M
Traffic	S	N	N	-SL	-S	M	-S	--	-M
Regulatory	N	M	-S	-A	N	M	-M	M	--
Legend A- Absolute Dependency = 9 SL- Slight Dependency = 3			S- Strong Dependency = 7 N- No Dependency = 0			M- Moderate Dependency = 5			

Table 4.33 Interdependency Relationships between Constraints for the Installation of Ceiling Suspension System (Correlation Matrix-1a)

Constraints	Physical	Utility	Pollution	Uncertainty	Coordination	Schedule	Safety	Traffic	Regulatory
Physical	--	-S	-M	SL	-S	A	A	A	N
Utility	S	--	M	-S	-A	S	S	N	-M
Pollution	M	-M	--	S	-M	S	M	N	S
Uncertainty	-SL	S	-S	--	SL	S	SL	SL	A
Coordination	S	A	M	-SL	--	A	-S	A	N
Schedule	-A	-S	-S	-S	-A	--	-SL	-S	-M
Safety	-A	-S	-M	-SL	S	SL	--	S	M
Traffic	-A	N	N	-SL	-A	S	-S	--	-M
Regulatory	N	M	-S	-A	N	M	-M	M	--
Legend A- Absolute Dependency = 9 SL- Slight Dependency = 3			S- Strong Dependency = 7 N- No Dependency = 0			M- Moderate Dependency = 5			

4.8.9 Reduction of Number of Constraints Based on Interdependency Levels-Constraints Reduction Process

After conducting correlation analysis between constraints for both critical activities, the dependency levels should be reviewed to identify maximum degree of relationships (absolute dependency) between constraints. Based on maximum degree of relationship, all those column constraints having absolute dependency over other row constraints could be removed from further CM-1 analysis and AHP calculations. If a column constraint has an absolute dependency on row constraint, it could be represented by the row constraint CM-1 analysis and AHP calculations. For instance, in Table 4.32, utility constraint is absolutely dependent on coordination constraint for the ceiling demolition activity, which leads to the consideration of coordination constraint, as a representative of utility constraint, in CM-1 and AHP. Therefore, utility constraint would not be considered for obtaining the hierarchy of constraints in impacting the duration of ceiling demolition activity, as the weightage of coordination constraint would be inclusive of the weight of utility constraint.

Using the correlation matrix-1a shown in Table 4.32 for the selective demolition activity, Table 4.34 was constructed. Table 4.34 shows that 4 constraints could be eliminated from further steps due to their absolute dependencies on 3 other constraints. Therefore, for performing further steps of the framework, only 5 constraints could be considered instead of 9.

Table 4.34 Constraint Reduction for Selective Demolition

Constraint to be Removed	Representative Constraint
Utility	Coordination
Schedule	Coordination
Safety	Pollution
Regulatory	Uncertainty

Similarly, using the CM-1a shown in Table 4.33 for installation of ceiling suspension system, Table 4.35 was derived. Table 4.35 shows that 5 constraints could be removed further.

Table 4.35 Constraint Reduction for Ceiling Installation

Constraint to be Removed	Representative Constraint
Utility	Coordination
Schedule	Coordination
Safety	Physical
Traffic	Physical
Regulatory	Uncertainty

4.8.10 Step-3 Mapping the Impact Levels of Reduced Number of Constraints on Estimated Production Duration of Selective Demolition

This section reiterates the correlation analysis between constraints and their impact on the duration of critical activities, based on the correlation analysis conducted in the first approach. Table 4.36 shows this analysis through CM-1 for the selective demolition activity. It should be noted that those constraints, which are representing other constraints in this matrix, have increased their impact levels because of the additional impact of their dependent constraints, as compared to their individual impacts in CM-1, shown in Table

4.17. Table 4.17 has been recreated below for an easier comparison between the impact levels of constraint in this Table and Table 4.36.

Table 4.17 Correlation Matrix-1 for Approach-1

Critical Processes / Constraints	Demolition- Ceiling assembly removal	Ceiling suspension system Installation
Physical	M	A
Utility	S	A
Pollution	S	M
Uncertainty	M	N
Coordination	A	A
Schedule	M	S
Safety	SL	SL
Traffic	SL	SL
Regulatory	N	S
Legend		
Absolute impact =A		Strong impact = S
Moderate impact = M		Slight impact = SL
No impact = N		

Table 4.36 Correlation Matrix-1 for Selective Demolition based on Reduced Number of Constraints

Critical Processes / Constraints	Demolition- Ceiling assembly removal
Physical	M
Pollution	S
Uncertainty	S
Coordination	A
Traffic	SL
Legend	
Absolute impact =A, Strong impact = S	
Moderate impact = M, Slight impact = SL	
No impact = N	

Similarly, Table 4.37 shows the correlation analysis between constraints and their impact on the duration of installation of ceiling suspension system, based on the correlation analysis conducted in CM-1a, Table 4.33. As stated before, it should be noted that those constraints, which are representing other constraints in CM-2, have increased their impact levels because of the additional impact of their dependent constraints, as compared to their individual impacts in CM-1 shown in Table 4.17.

Table 4.37 Correlation Matrix-1 for Ceiling Installation

Critical Processes / Constraints	Ceiling suspension system Installation
Physical	A
Pollution	S
Uncertainty	M
Coordination	A
Legend	
Absolute impact =A	Strong Impact = S
Moderate impact = M	Slight Impact = SL
No impact = N	

4.8.11 Step-4 Identification of Weighted Impacts of Reduced Number of Constraints on the Production Schedule of Critical Activities

The weighted impacts of reduced number of constraints, obtained from CM-1a, on the production duration of selective demolition activity, should be established using AHP in the similar manner as represented in the first approach (section 4.8.4). It should be noted that after having conducted the correlation analysis through CM-1a, only limited number of constraints including the representative ones would be considered in AHP.

As stated before, the pair-wise comparison matrix of constraints should be filled with reference to CM-1 conducted in Table 4.36 and 4.37, and the integrated scale of AHP and CM-1 shown in Table 4.18.

Tables 4.38 through 4.40 show the AHP calculations for obtaining the relative importance of 5 constraints in impacting the production schedule of selective demolition.

Table 4.38 Pair-wise Comparison Matrix

[A] =

	Physical	Pollution	Uncertainty	Coordination	Traffic
Physical	1	1/3	1/3	1/5	3
Pollution	3	1	1	1/3	5
Uncertainty	3	1	1	1/3	5
Coordination	5	3	3	1	7
Traffic	1/3	1/5	1/5	1/7	1

Table 4.39 Pair-wise Comparison Matrix (Decimal Form)

[A] =

	Physical	Pollution	Uncertainty	Coordination	Traffic
Physical	1	0.333	0.333	0.200	3
Pollution	3	1	1	0.333	5
Uncertainty	3	1	1	0.333	5
Coordination	5	3	3	1	7
Traffic	0.333	0.200	0.200	0.142	1

Table 4.40 Normalization Matrix

[A] =

	Physical	Pollution	Uncertainty	Coordination	Traffic
Physical	0.081	0.060	0.060	0.100	0.143
Pollution	0.243	0.181	0.181	0.166	0.238
Uncertainty	0.243	0.181	0.181	0.166	0.238
Coordination	0.405	0.542	0.542	0.498	0.333
Traffic	0.027	0.036	0.036	0.071	0.048

Table 4.41 Final weights

[W]=

Physical	Pollution	Uncertainty	Coordination	Traffic
0.088	0.202	0.202	0.464	0.043

Table 4.41 shows the final weights of constraints in impacting the production schedule of selective demolition of ceiling suspension system.

Similarly, Tables 4.42 through 4.44 show the AHP calculations for obtaining the relative importance of 4 constraints in impacting the production schedule of installation of ceiling suspension system.

Table 4.42 Pair-wise Comparison Matrix

[A] =

	Physical	Pollution	Uncertainty	Coordination
Physical	1	3	5	1
Pollution	1/3	1	3	1/3
Uncertainty	1/5	1/3	1	1/5
Coordination	1	3	5	1

Table 4.43 Pair-wise Comparison Matrix (Decimal Form)

[A] =

	Physical	Pollution	Uncertainty	Coordination
Physical	1	3	5	1
Pollution	0.333	1	3	0.333
Uncertainty	0.200	0.333	1	0.200
Coordination	1	3	5	1

Table 4.44 Normalization Matrix

[A] =

	Physical	Pollution	Uncertainty	Coordination
Physical	0.395	0.409	0.357	0.395
Pollution	0.131	0.136	0.214	0.131
Uncertainty	0.079	0.045	0.071	0.079
Coordination	0.395	0.409	0.357	0.395

Table 4.45 Final weights

	Physical	Pollution	Uncertainty	Coordination
[W]=	0.389	0.153	0.068	0.389

Table 4.45 shows the final weights of constraints in impacting the production schedule of installation of ceiling suspension system.

4.8.11.1 Consistency Measurement for AHP of Selective Demolition

Table 4.46 shows how to calculate the maximum eigenvalue of the normalized comparison matrix (λ_{max}) for selective demolition activity.

For reader's reference, Table 4.23 of random index values is recreated below.

Table 4.46 Multiplication of Pair-wise Comparison Matrix with Final Weights

λ_{max} =

	Physical	. . .	Traffic
Physical	1	. . .	3
Pollution	3	. . .	5
Uncertainty	3	. . .	5
Coordination	5	. . .	7
Traffic	1/3	. . .	1

X

0.088
0.202
0.202
0.464
0.043

Table 4.23 Random Index Values (Nassar 2005)

N	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

From Table 4.46, $\lambda_{max} = 5.129$

CI = 5.129 – 5 / (5 -1) = 0.032

Value of RI is = 1.12 (for n= 5, from Table 4.23)

CR = 0.032 / 1.12 = 0.029

The CR value of 0.029 (less than 0.1) signifies that the consistency in the pair-wise comparison of constraints for the selective demolition activity was high and therefore, there is no need to re-evaluate pair-wise judgments.

4.8.11.2 Consistency Measurement for AHP of Installation of Ceiling Suspension System

Table 4.47 shows how to calculate the maximum eigenvalue of the normalized comparison matrix (λ_{max}) for installation of ceiling suspension system.

Table 4.47 Multiplication of Pair-wise Comparison Matrix with Final Weights

λ_{max} =

	Physical	. .	Coordination
Physical	1	. .	1
Pollution	1/3	. .	1/3
Uncertainty	1/5	. .	1/5
Coordination	5	. .	1

X

0.389
0.153
0.068
0.389

From Table 4.47, λ_{max} = 4.043

CI = 4.043 – 4 / (4 -1) = 0.014

Value of RI is = 0.9 (for n= 4, from Table 4.23)

CR = 0.014/ 0.9 = 0.016

The CR value of 0.016 (less than 0.1) signifies that the consistency in the pair-wise comparison of constraints for the activity of installation of ceiling suspension system was high and therefore, there is no need to re-evaluate pair-wise judgments.

4.8.12 Step-5 Quantification of Additional Production Duration of Critical Activities based on Project Conditions- Constraint Assessment Matrix (CAM)

Similar to the constraint assessment matrix (CAM) demonstrated for all the constraints in section 4.8.5, this section also involves assessing the project conditions of all constraints for estimating the additional duration of critical activities. As stated in the framework discussion, there are two main deviations in the CAM of second approach, which are:

1. Normalizing the estimated additional duration based on the relative weights of constraints, obtained from CM-1a and constraint removal process.
2. Those constraints which were observed to be absolutely dependent on others, the estimated additional duration due to their project conditions should be added to the additional duration due to their representative constraints.

Based on these deviations, Tables 4.48 and 4.49 show the CAM for selective demolition and ceiling installation activity, respectively, in which the dependent constraints have been assigned a relative weight of 0 and all other constraints' weightages have been obtained from AHP conducted in the previous step. In these constraint assessment matrices shown in Tables 4.48 and 4.49, the calculations for obtaining additional duration are similar to those conducted in the first approach.

4.8.12.1 Query Node-1

Assuming that all the constraints have been addressed for both critical activities, the answer to the query node-1 would be "yes" and the production duration of critical activities would be revised as follows.

From Table 4.48,

AD_{min} (selective demolition) = (0.5 x 0.088) + (1.25 x 0.202) + (0.5 x 0.202) + (4 x

0.464) + (0.625 x 0.043) = 2.28

= 3 days (approx.)

AD_{max} (selective demolition) = 0.5 + 1.25 + 0.5 + 4 + 0.625 = 6.875

= 7 days (approx.)

Therefore, the constraint assessment matrix shown in Table 4.48 has resulted into a range of additional duration for selective demolition activity, having a minimum and maximum value. An estimated additional duration (EAD) would be a middle value of its range.

$$EAD = \{(AD_{min}) + (AD_{max})\} / 2 = (3 + 7) /2 = 5 \text{ days}$$

The Revised Production Duration (RPD) for selective demolition activity, based on the assessment of reduced number of constraints would be:

RPD = Estimated duration (without consideration of constraints) + EAD

= 5 + 5 = 10 days

Similarly, from Table 4.49 for ceiling installation activity,

AD_{min} (installation) = (3.47 x 0.389) + (1.25 x 0.153) + (2 x 0.068) + (5.9 x 0.389)

= 3.972 = 4 days (approx.)

AD_{max} (installation) = 3.47 + 1.25 + 2 + 5.9 = 14.525

= 15 days (approx.)

An estimated additional duration (EAD) would be a middle value of its range.

$$EAD = \{(AD_{min}) + (AD_{max})\} / 2 = (4 + 15) /2 = 9.5 \text{ or } 10 \text{ days}$$

The Revised Production Duration (RPD) for installation of ceiling suspension system, based on the assessment of reduced number of constraints would be:

RPD = Estimated duration (without consideration of constraints) + EAD

= 9 + 10 = 19 days

It could be seen that in the second approach, while calculating the AD_{min} and AD_{max} for both critical activities, only reduced number of constraints are considered, involving those, which are either representatives of other constraints or which are not absolutely dependent on any other constraint.

Table 4.48 Constraint Assessment Matrix for Approach-2 for Selective Demolition of Ceiling Suspension System

Constraints	Project Conditions or Performance Indicators (PI)	Assessment Method	Additional Duration based on assessment	Constraint Weightage from AHP	Normalized Additional Duration based on Constraint weightage [additional duration due to constraint x relative weight of constraint]	Explanation of Assessment
Utility Constraint	1Capacity of downstream system	If the available capacity of the utilities and/or the load bearing capacity of the structure is less than the required capacity for construction activities (loading capacity, electrical loading etc.), then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			The required capacities for ceiling demolition activity is with in the existing capacity of the building.
	2.Non-disruption to existing utilities	Non work period due to non-disruption to existing utilities	1 day			Due to the project condition of not shutting down any services between 7am to 8pm during weekdays, it has been assumed that one extra day during weekend will be required to remove ceiling mounted fixtures.

Table 4.48 (cont'd)

	3.Impact of existing utilities and/or structural systems on the design of new systems	If the existing capacity of utilities and/or the structural system is less than the required capacities for supporting new and/or upgraded systems, then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	Additional duration due to represented constraints		0			
	Total additional duration due to utility constraint		1 day			
Is Utility constraint being represented by any other constraint	**If Yes, the additional duration due to utility constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to utility constraint should remain the same.**	**Yes- Coordination constraint**	**0 day**	0	0 x 0 = 0 day	

Table 4.48 (cont'd)

Physical constraint	1. Space limitations for construction	Available space / Additional duration (in % of original duration) • More than required: 0 • Required: 0 to 10 • Limited: 10 to 20 • Very limited: more than 20	0.1x5 = 0.5 day			Given that the construction is to be executed in a temporary enclosure during all 5 phases, the estimated duration will be increased by 10% for not disturbing the existing structure outside the enclosure, and due to multiple mobilization and demobilization in limited space.
	2. Space limitations for material storage	For on-site storage: Available space / Additional duration (in % of original duration) • More than required: 0 • Required: 0 to 10 • Limited: 10 to 20 • Very limited: more than 20	0			
		For off-site storage: Cycle time to install the material on site / cycle time to deliver the material from off-site storage space to construction site (time lapse between material procurement and material installation) or 1- wait time of crew for receiving the material on site/ cycle time to install the material on site	0			

Table 4.48 (cont'd)

	3. Space limitation for installing new equipment/material	If the available space is less than the space required to install equipment or material, then how much percentage of activity duration would be increased Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	Additional duration due to represented constraints		0			
	Total additional duration due to physical constraint		0.5 day			
Is Physical constraint being represented by any other constraint	**If Yes, the additional duration due to physical constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to physical constraint should remain the same.**	**No**	**0.5 day**	0.088	0.5 x 0.088 = 0.044 day	
Pollution control	1. Noise, dust, debris, vibration and odor control	(Time for enclosing construction zone + time for installing peripheral sound & vibration insulation + time for installing negative air machines + any other time for pollution control activities+ non-work period specified by owner due to pollution problems)	1.25 days			The contractor has assumed that approx. 2 hrs./phase (for 5 phases, each of 700 sqft) will be expended for erecting temporary enclosure that comprises of drywalls taped to the floor.
	Additional duration due to represented constraints (Safety)		1.25 days			

Table 4.48 (cont'd)

	Total additional duration due to pollution constraint		1.25 days			
Is Pollution constraint being represented by any other constraint	**If Yes, the additional duration due to pollution constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to pollution constraint should remain the same.**	**No**	**1.25 days**	0.202	(1.25+0) x 0.202 = 0.252 day	
Uncertainty constraint	1. Non-availability of As-built Drawings	Time required/expended for site investigation	0.5 day			Due to the non-availability of as-built drawings of lift lobby, prior to start the work, the contractor will conduct a thorough site investigation to identify any inconsistencies between new design and existing conditions. The site investigation will take about 4 hrs.
	2. Presence of unforeseen conditions	Planned time buffer based on site investigation	0			
	3. Presence of hazardous material	Abatement period for hazardous material	0			
	Additional duration due to represented constraints (Regulatory)		0			

Table 4.48 (cont'd)

	Total additional duration due to uncertainty constraint		0.5 day			
Is Uncertainty constraint being represented by any other constraint	**If Yes, the additional duration due to uncertainty constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to uncertainty constraint should remain the same.**	No	**0.5 day**	0.202	(0.5+0) x 0.202 = 0.101 day	
Coordination constraint	1. Timing limitations due to owner operations	Non-work period	1.5 days			Given that the work cannot take place Monday through Wednesday, from Noon to 8 pm, an additional 1.5 days (12 hrs.) will be required to complete the demolition.
	2. Relocation of owner operations to and from swing space	(Minimum time for relocating owner operations to swing space for starting construction + non-work period due to owner relocation from swing space to the renovated space)	0			
	3. Owner furnished equipments	If the work is dependent on installation of owner furnished equipment/material, then value of PI= (Lead time + installation time)	0			

Table 4.48 (cont'd)

	4. Removal & reinstallation of owner's furniture	Expected removal time for floor mounted furniture in the lobby	0.5 day			Floor mounted furniture comprises of wooden seats, tables and display boards. After removal, the furniture has to be moved to the storage room located on ground floor.
	5. Multiple inspections by end-users, owner's representatives and hazardous material inspection team	expected inspection time (multiple no.)	0.5 day			An inspection might be conducted by the Hazardous material abatement team, if, during demolition, the existing conditions pose any risk of asbestos presence.
	Additional duration due to represented constraints (Utility and Schedule)		1 + 0.5 = 1.5 days			
	Total additional duration due to coordination constraint		4 days			
Is Coordination constraint being represented by any other constraint	**If Yes, the additional duration due to coordination constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to coordination constraint should remain the same.**	No	**4 days**	0.464	(2.5 +1.5)x 0.464 = 1.856 days	

Table 4.48 (cont'd)

Regulatory constraint	1. Non conformance of existing materials or project conditions with current codes	If the existing materials or project conditions do not conform to the current building codes then how much additional duration is required to complete the activity Additional duration (% of original duration) • 0 • 0 to 10 • 10 to 20 • more than 20	0			
	Additional duration due to represented constraints		0			
	Total additional duration due to regulatory constraint		0			
Is Regulatory constraint being represented by any other constraint	**If Yes, the additional duration due to regulatory constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to regulatory constraint should remain the same.**	**Yes- Uncertainty constraint**	**0 day**	0	0 x 0 = 0 day	
Traffic constraint	1. Limitations of materials and equipment movement	(Wait time + time lapse b/w material handling from storage space and delivery on site) and/or (Time required for moving or maneuvering equipment/scaffold from one construction location to another) and/or (Labor movement restriction period)	0.625 day			An additional 1 hr. will be required per phase for moving and maneuvering scaffold from one phase location to another, due to owner traffic and limited space.
	Additional duration due to represented constraints		0			
	Total additional duration due to traffic constraint		0.625 day			

Table 4.48 (cont'd)

Is Traffic constraint being represented by any other constraint	**If Yes, the additional duration due to traffic constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to traffic constraint should remain the same.**	**No**	**0.625 day**	0.043	0.625 x 0.043 = 0.027 day	
Schedule constraint	1. Work Restructuring and/or Sequencing of Trades	Additional duration due to work restructuring	0			
	2. Impact on crew productivities	Decrease in productivity/estimated productivity x original duration	72/720x5 = 0.5 day			The contractor has assumed that the crew productivity will get decreased by 10% due crowding conditions and limited space.
	Additional duration due to represented constraints		0			
	Total additional duration due to schedule constraint		0.5 day			

Table 4.48 (cont'd)

Is Schedule constraint being represented by any other constraint	**If Yes, the additional duration due to schedule constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to schedule constraint should remain the same.**	**Yes- Coordination constraint**	**0 day**	0	0.5 x 0 = 0 day	
Safety constraint	1. Users & public	Time to be expended in special safety consideration	0			
	Additional duration due to represented constraints		0			
	Total additional duration due to safety constraint		0			
Is Safety constraint being represented by any other constraint	**If Yes, the additional duration due to safety constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to safety constraint should remain the same.**	**Yes- Pollution constraint**	**0 day**	0	0 x 0 = 0 day	
Range of Additional Duration			**Maximum 6.875 = 7**		**Minimum 2.28 = 3**	
Estimated Additional Duration (EAD)			**5 days**			
Revised Production Duration of selective demolition of ceiling system = Original Duration + Estimated Additional Duration			**5 + 5 = 10 days**			

Table 4.49 Constraint Assessment Matrix for Approach-2 for Installation of Ceiling Suspension System

Constraints	Project Conditions or Performance Indicators (PI)	Assessment Method	Additional Duration based on assessment	Constraint Weightage from AHP	Normalized Additional Duration based on Constraint weightage [additional duration due to constraint x relative weight of constraint]	Explanation of Assessment
Utility Constraint	1Capacity of downstream system	If the available capacity of the utilities and/or the load bearing capacity of the structure is less than the required capacity for construction activities (loading capacity, electrical loading etc.), then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	2.Non-disruption to existing utilities	Non work period due to non-disruption to existing utilities	2 days			As the installation of fixtures can only be done during weekend and night, an additional 2 days will be required.
	3.Impact of existing utilities and/or structural systems on the design of new systems	If the existing capacity of utilities and/or the structural system is less than the required capacities for supporting new and/or upgraded systems, then how much additional duration is required to complete the activity Available capacity — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0.1 x 9 = 0.9 day			The contractor might expect some joists that need structural bracing for supporting new ceiling.
	Additional duration due to represented constraints		0			
	Total additional duration due to utility constraint		2.9 days			

Table 4.49 (cont'd)

Is Utility constraint being represented by any other constraint	**If Yes, the additional duration due to utility constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to utility constraint should remain the same.**	**Yes- Coordination constraint**	**0 day**	0	0 x 0 = 0 day	
Physical constraint	1. Space limitations for construction	Available space / Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0.15x9 = 1.35 day			Given that the construction is to be executed in a temporary enclosure during all 5 phases, the estimated duration will be increased by 10% for not disturbing the existing structure outside the enclosure, and due to multiple mobilization and demobilization in limited space. In addition, there will be a 5% increase in the estimated duration as the space will also be limited by inclusion of all tools and materials within the enclosure.

Table 4.49 (cont'd)

	2. Space limitations for material storage	For on-site storage: Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20 and/or	0			
		For off-site storage: Cycle time to install the material on site / cycle time to deliver the material from off-site storage space to construction site (time lapse between material procurement and material installation) or 1- wait time of crew for receiving the material on site/ cycle time to install the material on site	3500/ (4 sqft x 75 panels/hr. x 8 hr./day) = 1.5 day			Given that the storage space is not availbale in the lift lobby, the contractor would have to store the material on ground floor parking area. Assuming the cycle time of 1 labor for delivering ceiling panels to the lift lobby is 75 panels/hr.
	3. Space limitation for installing new equipment/material	If the available space is less than the space required to install equipment or material, then how much percentage of activity duration would be increased Available space — Additional duration (in % of original duration) • More than required — 0 • Required — 0 to 10 • Limited — 10 to 20 • Very limited — more than 20	0			
	Additional duration due to represented constraints (Traffic and Safety)		0.625+0 = 0.625 day			
	Total additional duration due to physical constraint		3.47 days			

Table 4.49 (cont'd)

Is Physical constraint being represented by any other constraint	**If Yes, the additional duration due to physical constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to physical constraint should remain the same.**	**No**	**3.47 days**	0.389	3.47 x 0.389 = 1.35 day	
Pollution control	1. Noise, dust, debris, vibration and odor control	(Time for enclosing construction zone + time for installing peripheral sound & vibration insulation + time for installing negative air machines + any other time for pollution control activities+ non-work period specified by owner due to pollution problems)	1.25 days			The contractor has assumed that approx. 2 hrs./phase (for 5 phases, each of 700 sqft) will be expended for erecting temporary enclosure that comprises of drywalls taped to the floor.
	Additional duration due to represented constraints		0			
	Total additional duration due to pollution constraint		1.25 days			
Is Pollution constraint being represented by any other constraint	**If Yes, the additional duration due to pollution constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to pollution constraint should remain the same.**	**No**	**1.25 days**	0.153	1.25 x 0.153 = 0.191 day	

Table 4.49 (cont'd)

Uncertainty constraint	1. Non-availability of As-built Drawings	Time required/expended for site investigation	0			
	2. Presence of unforeseen conditions	Planned time buffer based on site investigation	0			
	3. Presence of hazardous material	Abatement period for hazardous material	0			
	Additional duration due to represented constraints (Regulatory)		2 days			
	Total additional duration due to uncertainty constraint		2 days			
Is Uncertainty constraint being represented by any other constraint	**If Yes, the additional duration due to uncertainty constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to uncertainty constraint should remain the same.**	**No**	**2 days**	0.068	2 x 0.068 = 0.136 day	
Coordination constraint	1. Timing limitations due to owner operations	Non-work period	1.5 days			Given that the work cannot take place Monday through Wednesday, from Noon to 8 pm, an additional 1.5 days (12 hrs.) will be required to complete the demolition.
	2. Relocation of owner operations to and from swing space	(Minimum time for relocating owner operations to swing space for starting construction + non-work period due to owner relocation from swing space to the renovated space)	0			

Table 4.49 (cont'd)

	3. Owner furnished equipments	If the work is dependent on installation of owner furnished equipment/material, then value of PI= (Lead time + installation time)	0.5			The floor mounted sculpture is to be installed bt owner's self-performed crew and its estimated duration will be approx. 4 hrs. During installation, due to limited space, the contractor cannot work on ceiling installation activity.
	4. Removal & reinstallation of owner's furniture	Expected installation time for floor mounted furniture in the lobby	0.5 day			Floor mounted furniture comprises of wooden seats, tables and display boards. After removal, the furniture has to be moved to the storage room located on ground floor.
	[illegible] inspections by end-users, owner's representatives and hazardous material inspection team	expected inspection time (multiple no.)	0.5 day			The contractor would expect multiple inspections from facilities management, and building users which will approx. consume 4 hrs.
	Additional duration due to represented constraints (Utility and Schedule)		2 + 0.9 = 2.9 days			
	Total additional duration due to coordination constraint		5.9 days			
Is Coordination constraint being represented by any other constraint	**If Yes, the additional duration due to coordination constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to coordination constraint should remain the same.**	No	**5.9 days**	0.389	5.9 x 0.389 = 2.295 days	

Table 4.49 (cont'd)

Regulatory constraint	1. Non conformance of existing materials or project conditions with current codes	If the existing materials or project conditions do not conform to current building codes then how much additional duration is required to complete the activity Additional duration (% of original duration) • 0 • 0 to 10 • 10 to 20 • more than 20	2 days			After selective demolition of ceiling assembly, it was found that the existing batt insulation do not conform to the fire safety requirements of current building codes. The order and installation of new insulation will result in 2 additional days to the estimated duration.
	Additional duration due to represented constraints		0			
	Total additional duration due to regulatory constraint		2 days			
Is Regulatory constraint being represented by any other constraint	**If Yes, the additional duration due to regulatory constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to regulatory constraint should remain the same.**	**Yes- Uncertainty constraint**	**0 day**	0	0 x 0 = 0 day	
Traffic constraint	1. Limitations of materials and equipment movement	(Wait time + time lapse b/w material handling from storage space and delivery on site) and/or (Time required for moving or maneuvering equipment/scaffold from one construction location to another) and/or (Labor movement restriction period)	0.625 day			An additional 1 hr. will be required per phase for moving and maneuvering scaffold from one phase location to another, due to owner traffic and limited space.
	Additional duration due to represented constraints		0			
	Total additional duration due to traffic constraint		0.625 day			

Table 4.49 (cont'd)

Is Traffic constraint being represented by any other constraint	**If Yes, the additional duration due to traffic constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to traffic constraint should remain the same.**	**Yes- Physical constraint**	**0 day**	0	0 x 0 = 0 day	
Schedule constraint	1. Work Restructuring and/or Sequencing of Trades	Additional duration due to work restructuring	1 day			Assuming that the contractor has to change the sequence of reinstallation activities that includes first installing all the fixtures and then the panels. This change in logic has increased the installation duration by 1 day.
	2. Impact on crew productivities	[{Estimated productivity/(estimated - decrease in productivity) x original duration} - original duration	[{1170/(1170-117) x3} -3] +[{828/(828-82.8)x 5} -5 = 0.9 day			The contractor has assumed that the crew productivity will get decreased by 10% due crowding conditions and limited space.
	Additional duration due to represented constraints		0			
	Total additional duration due to schedule constraint		1.9 day			

Table 4.49 (cont'd)

Is Schedule constraint being represented by any other constraint	**If Yes, the additional duration due to schedule constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to schedule constraint should remain the same.**	**Yes- Coordination constraint**	**0 day**	0	0 x 0 = 0 day	
Safety constraint	1. Users & public	Time to be expended in special safety consideration	0			
	Additional duration due to represented constraints		0			
	Total additional duration due to safety constraint		0			
Is Safety constraint being represented by any other constraint	**If Yes, the additional duration due to safety constraint should become 0 and carry over it's original duration to representative constraint. If No, the additional duration due to safety constraint should remain the same.**	**Yes- Physical constraint**	**0 day**	0	0 x 0 = 0 day	
Range of Additional Duration			**Maximum 14.525 = 15**		**Minimum 3.972 = 4**	
Estimated Additional Duration (EAD)			**9.5 = 10 days**			
Revised Duration of selective demolition of ceiling system = Original Duration + Estimated Additional Duration			**9 + 10 = 19 days**			

4.8.13 Comparison between Approach 1 and 2

Both approaches have resulted in similar value of the maximum additional duration for both critical activities. However, second approach results in a greater value of minimum additional duration as compared to the first one. For instance, approach-1 resulted in minimum additional duration of 2 days for selective demolition activity, while approach-2 resulted in 3 days of minimum additional duration. Similarly, for ceiling installation activity, approach-1 resulted in 4 minimum additional days, while approach-2 resulted in 3 days. These differences of 1 and 2 days indicate that the incorporation of constraints interdependencies in the constraint assessment process will result in more additional duration to critical activities. The correlation analysis between constraints provides a more comprehensive method for planning the additional duration. Therefore, approach-2 should be preferable over approach-1.

For the remaining steps of demonstration (from steps 6 through 10), the additional duration resulted from approach-2 is considered as the one that the contractor will plan for. In addition, for the purpose of avoiding any complexities in the reader's understanding, only selective demolition activity is considered for the following steps.

4.8.14 Step-6 Enter and Move Production Assignments in Lookahead Schedule

The lookahead schedule would be prepared by the contractor after assessing the impacts of constraints and revising the duration of critical activities. Therefore, this schedule would maintain a reliable workflow between trades, as all the constraints' impacts have been considered.

Table 4.50 shows the lookahead schedule for the first three weeks of the demonstration example. This table is created on the template of lookahead schedule as suggested by Ballard (2000) in the explanation of the Last Planner System. In the lookahead schedule, the critical activities are broken down further to define their sub-activities on day-to-day level, and the sub-activities of each week would be advanced forward as they are being considered for further steps of the framework.

Table 4.50 Example of Lookahead Schedule for the Demonstration

	9/3/2007							9/10/2007							9/17/2007						
Activity	**M**	**T**	**W**	**T**	**F**	**S**	**S**	**M**	**T**	**W**	**T**	**F**	**S**	**S**	**M**	**T**	**W**	**T**	**F**	**S**	**S**
Demolition Crew (Selective Demolition)																					
Site Investigation	X																				
Work on Phase-1		X	X	X																	
Work on Phase-2				X	X																
Remove and reinstall fixtures						X															
Work on Phase-3							X	X													
Work on Phase-4								X	X												
Work on Phase-5									X	X											
Ceiling Installation Crew (Installation)																					
Work on Phase-1										X	X	X			X	X					
Work on Phase-2																	X	X	X	X	

4.8.15 Step-7 Match Production Assignments and Resource Capacities

In this step, the four external constraints would be analyzed with regard to the scope of work of each critical activity and its revised production duration (RPD) in order to create a balance between the RPD and available resources. The external constraints are; prerequisite work, available resources, directives, and maximum time buffer. Each activity would be selected from the lookahead schedule for the analysis of its external constraints, as the work proceeds on site.

This research assumes that the prerequisite work and planned resources (2 laborers) are available for the selective demolition activity. In addition, for executing the activity, clear directives in terms of project conditions and specifications are provided in the contract and design drawings. From the constraint assessment matrix of selective demolition activity (Table 4.48), the maximum time buffer available is as follows.

Maximum Time buffer = AD_{max} - EAD = 7 – 5 = 2 days (From Table 4.48)

As the available buffer is 20% of the production duration (10 days) of selective demolition activity, this constraint would not require any additional resources to expedite the activity.

Based on the review of external constraints, it is assumed that there would be no need to adjust either resources or production duration of selective demolition activity, and its execution plan could be constructed in the next step.

4.8.16 Step-8 Activity Execution Plan

The contractor would prepare an Activity Execution Plan (AEP) after estimating the revised production duration of each critical activity and balancing it with the review of external constraints. As suggested by the framework, the AEP would stipulate the planned resources, revised production duration, estimated work quantity, maximum time buffer, and prerequisite work.

Table 4.51 shows the AEP for selective demolition of ceiling system that the contractor would prepare before starting demolition activity as a proactive measure of planning its production in the presence of constraints. This plan reflects the production schedule that lists the crew production assignments on daily basis that were established on the basis of constraint analysis and revised production duration. By keeping track of daily production assignments, the contractor could minimize the wait time between the selective demolition and installation activities.

This plan would be directly communicated with the demolition crew on daily basis in order to make it aware of the production assignments, which are to be completed on the current day, and which are expected to complete on the next day. Thus, this activity execution plan would provide guidance for executing the selective demolition activity by planning and controlling daily production assignments.

4.8.16.1 Query Node-2

It is assumed that the developed AEP for selective demolition activity meets the quality criteria of definition, soundness, sequence, and size. Being the first activity, the fifth criterion of "learning" does not apply to it. Therefore, at the query node-2 of the framework, the contractor would answer "yes", and the selective demolition activity would be performed on site.

Table 4.51 Activity Execution Plan for Selective Demolition Activity

Activity	Selective Demolition of Ceiling System
Prerequisite Work	None
Planned Resources	1 Foreman, 2Labors
Estimated Quantity	3500 sqft (5 Phases)
Critical Activity	Selective Demolition
Optimum Schedule	09-03-07 to 09-12-07
Optimum Production Duration	10 Days
Maximum Buffer	2 Days (till 09-14-07)
Next Activity	Installation of Ceiling Suspension System scheduled to be started on 09-13-07
Production Schedule	
Days	**Production Assignment**
09-03-07 - Monday	The crew forman will conduct a thorough site investigation and an inspection might be conducted by the Hazardous material abatement team.
09-04-07 - Tuesday	Floor mounted fixtures will be uninstalled and stored on the ground floor.Crew will install temporary walls around Phase-1 and work on demolition till Noon.
09-05-07 - Wednesday	Work on demolition of Phase-1 till Noon.
09-06-07 - Thursday	Finish Phase-1 demolition and uninstall temporary walls around Phase-1 and re-install around Phase-2 and start demolition of Phase-2.
09-07-07 - Friday	Finish demolition of Phase-2.
09-08-07 - Saturday	Remove and reinstall fixtures for all Phases from 1 to 5 .
09-09-07 - Sunday	Install temporary walls around Phase-3 and start demolition.
09-10-07 - Monday	Finish demolition of Phase-3, uninstall temporary walls and reinstall around Phase-4 till Noon.
09-11-07 - Tuesday	Finish Phase-4 demolition and uninstall temporary walls around Phase-4 and re-install around Phase-5 and work on demolition of Phase-5 till Noon.
09-12-07 - Wednesday	Finish Phase -5 demolition and uninstall temporary walls

4.8.17 Step-9 Production Performance Evaluation

After executing the work on site, the contractor would evaluate the production performance of each critical activity by comparing its actual and revised production duration. As suggested by the framework, the production evaluation should also include the quality of workflow between hand-offs and the utilization of planned buffer.

Assuming that the selective demolition activity was completed in 11 days, it has used 50% of its maximum time buffer (2 days). However, the demolition was done consistently with drawings and specifications, without any reworks. Therefore, the quality of work delivered to ceiling installation crew was 100%. The production performance of selective demolition activity would be evaluated in terms of its production factor, as shown below.

Activity Production Factor $(APF)_{\text{Selective demolition}}$ = (Revised production duration/ Actual duration) + (% of quality work delivered to the next trade/100) + (1- % of buffer) } / 3

= [(10 days /11 days) + (100/100) + (1-0.5)] /3 = 0.803

As the quality of work of selective demolition activity was 100%, it could be handed off to the ceiling installation crew without any rework.

Similarly, production performance of ceiling installation activity could be evaluated. The maximum planned buffer for this activity was:

Maximum Time buffer = AD_{max} - EAD = 15 – 10 = 5 days (From Table 4.49)

Assuming that ceiling installation was completed in 21 days, its activity production factor would be:

Activity Production Factor (APF) $_{\text{Ceiling installation}}$ = (Revised production duration/ Actual duration) + (% of quality work delivered to the next trade/100) + (1- % of buffer) } / 3

= [(19 days /21 days) + (90/100) + (1-2/5)] /3 = 0.801

Although, the ceiling installation activity used 10% less amount of maximum time buffer as compared to selective demolition activity, but given that 10% of the installed ceiling system was found to be unacceptable on inspection, its activity production factor resulted as similar to that of selective demolition activity.

4.8.17.1 Query Node-3

Based on the assumption that the planned minimum performance criterion for the selective demolition activity was 0.9 APF, the contractor would conduct a production failure analysis after answering "no" at the query node-3 of the framework, and simultaneously release the work to the next trade without any rework. It is assumed that the criterion of achieving 0.9 APF was decided based on the subjective judgment of the contractor per its past experience of performing demolition activities under similar project conditions.

4.8.18 Step-10 Production Failure Analysis

Based on the values of APFs of critical activities, the contractor would conduct a production failure analysis to understand the causes of production delay and apply it in future constraint assessment processes. In comparing the actual APFs of critical activities with the desired APF value of 1, it could be observed that both crews fell approximately

20% short of completing their production assignments within revised duration and of desired quality. The 20% production failure could be attributed to either single or multiple constraints. If the contractor had documented actual crew productions against the production schedule of AEP on daily basis, the causes of production delay or poor quality could be explored. Therefore, one of the methods of performing production failure analysis could be to document daily production and compare and analyze it against the production schedule.

Table 4.52 shows the actual daily production of demolition crew against the production schedule of its AEP. The daily production documentation shows that the demolition crew took more time than estimated in uninstalling the floor mounted fixtures in the lift lobby, and transporting them to the storage room located on ground floor. The labor foreman reported that the immense student and faculty traffic in the stairways, due to the continuous class schedule, resulted in decreased crew productivity.

In addition, it was reported that the production of Phase-3, being located next to the auditorium was not appropriately planned in consideration with the class schedules in auditorium. As the crew could not block the auditorium exits till Noon, the crew had to uninstall the temporary walls and re-install them around Phase-4.

The actual production documentation justifies that the contractor did not give much importance to coordination and traffic constraints while planning the production of selective demolition activity. The contractor should have strategically located all the phases, not only in floor plan but also according to the class schedule and public traffic.

Table 4.52 Actual Daily Production Documentation of Selective Demolition Activity for Production Failure Analysis

Activity	Selective Demolition of Ceiling System	
Prerequisite Work	None	
Planned Resources	1 Foreman, 2Labors	
Estimated Quantity	3500 sqft (5 Phases)	
Critical Activity	Selective Demolition	
Optimum Schedule	09-03-07 to 09-12-07	
Optimum Production Duration	10 Days	
Maximum Buffer	2 Days (till 09-14-07)	
Next Activity	Installation of Ceiling Suspension System scheduled to be started on 09-13-07	
Production Schedule		**Daily Production Documentation**
Days	**Production Assignment Planned**	**Production Assignment Completed (Yes/No)**
09-03-07 - Monday	The crew forman will conduct a thorough site investigation and an inspection might be conducted by the Hazardous material abatement team.	Site investigation and Inspection completed
09-04-07 - Tuesday	Floor mounted fixtures will be uninstalled and stored on the ground floor.Crew will install temporary walls around Phase-1 and work on demolition till Noon.	Floor mounted fixtures were uninstalled and stored on the ground floor.
09-05-07 - Wednesday	Work on demolition of Phase-1 till Noon.	Crew has installed temporary walls for Phase-1 and started demolition.
09-06-07 - Thursday	Finish Phase-1 demolition and uninstall temporary walls around Phase-1 and re-install around Phase-2 and start demolition of Phase-2.	Finished Phase-1 demolition and uninstalled temporary walls around Phase-1
09-07-07 - Friday	Finish demolition of Phase-2.	Crew has installed temporary walls for Phase-2 and started demolition.
09-08-07 - Saturday	Remove and reinstall fixtures for all Phases from 1 to 5 .	Finish demolition of Phase-2 and removed fixtures of all phases.
09-09-07 - Sunday	Install temporary walls around Phase-3 and start demolition.	Reinstalled fixtures and erected temporary walls around Phase-3.
09-10-07 - Monday	Finish demolition of Phase-3, uninstall temporary walls and reinstall around Phase-4 till Noon.	Crew could not start Phase-3 demolition. Uninstalled temporary walls and re-installed around Phase-4 and started Phase-4 demolition.
09-11-07 - Tuesday	Finish Phase-4 demolition and uninstall temporary walls around Phase-4 and re-install around Phase-5 and work on demolition of Phase-5 till Noon.	Finished Phase-4 demolition and uninstalled temporary walls around Phase-4 and re-installed around Phase-5 and worked on demolition of Phase-5 till Noon.
09-12-07 - Wednesday	Finish Phase -5 demolition and uninstall temporary walls	Finished Phase -5 demolition and uninstalled temporary walls
09-13-07 - Thursday	Start Ceiling Installation	Installed temporary walls for Phase-3 and completed demolition and unsintalled temporary walls.
09-14-07 - Friday		Start Ceiling Installation

4.9 Framework Verification

The verification of the developed framework for production management of renovation projects forms the last phase of this research. The purpose of conducting verification was to understand the usefulness, and identify the limitations and improvement areas of the framework for its appropriate application to renovation projects.

4.9.1 Verification Procedure

The verification of the developed framework was conducted by obtaining construction professionals' views regarding the proposed production planning and assessment methods. The researcher selected a project engineer, a superintendent, and a project manager as interviewees from a mid-size construction company. This company primarily works as a general contractor, and had completed over $3 billion worth of projects with an average annual volume $130 million. The company had experience in institutional, health care, commercial, and hospitality sectors, both for new construction and renovation work. The interviewed project manager and superintendent had an average experience of 7 to 9 years of working on renovation projects, while the project engineer had 2 years of experience in new construction projects.

The verification process was conducted in a group session involving all interviewees. Interview questions for verification were not drafted, as an open-ended discussion was essential for reaching on consensus regarding the improvement areas and usefulness of the framework. In order to explain the framework to the interviewees, the researcher first presented its demonstration, discussing each suggested step in detail. All the matrices and quantitative calculations such as RPD, APF etc. were explained with hypothetical facts and figures. The demonstration was similar to what has been presented in Phase-4 of this research. Based on the demonstration of framework, the interviewees were asked to provide their feedback in a formal discussion. Overall, the verification process was completed in a 4 hours session.

4.9.2 Verification Findings

The interviewees acknowledged that the developed framework involves a comprehensive process of production planning, execution, and assessment and it can be used as a vital tool by construction professionals for managing renovation projects. However, the interviewees found the framework to be time consuming, as it involves numerous steps, which could limit its application in managing smaller renovation projects. In addition, in smaller projects, the indirect cost associated with implementing the framework could increase the overall budget of the contractor. Therefore, the interviewees suggested that for smaller projects, a miniature or a compact form of the framework should be developed by combining some of the time consuming steps. Nonetheless, for larger projects, the interviewees agreed that the number of steps as suggested by the developed framework should be undertaken, as the constraints and project conditions become significant and may have a considerable impact on the project cost, time, and quality. Therefore, the time spent in implementing the framework steps and its associated indirect cost could be offset in larger renovation projects by improving the production performance of construction crews and completing the project on time and within budget.

Another major observation found in the verification was that the implementation of the framework requires a close coordination of all trade subcontractors for performing most of the suggested steps. For instance, while filling out correlation matrix-1 (CM 1), in order to identify the impact level of "coordination" constraint on the schedule of an activity involving mechanical system replacement, a proper communication and feedback is required from the HVAC, plumbing, electrical, and fire-protection subcontractors. This coordination can become an arduous task for a project manager or a project engineer working for the general contractor who is conducting the framework steps, as subcontractors might not be available through out the required steps or may not show interests. Therefore, the interviewees suggested that the process of framework implementation should be formalized by including it in the subcontract conditions of major trade contractors such as HVAC, plumbing, electrical etc., which would make the framework application more effective by involving major subcontractors during the construction process.

At the micro level, the interviewees also recommended on the qualitative measurement methods of the project conditions of constraints, as proposed by the framework. According to the interviewees, the assessment of project conditions is function of the experience and judgment of the evaluator, and thus the measurement methods would change from person to person and project to project. Therefore, in case of qualitative assessment of project conditions, it would become difficult to strictly follow a definitive set of measurement methods as suggested by the framework. However, the interviewees agreed that irrespective of the measurement methods, the project conditions should be measured in order to ascertain the additional duration of critical activities due to the impact of constraints generated from them. Thus, the interviewees consented on the overall process of assessing project conditions in the "constraint assessment matrix" (CAM) of the framework.

At the macro level of the framework, the interviewees commented on managing the cost aspect of production assignments also, in addition to their schedule. The interviewees stated that in most of the cases of renovation projects, as the owner's budget is limited, production performance of crews should be assessed from the perspective of budget management also. This should entail assessing the impact of constraints on the cost of production assignments for preparing an accurate cost estimate for renovation projects so that the cost impacts can be planned for. As stated by the interviewees, time and cost should go hand in hand when managing daily production in the presence of constraints. Therefore, the budget and schedule of production assignments should be planned simultaneously by thorough consideration of constraints and the production performance of construction crews should be assessed accordingly. Thus, the interviewees suggested using an integrated approach where the framework can be used to manage time and cost impacts of constraints on the production assignments.

Overall, the interviewees stated that the developed framework covered most of the essential attributes of a production management system for renovation projects and the exemplified constraints, their project conditions, and critical activities were encountered in actual practice also. Having reviewed the framework demonstration, the interviewees stated that a separate production management system should be in place for renovation projects, as they involve greater complexities, risk and uncertainty, as compared to new construction projects. In regard of this view, the interviewees stated that the developed framework presented a detailed approach to renovation project management as it suggests a systematic method for production planning, execution and assessment.

4.10 Chapter Summary

This chapter discusses the interview procedure including the interview questions, data collection process, and synthesis of the collected data. Further, a stepwise development of the framework for production management of renovation projects is discussed. This chapter brings forward the significance of essential attributes identified from literature review in formulating the construct of the framework. This chapter also explains how the framework adopted some of the components of the Last Planner System ™ of production control for production planning in renovation projects.

Further, a detailed demonstration of the developed framework with an example of a suspended ceiling replacement work in an operational institution is discussed. Having explained each step of the framework with hypothetical facts and figures, the demonstration example provides guidance for how to apply the suggested steps of the framework to production planning, execution, and control in renovation projects. The demonstration illustrated the use of quantitative tools such as AHP and correlation analysis for production planning, as suggested by the framework. In the demonstration, it was found that the consideration of dependency relationships between constraints, through approach-2 in production planning provided a better estimate of production duration of critical activities.

Overall, the demonstration exemplified that the developed framework could be employed in renovation projects, given the fact that the subjective assessments of constraints and their project conditions in CM-1, CM-1a, and CAM are based on evaluator's prior knowledge and experience in managing renovation projects. However, considering that renovation projects exhibit constantly changing conditions, the overall process suggested by the framework should be constantly updated for each critical activity. Although, the demonstration example was completely hypothetical, but it can be observed that the framework resulted in a production schedule, which "can" be implemented based on a thorough analysis and assessment of constraints with regard to the project conditions and scope of work, rather than what "should" be done as per the initial estimate of work duration based on the Means Building Construction Cost Data 2005.

As the final phase of this research, the chapter explains how the researcher conducted the verification process of the framework through a second round of interview, and discusses the findings regarding framework's limitations and usefulness for its application to renovation projects.

CHAPTER-5

SUMMARY AND CONCLUSIONS

5.1 Introduction

As a concluding part of this thesis, chapter-5 provides an overview of this research and its major findings along with a brief discussion of how the goals and objectives were accomplished. This chapter also discusses the limitations of this research and other future research based on those limitations.

5.2 Research Overview

This research provided a framework for production management of renovation projects which was constructed based on the literature review and verified through interviews of contractors. To reiterate, the last four chapters are briefly discussed below explaining how this framework was constructed.

Chapter 1 presented the current problems of renovation projects that lead to schedule and cost overruns, and discussed the need for their production management in addition to the traditional performance measurement. Based on the need statement, this chapter stated the overall goal and objectives of this research along with its scope, and the potential benefits that might be achieved with the research goal accomplishment. In addition, chapter 1 defined what production management meant in the context of renovation projects for this research.

Chapter 2 provided a detailed account to some of the past researches in the field of state-of-the-art construction performance measurement systems, renovation projects, and production management. In this chapter, the research has extensively reviewed performance indicators and measurement methods of state-of-the-art performance measurement systems for their application to production management of renovation projects. Production management methods such as Last Planner System prevalent in the construction industry are also discussed for their significance in the developed framework. From the literature of renovation projects, chapter-2 provided an insight to some of the constraints encountered in renovation projects that mostly inhibit the schedule and budget performance. These constraints were identified by past researches that focused on renovation projects. Overall, chapter 2 provided the essential attributes from literature review which were used in the development of a framework for production management of renovation projects.

Chapter 3 explained a five phased methodology that was adopted to accomplish the research goal and objectives based on the literature review and contractors' and subcontractors' interviews. Each phase was discussed in detail to explain what was done, and how did it contribute to achieving the research objectives. This chapter also underscored the need for reviewing literature in the categories of state-of-the-art construction performance measurement systems, renovation projects, and production management. The procedure adopted for conducting contractors' and subcontractors' interviews is also discussed.

Chapter 4 represented the main contribution of this research as it documented and discussed the data collected from interviews of contractors and subcontractors, and conducted its analysis in context of the framework. Therefore, chapter 2 and the initial part of chapter 4 were instrumental in achieving the first objective, which was to document state-of-the-art construction performance measurement systems and production management practices for renovation projects.

In addition, chapter 4 explained a stepwise development of a framework for production management of renovation projects. A thorough discussion of how to conduct each step suggested by the framework is presented in this chapter. In order to provide a better understanding of the framework, this chapter presented its detailed demonstration with a hypothetical example of a construction activity of renovation project. In the end, this chapter discussed the procedure adopted for verification of the developed framework through second round of interview with contractors, and its results.

Building upon the understanding gained in the last four chapters, chapter-5 draws major conclusions based on the key observations found in the literature review and the interviews. Prior to discussing the conclusions, the fulfillment of research goal and objectives is discussed.

5.3 Research Goal and Objectives

The overall goal of this research was to develop a framework for production management of renovation projects. In order to achieve this goal, two objectives were proposed in chapter 1, which are:

1. Document state-of-the-art construction performance measurement systems and production management practices for renovation projects.
2. Develop a framework for planning, execution and performance assessment of production operations of renovation projects.

Objective 1 was partly achieved by reviewing the literature of state-of-the-art construction performance measurement systems, renovation projects, and production management, and partly by conducting interviews of contractors and subcontractors for identifying their production management practices in renovation projects. Both literature review and interviews provided the essential attributes that were considered for developing a framework for production management of renovation projects. Some of these essential attributes are; constraints, critical activities, performance indicators, measurement methods, performance categories, performance failure analysis etc.

Based on these essential attributes, the research drafted interview questions to be asked from contractors and subcontractors. The interview responses facilitated in identifying any additional essential attributes of production management currently in practice for renovation projects. Therefore, this research documented the state-of-the-art performance measurement systems and production management practices in terms of literature review, in chapter 2, and interview data analysis in chapter 4.

In order to attain objective 2, based on the literature review, the essential attributes were analyzed to identify appropriate links between them so that they result in a comprehensive process of production planning, execution, and assessment for renovation projects that could be implemented through a framework. The primary essential attributes in developing this framework were the constraints and critical activities of renovation projects, which were mostly identified in the literature review, and the interviews, to some extent. The developed framework suggested a number steps to be performed in renovation projects, where the first few steps required analyzing the project conditions and their resultant constraints for production planning and execution, while others entailed production control technique including production performance assessment and production failure analysis.

Quantitative techniques such as AHP and correlation analysis were applied to the framework so that the impact of constraints on the critical activities could be quantified and therefore, planned for. Although, this research focused only on the schedule impacts for limiting the complexity levels of the thesis, the framework could be further adopted and modified for identifying the budget and quality impacts also.

Therefore, objective 2 was achieved by developing a framework from essential attributes identified from the first objective, and demonstrating it with a hypothetical example of construction activity in a renovation project. The demonstration played a major role in achieving this objective as it exemplified each step of the framework with theoretical facts and figures, and provided clear directions for conducting each step, which could be applied to different construction activities under varying project conditions of renovation projects.

5.4 Conclusions and Inferences

This section discusses the conclusions drawn from the literature review, interviews of contractors and subcontractors, and the feedback obtained on the developed framework of production management for renovation projects. The literature of renovation projects and the interviews emphasized the significance of constraints in the growing underperformance of renovation projects, as compared to new construction. Most of the project conditions and constraints stated in literature that lead to budget and schedule overruns were also reported by the interviewees to be encountered in actual practice. These potential constraints of renovation projects involve uncertainty, dynamic nature, physical space, coordination with owner's operations, traffic, and safety which impact time, cost and quality performance. Therefore, they require a thorough consideration before planning crew assignments. As the state-of-the-art construction performance measurement systems mainly focus on assessing performance of construction projects in three categories of cost, time, and quality, it becomes imperative to investigate the impacts of constraints on the cost, time, and quality performance of renovation projects.

Although, the reviewed performance measurement systems proposed different sets of performance indicators for assessing the performance in the three categories mentioned above, but a consensus has not been arrived at the most appropriate set of performance indicators that define the actual performance of construction projects and identify the sources of inefficiencies. In addition, some of the reviewed researches focused on developing different performance measurement methods but each of them had certain limitations and the most suitable performance measurement methods have not been concluded.

In addition, the reviewed state-of-the-art performance measurement systems do not involve the assessment methods for the constraints and/or project conditions encountered in renovation projects. Consequently, state-of-the-systems will find limited application in assessing the performance of renovation projects at the activity level. Therefore, to assess the performance of renovation projects, an appropriate set of performance indicators need to be investigated that can assess the impact of constraints on the cost, time, and quality of construction activities.

Despite the complex, uncertain, and dynamic nature of renovation projects, unlike new construction, the interviews of contractors and subcontractors revealed that there are no perceived differences in performance assessment methods for new construction and renovation projects. The critical success factors, measurement methods, and their hierarchies were reported to be same in the interviews for both new construction and renovation projects. Due to the uncertainty and other numerous constraints involved in renovation projects, the literature of production management underscores the importance of production planning and performance assessment through the use of operational level indicators such as percentage of plan completed (PPC). However, the critical success factors reported in the interviews were on a very broad level of the project such as quality, under budget, repeat business, and client satisfaction. None of the respondents reported a success factor or performance indicator for renovation projects that deal with the production level. Moreover, the respondents did not state constraint management as a critical success factor for renovation projects.

As the increasing cost and schedule overruns of renovation projects is an aftermath of constraints' impacts on the construction activities, performance measurement of renovation projects should be handled at the activity level where the constraints generate their impacts. Performance planning and assessment at the activity level will identify the causes of inefficiencies at their sources and improve the performance at project level. Therefore, production planning should be undertaken by analyzing all constraints in establishing suitable crew assignments and the performance should be assessed by using operational level indicators. Nonetheless, this research concluded that currently, the analysis of project conditions and constraints of renovation projects is done in an informal basis. There is a lack of formalized and documented procedure for assessing the constraints in production planning of renovation projects.

This is also exemplified by the fact the researcher did not obtain a documented process map of establishing crew assignments from any of the interviewees.

The data collected from interviews and literature review underscored the need for developing a formalized process of production planning and assessment of renovation projects. This process should consider the impact of constraints on the production of construction activities in the categories of their cost, time, and quality. In this view, the developed framework presented one of the processes for production management of renovation projects by suggesting a number of steps to be undertaken. Due to time limitations for conducting this research, as the developed framework focused on assessing only the schedule impacts of constraints, the verification process concluded that their cost impacts on the production should also be incorporated.

5.5 Research Benefits and Contribution

As identified by previous researchers, performance in renovation projects is typically lower than new construction projects due to the challenges and risks imposed by various constraints inherent in project conditions (McKim et al. 2000, Attalla et al. 2003). This research has developed methods to quantify the impacts of these constraints on production schedule of construction activities, which can be employed by project teams in planning for these constraints, and improve the schedule performance of renovation projects.

As there has been a lack of research in production management of renovation projects, this research contributes to their construction management practices by delivering a framework for improving their schedule performance. This framework can

be adopted as a measurement tool by construction professionals for self-assessment, for meeting owners' requirements, and improving production planning techniques. It can be employed by end-users or owners for evaluating the production performance of contractors in renovation projects. The framework can also aid contractors in assessing the production performance of subcontractors.

In addition to the framework's application to production management in new renovation projects, the developed framework can be used to review the health of an ongoing renovation project by evaluating its production performance and assessing the effectiveness of production planning techniques being undertaken. This can be achieved by measuring the Activity Production Factor (APF) of various critical activities in an ongoing project and comparing it with what the project teams desired to be.

This research presents a new and comprehensive approach for production planning of renovation projects that involves unique methods to arrive at the Revised Production Duration (RPD) of critical activities after assessment of possible constraints. In addition, the research proposes a thorough assessment method of production performance through the Activity Production Factor (APF). The APF incorporates usage of production level performance indicators such as the percentage of quality work delivered to the next trade, and the usage of planned buffer. As the reviewed state-of-the-art construction performance measurement systems do not suggest any production performance indicators specifically for renovation projects, the APF surfaces as a major contribution of the framework in production performance assessment. In addition, the proposed qualitative and quantitative assessment methods of project conditions of constraints can assist state-of-the-art performance measurement systems to develop performance indicators for assessing production performance in renovation projects.

Another significant contribution of this thesis is the way researcher investigated the application of state-of-the-art construction performance measurement systems to renovation projects by constructing a graphical interface between their essential attributes. Similar investigation has not been covered by the reviewed literature for the performance measurement of renovation projects. The constructed interface can be adopted as a potential research area to conduct further analysis for better application of state-of-the-art performance measurement systems to renovation projects for assessing and improving their cost, time, quality, and safety performance.

With the growing underperformance of renovation projects, this research can be employed in an outreach effort to engage contractors and other construction professionals in collaborative work sessions for disseminating efficient production planning and assessment techniques for renovation projects. On an educational front, this outreach effort would drive construction organizations to share best practices and different ideas regarding production planning of renovation projects, and develop better methods to cope with the encountered constraints. The developed framework can serve as a common platform in these collaborative sessions where construction professionals can explore further research areas in production management of renovation projects for improving their performance levels.

This research will primarily benefit public owners and governmental agencies due to their major involvement in renovation of institutional and commercial buildings (Beatham et al. 2003, Attalla et al. 2003). The framework will facilitate owners' understanding of production management systems of contractors, and would equip the owners in acquainting themselves with the metrics for evaluating contractors' production performance or verifying the performance measurement methods implemented by contractors in renovation projects.

5.6 Future Areas of Research

Building upon the findings from the framework verification, this research proposes two areas that can be investigated in production management of renovation projects making the framework more applicable.

As observed in the verification, further research is required for assessing the cost and quality impact of constraints on the production of renovation projects. The developed framework could be modified to incorporate the production planning, execution, and assessment methods focusing on the cost and quality of production also. This will lead to a better cost estimate at the activity level and identify the indirect and direct costs associated with the coping of constraints in renovation projects. This will involve investigating the assessment methods of project conditions of constraints for estimating the additional cost involved in completing an activity at the desired quality in the presence of constraints. For instance, for the demonstration example discussed in Chapter-4, the developed framework could be modified to plan the direct and indirect cost involved in completing the demonstrated activity under the specified project conditions and constraints. Accordingly, research is required to develop assessment methods for measuring production performance of crew from the cost and quality standpoints. In addition, the interdependencies between constraints in impacting cost and quality of construction activities should be explored which will lead to identifying the constraints' hierarchies in impacting the cost and quality of different activities.

As a second potential area of research, a simulated approach could be investigated for the developed framework that can reduce the time consumed in performing the suggested steps. This will involve modeling all the suggested steps of the framework by developing a template that would require variables of constraints depending on the project conditions. These variables will involve the constraints' interdependencies, constraints' hierarchies in impacting the cost, time, and quality, and the assessment methods of project conditions for estimating the schedule and cost of the production. By changing the variables for different critical activities, the simulation model would make predictions regarding the additional duration and cost associated with coping of constraints that will facilitate in production planning. The simulation could be done on stroboscope software or as a mote Carlo simulation model.

5.7 Chapter Summary

This chapter concludes this research by discussing how the research goal and objectives were achieved, summarizing what was done in the previous chapters, and presenting the final conclusions of the thesis. The chapter also suggests two major areas for further investigation in production management of renovation projects.

APPENDICES

APPENDIX-1
INTERVIEW RESPONSES

Contractors' Responses
(Abdelhamid et al. 2007)

No.	Questions	Responses
	Vendor Performance Assessment Questions	
VP2	**Define in your own terms project success (critical success factors), i.e. what is a successful project to you? Is this same for renovation projects?**	1. Profitable project 2. On time 3. Owner satisfaction 4. Vendor satisfaction Yes
		When it meets and exceeds all of client's expectations. Profit is not the main aim of the firm Yes, both are client driven.
		When the end user is happy, the company makes profit and no one gets hurt. Yes (it is more invasive when owner is occupying the premises)
		For a successful project we consider following factors fulfilled: A Happy Owner, future work, On schedule, Good relationships, Make profit, Good quality product, Add value to the life of entity, negotiate more work. Yes
		A successful project is which is done on time, its on budget (which makes owner happy), should have a good profit margin Yes.
		Schedule completion, Within Budget, Owner completely satisfied with process and product. Yes
VP3	**How should each of these critical success factors be measured? Is this same for renovation projects?**	1. Profit - By money made, measured through cost accounting. Usually, the company profit and overhead should be 2% for major projects which is accrued . 2. Time- by dates specified on schedule 3. & 4 Owner vendor staisfaction- by communication Yes, but the performance is measured to a lesser extent due to more unknowns that affect the production. For instance, there are lesser fixed dates in the schedule. The contractor carries contingency for his use but the contingency is generally higher for renovation projects as compared to new construction.
		If the firm is able to build lasting relationships; repeat business is the key. Yes
		Ask feedback from end user. We have a ISO-certified customer satisfaction survey form. Yes

APPENDIX-1 (cont'd)

		We measure it through reputation in the market, customer feedback survey, repeat business is a huge measure. Yes
		All need equal attention. Yes
		We interview the owner at the end. For longer projects we interview them every 6 months. Yes
VP4	Do critical success factors remain constant for all project types? Is this same for renovation projects?	Yes Yes
		Yes Yes
		Yes, for projects over $100K, factors are critically looked at. Yes
		Yes Yes
		Yes Yes
		Yes Yes
VP14	Do you use the same evaluation form for renovation projects? Explain why or why not.	Yes we use the same evaluation because the criteria don't change.
		Yes, but only for projects above $100K.
		Yes
VP17	Do you think that for renovation projects the form should be filled more often than new construction projects? Explain why or why not	We do it at the end, we don't do mid-stream review.
		No, because we get feedback informally from the user during the job.
		No, we treat them the same way.
VP32	If you develop a form, what factors would you look to evaluate? Is this same for renovation projects?	Change order rate, RFI rate, Meeting attendance, working style of personnel, safety etc.
		Yes
		Quality, Safety records, Interaction w/ owner, timeliness, attentiveness and responsiveness
		Yes
		To determine which subs help us make more money, whether their submittals are approved quickly, work is done on time. We would use it
		Yes
	Renovation Projects Questions	
RP1	For your key trade, does your organization have a formal process for planning day-to-day construction activities and establishing crew assignments on renovation projects? If yes, can we obtain a copy of that? If no, can you describe the informal process in your own words?	The VP in charge of field operations assigns crews or self performed work through communication with superintendent. It is hard to forecast the required manpower in renovation projects on daily basis.
		Yes we have it. But since it is proprietary, we cant share it with you.

APPENDIX-1 (cont'd)

		No there is no formal process. One person schedules the crew on a daily basis.
		Yes, a copy is provided for your reference. The VP of filed operations assigns crew to super intendent and the superintendent assigns crew to tasks. This process happens in every Thursday meeting.
		We have no formal process. The foreman is responsible for assigning tasks to the crew everyday. Even the truck drivers are made responsible for all the tools at site.
		Yes, if it is a big even like hoisting equipment. But we don't have it for daily activity.
RP2	**What project conditions do you experience in renovation projects that impact the estimated budget, schedule, and quality the most?**	Inadequate design, Concealed conditions, Poor as-built drawings
		Unforeseen conditions, Presence of Haardous materials, Suitability of infrastructure to accommodate project requirements. Dimensional analysis of design (proper survey is a must before design as it causes maximum problems).
		Differing site conditions, often the site doesn't match the construction documents supplied to us.
		Unforeseen Conditions, Design-Build method works really well for us in renovation projects.
		Irregularities in plans, specs, omissions.
		If the facility is occupied by the owner, that causes more time. Unknowns on the site also cause delay.
RP3	**How and when do you identify/address these project conditions as they relate to daily crew assignments?**	We try to identify as early as possible and plan for them. We use the lessons learned from previous renovation projects. We communicate with the superintendent and identify important details.
		As soon as they come up.
		Make adjustments as needed, shift work as needed between projects. (Shifting of man power)
		We address these issues daily, but if the performance is scheduled for following week then we assign it every Thursday.
		The foreman contacts the Project Manager if necessary.
		Plan as best as we can. Do it hands on
RP4	**Is the crew foreman responsible for addressing these project conditions? If not, who is?**	Primarily, the foreman or superintendent and then the Project manager gets alerted.
		Superintendent is responsible for assessing the conditions and giving constructable solutions.
		Yes, we have a working foreman, or sometimes the PM.
		Yes, he does it on thursdays for the coming week
		The foreman is responsible.

APPENDIX-1 (cont'd)

		Yes, they have certain responsibility to get it done, but if those conditions entail change in cost, schedule then the responsibility go to PM
RP5	**Which construction processes (e.g., mobilize, demobilize, demolition, hazardous material abatement, demolition waste management etc.) impact the schedule performance of renovation projects the most?**	Hazardous material abatement, Demolition, Duct-work, Flooring, Finishes etc.
		In order of importance: 1. Hazardous material abatement, 2. Managing unforeseen conditions. Mobilization and demobilization are treated as part of usual mangement.
		Hazardous material abatement that is not
		Hazardous Material Abatement, In MSU parking is a problem
		Demobilization due to job disruption at site.
		Demolition, Demobilization. Hazardous material abatement is usually well planned so that is not a problem.

APPENDIX-1 (cont'd)

Subcontractors' Responses

(Abdelhamid et al. 2007)

No.	Questions	Responses
	Vendor Performance Assessment Questions	
VP2	**Define in your own terms project success (critical success factors), i.e. what is a successful project to you? Is this same for renovation projects?**	1.Finishing Projects on time 2. Within budget and 3.Happy owners Yes
		That the owner should be happy, project completed in time, make profit Yes
		customer satisfaction, profit, learning from project, better relationship. Yes
		The critical success factors for any job would be a good Profit margin, high level of owner satisfaction, no repair calls, lack of warranty issues. Yes
VP3	**How should each of these critical success factors be measured? Is this same for renovation projects?**	Measurement of on-time and within budget is pretty black and white, but customer satisfaction is difficult to measure which I am not sure of. We might have done some phone surveys in the past. Yes
		For owner satisfaction talk personally to the client; and money Yes
		By conducting surveys with C.M., G.C. Yes
		Repeat business, relationship with owner yes
VP4	**Do critical success factors remain constant for all project types? Is this same for renovation projects?**	Yes Yes
		Yes Yes
		Yes Yes
		Yes Yes
VP32	**If you develop a form, what factors would you look to evaluate? Is this same for renovation projects?**	1. Met Schedule, 2. Being a WBE itself, we would also look for a vendor which is minority company (MBE & WBE), 3. Quality of work, 4. Responsiveness, and 5. Value added. Yes
		That the material is delivered on time, competitive pricing, and quality. Yes
		Quality, Cost, and Delivery time. Will obtain feedback from personnel Yes
		Quality of work, Size of contractor (manpower), Type of work Yes

APPENDIX-1 (cont'd)

	Renovation Projects Questions	
RP1	**For your key trade, does your organization have a formal process for planning day-to-day construction activities and establishing crew assignments on renovation projects? If yes, can we obtain a copy of that? If no, can you describe the informal process in your own words?**	There is not a formal process. We conduct evaluations on project basis such as type and size. Evaluations are conducted on daily basis which includes; what areas are we working on and other trades working on to avoid any clash.
		No formal process in place. Foreman meetings take place to assign projects to personnel, ordering of materials, procurement of projects.
		we only have an informal process in place, too much formal is a waste of time. We use daily log reports which are required by the CM at times.
		Yes we do have formal process for planning but that is not on a day to day basis, but atleast 3 days in advance. The PM discusses with suprintendent and foreman to assign crew and coordinates so that material and equipment reach on site before labor.
RP2	**What project conditions do you experience in renovation projects that impact the estimated budget, schedule, and quality the most?**	1.Unforeseen conditions, 2. concealed things or something embedded such as above ceiling or in the walls, and 3. in monor works, to make something look good or of better quality so that it does not look out of place (aesthetics maintenance)
		The location of the project creates difficult situation like ground floor or the 10th storey. For example in a swimming pool project, to repair leaks, concrete slab is cut up.
		Undoing of the old installations which effects budgets, schedules.
		Unknown items mostly impact the project.
RP3	**How and when do you identify/address these project conditions as they relate to daily crew assignments?**	We address these conditions daily (first thing in the morning). As these projects are very dynamic, we handle them as the changes occur.
		According to the qualifications of the guy who you are sending to work.
		React accordingly to the situation on a daily basis. Wait for an answer from owner through RFI.
		The foreman writes the RFIs to A/E to communicate project conditions or we often do it ourselves.
RP4	**Is the crew foreman responsible for addressing these project conditions? If not, who is?**	Primarily, yes, the foreman is responsible, but it's a team effort also.
		Yes
		Yes
		Yes, the foreman is responsible

APPENDIX-1 (cont'd)

RP5	**Which construction processes (e.g., mobilize, demobilize, demolition, hazardous material abatement, demolition waste management etc.) impact the schedule performance of renovation projects the most?**	1. Demolition, 2. Hazardous materials abatement, and 3. Taking care of not to damage existing things.
		The time between demolition and mobilization create an impact, getting the right tools to right people is troublesome. Also anything outside the normal project scope has an impact.
		Hazardous material abatement, identifying it prior to construction.
		abatement

APPENDIX 2

Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) is a proven decision making technique, developed by Thomas Saaty in 1980 for setting priorities of multiple objectives in a hierarchical structure. AHP facilitates assessment, prioritization, and selection of multiple objectives for different alternatives by providing their overall ranking. It reduces complex decisions to a series of pair wise comparisons that synthesize the ranking of multiple objectives. Being recognized as an appropriate technique for making complex decisions in teams, AHP incorporates both subjective and objective assessment of each criterion, and checks the consistency throughout the assessment (Saaty 1980, Nassar 2005).

An example of a typical AHP application process is explained below. This example does not relate to any real project and all the judgments are assumed for the purpose of explaining each step of AHP.

Assume that there are five objectives of a construction project which are required to be ranked in their contribution to overall project performance. These five objectives are:

Objective 1 (O_1) = on time

Objective 2 (O_2) = within budget

Objective 3 (O_3) = desired quality

Objective 4 (O4) = safety

Objective 5 (O5) = functionality

A pair wise comparison matrix of five rows ($i_{1\text{-}5}$) and five columns ($j_{1\text{-}5}$) is formed for the four objectives, where the number in each cell (a_{ij}) represents the relative importance of the row objective (O_i) over the column objective (O_j). The number in each cell is assigned based on the importance scales of AHP developed by Saaty (1980). The importance scale is shown in Table 1. The pair wise comparison matrix of five objectives is shown in Table 2 where each cell (a_{ij}) represents the importance of row objective over column objective. For instance, the assignment of "1/3" to cell a_{12} represents that "objective 1" is weakly less important than "objective 2". Similarly, the assignment of "5" to cell a_{25} represents that "objective 2" is moderately more important than "objective 5". It should be noted that in the pair wise comparison matrix, the left most column and the top most row that list the objectives are excluded from 1 to 5 numbering of "i" rows and "j" columns.

Table 1 Scale of Importance Levels in AHP (Saaty 1980)

Scale	Definition{Importance of row constraint over column constraint}
1	Equal Importance
3	Weakly more
5	Moderately more
7	Strongly more
9	Absolutely more
1/3	Weakly less
1/5	Moderately less
1/7	Strongly less
1/9	Absolutely less

Table 2 Pair-wise Comparison Matrix

[A] =

	O1	O2	O3	O4	O5
O1	1	1/3	1/3	1/5	3
O2	3	1	1	1/3	5
O3	3	1	1	1/3	5
O4	5	3	3	1	7
O5	1/3	1/5	1/5	1/7	1

The pair-wise comparison matrix shown in Table 1 is converted to its decimal form as shown in Table 3 where the fractions are converted to their decimal forms.

Table 3 Pair-wise Comparison Matrix (Decimal Form)

[A] =

	O1	O2	O3	O4	O5
O1	1	0.333	0.333	0.200	3
O2	3	1	1	0.333	5
O3	3	1	1	0.333	5
O4	5	3	3	1	7
O5	0.333	0.200	0.200	0.142	1

The next step is to normalize the pair wise matrix shown in Table 3 by normalizing the weight assigned to each cell. The formula for normalizing the weights is; compute the sum of each column and then divide the scale assignment in each cell by that sum. The normalization matrix is shown in Table 4.

For instance, in Table 4, the value of cell a_{11} is normalized as:

1/ (1+3+3+5+0.333) = 0.081

Similarly, for cell a_{12}, the normalized value is calculated as:

0.333/ (0.333+1+1+3+0.200) = 0.060

Table 4 Normalization Matrix

[A] =

	O1	O2	O3	O4	O5
O1	0.081	0.060	0.060	0.100	0.143
O2	0.243	0.181	0.181	0.166	0.238
O3	0.243	0.181	0.181	0.166	0.238
O4	0.405	0.542	0.542	0.498	0.333
O5	0.027	0.036	0.036	0.071	0.048

Once the normalization matrix is prepared, the final weights of objectives are obtained by averaging the sum of each row. For instance, the final weight of "objective 1" is calculated as:

(0.081+0.060+0.060+0.100+0.143)/5 = 0.088

Similarly, final weights of other objectives are calculated. The final weights are shown in Table 5.

Table 5 Final Weights

$$[W]= \begin{bmatrix} O1 & O2 & O3 & O4 & O5 \\ 0.088 & 0.202 & 0.202 & 0.464 & 0.043 \end{bmatrix}$$

Table 5 shows the final relative weights of five objectives in contribution to the overall project performance. However, there is a need to check the degree of consistency in evaluators' judgments of pair-wise comparison. Saaty (1980) stated that perfect consistency is impossible to achieve, but, a low consistency will result in inconsistent results and therefore, all pair-wise judgments should be re-evaluated. Therefore, Saaty (1980) proposed Consistency Ratio (CR) as a measure of consistency used in AHP. If the value of consistency ratio exceeds 0.1, it signifies inconsistent judgments of the decision-maker (contractor) in pair-wise comparison, which need to be revised (Nassar 2005). The value of CR depends on the value of Consistency Index (CI) which is defined as:

$CI = \lambda_{max} - n / (n-1)$

n = number of items being compared

λ_{max} = maximum eigenvalue of the normalized comparison matrix

There are 3 steps to calculate λ_{max}:

1. In the pair-wise comparison matrix, multiply each column with the corresponding final weight.
2. Divide the sum of rows with the corresponding final weights.
3. Compute the average of values from step 2 and denote it by $\lambda_{max.}$

The value of CR = Consistency Index (CI) / Random Index (RI)

Random index is the value of consistency index of a randomly generated pair-wise comparison matrix for 'n' number of items. Based on the "n" value, the value of random index should be obtained from Table 6 (Nassar 2005).

Table 6 Random Index Values (Nassar 2005)

N	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Table 7 shows how to calculate the maximum eigenvalue of the normalized comparison matrix (λ_{max}) for five objectives.

Table 7 Multiplication of Pair-wise Comparison Matrix with Final Weights

$$\lambda_{max} = \begin{array}{c|cccc|} & O1 & \cdots & & O2 \\ O1 & 1 & . & . & 3 \\ O2 & 3 & . & . & 5 \\ O3 & 3 & . & . & 5 \\ O4 & 5 & . & . & 7 \\ O5 & 1/3 & . & . & 1 \end{array} \quad X \quad \begin{bmatrix} 0.088 \\ 0.202 \\ 0.202 \\ 0.464 \\ 0.043 \end{bmatrix}$$

From Table 7, $\lambda_{max} = 5.129$

CI = 5.129 – 5 / (5 -1) = 0.032

Value of RI is = 1.12 (for n= 5, from Table 6)

CR = 0.032 / 1.12 = 0.029

The CR value of 0.029 (less than 0.1) signifies that the consistency in the pair-wise comparison of five objectives for project performance was high and therefore, there is no need to re-evaluate pair-wise judgments.

Thus, the final hierarchy of five objectives in contributing to the overall project performance, as obtained through the AHP is:

Objective 4 = Safety = 0.464

Objective 2 = Within budget = 0.202

Objective 3 = Desired quality = 0.202

Objective 1 = On time = 0.088

Objective 5 = Functionality = 0.043

REFERENCES

REFERENCES

Alarcón, L.F., Grillo A., Freire, J., and Diethelm, S. (2000). *Learning from Collaborative Benchmarking in the Construction Industry.* Chilean Chamber of Construction, Santiago, Chile.

Attalla, M., Hegazy, T., and Haas, R. (2003). *Reconstruction of the Building Infrastructure: Two Performance Prediction Models.* Journal of Construction Engineering and Management, Vol. 9, No. 1, March, 2003.

Ballard G. (2000). *Last Planner System of Production Control.* Doctoral Thesis, University of Birmingham, May 2000.

Ballard, G. (2000). *Lean Project Delivery System.* Lean Construction Institute. White Paper No. 7, September 2000.

Ballard, G., and Howell G. (1998). *Shielding Production: Essential Step in Production Control.* Journal of Construction Engineering and Management. Vol.124, No.1.

Bassioni, H.A., Price, A.D.F., and Hassan, T.M. (2004). *Performance Measurement in Construction.* Journal of Management in Engineering, Vol. 20, No. 2, April 2004.

Beatham, S., Anumba, C., Thorpe, T., and Hedges, I. (2003). *KPIs-A Critical Appraisal of their Use in Construction.* Center for Innovative Construction Engineering (CICE), Loughborough University, UK.

Beatham, S., Anumba, C., and Thorpe, T. (2003). *An Integrated Business Improvement System (IBIS) for Construction.* Center for Innovative Construction Engineering (CICE), Loughborough University, UK.

Cain C. (2004). *Performance Measurement for Construction Profitability.* Published by Blackwell Publishing Ltd. MA, U.S.A, 2004.

Chin G. (2004). *Agile Project Management: How to Succeed in the Face of Changing Project Requirements.* Published by American Management Association, NY, 2004.

Chitla, V.R., and Abdelhamid, T.S. (2002). *Comparing Process Improvement Initiatives Based on Percent Plan Complete and Labor Utilization Factors*. Construction Management Program, Michigan State University.

Chan, A.P.C., and Chan, A.P.L. (2004).*Key Performance Indicators for Measuring Construction Success*. Benchmarking: An International Journal, Vol. 11, No. 2, November 2004.

Chua, D.K.H., Kog, Y.C., and Loh, P.K. (1999). *Critical Success Factors for Different Project Objectives*. Journal of Construction Engineering and Management, Vol.125, No.3, May/June 1999

Construction Management Association of America (2005), Sixth Annual Survey of Owners, FMI, Management Consulting, USA 2005 http://cmaanet.org/user_images/sixth_owners_survey.pdf

Costa, D.B., and Carlos, T.F. (2002). *Guidelines for Conception, Implementation and Use of Performance Measurement Systems in Construction Companies*. Building Innovation Research Group (NORIE), Brazil.

Costa, D.B., Formoso, C.T., Kagioglou, M., Alarcon, L.F., and Carlos, H.C. (2006). *Benchmarking Initiatives in the Construction Industry: Lessons learned and Improvement Opportunities*. Journal of Management in Engineering, Vol. 22, No.4, October, 2006.

Costa, D.B., Formoso, C.T., Kagioglou, M., and Alarcon, L.F. (2004). *Performance Measurement Systems for Benchmarking in the Construction Industry*. Building Innovation Research Group (NORIE), Brazil.

Cox, R.F., Issa, R.R.A., and Ahrens D. (2003). *Management Perception of Key Performance Indicators for Construction*. Journal of Construction Engineering and Management, Vol. 129, No.2, April 1, 2003.

Cusumano, M.A., and Nobeoka, A. (1998). *Thinking Beyond Lean*. Published by The Free Press, NY, 1998

Griffith, A.F., Gibson, G.E., Hamilton, M.R., Tortora, A.L., and Wilson, C.T. (1999). *Project Success Index for Capital Facility Construction Projects.* Journal of Performance of Constructed Facilities, Vol.13, No.1, February 1999.

Hug Consulting and Management Services (2004). *Renovation Project Delivery Process Analysis.* The University of Texas at Austin, Physical Plant, May 2004.

Hao, Q., and Zhao, G. (2005). *Performance Measurement Based on Balanced Scorecard.* National Social Science Foundation of China, Chinese Business Review, ISSN 1537-1506, USA, Mar. 2005, Volume 4, No.3 (Serial No.21).

Horman, M.J., Messner, J.I., Riley, D.R., and Pulaski, M.H. (2003). *Using Buffers to Manage Production: A Case Study of the Pentagon Renovation Project.* IGLC 12 http://strobos.cee.vt.edu/IGLC11/PDF%20Files/34.pdf

Jimenez J. (1999). *Feasibility of SIMSUPER Simulation Model in the Renovation of Building Projects.* Department of Civil and Environmental Engineering, Massachusetts, 1999.

Koskela (1999). *Management of Production in Construction: A Theoretical View.* Proceedings of the 7th Annual Conference of the International Group for Lean Construction, University of California, Berkley, 1998.

Koskela L., and Howell, G. (2001). *Reforming Project Management: The Role of Planning, Execution, and Control.* Proceedings of 9th Annual Conference of the International Group for Lean Construction, Singapore, August 2001.

Korde, T., Li, M., and Russell, A.D. (2004). *State-Of-The-Art Review of Construction Performance Models and Factors.* Department of Civil Engineering, University of British Columbia, Vancouver, Canada.

Krizek, R.J., Lo, W., and Hadavi, A. (1996). *Lessons Learned from Multiphase Reconstruction Project.* Journal of Construction Engineering and Management, Vol.122, No.1, March 1996.

Lantelme, E., and Formoso, C.T. (2000). *Improving Performance through Measurement: The Application Of Lean Production And Organizational Learning Principles*. Building Innovation Research Group (NORIE), Brazil.

Liker J. (2004). *The Toyota Way. 14 Management Principles From The World of Greatest Manufacturer.* Published by Mc Graw-Hill, New York, 2004.

McKim, R., Hegazy, T., and Attalla, M. (2000). *Project Performance Control in Renovation Projects*. Journal of Construction Engineering and Management, Vol. 126, No. 2, March/April 2000.

Mitropoulos, P., and Howell, G. (2002). *Renovation Projects: Design Process Problems and Improvement Mechanisms*. Journal of Management in Engineering, Vol.18, No.4, October, 2002.

Mitropoulos P. (2003). *Planned Work Ready': A Proactive Metric for Project Control.* Webb School of Construction, Arizona State University.

Abdelhamid, T.S., Mrozowski, T., Schafer, D., Rao, S., Jain, S., Bhawani, S., and Singh, Y.P. (2007). *Assessment and Improvement of Construction Project Closeout at Michigan State University*. Unpublished research report, School of Planning, Design and Construction. MSU Center for Construction Project Performance Assessment and Improvement. Michigan State University, August 2007.

Nassar N. (2005). *An Integrated Framework for Evaluation, Forecasting and Optimization of Performance of Construction Projects.* University of Alberta, Canada, 2005

Picard H. (2002). *Construction Process Measurement and Improvement*. Proceedings IGLC-10, Aug. 2002, Gramado, Brazil.

Pryke S., Cova, B., Cox, A., Druskat, V.A., Kumaraswamy, M., Loosemore, M., Morris, P., Green, S., and Ive, G. (2006). *The Management of Complex Projects*. Published by Blackwell Publishing Ltd. MA, U.S.A, 2006.

Russell, J.S., Jaselskis, E.J., and Lawrence, S.P. (1997). *Continuous Assessment of Project Performance.* Journal of Construction Engineering and Management, Vol. 123, No. 1, March 1997.

Rush R. (2002). *Construction in the Mix.* American School and University. http://www.asumag.com/mag/university_construction_mix/index.html

Samson, M., and Lema, N.M. (2002). *Development of Construction Contractors Performance Measurement Framework.* Department of Construction Technology and Management, University of Dar es Salaam, Tanzania.

Salminen, J. (2004). *Measuring Performance and Determining Success Factors of Construction Sites.* Doctoral Dissertation, Civil and Environmental Engineering, Helsinki University of Technology, Finland.

Saaty, T.L. (1980). *The Analytic Hierarchy Process*, McGraw-Hill, New York, NY

U.S. Census Bureau. (2002). *Commercial and Institutional Building Construction 2002.* Economic Census 2002. http://www.census.gov/prod/ec02/ec0223i236220.pdf

U.S. Census Bureau. (1997). *Commercial and Institutional Building Construction 1997.* Economic Census 1997.

U.S. Department of Energy (1996). *Guidelines for Performance Measurement.* Office of Human Resources and Administration, Washington D.C. http://www.orau.gov/pbm/documents/g1201-5.pdf

United States General Accounting Office (2003). *United Nations: Early Renovation Planning Reasonable, but Additional Management Controls and Oversight will be Needed.* May 2003.

Virginia Tech Institute. *Analytical Hierarchy Process.* http://www.aoe.vt.edu/~cdhall/courses/aoe4065/AHPslides.pdf

Wayne, E.W., and Irwig, H.G. (1988). *Disturbance Scheduling Technique for Managing Renovation Works*. Journal of Construction Engineering and Management, Vol.114, No.2, June 1988.