ORGANIZATIONAL PROGRAM MANAGEMENT FOR MULTIPLE MAINTENANCE PROJECTS UNDER MULTI-TRADE CAPACITY CONSTRAINTS

by

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A dissertation submitted in partial fulfillment of

The requirements for the degree of

Doctor of Philosophy

(Civil and Environmental Engineering)

at the

UNIVERSITY OF WISCONSIN – MADISON

2000

UMI Number: 9996914

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

A dissertation entitled

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Date of Final Oral Examination: November 22, 2000

Month & Year Degree to be awarded: **December** 2000 **May** **August**

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Approval Signatures of Dissertation Readers:

Signature, Dean of Graduate School

Readers' Page. This page is not to be hand-written except for the signatures

ACKNOWLEDGEMENTS

During the last research period, a number of great men have contributed to development of this dissertation. The author heartily acknowledges the tremendous efforts of his committee, professors Jeffrey S. Russell, Awad S. Hanna, Bin Ran, David F. Mezera, and C. Allen Wortley. Professor Russell supported my research for five years, and he provided sharp insight and general encouragement for the entire research project. His vision about the construction industry and management will continue to play out in my life. Professor Hanna is especially thanked for his suggestions on the research proposal that helped form simulation experiments, and his care about author's future. Professor Bin Ran is appreciated especially for his good words at right time and very constructive questions. Professor Mezera thoroughly reviewed the final product, and Professor Wortley provided me with critical insights into the nature of organizations. Most importantly, all provided friendly ears and constructive criticism.

The research on program management has benefited a great deal from the Facilities Planning and Management at the University of Wisconsin-Madison, especially Mr. Gary L. Beck, Mr. Faramarz Vakili, Mr. Kevin Corcoran, Ms. Cindy A. Telvick, Mr. Kevin Smith, Mr. Tim Carew, and Mr. Peter J. Heaslett. A number of colleagues have reviewed the manuscript and made valuable comments. Author's appreciation goes to all of these colleagues; in particular, to Mr. H.K. Park and Mr. S.K. Kim of University of Wisconsin-Madison. The author owes a great deal to Mr. K.S. Kim of Stanford University, Mr. H.J. Kim of University of Illinois at Urbana-Champaign, and Mr. M.S. Park of Massachusetts Institute of Technology for their support and constructive discussion on the basic framework of this dissertation.

Next, the author would like to express special thanks to four parents of his own. The ideas presented in this dissertation would not have been conceived and nurtured without their constant love and inspiration, and to them goes his heartfelt gratitude. And Finally, the author wishes to thank to his wife, who sacrificed her life to his research and family.

TO

An Angel Who Loves A Devil

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ACRONYMS AND SYMBOLS

A/E: Architectural and Engineering

AI: Artificial Intelligence

CCR: Capacity Constraint Resource

CDF: Cumulative Distribution Function

CDR: Project Duration/Completion-time Ratio

CPM: Critical Path Method

DBR: Drum-Buffer-Rope System

DCD: Difference between Completion-time and Project Duration

ES: Early Start

FCFS: First Come First Serve

FHZ: Fixed Horizon Approach

GA: Genetic Algorithm

IBA: Individual Buffer Allocation

JIT: Just-In-Time

LAC: Longest After-Chain

MBO: Management By Objectives

MBS: Management By Self-Control

MCS: Master construction schedule

MPS: Master Production Scheduling

M/R: Maintenance and Remodeling

MRP: Material Requirements Planning

MRPII: Manufacturing Resource Planning

NBA: Non-Buffer Allocation

NOP: Number Of Projects those have not been completed at the end of the last scheduling window

NWD: Net Work-Days which are at least required to finish the incomplete projects

PAC: Program Administration Center

PBA: Periodic PCR Buffer Allocation

PCR: Program Constraint Resource

PERT: Program Evaluation and Review Technique

PIP: Projects-In-Progress

PMP: Program Master Plan

RFI: Request For Information

RHZ: Rolling Horizon Approach

RUR: Resource Utilization Ratio

SA: Simulation Annealing Algorithm

SAC: Shortest After-Chain

SASP: Shortest Activity from Shortest Project

SUP: Shop Utilization Ratio

SUR: Shop Utilization Percentage

TOC: Theory of Constraint

TOW: Tardiness Over Windows

VBA: Visual Basic for Applications

WCE: Amount of Work-days between Scheduled Project Completion Date and the End of the last scheduling window

α: Duration Variance Factor

β: Buffer Factor

β_P: Periodic Buffer Ratio

γ: Duration Safety Factor

λ: Capacity Utilization Ratio of Each Day

μ_i: Mean Duration

θ: Sentinel Ratio

ρ: Mostness of PCR

σ: Standard Deviation

CHAPTER 1: INTRODUCTION

1.1. MAINTENANCE PLANNING IN OWNER ORGANIZATION

Maintenance and remodeling (M/R) of a building are restorative and revamping actions to make building systems fulfill functional requirements during its service life. The M/R consist of repair, replacement, and/or modifications of components and sub-systems in the building. Most researches on maintenance and facility management by professional practitioners and academia have identified *"a need for improvement in decision-making regarding building maintenance"* (Watson et al., 1991, p. 303).

As a large owner, the University of Wisconsin-Madison (UW-Madison) possesses over 330 buildings for accommodating educational and operational demands. The constructed facilities require continuous maintenance work, and the degree and extent of maintenance work increase as buildings continue to age. Moreover, the buildings need to be remodeled frequently, because they need to be adapted for changes in functional space requirements. In contrast to the facility delivery project of a new construction, the facility management of an M/R program[1] is characterized as a continuous process based on the physical life cycle of the facility (refer to Figures 1.1 and 1.2).

[1] Archibald (1976) defines a program as "a long-term undertaking which is usually made up of more than one project" (p. 18). Another definition by Duncan (1996) is "a group of related projects managed in a coordinated way" (p. 167).

At the UW-Madison, the department of Physical Plant is in charge of the M/R and operation of buildings. It concurrently executes multiple M/R projects (i.e., simple maintenance, departmental work, and remodeling projects) by using in-house technicians who belong to 10 shops (e.g., carpenter shop and electric shop).

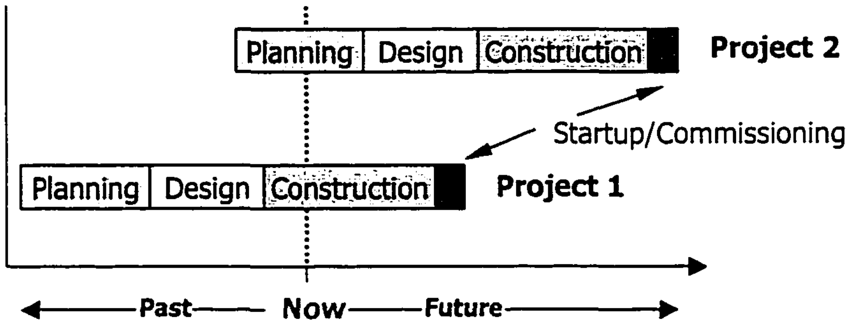

Figure 1.1 Facility Delivery Model

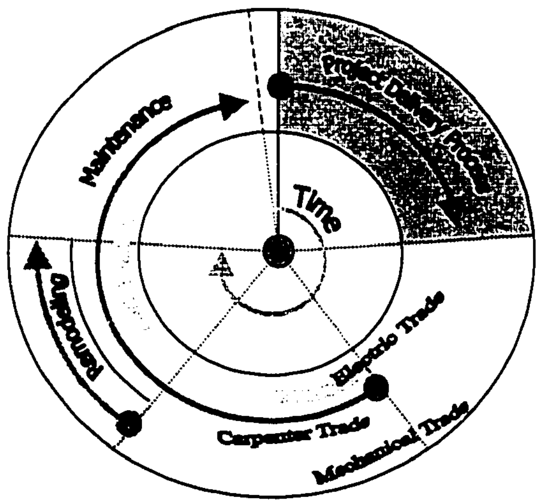

Figure 1.2 Continuity Model of Facility Management (Koo and Russell, 2000)

The department is required to coordinate the activities of each project and the utilization of each shop's technicians. As the scale and interdependence of the multi-resources constrained multiple projects increase, program management in the department is inevitably confronted with an increasing complexity of long-term coordination. Since M/R management has traditionally been a field with a relatively low priority (Shimodaira, 1992; Carlqvist, 1997; and Shen et al., 1998), however, application of scientific management techniques to the M/R program is behind other industry fields including new construction. Therefore, there is a need to develop a system of planning, scheduling, and control to enable a program manager to effectively and efficiently manage multiple interdependent projects. In this context, this research starts from management continuity of a facility (refer to Figure 1.2), and proceeds to further investigate the organizational continuity of multiple M/R projects.

1.2. PROBLEM STATEMENT

1.2.1. Application of Production Management Techniques

In the context of applying production control concepts[2] to the construction industry, Ballard and Howell (1998) pointed out segregated phases of planning and control in the construction industry.[3] They explained this lack of integration as a consequence of the fact

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[2] As a concept of the manufacturing industry, Bertrand et al. (1990) explain that production control consists of aggregate production planning, material coordination, work load control, work order release, and production unit control.

[3] In manufacturing, control is conceived as the progressively more detailed shaping of material and information flows.

that most direct construction works are performed by specialty/sub-contractors under contractual agreements, and that construction managers conceive the control as an enforcement of contractual commitments. Therefore, direct controls of the production itself occur only within a subcontractor's units, and are not addressed by the discipline of construction management (e.g., a general contractor). They concluded that there was significant difficulty that deterred a construction manager from incorporating theories/ techniques of production control on construction projects (p. 11).

Their observation concerning production control may be appropriate with regard to a new construction project, but it does not directly apply to the M/R program in a large owner organization such as UW-Madison. As previously described, the university has multi-shop labor resources in the Physical Plant department. Small M/R projects under budget of $100,000 are usually executed by the internal technicians of this department without external contracts. Therefore, there is a need for the department's program manager to re-examine possible application of production control concepts to the M/R environment of multi-resources constrained multiple projects.

1.2.2. Reliability of Project Control

Time and cost are two important measures of program performance in an M/R environment. To a great extent, the costs of M/R projects depend on project durations, and project delays are becoming a major management issue in the M/R program. To control project progress in the program, it is imperative for the projects coordinator not only to accurately forecast the duration of each project, but also to manage impacts of duration variance on the program's global progress. Currently, these impacts are considered intuitively, and the effectiveness of uncertainty management depends upon the scheduling skill of the projects coordinator. Intuitive consideration of this dynamic uncertainty does not yield reliable project progress estimates, resulting in difficulty in controlling multi-project processes. To overcome this limitation, there is a need to explicitly generate and incorporate estimates of activity durations along with uncertainties of these estimates. Among researches in construction academia, there have been two approaches used to handle the uncertainty problem of project control: (1) *lean construction* and (2) *buffer management.*

While explaining "pull-driven" lean construction, Tommelein (1997a) argued that the traditional, "push-driven approach[4] to scheduling construction work leads to waste[5], and that the pull-driven technique aims at selectively pulling resources from queues without "unduly" waiting, if the required resources are matched up with resources already available (p. 158). However, this approach has two limitations. First, the pulling procedure of *just-in-time* (JIT) is based on the assumption that resources can be repetitively and continuously supplied. In the non-repetitive, multiple M/R environment, the passive[6] JIT strategy should be integrated with a proactive coordination strategy to limit resources available on each project site to what

[4] The early-start based critical path method (CPM) schedule is defined as push-driven.

[5] The reasons are: (1) because of uncertainty in duration as well as variation in execution quality and dependency logic of activities; and (2) because of the current expediting practice that makes rescheduling efforts difficult (Tommelein, 1997a, p. 158).

[6] The pulling procedure is *passive* from the perspective of organization-wide strategic planning, because it is based on availability of operations and resources at job sites. However, from the decentralized viewpoints of job-site crews/foreman, it might be a more active strategy.

are needed at the time they are needed. Second, because of the current contractual practice by which a foreman's discretion on selective pulling is limited within sub-contractor's own trade, it is difficult to apply that concept into the whole process of the M/R program.

Another approach is "shielding production" from workflow uncertainty through a buffer of each activity. Ballard and Howell (1998) argued that the schedule of each activity needed to maintain a small time buffer, to the extent that all production units practice shielding and consequently became more reliable at keeping their near-term commitments (p. 16). If all production units practice shielding, however, total productivity of a program inevitably decreases and its duration increases. Moreover, an individual buffer is often exhausted by a disruption of an activity, and a process containing series of the activities would not be protected from the disruption. They did not further investigate the selection criteria for which activity to shield by the buffer, and what impact buffering would have on the project network.

Both the lean construction and the shielding production have the same application scope of single trade and/or single project management, not considering multiple projects from an organizational program view as much. Therefore, there is a need for another methodology to fulfill the objective of multi-resources constrained multi-project management in the M/R environment: *manageability* and *productivity* of the overall program.

1.3. OBJECTIVES AND SCOPE

1.3.1. Program Master Planning

When a maintenance department undertakes multiple projects with involving technicians at each trade shop, a program manager is confronted with the following two, and in some cases, conflicting objectives: (1) timely completion of all projects within a limited budget and specified quality[7], and (2) maintaining a stable resource utilization profile to minimize the under/over utilization of each shop's capacity (Mohanty and Siddiq, 1989). Thus, in the multi-project situation, the program manager needs to construct a *program master plan* (PMP) as a simultaneous solution of timely completion of current/future projects and stable/efficient use of finite resources.

Moreover, the complexity of PMP is further increased by the uncertainties of a dynamic M/R environment. Since requests for one-of-a-kind projects arrive over several time periods, the request profile for M/R projects in a future period is unknown. In this environment, the program management should cope, first, with the *external* uncertainty of unknown stream of project requests. From the *internal* perspective of program execution, a project is delayed due to unpredictable events such as defective design followed by reworks and untimely supply of required material/components. The disturbance of an activity and/or project tends to

[7] The direct costs of an M/R project are composed of cost of building components and product of labor unit-costs and work-hours. Given a defined design and in-house crews, the cost performance can be transformed to a time performance (Malcolm et al., 1959, p. 650; Drucker, 1990, p. 98). The dissertation is based on the assumption that management performance of the M/R program is evaluated by the total time performance.

propagate throughout the whole M/R program. The internal and external uncertainties[8] lead to significant complexity for planning and scheduling of the M/R program. To deal with the external uncertainty, this research investigates the applicability of *master production scheduling* (MPS)[9] in production management. A rolling horizon approach to MPS will be adopted to transform the dynamic nature of continuously arriving project requests into a series of static scheduling sub-problems within multiple periods. This research, therefore, aims at developing an intra-organization strategy to stabilize the program master plan against the external uncertainty of the dynamic M/R environment as well as internal uncertainty during execution of multiple projects.

1.3.2. Resource-Constrained Program Schedule

When a projects coordinator at the maintenance department schedules M/R projects under multiple "resources contention" (Gordon et al., 1991, p. 714), some heuristic procedures could be used to prioritize activities and schedule the multiple projects considering finite resource capacities. Even though heuristic rules[10] based on the conventional *critical-path method* (CPM) and the *program evaluation and review technique*

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[8] This classification of external and internal uncertainties is based on the perspective of organizational planning, rather than operational scheduling of the delivery process for a physical facility.

[9] *"The purpose of a master production schedule (MPS) is to specify production quantities and resource allocations, with the objective of minimizing resource utilization costs and inventory holding costs."* (Das, 1993, p. 353)

[10] The examples of CPM-based heuristics are MINSLK (minimum slack), MINES (minimum early start), and MINLS (minimum late start) rules.

(PERT) differentiate critical activities from floating activities[11], the definition of criticality is valid only when unlimited, or at least sufficient, resource availabilities are assumed. In construction industry literature, myopic approaches to resource leveling or allocation strategies yield only adjustments to the initial CPM/PERT schedule to meet a project completion due date (Tommelein, 1997a). They do not fundamentally integrate resource constraints with CPM schedules. In reality, as limited resources are allocated into activities, a project's critical path changes[12] and the minimum project duration should be extended at the same time (Gharbi et al., 1999). In this context, the current research investigates a practical procedure to integrate limited technician resources into the program schedule based on the invalidity of the critical path concept in the M/R environment.

1.3.3. Buffer Management against Internal Uncertainty

To coordinate the internal processes of multiple M/R projects, it is imperative for a projects coordinator not only to generate an accurate resource-constrained program schedule, but also to manage the impact of uncertainties on the holistic progress of the program. Due to highly-linked network characteristics, resource availabilities will be affected by unpredictable events, and the consequent variability in activity/project duration often results in a significant completion delay. Given the previously described limitation of applying

[11] Mohanty and Siddiq (1989) used priority rules to first assign resources to critical activities. And Zouein and Tommelein (1993) defined that the highest priority for resolving spacial conflicts was to decrease the resource level of non-critical activity. In an "exhausted" situation under limited resources availability, however, all activities will be easily on the non-float critical path (p. 1777).

[12] The changed critical path was named as a "critical sequence" (Wiest, 1964) and a "critical chain" (Goldratt, 1997, p. 215) to differentiate it from the conventional critical path.

JIT/lean production strategies into the M/R environment, the way that makes a program schedule of multiple projects manageable and predictable against the impact of uncertainty is through allocating protective time buffers in the planned program flow. The "*buffers can be used to look ahead and predict the effects of schedule disruptions on the projects as a whole*" (Newbold, 1998, p. 71). This ability to look ahead provides more opportunity to resolve problems with greater confidence for further management decisions. The buffer is a planning tool that supports development of more reliable schedules, and an effective buffer management strategy provides a mechanism for protecting/coordinating the overall progress of multi-projects with a minimal premium of insurance.

As one technique of buffer management, shielding production (Ballard and Howell, 1998) distributes buffers to every activity to ensure reliable commitments. If all production units practice shielding, however, the duration of each project increases, and total productivity of the M/R program inevitably decreases. Moreover, individual buffers are often exhausted by a single disruption or delay of an activity. To prevent "chain reactions" (Semenoff, 1935, p. v) from occurring due to the delay, management may be forced to resort to ad hoc alternatives, such as use of overtime, to remain on schedule. Therefore, to increase predictability performance and to improve productivity of the overall program, therefore, other methodologies for allocating buffers into the M/R program network should be considered.

As the first step in developing a buffer management strategy, this research investigates possible applications of two principles of production management to the M/R program: (1)

the *theory of constraints* (TOC)[13] and (2) the *drum-buffer-rope* (DBR)[14]. After exploring implication and limitation of the TOC and DBR principles to the program management, this research identifies the critical resource constraints of the M/R program, and develops a buffer allocation strategy by that periodic buffers will be allocated in flows of the program constraint resource to protect the stability of the global program rather than individual activities. Therefore, any disturbance less than a capacity of the buffer, wherever it was first activated, will only be propagated until the strategic buffer is reached. This termination mechanism for the propagation will decrease the impact of the disturbance on the global program stability. Also, the productivity and completion performance of the projects could not be significantly deteriorated, by strategically allocating buffers whose total size is smaller than the sum of the individual buffers. In this context, the research will find out an effective buffer management strategy of transforming the internal uncertainty of activity disturbance to stability and manageability of the multiple M/R projects sustaining the productivity of the program.

[13] TOC is a principle of production management presented by Goldratt (1990), where a five-step process of improvement is defined.

[14] DBR is a recently developed alternative to traditional planning and control systems such as material requirements planning (MRP) and just-in-time (JIT). DBR is described as a combination of push and pull logistical procedures (refer to Section 2.2).

1.3.4. Maintenance/Remodeling (M/R) Program Management Model

For the effective and efficient management of maintenance and remodeling projects in a large owner organization, Koo and Russell (2000) proposed M/R program management model (named ABC model). The model consists of three components: (1) an active contracting strategy, (2) the buffer management with organizational grouping, and (3) concurrent construction by work-zoning. To improve manageability and productivity of the program, this total process management model needs a coordination mechanism of the multiple projects in the M/R program environment. This dissertation investigates a rhythmical management strategy of the M/R program through organizational resource flows, focusing on integrating the internal and external uncertainty of the program into the resource-constrained program master schedule.

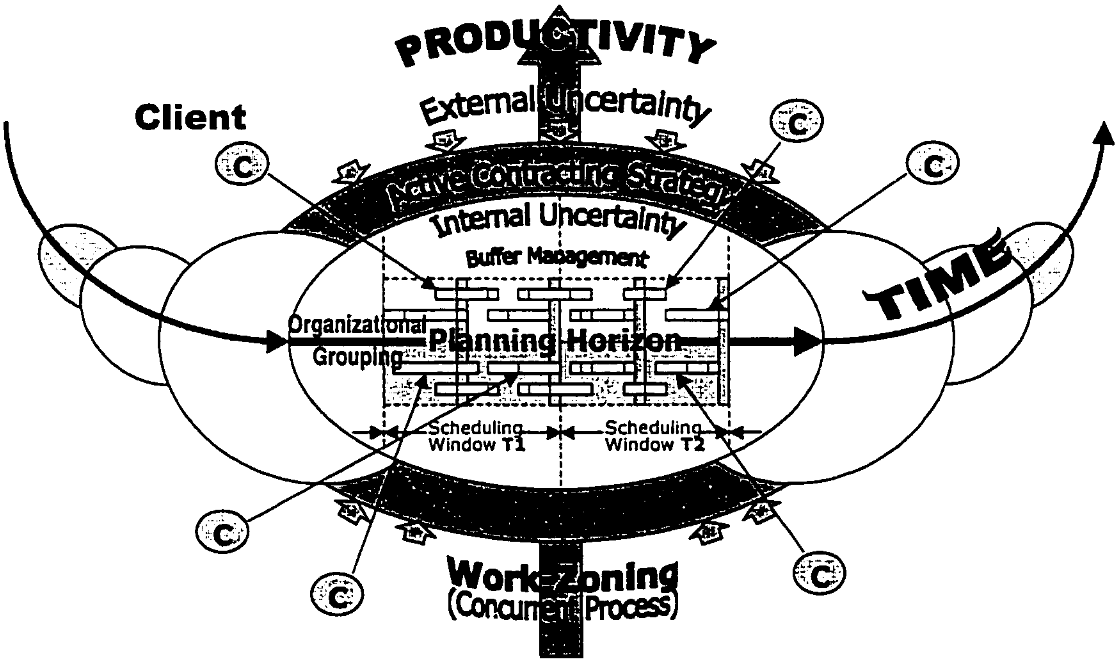

Figure 1.3 M/R Program Management Model: ABC Model (Koo and Russell, 2000)

1.4. ASSUMPTIONS

Throughout the dissertation, several assumptions commonly used in project network analysis are used in modeling the multi-resources constrained multiple projects of the M/R program.

1. All resources are owned by the M/R organization planning and controlling the multiple projects. Current and future projects will be scheduled based on currently available resources without any strategic adjustment of shop capacities. Also contractual outsourcing and operational overtime and multi-shifts are not considered. Thus reducing backlogging or backorders in a scheduling window is pursued through utilization of the in-house technicians.

2. Program manager has some authority over decision of project start-dates and completion-dates, and can negotiate with the clients for the final agreements. During the negotiation, each project request is treated as having the same priority.

3. Multi-tasking that a technician carries out jobs of other trade shops is not allowed.

4. In a trade shop, each technician produces identical quality of work and the same productivity, while the productivity level remains constant during execution of an activity. Also, monetary consideration of different labor charge rates among trade shops is not included in this dissertation.

5. Under the current practice of workspace use, a project-site may be occupied by only one trade at a time. A given activity is executed by one or two technician(s) from a trade shop. The amount of different resources required by an activity and the resource-availability level remain constant throughout the activity duration.

6. Activity precedence in any project is known in advance based on specified technological sequence. Set-up times and resource transfer times between projects and trade shops are negligible.

7. Activity splitting and partial resource assignments are not allowed[15]. Once started, no activity may be interrupted until a new schedule is generated for the next scheduling window.

8. A deterministic integer value is first assumed for activity duration in generating the initial program master schedule (Chapters 4 and 5), while stochastic nature of the activity duration are integrated in buffer allocation strategy (Chapters 6, 7, and 8). The stochastic distribution of an activity duration is also assumed to be independent of those of precedent activities.

9. Work force behavioral issues with a given schedule (e.g., Parkinson's Law[16]) are not considered (refer to Gutierrez and Kouvelis (1991) for their implications for project management).

1.5. METHODOLOGY AND ORGANIZATION OF DISSERTATION

As the first step of developing an effective and efficient management strategy for the M/R program, Chapter 1 of this dissertation identifies specific characteristics of the M/R program in an owner organization. The current problem of the program management and

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[15] "*If splitting and partial assignments are allowed, the scheduling process will still be the same except that more record keeping will be required to keep track of pending jobs.*" (Badiru, 1996, p. 176)

[16] "*Work expands so as to fill the time available for its completion.*" (Parkinson, 1957, p. 2)

limitation of the previous research studies are explained, before introducing the objectives and assumption of the dissertation.

To develop a theoretical basis of the program management, Chapter 2 reviews literatures on management theories and planning/scheduling/control techniques of production/project. Drucker (1954)'s the "philosophy of management" is adopted as the backbone strategy to coordinate the multi-resource constrained multiple projects. To deal with the external uncertainty, the chapter proposes a rolling horizon approach to program master plan, which is based on the current negotiation process between the program manager and clients.

In Chapter 3, a resource-constrained scheduling algorithm is developed to generate the master construction schedule in a scheduling window. During development of the algorithm, more emphasis is placed on long-term organizational resource continuity, especially rhythmical flows of program constraint resources (PCRs), than ephemeral events of individual activity and project. The performance of the algorithm is evaluated in Chapter 4 by limited simulation experiments that are implemented in a commercial spreadsheet package using a programming language, Visual Basic® for Applications (VBA).

To stabilize the master construction schedule generated in Chapter 3, Chapter 5 proposes the periodic PCR buffer allocation strategy. The buffer management strategy terminates the propagation of internal disturbance at periodic points of organizational PCR flows. Chapter 6 presents experiment models for Monte Carlo simulation that evaluate and compare the performance the developed buffer management strategy against the buffer strategy proposed by previous research studies. During the simulation experiment, four distribution types of activity duration are used while changing the total size of buffers. The results of the simulation experiment are presented in Chapter 7, and the results are analyzed based on two major evaluation criteria.

Chapter 8 summarizes the results of the research and its contribution to the body of knowledge and the construction industry. The limitations of the M/R program management model are indicated, and several suggestions are made for future research.

CHAPTER 2

PLANNING HORIZON OF M/R PROGRAM MANAGEMENT

2.1. PROGRAM MANAGEMENT AT M/R DEPARTMENT

Facilities Planning and Management (FP&M), one of eight divisions at UW-Madison, is composed of the most fundamental operating branches of the university. In the division, the Physical Plants department is in charge of the maintenance and remodeling (M/R) and custodial works of buildings at the UW-Madison. The multiple small M/R projects within a budget of $100,000 are concurrently executed by using in-house technicians who belong to trade shops. The Physical Plant currently has 10 shops where each supervisor manages shop technicians, and is responsible for work items relevant to their own trades. Table 2.1 shows 10 shops in the Physical Plant.

Table 2.1 Trade Shops in Physical Plant

No.	Shop Name	Crews	No.	Shop Name	Crews
1	Carpenter Shop	35	6	Mason Shop	14
2	Electric Shop	54	7	Paint Shop	30
3	Insulator Shop	14	8	Plumbing Shop	3
4	Locksmith Shop	13	9	Sheetmetal Shop	22
5	Machine Shop	6	10	Steamfitter Shop	41

Project Administration Center (PAC) in the Physical Plant manages/coordinates small remodeling projects through *service* delivery processes: planning, design, and construction. "A dual level management structure" (Yang and Sum, 1997, p.139) is used in the PAC due to complexity of managing multiple projects, which is composed of a program manager and a projects coordinator according to their roles and responsibilities. The program manager, as a higher level manager, serves as the organizational "liaisons" who coordinate architectural and engineering (A/E) services provided by the Planning & Construction Department and the construction services from the Physical Plant shops (Physical Plant, 1999, p.8). Given multiple M/R projects and multiple functional shops, the program manager subordinates objectives of each project to long-term vision[1] of the M/R organization. To manage a M/R program, the program manager must (1) facilitate strategic planning and organizing of resources in the program and (2) propose a start date, a completion date, and budget of a requested project, and negotiate with the client for the final agreement.

The projects coordinator, on the contrary, must (1) generate an operational scheduling and (2) coordinate trades shops and schedules outside vendors to provide smooth flow of each project during actual construction. When a request for information (RFI) or a change order[2] arise, the projects coordinator resolves them while trying to keep the project within the budget and the planned completion date. For the effectiveness and efficiency of the M/R program, the dual level management structure needs to be integrated from the total process perspective. In this context, this research investigates a program management strategy that

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[1] An external goal is "*quality service on a timely manner at a reasonable cost while [customers are] being kept informed.*" Internal goals are "*an organizational efficiency and workload balance*" (Physical Plant, 1999, p. 14).

[2] "*A client-requested and approved change ... in the scope of the contract, or in specifications, etc.*" (Cleland and Kerzner, 1985, p. 38)

manages the multi-resource constrained multiple projects in the organizational long-term horizon of the present and the future.

2.2. THEORETICAL BACKGROUND FOR PROGRAM MANAGEMENT

爲無爲, 則無不治. – 老子

(Do not-doing, and yet there is nothing left undone. – Lao-tzu)

To develop a management strategy of M/R program, first, this research reviewed roles of management in literatures. Among management theorists, Drucker (1954) explained a principle of management as:

> *[A principle] will give full scope to individual strength and responsibility, and at the same time give common direction of vision and effort, establish team work and harmonize the goals of the individual with the common weal. The only principle that can do this is management by objectives and self-control.* (p. 135)

He called the management by objectives and self-control as a "philosophy" of management, and interpreted the management as "freedom under the law" (p. 136).

From the viewpoint of this philosophy, material requirements planning (MRP) and manufacturing resource planning (MRPII) systems in manufacturing industry can be interpreted as a *top-down* approach based on the management by objectives, because the systems drive individual efforts toward a common goal of an organization. And just-in-time

(JIT) and lean systems may be interpreted as a *pull-driven* approach based on the management by self-control. Above two categories of management systems deal with planning/scheduling issues of production management via their own theoretical backgrounds; each of them is only a part of the management philosophy.

In construction academia, recently the concept of "lean construction" has been actively researched (Tommelein, 1997b; Ballard, 1999; Howell, 1999; and Koskela, 1999a). The implementation of the lean construction is based on self-controlled subcontractors, "Last Planners," who actively decide process of a construction project within their contracted responsibilities (Ballard et al., 1994, p. 1564). If the decentralized or distributed decision-making is not directed by global/common objectives, however, the highly linked/cooperated system may meet a management chaos. When internal/external disturbance occurs in the construction project, a mechanism of coordination is needed between subcontractors and general contractor(s). If a program/project manager follows only the philosophy of the lean construction, he/she may not find and use the coordination mechanism, and loose the direction of the entire construction process. The lean approach is oriented to single-trade and/or single-project management, therefore, it is difficult to apply lean principles into the M/R environment of multiple projects. In the same context, Cusumano and Kentaro (1998) indicate the limitation of lean thinking in automobile industry, in terms of linking a set of projects strategically, technologically, and organizationally.

The theory of constraints (TOC: McMullen, 1998 and Stein, 1996) and the drum-buffer-rope (DBR: Umble and Srikanth, 1990) are other approaches to integrate the management by objectives and by self-control. Russell and Fry (1997) describes TOC and DBR as:

> "*The underlying principle of the TOC [theory of constraints] and the DBR [drum-buffer-rope] is that the performance of every organization is limited by constraints and to maximize the performance of the entire organization requires the maximization of the performance of each system constraint.*" (p. 827)

In the DBR system that presents the basic manufacturing planning and control system behind the TOC, key schedule release points[3] in a plant is strictly controlled with a detailed schedule, and non-constraint work centers simply process materials based on "first-in, first-out priority" (Umble and Srikanth, 1990, p. 167). From this perspective, the DBR may be a logistical combination of MRP/MRPII and JIT/Lean production managements, and a manufacturing-based interpretation of Drucker's management principle: common direction, individual, and to harmonize. This research investigates applicability and limitations of the TOC/DBR to the M/R environment, and develops a new process management framework that logically integrates the conventional CPM/PERT and Lean construction. The new framework or model may be considered as a construction-based interpretation of the management principle that aims at stability and flexibility of the program.

[3] Umble and Srikanth (1998) define four categories of the schedule release points: (1) material release points, (2) capacity constraint resources (CCRs), (3) divergence points, and (4) assembly points.

In addition to implementing the principle of management by objectives and self-control, this research investigates an additional dimension of management, time, in the context of the multiple M/R projects environment. Drucker (1954) defines time as one of major factor in management: *"Management always has to consider both the present and the long-range future"* (p. 14). In the multiple M/R project environment, a program manager should consider not only the current on-going projects, but also future projects that will be continuously requested and contracted. This research develops a planning horizon and scheduling window approach to cope with the organizational time-dimension of the M/R program management.

In short, this research takes Drucker's philosophy as the theoretical basis. The first principle of the philosophy, management by objectives, is addressed by a program master plan (PMP) in long-time horizon and a master construction schedule within a scheduling window (MCS). While constructing logical and time-based backbone of the program, the PMP and the MCS, the program manager effectively and efficiently plans/schedules the multi-resource constrained multiple projects, and achieves the long-term organizational goals.

The second principle, management by self-control, is implemented by periodic PCR buffers in organizational PCR flows. When unexpected delay of an activity/project (i.e., the internal uncertainty) is developed, the projects coordinator and the shop supervisors adjust the progress of the projects within the buffer period of the MCS. Therefore, this buffer management strategy stabilizes the program by terminating propagation of a disturbance at the time-points of periodic buffers, and improves the flexibility of MCS preserving the productivity of the M/R program by smaller total size of the PCR buffers than individual activity buffers. The remained part of this chapter describes a rolling horizon approach to the program master plan (PMP).

2.3. EXTERNAL AND INTERNAL UNCERTAINTY

When the M/R department undertakes multiple, interdependent projects simultaneously, difficulty of planning/scheduling the multiple projects is further increased by the dynamic nature of the M/R environment. In reality, requests for the M/R projects do not arrive at the same time, but gradually over several periods. Moreover the complexity of the program management is amplified by characteristics of the order-driven industry: (1) each one-of-a-kind project has a different design in a different building context specified by a client (usually an academic department) and (2) a future delivery process is highly unknown (e.g., starting time and completion time). Therefore, construction of the M/R project is inevitably scheduled only after a service contract. Under this environment, the program management should deal with above 'external' uncertainty.

From the perspective of 'internal' project execution, a project is delayed due to unpredictable events such as incomplete/defective design and followed reworks, untimely supply of required material/components, and absenteeism of shop technicians. The delay of an activity and/or the project makes sequential problems for a projects coordinator, since disturbance at one project tends to propagate throughout the whole program (refer to Chapter 5).

2.4. STABILIZATION OF PROGRAM MASTER PLAN

The internal and external uncertainties lead to significant complexity/difficulty of planning and scheduling multiple M/R projects. To deal with the external uncertainty, it may be appropriate for the program manager to consider applying the master production scheduling (MPS)[4] of the production management into the program master plan (PMP). There are three main approaches to MPS: (1) a fixed horizon (FHZ) approach, (2) a first-come-first-service (FCFS) approach, and (3) a rolling horizon (RHZ) approach. Since the request profile of M/R projects is very uncertain and dynamic, it is not feasible to use the FHZ approach under a dynamic environment like the M/R program (Das, 1993).

The FCFS approach has been widely used in production management (e.g., a priority dispatching rule: Church and Uzsoy, 1992; a period loading Gantt chart method: Das, 1993) and project management (a successive approach: Newbold, 1998), and is the current practice of the M/R department. The FCFS approach schedules projects individually one at a time, as a new contact is made. Then the new project is placed to the end of existing multi-project schedule, and activities of the new project are left-shifted over activities of the existing multi-project (Newbold, 1998). During the series of "local left-shifts" (Wiest, 1964, p. 400), if resource contention between activities/projects is not resolved within an expected start and completion time of the project, the delivery duration of the project is lengthened and/or backlogged. As an alternative, the project may be subcontracted out based on client's

[4] *"The primary advantage of a master schedule is that it permits managers to plan for future production activities, so as to ensure that product demand is satisfied and the associated cost are minimized."* (Das, 1993, p. 353)

urgency and comparison with in-house costs, even though it is very rare case in the M/R program.

However, the *myopic* nature of FCFS approach results in sub-optimal schedules over a long time horizon, due to its priority rule that tends to preferentially schedule a first-come project. Other drawbacks of FCFS are the facts that it gives a program manager continuous rescheduling burden, and that he/she lacks predictability of the M/R program in the long-term horizon (Church and Uzsoy, 1992)[5].

The rolling horizon approach (RHZ) is another scheduling method for dealing with the external uncertainty in the M/R environment. In the RHZ framework, the MPS is derived by solving a multi-period MPS problem and implementing only the first period's decisions. Then the schedule is "rolled forward" to the next decision period with new demands appended to the horizon (Blackburn et al., 1986, p. 413). This period-based approach results in less frequent intervention than the FCFS approach, thus more predictability of the M/R schedule system.

Another motivation for using RHZ approach is the fact that there is, in practice, a time lag between a M/R project request and construction of the project (refer to the next section). Since the M/R project delivery process is composed of several phases, program manager can release the requested projects into the construction phase periodically, rather than as the

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[5] Further, this continuous rescheduling will often result in confusion on the shop floor and a general reduction in plant productivity (Mather, 1977; Sridharan and LaForge, 1990).

requests arrive. That is, the program manager can actively transform the dynamic nature of continuous request arrivals into a series of static scheduling sub-problems within the multiple periods by using active contracting strategy.

2.5. ROLLING HORIZON APPROACH TO PROGRAM MASTER PLAN

This section identifies program design issues of the rolling horizon (RHZ) approach, and describes benefits of RHZ approach in the M/R environment. To apply the RHZ approach into dynamic context of the M/R program, first the characteristics of M/R project delivery process are defined.

2.5.1. Process Model of M/R Project Delivery

Design decisions on a planning horizon need understanding the delivery process of M/R projects. After intake of each project request, the program manager develops an "expectation-based" project delivery procedure by negotiating specific milestones and timetable agreements with customers. Figure 2.1 shows the process flow of a M/R project delivery, and the typical delivery process model with statistics[6] of duration percentage is presented at Figure 2.2. The delivery process is composed of three main categories: (1) assessment, (2) design and estimation, and (3) construction phases. The assessment phase is a process segment that consists of scope definition, preliminary estimation and plan, and assessment approval. The assessment approval from an academic department (t_1 at Figure 2.2) is a kind

[6] The statistics are based on data between February 1996 and December 1998.

of *soft* contract between the client and the M/R department, because it is an approval of the service proposal provided by the Physical Plant, even though it does not involve complete contract documents, such as architectural and engineering (A/E) design and specifications, cost estimates, and schedule.

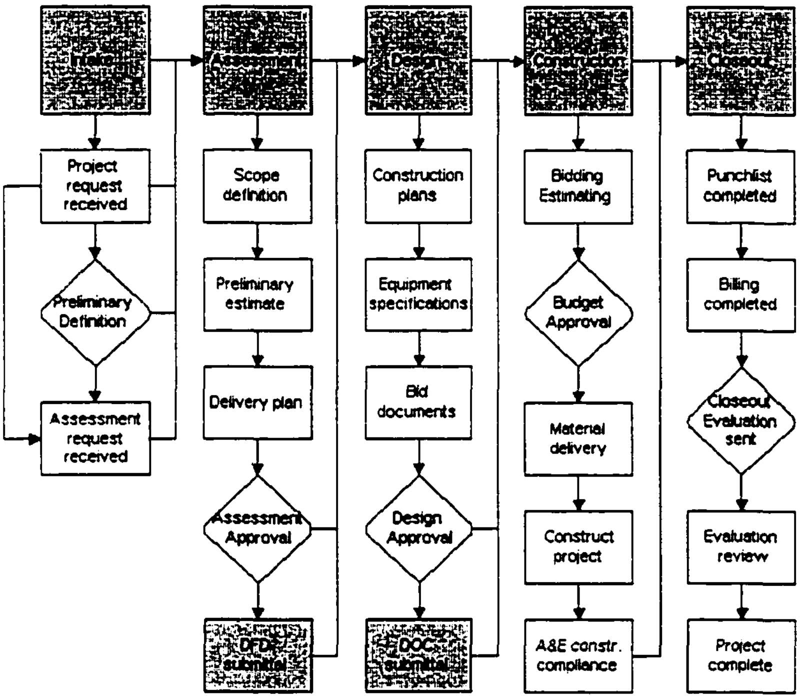

Figure 2.1 Process Flow of a M/R Project Delivery (http://www.fpm.wisc.edu/pp/pacprocess.htm)

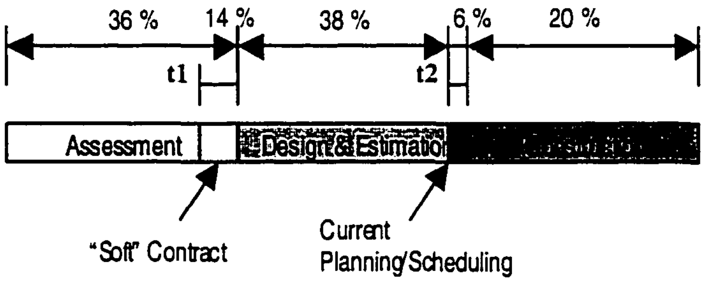

Figure 2.2 Typical M/R Delivery Process Model and Duration Statistics

The following phase, design and estimation, is composed of construction plan, design, and budget approval. In the current practice, planning and scheduling a M/R project is executed just before the construction phase (t_2 at Figure 2.2). This practice is similar to the first-come-first-service (FCFS) approach of master production scheduling (MPS) in the manufacturing industry. When a program manger deals with the dynamic and continuous project requests, however, this approach give the disadvantages described in Section 2.4.

2.5.2. Predictability and Manageability of RHZ Approach

For a stable PMP against external uncertainties in M/R environment, one possible management technique is to perform an approximate program planning earlier than the current practice (construction-oriented). It means a program manger considers the program master planning during assessment approval (t_1 in Figure 2.2), instead of just before construction of a project (t_2). From the program manager's view, the new strategy based on the RHZ approach consequently provides a time lag between the planning phase and scheduling phase (just before construction). In fact, the time lag is realized by the phase of design and estimation in Figure 2.2. Considering this time lag during planning phases, the program manager is able to allocate potential construction times of several projects around scheduling windows. This allocation of projects based on the RHZ approach does not count on exact resource availability and duration uncertainty of the project process as much. The construction phase of a prcject is dealt as one block that has estimated duration (βD_i) based on a time buffer ratio (β) and the average duration (D_i) of previous similar projects.

One advantage of this approximate planning is predictability of a construction scheduling window, even though a realizable scheduling will be implemented considering resource contention and a capacity utilization ratio (λ) (refer to section 5.2 of Chapter 3)[7]. The manager has the possibility of adjusting/controlling a pace of an intermediary phase (design and estimation in Figure 2.2), coordinating the progress of concurrent projects. Since construction peaks are periodically expected during a summer session and specific holidays in the planning horizon, the program manager is able to distribute construction loads of the peak window by expediting the intermediary phases of requested projects. When this look-ahead strategy is combined with work-zone based concurrent construction (refer to Chapter 8), this strategy might contribute to generating flatter profiles of resources use and decreasing the amount of overtimes, backlog, and inevitable subcontracts.

2.5.3. Planning Horizon and Scheduling Window

Under the conventional rolling horizon (RHZ) strategy in the production management, the entire planning horizon has been composed of several periods (e.g., four periods in Sridharan, et al. 1987; six period in Das, 1993), which is based on management decisions in a particular problem context. In this research, the planning horizon is set to twelve months, because there are annual cyclic peaks of construction demand (e.g., during a summer session and other holidays). And an intermediary time unit, a scheduling window, is introduced to reflect peculiar characteristics of the M/R program. A longer scheduling window can decrease planning frequency of a master construction schedule (MCS). But, lengthening the

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[7] The value of λ depends on management policy (e.g., 75%).

scheduling window decreases performance of timely project delivery, and increases magnitude of internal uncertainty and a time buffer size. The length of scheduling window is set to one month according to the current practice of revising construction program plan once a month (Kerzner, 1994). And an adjustment period has one week's length based on the current *weekly meeting* among shop supervisors and projects coordinators. This weekly period is related with periodic buffer management to deal with internal uncertainty (refer to Chapter 5 for detailed description).

Based on the delivery process model of a single M/R project, a simplified model of multi-project planning is presented in Figure 2.3 to describe implementation process of scheduling windows. S_1 of project 1 (P_1) and S_2 of project 2 (P_2) represent planning phases, and C_1 of P_1 and C_2 of P_2 represent construction phases. In Figure 2.3, a segment of planning horizon is shown from time T_1 to T_4 ($\overline{T_1T_4}$) that is composed of three scheduling windows ($\overline{T_1T_2}$, $\overline{T_2T_3}$, and $\overline{T_3T_4}$). Under the developed RHZ approach with active contracting strategy, construction of project 5 (C_5) is contractually allocated in scheduling window $\overline{T_2T_3}$, even though the intermediary phase of the project (design and estimation) is completed at a time-point within $\overline{T_1T_2}$.

At time T_2, a projects coordinator simultaneously schedules constructions of multiple M/R projects those were allocated into $\overline{T_2T_3}$ (C_4, C_5, and C_8), while integrating them with remained activities of those have been started since a time-point of $\overline{T_1T_2}$ (e.g., C_3). During this scheduling process, a construction of a project may be allocated into the next scheduling window $\overline{T_3T_4}$ because of resource contention with other projects. For example, construction of project 7 (C_7) is scheduled in scheduling window $\overline{T_3T_4}$ while resolving resource contentions with P_3-P_6 and P_8.

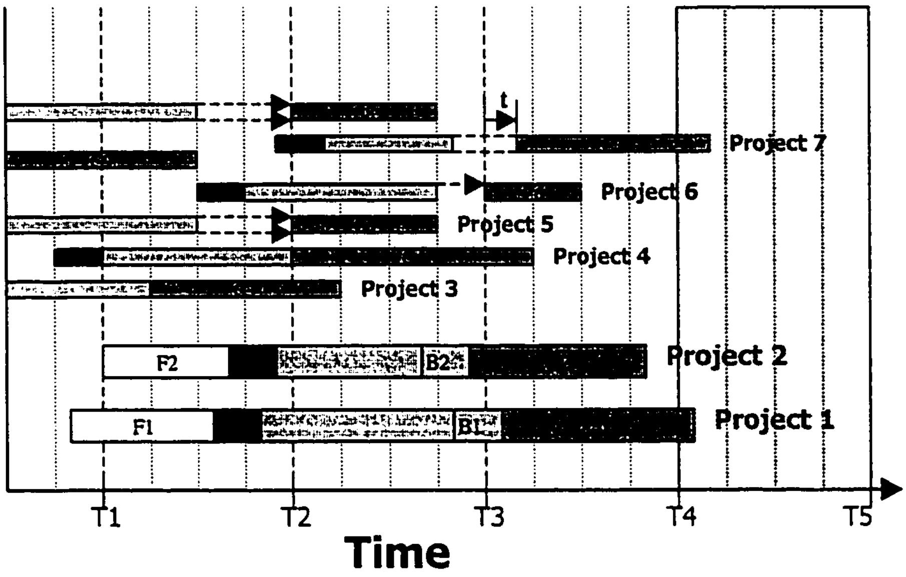

Figure 2.3 Planning Horizon and Scheduling Windows

As a result, the program manager can release the requested projects into the construction phase periodically, rather than as the requests arrive. By using the active contracting strategy, the program manager can transform the dynamic nature of continuous request arrivals to a series of static sub-problems within the multiple scheduling windows.

The next chapter describes the detailed resource allocation algorithm within a scheduling window that heuristically resolves the resource contention among activities of M/R projects.

CHAPTER 3

RESOURCE-CONSTRAINED MASTER CONSTRUCTION SCHEDULE

3.1. INTRODUCTION

The program master plan in the M/R department determines which project needs to be contractually allocated in which scheduling window from the long-term perspective of organizational strategy[1]. When a program manager schedules constructions of multiple projects in a scheduling window, a project should be completed as early as possible within predetermined design quality and budget. This goal of the M/R program management are achieved mainly through (1) the effective and efficient use of technicians at each trade shop and (2) timely and pertinent supply of system components during building M/R services. The lack or untimely availability of the resources is a major impediment (Badiru, 1996, p. 169) to effective and efficient management of highly-linked project networks. From an internal coordination view of multiple M/R projects and multiple shop trades, the master construction schedule (MCS) needs to be developed through considering capacity of the in-house resources, i.e., shop technicians[2].

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[1] Grant (1991) presented the earlier definition of strategy: "*the match an organization makes between its internal resources and skills ... and the opportunities and risks created by its external environment*" (p. 114).

[2] In general, project management literatures widely use the term 'resource' to represent labors, tools and equipment, materials, money, and even information.

Badiru (1996) indicated the following two components to be addressed by resource constrained scheduling: (1) "*a logical and time-based organization of the tasks and milestones contained in the project that is typically influenced by resource limitations*" and (2) "*the identification of complementary actions to be taken in case of unexpected developments in the project*" (p. 170). As the first component of the MCS in the M/R program, this chapter develops scheduling heuristics and an algorithm that fit the long-term organizational goals. The second component of the MCS, contingency plan and buffer management, will be studied in Chapter 5 that is based on the initial MCS generated in this chapter.

3.2. CHARACTERISTICS OF M/R MASTER CONSTRUCTION SCHEDULE

3.2.1. Goals

Even though the conventional CPM/PERT approaches assume unlimited resource availability in project network analysis, a program manager ought to plan/schedule multiple M/R projects based on the current availability of each shop's resource as well as due date constraints, budget limitations, and performance requirements (Fendley, 1968; Dumond and Mabert, 1988; Mohanty and Siddiq, 1989). Given the resource constraints, the program manager inevitably confronts the problem of a "resource contention" (Gordon et al, 1991, p. 714; Newbold, 1998, p. 173), during scheduling procedure to achieve goals of project coordination in M/R projects: customer satisfaction, organization efficiency, and workload balance (PAC, 1999)[3].

From the perspective of project planning and scheduling, the customer satisfaction means a timely project delivery, if possible, a faster completion of the project. The issue of faster project completion needs to be addressed, considering multiple projects simultaneously that could have various durations and resource requirements.

For organization efficiency and workload balance, on the contrary, the amount of technician's idle time should be decreased (i.e., higher resource use ratio), and the use profile of each shop's resource capacity ought to be stabilized for the long-term planning horizon of organizational program management. Since the resource capacity of each trade shop is finite at the current planning horizon, another objective of the MCS is to maximize resource use, if possible, without any idle time or under-use of shop capacity. From a perspective of organizational inventory, a less projects-in-progress (PIP) prevents projects coordinator's focus from being dispersed by more number of PIP, and might be considered as a complementary scheduling criterion for the M/R program efficiency.

Under the dynamic nature of M/R project requests, it needs more consideration to decide the optimum capacity of the internal organization. This research leaves the possibility of adjusting the organizational capacity for future research, and focuses on maximizing use of

[3] Badiru (1996) suggests three common objectives in project network analysis: to minimize project duration, to minimize total project cost, and to maximize resource use (p. 173).

shop capacity and expediting project completion under the M/R environment of multi-resource constrained multiple projects.

3.2.2. Constraints

When a program manager schedules multiple M/R projects to achieve the goals of the M/R organization, on the other hand, he/she is subject to multiple constraints synchronously, e.g., time, resource, technical, and practice restrictions. When a M/R project is requested, in most cases both the program manager and a client are involved in setting its start-date and completion-date. In the developed M/R program management model, the program manager proposes the initial project milestone-dates considering resource demands of the new project and existing projects-in-progress (PIP) and resource availability of each trade shop. The negotiated and agreed milestones of the project will be the major time and resource constraints on planning and scheduling the next coming project(s) (Yang and Sum, 1997, p.139).

During scheduling a project, technical constraints of each activity and their interaction or interference should be reflected on deciding logical activity precedence as well as physical space demand (Echeverry et al., 1990; Riley and Sanvido, 1997; Tommelein et al., 1999). Under the current space utilization practice in the M/R environment (refer to section 4 of Chapter 1), the major activities of a project are linearly scheduled. This linearity of sequence relations among the activities gives significant effect on the master construction schedule. Since few parallel activities exist in the project, it is inappropriate to apply the conventional

CPM/PERT analyses[4] to the M/R project, and resultant schedule of the project will be elongated. Given multiple objectives of the program management, therefore, above constraints increase the complexity and difficulty of generating the MCS in the M/R program.

3.3. RESOURCE-CONSTRAINED SCHEDULING

As described earlier, the M/R program scheduling problem is that of minimizing durations of multiple projects under finite capacity constraints of multiple trade shops. Since the resource demands of the projects are frequently over the available capacities of the shops, the program manger needs to prioritize or sequence activities that require the common resources concurrently. To yield the MCS under the multiple resource constraints, this research investigated project management literatures[5]. Resource-constrained scheduling procedures can be categorized into two major groups: (1) mathematical programming and (2) heuristic procedures[6]. This section briefly summarizes previous research studies on project

[4] The major concepts of the CPM/PERT analyses are early/late start/finish (ES/LS, EF/LF), forward and backward passes, slacks/floats (TF, FF, and IF), and the critical path.

[5] For detailed information on the resource-constrained project scheduling, refer to Davis and Patterson (1975), Kurtulus and Davis (1982), and Özdamar and Ulusoy (1995).

[6] Recently artificial intelligence (AI) based search techniques have been applied into the resource constrained project scheduling problem: e.g., genetic algorithm (Chan et al, 1996; Mori and Tseng, 1997; Hegazy, 1999; and Leu and Yang, 1999), simulated annealing algorithm (Gemmill and Tsai, 1997; Son and Skibniewski, 1999). The techniques can be interpreted as hybrid heuristics based on random search.

scheduling according to the two categories, and discusses applicability of scheduling procedures into the MCS of the M/R program.

3.3.1. Mathematical Programming Procedures

The first group intends to find the exact optimal solution to the multi-resource constrained scheduling problem, and includes linear programming (Wiest, 1964), integer programming (Mohanty and Siddiq, 1989; Patterson et al., 1990; Alfares et al., 1999); 0-1 (goal) programming (Pritsker et al, 1969; Patterson and Roth, 1976; Chen, 1994), dynamic programming (Drexl, 1991; Carraway and Schmidt, 1991; Elmaghraby, 1993), partial enumeration and branch-and-bound (Patterson, 1984; Demeulemeester and Herroelen, 1997), and other mathematical techniques.

Unfortunately, the mathematical programming techniques are appropriate only for small- or moderate-size projects (e.g., up to 50 activities: Davis and Patterson, 1975, p. 944; Bell and Han, 1991, p. 315) and have not used in practice because of the complexity of real project networks. Despite availability of state-of-an-art computer technology, required implementation burdens[7] are the main impediments toward applying the mathematical optimization procedure to the multiple project scheduling in the M/R program environment, even for small size problems (Davis and Patterson, 1975).

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[7] For example, "*modeling requirements, drudgery of [numerous variable/constraint entries], and the combinatorial nature of interactions among activities*" (Badiru, 1996, p. 173).

For example, a linear programming formulation of a 55-activity network with four resource types required more than 5,000 equations and 1,600 variables (Wiest, 1964). A 0-1 programming formulation of a three-project, eight-job, three-resource-type problem was modeled by 33 variables and 37 constraints (Pritsker et al., 1969), which had involved 72 variables and 125 constraints (Bowman, 1959). Another example of the mathematical formulation was a 0-1 goal programming model of four-projects, 40-jobs, and nine-resource-types (Chen, 1994). Even though his formulation simplified the generalized model of 1057 0-1 decision variables and 1360 rigid constraints to 104 variables and 53 constraints, it is still far from practically solving real organizational multi-project scheduling problems. Davis (1974) noted that "*[mathematical programming procedures] remained today primarily an interesting research topic for academicians*" (p. 30).

3.3.2. Heuristic Procedures

Because of the impracticality of the mathematical optimization procedures, many scheduling heuristic rules have been developed in the field of multi-resource constrained multi-project management (e.g., Kurtulus and Davis, 1982; Kurtulus and Narula, 1985; Tsubakitani and Deckro, 1990). A scheduling heuristic uses logical rules to prioritize and sequence activities in resource contention, and produces "good" feasible solutions (Davis and Patterson, 1975, p. 944).

In literatures of multiple project management, numerous scheduling heuristic rules have been presented to facilitate ease of resource allocation into to typical project networks. Some researchers had used very simple and intuitive heuristics that were categorized and compared by and Patterson (1976) and Kurtulus and Davis (1982), while others developed complex and combined heuristics (e.g., Wiest, 1967; Badiru, 1988; Kim and Leachman, 1993; Ulusoy and Özdamar, 1994)[8]. A good scheduling heuristic are defined by Badiru (1996):

> *"[It] should be simple, unambiguous, and easily executable by those who must use it. The heuristic should not only avoids subjectivity and arbitrariness of the procedures, but also be flexible and capable for resolving schedule conflicts."* (p. 177)

Table 3.1 presents some of scheduling heuristic rules and researches that used the rules and two new rules used in this research for special characteristics of the M/R environment.

There are advantages and disadvantages to using specific heuristics. For example, the SOF, SASP, and SAC are useful for quickly reducing the number of projects-in-progress (PIP). For control purposes, preventing resources from spreading over too many active projects will lower the burden of a projects coordinator (Badiru, 1996; and Yang and Sum, 1997). From the project-slack view, Fendley (1968) also proposed that projects with little work remaining should have the scheduling priority, because a project approaching its completion-date should have less slack than newer projects (p. 515).

Under these rules, however, the larger duration projects have a tendency to be postponed too long, increasing project completion-times (Patterson, 1976). In general, the larger

[8] Also, these heuristic rules can classified by their subjects of orientation: time-oriented, resource-oriented, and combination of the both.

projects have greater budget and uncertainty, delay penalties (e.g., liquidated damages), if any, accrue more rapidly for them (Dumond, 1992).

Table 3.1 Heuristic Rules and Researches

Heuristics	Explanation	Researches
FCFS	First Come, First Served	Mize (1964), Yang & Sum (1993)
SOF	Shortest Operation First	Patterson (1973)
SASP	Shortest Activity from Shortest Project	Kurtulus & Davis (1982), Tsubakitani & Deckro (1990)
SAC‡	Shortest After-Chain Time	
MINSLK	Minimum Slack First	Fendley (1968), Davis & Patterson (1975), Mohanty & Siddiq (1989), Bowers (1995)†
ACTIM*	Largest ACTIM	Whitehouse & Brown (1979)
MCA	Most Critical Activities	Fendley (1968)
LAC‡	Longest After-Chain Time	
GRD	Greatest Resource Demand	Badiru (1996)
ACTRES**	Largest ACTRES	Bedworth (1973)
CAF***	Largest Composite Allocation Factor	Badiru (1988)

Note: * ACTIM = (Critical path time) – (Activity latest start time)

** ACTRES = (Activity Time) × (Resource Requirement)

*** CAF = $(\omega)RAF + (1-\omega)SAF$

† Resource-constrained (RC) float was used to determine the critical sequence.

‡ New rules used in this research

Some of these are adopted by commercial project management software to schedule resource-constrained project network(s) (Hegazy and El-Zamzamy, 1998; Hegazy, 1999). Hegazy and El-Zamzamy (1998) examined resource allocation capabilities of five software systems (e.g., Primavera Project Planner® (P3®) and Microsoft® Project) with a sample project network. This case study indicated that "some inconsistency" in the implementation of a heuristic existed among the software systems, and resultant schedules were "far from optimum" (p. 31). Also, De Wit and Herroelen (1990) remark that the resource planning and monitoring capabilities of most commercial packages are "not only very primitive but dangerously misleading" (p. 116). Even though heuristic rules and their proprietary implementations in commercial software packages need to improve their performance on resource allocation, heuristic-based procedures are currently "the only practical means for generating workable solutions" for the multi-resource constrained multiple projects in the M/R program environment (Davis and Patterson, 1975, p. 944).

3.3.3. Application of Scheduling Heuristics into M/R Program

Before applying the heuristic-based procedures into the M/R program context, it is necessary to consider problem characteristics such as network structure of multiple projects as well as size of each project network (Davis and Patterson, 1975). Since this research considers a sub-set of the whole M/R projects, a natural question is whether results based on relatively small problem can be extended to the whole program scheduling problem. Davis and Patterson (1975) emphasized the network characteristics as a more important consideration than network size based on previous researches: Pascoe (1965) and Crownston (1968). Pascoe found that the most effective heuristics for the smaller problems were also most effective for the larger problems, and verified this conclusion with an additional test on one large building-construction network taken from practice. Also, Crownston (1968) argued that network size was not a possible determinant of the relative effectiveness of alternative sequencing rules. Based on their studies, this research assumes the M/R program model can be extended to the practical M/R environment.

The relationships between heuristic performance and characteristics of the network structure was systematically investigated by Kurtulus and Davis (1982). Tsubakitani and Deckro (1990) summarized their research:

> "*Different project scheduling settings required the use of different scheduling rules to provide the most effective schedule. One heuristic decision rule may perform well on a project with specific characteristics, but may not perform well on another project with different characteristics.*" (p. 82)

Kurtulus and Davis (1982) categorized the characteristics of a resource-constrained project network by average resource load factor (ARLF) and average utilization factor (AUF).

Most of surveyed literatures, however, assumed a static environment where all projects were in the system at the same time. Based on the assumption of the static multiple-project, numerous researchers (e.g., Mohanty and Siddiq, 1989; Meredith and Mantel, 1995; Walker, 1998) considered multiple projects as a single mega-project, and applied CPM-based heuristic rules into the mega-project network. Some researchers, on the contrary, suggested that a project scheduling model ought to treat multiple projects explicitly instead of binding them artificially into the mega-project (Bock and Patterson, 1990; Dumond and Mabert, 1988; Kurtulus and Davis, 1982).

In their literature review, Yang and Sum (1997) identified five papers for the dynamic multi-project environment (Yang and Sum, 1993; Dumond and Mabert, 1988; Bock and Patterson, 1990; Dumond and Johnson, 1990; Dumond, 1992), while Walker (1998) pointed out two articles that examined the introduction of new projects into a set of ongoing projects (Tsubakitani and Deckro, 1990; Dumond and Dumond, 1993). Another dynamic system approach was presented by Fendley (1968) to develop a multi-project scheduling system.

The mega-project model with dummy activities[9] has a limited capability on handling special characteristics of the dynamic M/R environment where multiple projects arrive continually over time and do not have a common start/completion date. Without consideration of these characteristics, some projects or parts of the projects may be repeatedly postponed depending on applied heuristics, and the objectives of the M/R program management will not be achieved.

In this chapter and throughout the dissertation, a different approach from the above modeling methods is applied to the multi-resource constrained multiple M/R projects. As a research starting point, this research takes an owner-based organization view instead of a contractor-driven project view. Under this perspective, more emphasis is placed on organizational resource flows than activity/project events that were the main subject of previous scheduling literatures. The following section presents the developed heuristics.

[9] The dummy activities are used to connect the multiple projects into the single mega-project, which are a common start-node and end-node of planning horizon.

3.4. RESOURCE ALLOCATION HEURISTICS

Since the performance of a heuristic depends on characteristics of a problem structure and management strategy in organization (e.g., objectives), there is a need to develop a scheduling heuristic procedure that reflects the special context of the M/R program. This section describes a more problem-oriented heuristic procedure that resolves resource contention between activities/projects.

3.4.1. Heuristic Application Procedure

For easy description of the procedure, a simple program network is considered, which consists of four M/R projects and three trade shops. Only for simplicity of description, the trade shops are referred to as shop E (electric), M (mechanical), and C (carpenter). Also it is assumed that there is one unit of technician available in each shop.

Rule 1: Earliest Activity First.

Sort the activities in ascending order of their early start (ES). When an activity has not been completed since its start time in the previous scheduling window, its pertinent shop technician is first assigned to that activity to continue and finish it. Even though ES of activities were different in the previous scheduling window, the new values of ES's have the same value (-1) in the current scheduling window. The reason for this unification is that the continuity itself is only meaningful, but the earliness of ES has not significant effect. If there are several activities whose ES's are the same then, the next rules are applied.

Rule 2: Shortest After-Chain First

When scheduling projects 1 and 2 within scheduling window $\overline{T_1T_2}$, there is a need to resolve the resource contention first between activity E_1 and E_2 (refer to Figure 3.1). A project coordinator cannot schedule E_1 and E_2 at the same time if trade shop E has the capacity of a technician. Based on the objective of less PIP, shortest *after-chain* rule is used to break the tie after application of rule 1. The after-chain is equivalent to the estimated throughput time (duration) of the project minus the earliest start time of the activity. E_1 of P_1 whose after-chain (remained project duration including E_1's duration) is shorter has higher priority over E_2 of P_2, and is allocated earlier than E_2. The decision of E_2's start time will be postponed until a technician of electric shops is available. If there is also competing resource requirement from other projects at that time, the same priority rule will be applied to E_2 and other all activities.

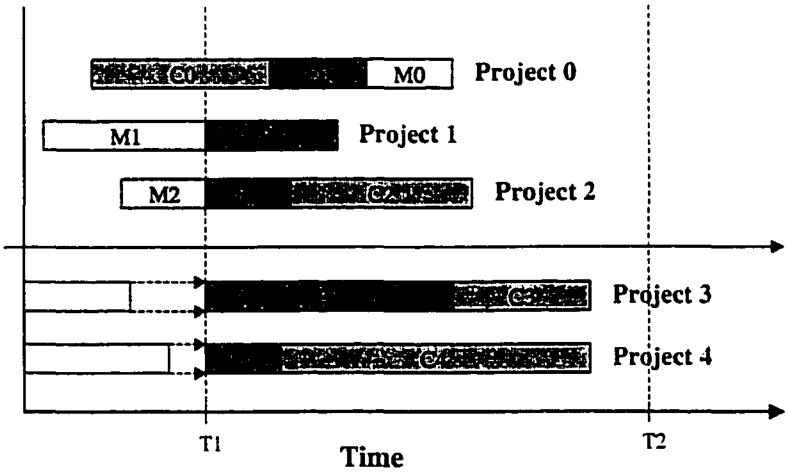

Figure 3.1 Program Layout in A Scheduling Window

Rule 3: Shortest Activity-Duration First

When several activities have the same after-chain length (E_3 of P_3 and E_4 of P_4), schedule first activity E_4 with shorter duration than E_3 of P_3. The underlying reason of this rule is the fact that if the longer E_3 is scheduled first, shorter activities of other projects (e.g., E_4) will be significantly shifted to the future. Since each activity is critical in a M/R projects (due to linearity of a project process), the right-shifts of these activities make completion delays of pertinent projects. However, this phenomenon preserving the large number of PIP should be avoided.

Rule 4: Most-Delayed Project First

If we follow above two rules, especially rule 2, a large project whose estimated duration (Di) is longer than others tend to be delayed. As a complement mechanism, this scheduling procedure uses a sentinel ratio (θ_j). Based on current progress and elapsed time of the project, a possible earliest completion time (D_i') is re-estimated without considering resource contention. The ratio (D_i'/D_i) is greater than the sentinel ratio (θ_j), it will have highest priority overriding rules 2 and 3 (refer to Figure 3.2).

3.4.2 Determination of Sentinel Ratio (θ)

One decision criteria for the size of θ_j can be the buffer size (B_i) of a project (P_i) that was used at the time of project contract: e.g., $\theta_j = (D_i + B_i) / D_i$. If the value of θ_j is constant from time t_0 to t_3, however, when scheduling activity E (near the starting time of the project), θ_1

(D_i'/D_i) is usually smaller than θ_j. Then the project P_i will have inferior priority to other concurrent projects, and tend to be delayed. In order to resolve this situation, the value of θ_j is dynamically determined as a function of time.

A buffer factor (β) is defined as $B_i = \beta D_i$[10], and time (t) as the elapsed time from the possible earliest start (t_0) of a project. If the value of D_i' is larger than that of $\theta_j D_i$ (see Equation 3.1), project P_i has higher priority, and pending activity of P_i is scheduled.

$$\theta_j D_i = D_i + \beta D_i \times \frac{t_j}{D_i} \qquad (3.1)$$

$$\theta_j = 1 + \beta \frac{t_j}{D_i} \qquad (3.2)$$

In P" of Figure 3.2, time t_j of activity S is longer than D_i, and the value of $\theta_j D_i$ is lager than $D_i + \beta D_i$. There is a need for another sentinel ratio (θ_k).

$$\theta_k D_i = D_i + \beta D_i \qquad (3.3)$$

$$\theta_k = 1 + \beta \qquad (3.4)$$

Therefore the final sentinel ratio will be minimum value of them.

$$\theta = \min(\theta_j, \theta_k) \qquad (3.5)$$

[10] The size of buffer is usually a management decision based on specific characteristic of a project. Even though this research uses periodic buffer strategy (refer to section 3 of Chapter 5), in this section the total amount of buffer is represented as B_i, and graphically showed in Figure 3.2 for simplicity.

In the case of a tie in above rules, tied activities could be scheduled in ascending order of resource requirements (i.e., the smallest labor-size activities first). In the case of a tie in labor-sizes, allocate the tied jobs in ascending order of their identifying numbers.

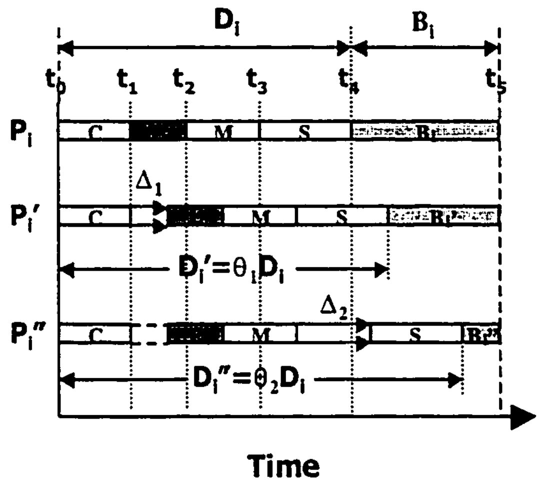

Figure 3.2 Determination of Sentinel Ratio θ_i

3.5. PROGRAM CONSTRAINT RESOURCES (PCRs) SCHEDULING ALGORITHM

This section describes the developed algorithm or procedures for generating a master construction schedule (MCS) within a scheduling window. The resource allocation algorithm is composed of six steps (refer to Figure 3.3). The following sub-sections explicate the six steps by using an example case of scheduling multi-resource constrained multiple M/R projects. Appendix A presents programming codes in Visual Basic® Application (VBA) language that implement the six-step scheduling procedure in a common spreadsheet package, Microsoft® Excel.

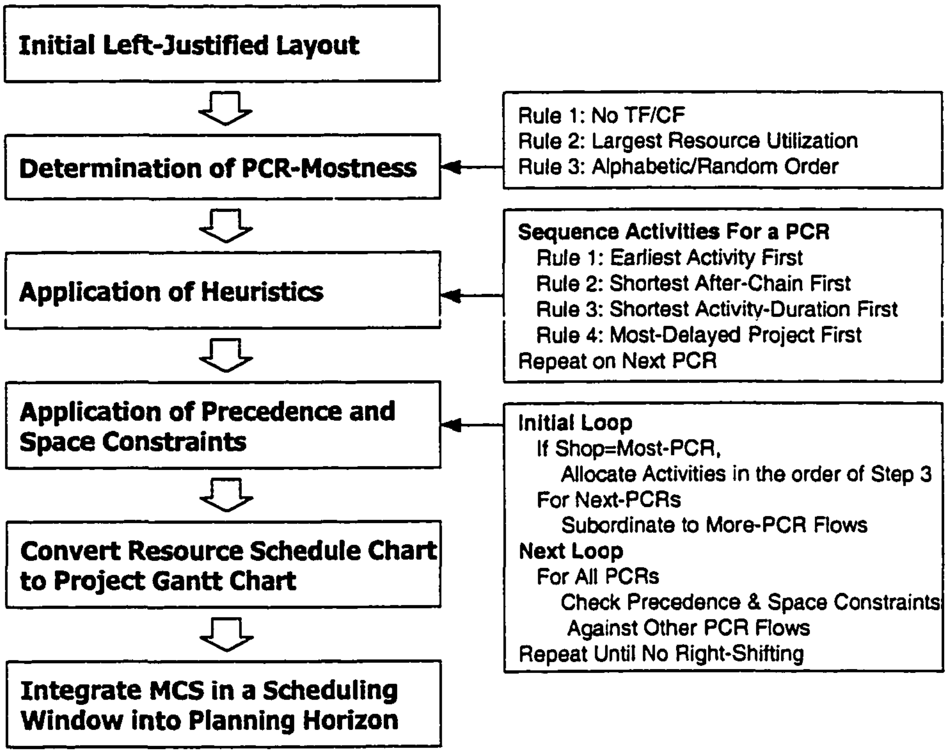

Figure 3.3 PCRs Scheduling Algorithm

3.5.1. Initial Left-Justified Layout

As a starting point for constructing the MCS, the initial plan of each project is first defined, and a layout of multiple projects within a scheduling window is shown in Figure 3.4. The figure shows the initial Gantt chart (a left-justified layout) of four M/R projects within a scheduling window (workday 1 – workday 20). Supplementary activities (e.g., supply of building components) are eliminated for simplicity of model. There are three trade shops: trade shop E (electric), M (mechanical), and C (carpenter). Only for simplicity of description, the example case assumes that there is one unit of technician available in each shop, and that the estimates for activity durations are represented in terms of days. After completion of its previous assignment, a technician will be idle if there are no eligible activities that satisfy constraints of activity precedence and resource sequence, or if available technician units of the relevant shop are less than resource demand of a new activity.

Step 1: Develop a program network in a scheduling window. Identify projects and activities, their estimated durations, and resource requirements (Badiru, 1996).

In Figure 3.4, all projects are placed as early as possible to their early start times, observing activity precedence relations: "left-justified" project layout (Wiest, 1964). Continuing projects (e.g., P_1 and P_3) are redefined as individuated projects those are composed of remained activities of themselves (e.g., E, M, and C of P1; and E, C, and M of P_3). If an activity is not completed in the previous scheduling window, the remained tasks of the activity are treated as a independent on-going activity whose ES has a negative value (e.g., the ES of E in P_3 is -1). And start times of new projects will be the start time of the scheduling window. Given the left-justified and a set of resource constraints (technician capacity in each shop and their availability), activities and resources are scheduled according to the following heuristic rules.

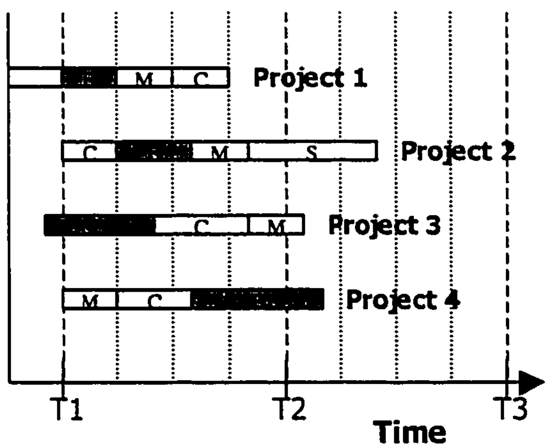

Figure 3.4 Initial Project Gantt Chart

3.5.2. Determination of PCR-Mostness

Step 2: Determine the 'mostness' of program constraint resource using the resource demand chart.

Resource demand refers to the required allocation of technicians in trade shops to activities of multiple project network in the M/R program. A resource demand chart graphically shows the level of load assigned to each shop's technicians over time. Figure 3.5 shows the resource demand chart of the example case. The resource demand chart is drawn for three different shop types (E, M, and C)[11] involved in the 4 M/R projects. The graph provides information useful for constructing the master construction schedule (MCS) and the buffer management strategy. For the resource allocation algorithm, it can help identify potential areas of resource contentions of each shop in multiple projects, and determine the 'mostness' (criticality) of the program constraint resources in a scheduling window (PCRs) based on interdependence among resource uses of the trade shops.

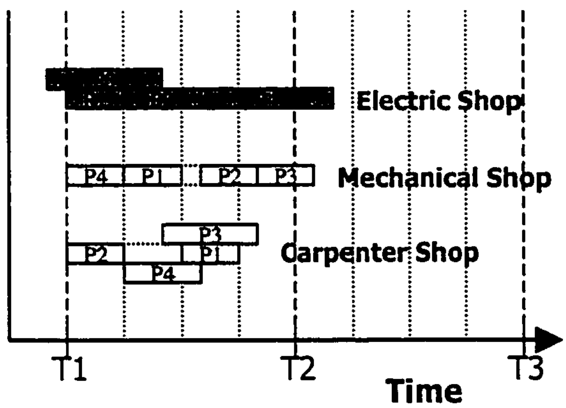

Figure 3.5 Resource Demand Chart

[11] Trade shop S is not considered in the resource demand chart, because the activity 'S' in project 2 has no resource contention with other activities.

The 'mostness' of the PCRs is defined based on the following rules.

First, no time float (TF) in the resource flow and no capacity float (CF) in the resource demand against the pre-determined number of technicians in each shop.

Second, if any capacity float, largest sum of resource utilization (RU: $\Sigma\lambda \times d$), where λ represents capacity utilization ratio of each work-day, and d represents time units of work-days.

Last, remained ties are broken by alphabetic order or random.

Based on these rules, the electric shop (E) is the most-PCR in the scheduling window $\overline{T_1T_2}$. The next-PCR is the carpenter shop (C) followed by the mechanical shop (M) (refer to Figure 3.6). The activities to which the most-PCR is assigned should be expedited (i.e., the most-PCR should be highly utilized) in order to avoid delaying dependent activities[12] executed by the next-PCR and/or less-PCR. In the example of Figures 3.4 and 3.5, activities P_{11}, P_{22}, P_{31}, and P_{43}[13] those require the technicians of the shop E are scheduled as early as possible according to following resource allocation heuristics. After allocation of the most-PCR activities, remained activities are scheduled in the order of PCR 'mostness' (ρ).

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[12] A dependent activity is an activity whose execution depends on the completion of immediately preceding activities. The preceding activities are activities those have technical precedence relationship in a project and/or organizational sequence relationship in the resource flow of a trade shop.

[13] The first subscript of each notation represents a project identification number, while the second represents an activity identification number of the project.

Shop	*Cap	**CF	*RU	**ρ
E	1	0	12	
M	1	1	8	
C	1	2	11	

(a) Before Sorting

Shop	**CF	*RU	**ρ
E	0	12	1
C	2	11	2
M	1	8	3

(b) After Sorting

* Cap (Capacity): The number of human resource (technicians) in each shop.

** CF: Frequency of Capacity Floats (units of duration below capacity)

* RU (Resource Utilization): $\Sigma(\lambda \times d)$, where λ = Resource Utilization Ratio, d = Time Units of Duration

** ρ: Mostness of Program Constraint Resource (PCR)

Figure 3.6 Determination of Most-PCR

3.5.3. Application of Heuristic Rules

Step 3: Determine scheduling order of activities in the resource flow of the specified PCR.

Step 3-1: Sort the activities of the most-PCR (e.g., E) in ascending order of their early start time (ES).

Step 3-2: Ties are broken by scheduling the activity in ascending order of after-chain (rule 2) and the shortest duration first (rule 3). Resultant scheduling order of the most-PCR activities is P_{11}, P_{31}, P_{22}, and P_{43}. For this example, the resource flow-length of the shop E is 12 work-days.

Step 3-3: Repeat above assignment process until all activities of the remained shops have been scheduled.

Figure 3.7 shows a resource schedule chart after applying the heuristics that contains resultant scheduling orders of activities for the three trade shops.

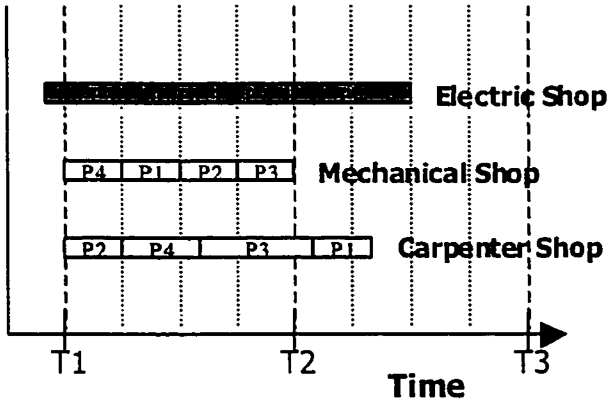

Figure 3.7 Resource Schedule Chart after Applying Heuristics

3.5.4. Application of Precedence and Space Constraints

Step 4: Apply technical precedence and space constraints among activities in all PCR flows.

In order to schedule the activities and the resources, the procedure first go from the start time of a scheduling window (T1=TNOW) to right (i.e., future). The activities in the most-PCR (E) are first scheduled in the order determined at step 3 without considering other less-PCR's (C and M). While the activities in the next-PCR flow are scheduled, they are subordinate to the scheduled more-PCR flows, except the case where the technical precedence of the scheduling activities have the prior to those of the scheduled more-PCR activities. At work-day 3, for example, P_{12} in the resource flow M should be right-shifted (delayed) to work-day 6, because the precedent activity P_{11} in the resource flow E is completed at work-day 5. With the similar reason, activity P_{23} in the resource flow M is right-shifted to work-day 9 after the completion of activity P_{22} in the resource flow E. After checking and the right-shifting the last activity of the least-PCR (P_{33}) against the technical precedence and space constraints, iterate the procedures until there is no right-shifting.

Figure 3.8 presents the generated resource schedule chart after applying activity precedence and space constraints to the example case. The length of the each resource flow is 12, 11, and 12 work-days, respectively. Interesting things in the resultant schedule are that the least-PCR (mechanical shop: M) has two periods of idle time in its resource flow, and that activity P_{12} has a free float.

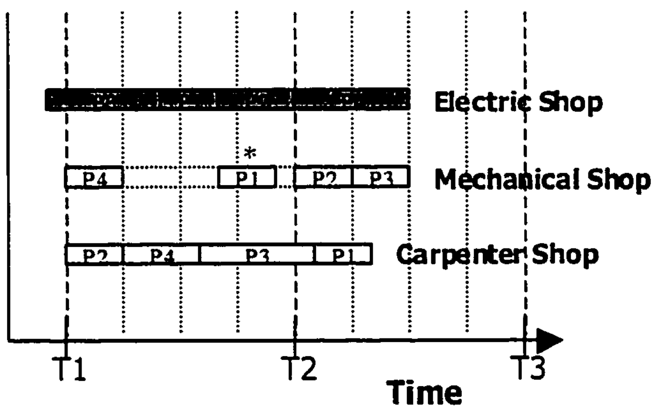

Figure 3.8 Resource Schedule Chart after Applying Constraints

Step 5: Convert the resource schedule chart to a project Gantt chart (refer to Figures 3.8 and 3.9).

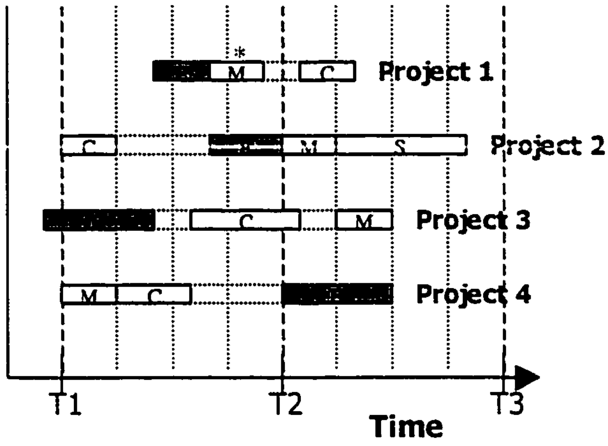

Figure 3.9 Project Gantt Chart after Applying Constraints

3.5.5. Integration of a Scheduling Window into Planning Horizon

Step 6: Integrate the generated schedule of the scheduling window into the planning horizon that is composed of multiple scheduling windows (refer to Appendix B).

As the final schedules, the algorithm produces a flow view of trade shops and an event view of activities/projects over the strategic planning-horizon. The main strategy of the algorithm is, therefore, to schedule the activities based on the organizational PCR-flows and to convert it to the project view of the schedule.

3.6. MODIFIED BROOKS' ALGORITHM FOR OTHER HEURISTICS

In order to compare the performance of heuristics including the developed procedures, this research conducts experimental simulation, and analyzes the results of the simulation. The implementations of other heuristics are based on Brook's algorithm, even though the original algorithm considers a single project – single resource case (Badiru, 1996, p.182). This section explained the application steps of the modified Brook's algorithm into the example of multiple M/R projects those are used at the previous section. The explanation of this section is an extended version of Whitehouse and Brown (1979), because the characteristics of the project network and the heuristics used in the illustration are different, and because OpenList is generated instead of considering ACT. ALLOW.

Step 1: Sort the activities in all projects based on the current heuristic rules (e.g., SASP, SAC, and LAC), Designate the list of the activities as the original 'StaticList'. The StaticList has attributes of each activity and the project that the activity belongs to: activity name (Act), early start (ES), activity duration (A-D), shop name (Shop); remained after-chain (RAC), and project duration (P-D). Also set TNOW (the current time of the resource allocation decision) to 0.

Step 2: Set the first activity in the StaticList as the current activity (i.e., P_{11} in Figure 3.10). The TNOW is set to the ES of the current activity (CurAct), and the current activity is scheduled into the resource schedule chart. The number of resources available is decreased by the resource demand of the CurAct. Apply the same process to the next activity (P_{12}). At the completion time of the CurAct (ES + A-D), the resource is restored to the common resource pool. The resource availability of the M/R system is increased by the resource demand of the CurAct, and the increase triggers scheduling the next activity.

No.	Act	P-D	RAC	ES	A-D	Shop
1	P11	6	6	0	2	E
2	P12	6	4	2	2	M
3	P13	6	2	4	2	C
4	P21	8	7	1	2	C
5	P23	8	2	6	2	M
6	P22	8	5	3	3	E
7	P33	11	2	9	2	M
8	P31	11	9	2	3	E
9	P32	11	6	5	4	C
10	P41	12	9	3	2	M
11	P42	12	7	5	3	C
12	P43	12	4	8	4	E

Figure 3.10 StaticList for Heuristic SASP

Step 3: For each CurAct, determine if the CurAct can be scheduled. After checking whether the immediately precedent activity of the CurAct is scheduled (precedence constraint), the resource demand of the CurAct is compared to resource availability of the M/R system (resource constraint). If the CurAct violates one of the constraints, place the CurAct into dynamic 'OpenList' that contains activities those have not scheduled due to the violation of the constraints. Increase the number of activities in the OpenList (set the number to 0 at the start time). Therefore the decision of the CurAct allocation is right-shifted (delayed) by the completion time of the immediately precedent activity and by the earliest restoration time of the resource.

Step 4: Sort the activities based on the current heuristic rules. Scan the activities from the top of the OpenList, and determine if the activities can be scheduled. A scheduled activity is removed from the OpenList. The OpenList dynamically increases and/or decreases in number, as the TNOW increases.

Step 5: TNOW is changed to the next activity in the StaticList, and the CurAct is the activity.

Step 6: Repeat this assignment process until all activities in the StaticList and the OpenList have been scheduled. (ES + A-D) of the last activity in the trade shop gives the flow length of the resource flow.

CHAPTER 4

SIMULATION EXPERIMENTS FOR SCHEDULING HEURISTICS

This chapter presents a detailed description of the simulation model and test environment, followed by a presentation of the results of the computer simulation experiments. These results are analyzed, and a summary of the experiments is presented.

4.1. SIMULATION MODELS AND ENVIRONMENT

To illustrate the use of the periodic-PCR scheduling model and heuristic, a subset of the overall M/R program problem is used. Three scheduling windows (3 months: 60 workdays) are considered in this experiment, in order to capture the dynamic nature of the M/R environment in which there is a continuous flow of new projects, arriving stochastically to the Physical Plant department. The actual organizational problem, however, involves planning and scheduling technician assignments over the planning horizon of an entire fiscal year.

A set of projects those are arrived during scheduling window W_{i-1}, are scheduled into scheduling window W_i of the master construction schedule (MCS). Activity durations are assumed deterministic, and each schedule generated by a heuristic establishes start and finish times for activities. The current schedule is maintained within the scheduling window W_i. At the end of the W_i, a new schedule is developed for the next scheduling window W_{i+1}, where unscheduled parts of W_i and newly arrived projects are simultaneously integrated.

The simulation experiment is composed of 40 observations. Each observation simulates the program operation of three sets of M/R projects, which was scheduled through three scheduling windows. During each scheduling-window, the early-start-time of each project service is randomly generated following a uniform distribution with the mean value of ten workdays ranging from 0 to 19 workdays (refer to Table 4.2). To simulate the dynamic nature of the M/R environment, a set of requested projects in a scheduling-window is selected from a subset of the overall M/R program projects.[1] The simplified project models of the subset have, on average, 4.85 activities and range of 3 to 6 activities, requiring from three to five different resources, C, E, M, S, and P (refer to Table 4.1). The mean activity duration is 2.81workdays, ranging from 2 to 4 workdays. The resource requirement of each activity is assumed to be one unit of the five resource categories for simplicity of the experiment.[2] Each project duration ranges from 6 to 20 workdays with the mean value of 13.64 workdays. The project models are constructed based on technical constraints of activities and their "sequential" and "reciprocal interdependences" (Thompson 1967, p. 54; Riley and Sanvido, 1997, p. 103).

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[1] "*The use of a predetermined project set is justified by Bock and Patterson (1990) who showed that the use of a different project set does not affect the relative ranking of different decision rules*" (Yang, 1997, p.144).

[2] As explained in section 4 of Chapter 1, in practice each activity of a M/R project is usually executed by one (sometimes two) technician due to the small size of the project.

Table 4.1 Simplified Models of M/R Projects

Project	Act 1		Act 2		Act 3		Act 4		Act 5		Act 6		Project Duration
No.	Shop	Dur.	Shop	Dur.	Shop	Dur.	Shop	Dur.	Shop	Dur.	Shop	Dur.	
1	E	2	S	2	C	2							6
2	E	2	S	3	C	4							9
3	E	4	S	2	C	3							9
4	S	4	E	4	P	2							10
5	S	3	E	3	P	3							9
6	S	2	E	2	P	4							8
7	E	2	S	3	P	2	C	2					9
8	E	2	S	4	P	3	C	3					12
9	E	3	S	3	P	2	C	4					12
10	E	4	S	2	P	3	C	2					11
11	E	3	S	2	P	4	C	3					12
12	S	2	P	3	E	2	C	2					9
13	S	2	P	4	E	3	C	3					12
14	S	3	P	3	E	2	C	4					12
15	S	4	P	2	E	3	C	2					11
16	S	3	P	2	E	4	C	3					12
17	S	2	E	3	M	2	C	2					9
18	S	2	E	4	M	3	C	3					12
19	S	3	E	3	M	2	C	4					12
20	S	4	E	2	M	3	C	2					11
21	S	3	E	2	M	4	C	3					12
22	M	2	E	3	S	2	C	2					9
23	M	2	E	4	S	3	C	3					12
24	M	3	E	3	S	2	C	4					12
25	M	4	E	2	S	3	C	2					11
26	M	3	E	2	S	4	C	3					12
27	C	2	P	3	S	2	E	2					9
28	C	2	P	4	S	3	E	3					12
29	C	3	P	3	S	2	E	4					12
30	C	4	P	2	S	3	E	2					11
31	C	3	P	2	S	4	E	3					12
32	E	2	S	4	P	2	M	3	C	2			13
33	E	2	S	3	P	2	M	4	C	3			14
34	E	3	S	2	P	3	M	2	C	2			12
35	E	3	S	3	P	4	M	2	C	3			15
36	E	4	S	3	P	2	M	3	C	4			16
37	C	2	E	4	S	2	M	3	C	2			13
38	C	2	E	3	S	2	M	4	C	3			14
39	C	3	E	2	S	3	M	2	C	2			12
40	C	3	E	3	S	4	M	2	C	3			15
41	C	4	E	3	S	2	M	3	C	4			16
42	S	2	E	4	P	2	C	3	M	2			13
43	S	2	E	3	P	2	C	4	M	3			14
44	S	3	E	2	P	3	C	2	M	2			12
45	S	3	E	3	P	4	C	2	M	3			15
46	S	4	E	3	P	2	C	3	M	4			16
47	P	2	M	4	S	2	E	3	S	2			13
48	P	2	M	3	S	2	E	4	S	3			14
49	P	3	M	2	S	3	E	2	S	2			12
50	P	3	M	3	S	4	E	2	S	3			15
51	P	4	M	3	S	2	E	3	S	4			16
52	M	2	E	4	C	2	S	3	E	2			13
53	M	2	E	3	C	2	S	4	E	3			14
54	M	3	E	2	C	3	S	2	E	2			12
55	M	3	E	3	C	4	S	2	E	3			15
56	M	4	E	3	C	2	S	3	E	4			16
57	E	2	S	3	P	2	C	2	M	4	C	2	15
58	E	2	S	4	P	3	C	3	M	2	C	3	17
59	E	3	S	3	P	2	C	4	M	3	C	2	17
60	E	4	S	2	P	3	C	2	M	2	C	3	16
61	E	3	S	2	P	4	C	3	M	3	C	4	19
62	S	2	P	3	E	2	C	2	S	3	M	3	15
63	S	2	P	4	E	3	C	3	S	4	M	4	20
64	S	3	P	3	E	2	C	4	S	3	M	3	18
65	S	4	P	2	E	3	C	2	S	2	M	2	15
66	S	3	P	2	E	4	C	3	S	2	M	3	17
67	S	2	E	3	M	2	C	2	E	3	C	3	15
68	S	2	E	4	M	3	C	3	E	4	C	4	20
69	S	3	E	3	M	2	C	4	E	3	C	3	18
70	S	4	E	2	M	3	C	2	E	2	C	2	15
71	S	3	E	2	M	4	C	3	E	2	C	3	17
72	M	2	E	3	S	2	C	2	P	3	C	3	15
73	M	2	E	4	S	3	C	3	P	4	C	4	20
74	M	3	E	3	S	2	C	4	P	3	C	3	18
75	M	4	E	2	S	3	C	2	P	2	C	2	15
76	M	3	E	2	S	4	C	3	P	2	C	3	17
77	C	2	P	3	S	2	E	2	M	3	P	3	15
78	C	2	P	4	S	3	E	3	M	4	P	4	20
79	C	3	P	3	S	2	E	4	M	3	P	3	18
80	C	4	P	2	S	3	E	2	M	2	P	2	15
81	C	3	P	2	S	4	E	3	M	2	P	3	17

Note: C: Carpenter shop, E: Electric shop, M: Mason shop & Paint shop, S: Sheet-metal shop, P: Plumbing shop & Steamfitter shop

Yang and Sum (1997) examined the effect of resource transfer time in a dynamic project environment, where several researchers[3] assumed zero or negligible resource transfer times between projects and a common resource pool (p. 141). The research showed consistent result with previous research that assumes negligible resource transfer times (p. 153). Based on the result, in this research transfer of resources between individual projects and the Physical Plant department (a central resource pool) is assumed to occur with zero transfer time (Yang, 1997, p. 144). That is, idle technicians at a shop of Physical Plant can be immediately transferred into a project within the limited territory of the campus.

To schedule multiple M/R projects, heuristic rules for resource allocation are used to prioritize the allocation of shop technicians into active projects competing to those technicians (Yang and Sum, 1997, p. 143). The developed P-PCR and three popular resource allocation rules are examined: (1) P-SASP, (2) P-SAC, and (3) P-LAC. Among resource allocation rules described Section 4.2.2, slack-based heuristics (e.g., minimum slack-first (MSF): Fendley, 1968; minimum-project-slack-first: Pritsker et al., 1969; MINSLK: Davis and Patterson, 1975) and resource-based heuristics (e.g., ACTRES: Badiru, 1996) are not considered in this simulation experiment. Because of linearity of a M/R project under the current practice of space utilization, most activities do not have slacks or floats, and are *critical* according to the critical path method (CPM) analysis. A slack-based heuristic rule is not applied well to prioritizing technician allocation of the M/R activities and projects. Moreover, simplicity of resource requirement in a M/R activity allows only one or two

[3] These researchers include the followings: Dumond and Mabert (1988), Bock and Patterson (1990), Dumond and Johnson (1990), and Dumond (1992).

technician(s) at a trade shop to be involved in the activity. A resource-based heuristic rule may not differentiate most of the M/R activities based on their resource demand.

The first resource allocation rule evaluated at the simulation experiment is the Period-based Program Constraint Resource (P-PCR) rule that is explained Section 4.2. The next three resource allocation rules are examined because of their effectiveness in past researches. The Period-based Shortest Activity from Shortest Project (P-SASP: Tsubakitani and Deckro, 1990; Kurtlus and Davis 1982) rule gives priority to the activity that has shortest duration that does not violate an activity precedence as a technical constraint of the shortest project in a scheduling window. The Period-based Shortest After-Chain (P-SAC) rule first schedules the activity whose remained project duration is shortest[4], while the Period-based Longest After-Chain (P-LAC)[5] rule ranks projects in the increasing order of remained project duration at the current time point of resource allocation.

After a combination of project set is developed, a Microsoft® Excel macro program coded in Visual Basic® for Application (VBA) language is developed to simulate the scheduling each project set according to the heuristic rules. No effort was made to control the projects during execution.

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[4] P-SAC rule is an extension of Patterson (1976)'s SOF (shortest imminent operation first) and Fisher and Thompson (1963)'s SIO (shortest imminent operation: also called FOFO for "first off, first on").
[5] P-LAC rule is an extension of ACTIM (Whitehouse and Brown, 1979) and LRT (longest remaining time: Fisher and Thompson, 1963).

Table 4.2 Input Compositions of Simulation Experiments

Simulation Run	Sch.Window-1 NoProjs	P-1	ES	P-2	ES	P-3	ES	P-4	ES	P-5	ES	P-6	ES
1	5	20	5	27	13	50	8	31	16	11	5		
2	6	21	1	11	1	50	8	22	1	31	1	15	12
3	4	50	17	37	2	46	1	38	15				
4	3	36	12	51	0	34	17						
5	4	29	11	51	1	19	16	36	2				
6	5	6	9	55	16	17	0	2	7	9	4		
7	6	31	6	20	12	46	18	10	15	26	2	2	4
8	3	16	10	20	0	38	5						
9	4	41	2	4	9	1	3	42	13				
10	4	5	5	4	18	54	11	52	16				
11	6	39	1	43	4	48	12	12	14	39	18	12	0
12	4	19	7	16	5	11	4	44	9				
13	3	59	0	38	15	55	0						
14	5	49	13	22	6	6	19	34	16	55	6		
15	3	28	7	72	18	42	8						
16	5	22	3	79	16	20	18	50	8	6	3		
17	3	7	16	31	4	66	16						
18	5	75	0	35	13	21	19	21	17	38	14		
19	4	1	16	62	9	48	5	9	3				
20	6	16	5	5	11	56	1	22	16	47	4	9	6
21	5	36	1	41	10	1	15	50	19	21	4		
22	6	29	2	15	5	47	10	54	9	39	11	17	18
23	3	56	6	76	15	10	18						
24	5	4	10	35	12	22	19	80	17	3	16		
25	4	52	0	39	10	65	11	44	9	14	7	10	4
26	5	53	17	49	13	45	12	12	5	61	4		
27	4	29	11	49	11	69	6	50	4				
28	3	80	7	59	5	49	18						
29	4	11	8	47	19	14	10	70	9				
30	5	8	9	72	3	49	15	29	12	6	0		
31	3	54	17	77	7	60	15						
32	4	33	13	54	2	11	1	81	11				
33	6	32	2	10	14	34	8	5	14	43	7	30	8
34	4	49	7	12	3	2	7	64	11				
35	4	3	13	78	2	28	2	14	18				
36	6	24	19	54	5	19	5	40	14	2	13	47	16
37	3	1	17	68	0	56	13						
38	3	59	2	27	8	65	14						
39	5	28	13	1	14	21	16	2	18	39	3		
40	4	15	13	32	1	37	18	54	6				

Simulation Run	Sch.Window-2 NoProjs	P-1	ES	P-2	ES	P-3	ES	P-4	ES	P-5	ES	P-6	ES
1	4	2	12	10	12	17	15	1	10				
2	3	54	10	44	19	33	11						
3	3	20	11	40	3	54	2						
4	5	25	3	50	9	21	0	32	13	26	3		
5	5	12	8	39	11	26	2	23	4	27	16		
6	6	23	2	34	3	47	9	31	1	6	9	42	5
7	3	4	10	32	7	31	10						
8	5	20	13	26	6	39	9	44	11	51	2		
9	4	41	11	6	9	13	2	31	15				
10	4	36	2	27	9	13	10	18	7				
11	4	12	19	21	10	35	4	20	7				
12	5	47	9	44	10	15	6	13	3	39	4		
13	5	27	12	51	15	53	17	2	7	67	1		
14	3	35	17	38	0	70	0						
15	6	51	16	9	15	24	18	78	13	7	6	53	2
16	4	8	10	48	16	29	6	50	4				
17	5	47	1	13	6	10	16	68	17	6	3		
18	3	24	14	49	9	59	11						
19	5	20	18	48	8	33	1	5	5	78	4		
20	3	76	7	4	16	51	8						
21	4	35	1	7	18	59	11	2	19				
22	3	67	12	52	10	29	0	49	15	54	17	23	15
23	5	22	11	5	8	46	7	25	3	59	15		
24	4	50	7	55	16	12	13	42	12				
25	3	80	1	44	18	6	7	38	14	37	16	21	16
26	4	13	17	2	0	76	8	7	9				
27	3	66	11	54	12	71	15						
28	6	26	1	79	16	52	2	4	3	19	7	71	18
29	3	34	9	75	1	22	16						
30	3	56	12	32	2	79	15						
31	5	38	8	26	9	71	17	40	2	11	18		
32	3	20	18	75	1	39	2						
33	3	6	11	49	2	74	6						
34	4	16	13	52	12	43	13	75	12				
35	5	10	2	19	0	43	18	25	19	41	16		
36	3	43	4	42	8	32	5						
37	5	37	14	27	16	7	6	53	14	50	11		
38	4	50	10	63	14	2	5	27	6				
39	3	38	13	24	18	5	17						
40	4	56	3	17	19	3	8	34	1				

Simulation Run	Sch.Window-3 NoProjs	P-1	ES	P-2	ES	P-3	ES	P-4	ES	P-5	ES	P-6	ES
1	4	39	12	24	10	24	3	53	17				
2	4	49	2	3	11	19	8	10	15				
3	6	3	17	11	8	31	18	5	7	25	12	26	8
4	4	33	16	41	1	22	14	33	5				
5	4	37	15	10	2	52	14	6	1				
6	4	17	19	27	19	39	10	27	7				
7	3	34	3	23	10	38	6						
8	4	50	2	20	6	54	10	51	14				
9	4	9	1	11	4	29	17	10	17				
10	4	51	4	53	2	4	4	41	1				
11	4	13	3	17	8	36	9	56	14				
12	5	47	11	25	1	14	17	48	11	3	15		
13	4	36	0	14	16	53	8	59	2				
14	6	53	0	5	13	24	11	48	7	1	3	37	5
15	3	53	7	68	3	3	8						
16	4	29	0	76	16	49	18	12	7				
17	4	20	12	63	18	12	13	22	15				
18	5	6	15	81	15	74	2	3	16	28	8		
19	4	20	1	40	1	25	6	15	14				
20	4	3	11	32	9	30	11	47	7				
21	4	71	0	5	18	44	6	10	4	26	17	39	5
22	4	7	10	19	10	80	1	51	7				
23	4	34	18	51	17	16	3	29	11	37	9	1	17
24	3	53	4	50	3	65	14						
25	5	36	8	18	1	34	6	30	18	45	5	29	3
26	3	68	12	22	1	55	17						
27	4	48	9	8	10	60	11	34	14				
28	3	2	15	60	18	26	9						
29	5	25	11	57	9	47	0	63	3	49	14		
30	4	59	7	28	0	36	6	3	13				
31	4	15	0	9	4	21	6	49	5				
32	5	51	0	29	1	61	17	7	11	77	1		
33	4	29	8	35	6	80	5	8	4				
34	4	30	11	13	6	71	18	51	5				
35	3	33	13	72	15	50	10						
36	4	5	6	60	1	55	6	44	6				
37	4	2	8	9	12	77	2	31	17				
38	4	46	14	56	0	22	12	12	13				
39	5	36	4	18	8	53	8	46	13	41	9		
40	4	4	2	61	18	1	8	20	4				

4.2. RESULTS OF EXPERIMENTS

Upon completion of each experiment plan, three major performance measures are collected for evaluation. They are: (1) completion-time/project duration ratio (CDR), (2) shop utilization ratio (SUR), and (3) tardiness over windows (TOW). The full set of experiment results are presented at Appendix C, and analyses on the results in terms of the criteria are presented at the following sub-sections.

4.2.1. Completion-Time / Project Duration Ratio (CDR)

The CDR is a measure of the average ratio between the initial project duration of left-justified layout ($D_{initial}$; refer to Section 4.3.1) and scheduled project completion-time according to the heuristic rules and constraints[6] of the M/R program ($C_{scheduled}$). It is calculated as:

$$\text{CDR} = \frac{\sum(\frac{C_{scheduled}}{D_{initial}})}{N}, \qquad (4.1)$$

$$\text{DCD} = \frac{\sum(C_{scheduled} - D_{initial})}{N}, \quad \text{where: N = the number of simulation runs.} \qquad (4.2)$$

As a complementary measure to CDR, average difference between completion time and project duration (DCD) is used to compare the performance of scheduling heuristics. The minimization of the CDR is used as a primary performance criterion, because it reflects the efficiency of the scheduling heuristic rules under the same constraints. The smaller

[6] These constraints include organizational resource constraints, technical precedence constraints, and the constraint of space use policy in the M/R program.

CDR/DCD of experiments means that the relevant heuristic rule to the CDR/DCD generates the program schedule to complete the project(s) more quickly. This reduces client's waiting time and, if applicable, it reduces average project-in-progress (PIP), if present. Table 4.3 presents the resultant CDR/DCD's of the simulation experiments. The major observation that can be made regards the overall relative performance of the four heuristic rules (Period-PCR, Period-SASP, Period-SAC, and Period-LAC rules).

Table 4.3 Average CDR and DCD

Sched. Window	Left-just. Duration	P-PCR CDR	P-PCR DCD	P-SASP CDR	P-SASP DCD	P-SAC CDR	P-SAC DCD	P-LAC CDR	P-LAC DCD
1	12.4	1.48	5.95	2.20	17.07	1.89	12.72	**2.72**	19.32
2	12.6	1.56	7.15	2.51	21.51	2.33	18.67	2.49	17.48
3	12.9	1.58	7.34	2.56	21.57	2.14	15.70	1.93	10.60
Avg.	12.6	**1.54**	**6.82**	2.42	**20.05**	2.12	15.70	2.38	15.80

To sum up the analysis on average CDR and DCD, it was found that the developed P-PCR heuristic performs best. P-SASP shows worst performance in terms of average CDR/DCD for 3 scheduling windows. While P-LAC performs better than P-SASP AND P-SAC at scheduling window 3, it does worse than the two heuristics at scheduling window 1. The P-LAC results in the widest range of performance variance across the scheduling windows. In short, the three heuristics (P-SASP, P-SAC, and P-LAC) generate slight performance difference among them, but are significantly worse than P-PCR.

One particular founding is performance variation of P-LAC. P-LAC first schedules remained activities of a project whose after-chain is longest, then the next project, etc. This procedure results in a smaller average completion time, when all activities are scheduled within a scheduling window. If a part of a project is scheduled in the next scheduling window, however, the project has frequently lower allocation priority during subsequent scheduling windows, because it's length of the remained activities (after-chain) is usually shorter than newly arrived projects. Even though the project started at a time point of the previous scheduling window, its remained activities might be scheduled latter part of the next window, or continuously transferred to the following windows. As shown in Table 4.3, therefore, P-LAC results in the largest variance in terms of both CDR and DCD, and lowest predictability from the program manager's viewpoint.

4.2.2. Shop Utilization Ratio (SUR)

Average shop utilization percentage (SUP) is the simple percentage of resource demand (allocated number of technicians multiplied by required workdays) over shop capacity (total number of technicians multiplied by the overall duration of 3 scheduling windows). Average shop utilization ratio (SUR) is a ratio of resulting SUP of each shop from a scheduling heuristic against that of P-PCR.

$$\text{SUP} = \frac{\sum\left(\frac{R_{demand} \times WD_{required}}{R_{capacity} \times WD_{sch-window}}\right)}{N}, \text{ where: N = the number of simulation runs} \quad (4.3)$$

$$\text{SUR} = \frac{SUP_{heuristic}}{SUP_{P-PCR}} \quad (4.4)$$

It is observed at Table 4.4 that P-PCR has the highest utilization ratio of all shops except shop M of P-LAC. In general, the four RA rules can be categorized into two groups: (1) P-PCR and P-LAC and (2) P-SASP and P-SAC. The first group of RA rules shows higher values of SUP and SUR, while the second group results in lower values. Similarity between SUP/SUR values of P-PCR and P-LAC is observed, and the average SUR of P-LAC is 0.970 across the five trade shops. P-SASP and P-SAC shows inferior average SUR of 0.688 and 0.746, respectively.

Table 4.4 Average SUP and SUR

Res. Type	P-PCR		P-SASP		P-SAC		P-LAC	
	SUP	SUR	SUP	SUR	SUP	SUR	SUP	SUR
E	62.38	1.00	43.21	0.692	47.54	0.762	60.88	0.975
M	37.33	1.00	24.38	0.643	26.21	0.693	37.88	**1.021**
C	50.21	1.00	33.38	0.667	38.00	0.763	43.92	0.884
S	63.17	1.00	44.71	0.711	47.42	0.755	61.17	0.972
P	37.33	1.00	26.83	0.725	28.13	0.760	37.21	0.999
Avg.	50.08	1.00	34.50	0.688	37.46	0.746	48.21	0.970

4.2.3. Tardiness Over Windows (TOW)

Tardiness over windows is compared in terms of (1) the number of projects those have not been completed at the end of the third scheduling window (NOP), (2) net workdays that are at least required to finish the incomplete projects (NWD), and (3) amount of workdays between scheduled project completion date and the end of the last scheduling-window (WCE). Like the cases of CDR and SUR, P-PCR performs best among four scheduling heuristics. The compared 3 heuristics show similar average NOP's, but significant difference in the values of WCE's that are remained durations over 3 scheduling–windows.

Table 4.5 Tardiness Over Windows

	P-PCR	P-SASP	P-SAC	P-LAC
NOP	1.88	4.68	4.03	4.85
NWD	7.65	53.53	44.98	13.15
WCE	10.43	101.60	67.43	32.45

4.3. SUMMARY

This chapter presents a resource allocation heuristic and algorithm for scheduling multiple M/R projects under multi-trade crew constraints. The rolling horizon (RHZ) approach intends to protect the program master plan (PMP) from the external uncertainty of continuously and dynamically arriving project requests. Within a scheduling window, the newly requested projects are integrated with the existing projects that have not completed during the previous scheduling window. The master construction schedule (MCS) is generated resolving resource contention among the M/R projects by scheduling heuristics. This research simulates limited numbers of experiments (40 iterations), and compares the performance of the four scheduling heuristics (P-PCR, P-SASP, P-SAC, and P-LAC) with three major evaluation criteria: (1) completion-time/project duration (CDR), (2) shop utilization ratio (SUR), and (3) tardiness over windows (TOW).

Based on the above simulation results, it is found that the developed heuristic, P-PCR, performs better than the competing heuristics (P-SASP, P-SAC, and P-LAC) on the performance measures, CDR, SUR, and TOW. Even though the experiment is simulated with the limited iteration (40 iteration), the consistent results give a strong indication about the performance of resource allocation heuristics. Therefore, this research adopts the P-PCR as a resource allocation heuristic for scheduling the multi-resources constrained multiple M/R projects in scheduling windows.

CHAPTER 5

PERIODIC PCR BUFFER ALLOCATION STRATEGY

5.1. PROPAGATION OF INTERNAL DISTURBANCE

While dealing with the *external uncertainty*, a project coordinator needs to manage the *internal uncertainty* [1] after resolving the resource contention among activities of interdependent M/R projects. An activity delay of one project makes "chain reactions" (Semenoff, 1935) to subsequent activities of that project, to make matters worse, instability of the project tends to propagate throughout the highly-linked structure of the whole program. That is, the chain reaction will delay all activities of the concurrent projects within a scheduling window that have activity precedence and/or resource sequences[2] of the activity and the delayed subsequent activities. Even though there is time/resource floats between activities and projects, this propagation will be continued, if the capacity of float is not enough. Even though the rolling horizon (RHZ) approach proposed in Chapter 2 has derivative effect[3] of terminating the propagation at the end of a scheduling window, the stability of M/R program is still unprotected within a scheduling window. Then a question is

[1] From the viewpoint of program scheduling, it is a source of project delay, for example, incomplete/defective design and followed by reworks, unpredictable events such as confronting bad weather and underground condition, and untimely supply of required material/components.

[2] These sequences have the same context with precedence relations defined in several literatures: an "active chain" (Giffler and Thompson, 1960, p. 493), a "critical sequence" (Wiest, 1964, p. 396), and a "critical chain" (Goldratt, 1997, p. 215).

[3] Its original purpose is to contractually stabilize the program master plan against the external uncertainty in the developed planning model.

how to develop a protection mechanism for the Master Construction Scheduling (MCS) in the M/R program, preventing the propagation of the internal disturbance.

Approaches proposed in the literature to reduce instability of production schedule is freezing (Sridharan et al., 1987; Blackburn et al. 1986) or rolling (Das, 1993; Kunreuther and Morton, 1973) a scheduling horizon of the MPS. Another approach is to use safety stock (Guerrero et al., 1986) or time buffer (Umble and Srikanth, 1990; Newbold, 1998), which may be located at end item level (Orlicky, 1975) or distributed throughout the production structure (Miller, 1979).

Compared to planning horizon for the external uncertainty (refer to Chapter 2), this chapter investigates applicability of the time buffer approach into the internal uncertainty of a scheduling window. There are two fundamental issues that must be addressed when applying time buffer or safety stock. The first issue is the location of the buffer, and the second issue has to do with the size of the buffer.

5.2. ALLOCATION OF TIME BUFFER

5.2.1. Concept of Time Buffer

In order to decide the location of the time buffer, this section first reviews the concept of the time buffer applied into DBR system by Umble and Srikanth (1990). The following description is modified version of M/R construction view from their production view. Figure 5.1 illustrates a sequence of five activities required 40 hours, on average, to complete the construction process. The example assumes that each of the five activities is performed by a different trade crew[4], and that a safety buffer of 20 hours is introduced into the process.

One way of providing the 20-hour time buffer in the process is to equally distribute the buffer to each activity (see Figure 5.1). This distribution strategy has the same conceptual background with of shielding production (Ballard and Howell, 1998). However, Umble and Srikanth (1990) argue that individual buffering system cannot protect the whole process from even a delay of a single activity, if the delay is longer than 4 hours.

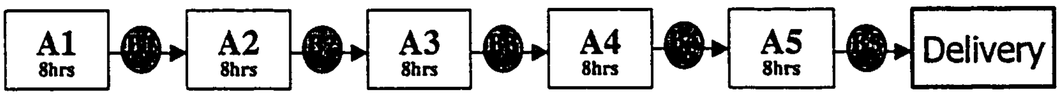

Figure 5.1 Process with Distributed Time Buffers (Umble and Srikanth, 1990, p. 141)

When a 10-hour delay occurs at activity 4 (A_4)[5], for example, the start of A_5 will be delayed by 6 hours. If there are no further delays at A_5, then the A_5 will end 6 hours behind schedule. Even though A_5 has a 4-hour time buffer, the completion of the project will be delayed by 2 hours. If a project coordinator did not expedite A_4 or A_5, there will be a conflict between a project manager and a customer (an academic department). This result is different from a possible presumption that the delivery of the project would be on time as long as the total amount of delay is less than 20 hours (p. 142).

[4] They assume that none of activities is a capacity constraint resource (CCR).

[5] That is, the total duration of A_4 is 18 hours.

From the above view point, Ballard and Howell (1998)'s shielding production can be re-evaluated, because it not only increases the duration of a project (i.e., decrease productivity), but also cannot protect the contracted due date of the project delivery by the individual buffers[6]. In order to overcome the limited protection performance of the individual buffering, another buffer strategy is proposed, which allocates the entire buffer just before the delivery of the project as showed in Figure 5.2.

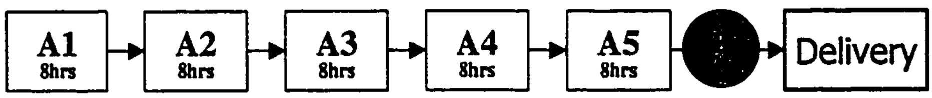

Figure 5.2 Process with a Delivery Buffer (Umble and Srikanth, 1990, p. 142)

In the new configuration, even though the 10-hour delay at activity 4 will postpone completion of the downstream activity (A_5), the delivery of the project is protected by a project buffer (Newbold, 1998)[7]. The individual activities might not be protected from the internal uncertainty, but the objective of the process, timely delivery of the single project, will be achieved (Umble and Srikanth, 1990, p. 142).

[6] In order to keep the contracted delivery day, project coordinator may use overtime or several shifts.

[7] The project buffer has the same concept as a shipping buffer in Umble and Srikanth (1990). In this chapter the project buffer is used as the term representing the two buffers.

Another consideration for the buffering strategy is the concept of a capacity constraint resource (CCR)[8] in the production management (Umble and Srikanth, 1990) and a strategic resource in the project management (Newbold, 1998). Both resources have the same role, and only difference is the environment where they are applied. For easiness of description, this chapter tentatively uses the CCR as the term representing those resources. The CCR is the critical constraint that determines the progress flow of the master production/project schedule. A protection mechanism of time buffer is needed in front of the CCR activity that is related with the CCR (refer to Figure 5.3). When the CCR activity is protected from a disruption at non-CCR activity, the whole process could be completed without any delay. Based on above consideration, Umble and Srikanth (1990) argue that the time buffers should be provided at the following two places: (1) at the end of the process, before shipping or delivery and (2) in front of the CCRs in the process.

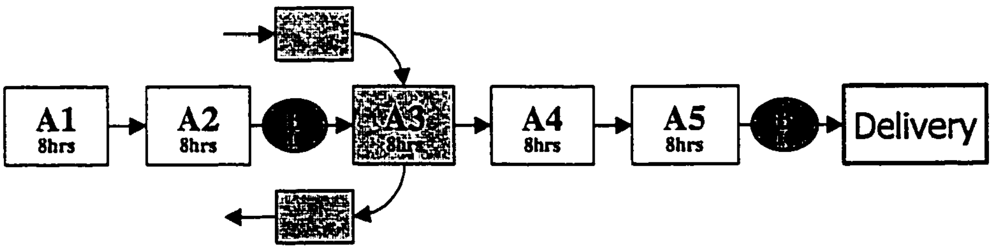

Figure 5.3 Process with Buffers in front of CCR and Delivery

(revised from Umble and Srikanth, 1990, p. 144)

[8] It was defined as "*any resource which, if not properly scheduled and managed, is likely to cause the actual flow of product through the plant to deviate from the planed product flow*" (Umble and Srikanth, 1990, p. 87).

5.2.2. Re-evaluation of Project Buffer

The concept of the CCR and buffer allocation strategy, however, may not be directly applied into the dynamic environment of multiple M/R projects because of two major reasons. First, the buffer strategy of placing a large buffer before shipping is based on protection for a single linear process. Second, the concept of the CCR is based on continuous static environment, where the CCR is unchangeable in a system: e.g., a manufacturing plant for Umble and Srikanth (1990), and a multi-project environment for Newbold (1998).

This section first re-evaluates the validity of the project buffer in the M/R environment. The project buffer intends to protect the timely completion of a project from the internal uncertainty. The logistic explanation of a single delivery buffer is described in Figure 5.2. However, in multiple M/R projects environment, the project buffer has a drawback from an internal view of coordinating multiple projects. Even though the project buffer for an individual project could assure commitment dates of each project, they cannot terminate the chain reactions of a disturbance that propagates beyond the project through the resource sequences. In Figure 5.4, for example, if activity E1 of project 1 is delayed, the delay will be propagated not only through the activity precedence of the project (i.e., $E_1>>M_1>>C_1>B_1$, where B_1 is the project buffer of P_1[9]), but also resource sequence of the trade shop E (e.g., $E_1>>E_2$). The subsequent delays through the dual passages of propagation, therefore, will deteriorate predictability and stability of the M/R program.

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[9] The symbol '<<' represents the "next-follow" relation that was used to define an "active chain" (Giffler and Thompson, 1960, p. 488, p. 493).

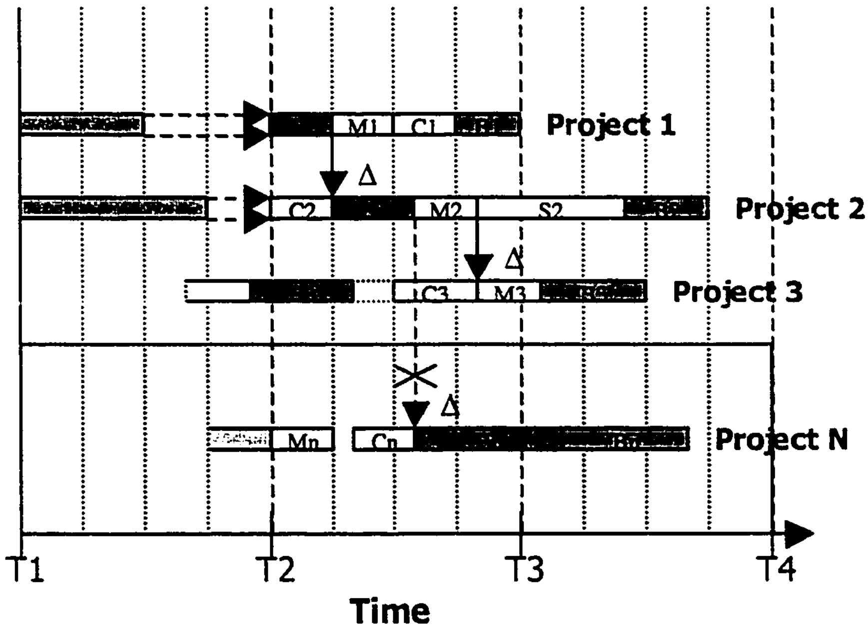


Figure 5.4 Propagation of Disturbance across M/R Projects (Koo and Russell, 2000)

Under the space utilization practice in the M/R environment, most activities may be critical (refer to section 4 of Chapter 1), and the propagation is rarely terminated without rescheduling the whole program or without additional mechanisms[10]. The next section describes the concept of 'delivery buffer' with periodic PCR buffers that is much smaller than the project buffer.

[10] Koo and Russell (2000) proposed two mechanisms for terminating the propagation: (1) periodic time buffers and (2) an organizational grouping.

5.2.3. Program Constraint Resources (PCRs)

The research proposes the concept of *program constraint resources in a scheduling window* (PCRs) to plan and schedule multiple M/R projects. The PCRs are different from the CCR and strategic resource from the fact that they are 'most' or 'more/less' critical constraints that may have capacity floats and even time floats. Even though the most-PCR significantly affects the progress of the master construction schedule (MCS), it is not the only resource that dominates the progress, but just most/more one. It is mainly due to the characteristic of M/R projects that have space constraints in the work site of each project as well as activity precedence relations. While the most-CCR may be first scheduled without any time/capacity float, if less-PCRs cannot be subsequently allocated into remained times, then most-PCR should be rescheduled and may have floats.

Another reason is that there is inevitable under-utilization of the most-PCR from mapping process between resource demand of requested projects and resource capacity of the M/R department. Under the developed planning horizon approach, the *mostness/moreness* is only valid within one scheduling window. Its characteristic is temporary and dynamic, and is different from the static and permanent characteristic of CCR/strategic resource in a system. Moreover, under the M/R scheduling environment, protection mechanism for the PCRs is different from that of those resources. The program stabilization strategy by periodic buffer management will be described at the next section.

5.3. PERIODIC PCR BUFFERS IN SCHEDULING WINDOW

5.3.1. Event-driven and Period-based Buffer Allocations

The basic concept of the developed buffer management is allocating time buffers according to resource sequence across projects (i.e., flow of crews who execute activities), instead of activity precedence in each project. The objective of the buffer management is to terminate the propagation of MCS instability at a time-point of the buffer, leaving some chained delays uncontrolled (from the centralized perspective) between the buffer points. The new strategy does not place buffers depending on individual activities/projects, but pools the buffers into periodic time points inside of the PCR flows. Within the buffer period of the MCS, projects coordinator and shop supervisors adjust the progress of M/R projects, when unexpected delays of activities and projects are developed. Therefore the buffer allocation strategy can be interpreted as *period-based* rather than *event-driven*[11] based on the principle of the management by self-control.

Considering the limitation of the project buffer application into the M/R program explained at the previous section, the following sub-section describes implementation issues of determining a time interval between buffers. By sequentially protecting a segment of PCR flows in the scheduling window level, the entire progress of the M/R program will be internally stabilized. The internal stabilization approach is developed in the consistent

[11] When buffers are allocated according to activity- and project-focus, this research interprets it as an event-driven allocation.

manner with the external stabilization strategy of the planning horizon. The buffer period of PCR flows is related with the adjustment period described at the section 5 of Chapter 2.

5.3.2. Periodic Buffers in PCR Flows

If there is a delay at activity M of project 4 (P_4) or P1 in Figure 5.5, this disturbance will not be propagated into period $\overline{T_2T_3}$, because there are resource sequence floats of shop M between P_4 - P_1 and between P_1 - P_2. When activity E of P_3 is delayed, however, its disturbance propagates to P_1 and P_2 through the resource precedence relations. The time buffer in the activity E of P_2 will terminate the chain-effect. After the completion of the E of P_2, as a result, the termination will prevent further disturbance in following activities of electric shop (E) and other shop's activities that have activity precedence and/or resource sequence.

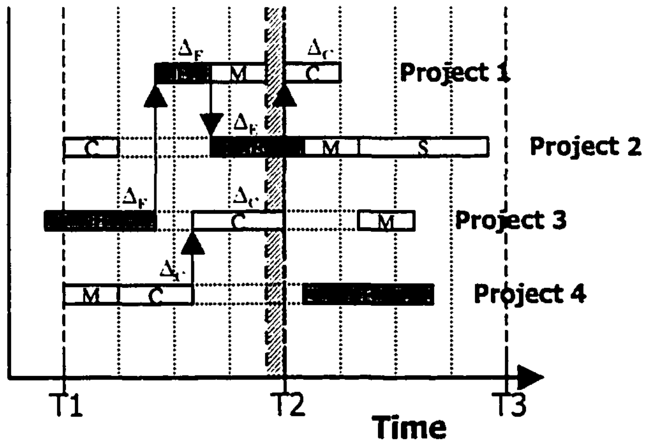
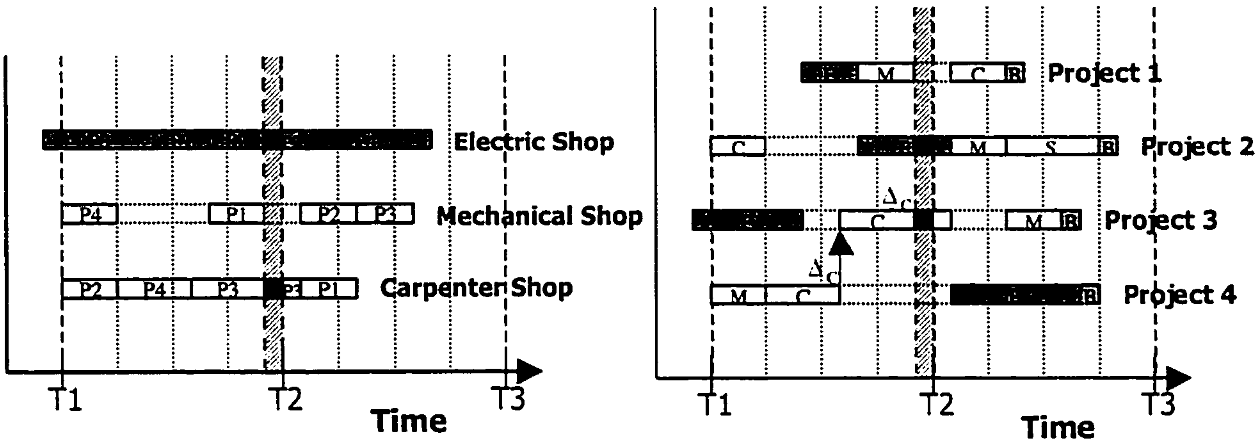


Figure 5.5 Periodic Buffer in Resource E: Project Gantt Chart

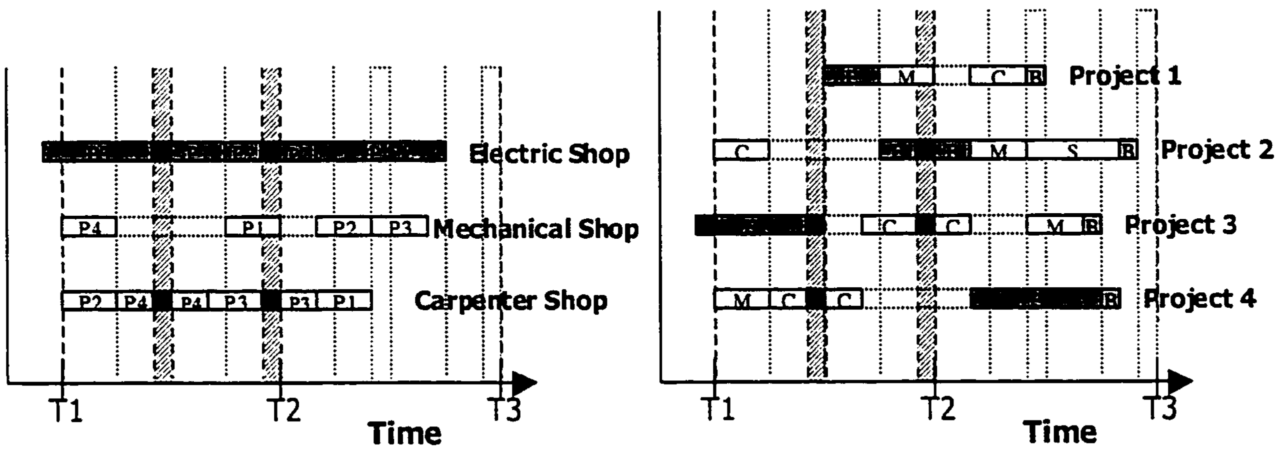
However, if there is a delay at activity C of P_4, its disturbance propagates P_3 and P_1. Since there is no buffer within the resource chain of C, chain reactions propagate across the tree structure of following activities and projects. Therefore another termination buffer is needed at the sequence flow of resource C, which is showed in Figure 5.6.



(a) Resource Schedule Chart (b) Project Gantt Chart

Figure 5.6 Periodic Buffers in E and C

Based on the two-adjustment periods of a scheduling window that have two-week intervals (King and Wilson, 1967, p. 309; Ballard et al., 1994, p. 1568), another buffer zone is added, and an updated schedule is showed in Figure 5.7. There are two issues to be commented in detail. First, the mechanical shop (M) is the least-PCR, and any buffer is not directly provided. Its schedule is just subordinated to schedule of more PCRs (E and C). All PCR flows in the MCS of a scheduling window, however, consequently protected by the periodic PCR buffers, because allocating buffers in the flows of shop E and C at time T_2 dichotomizes the progress of the MCS at that point, and right-shifts the PCR flows on the right side as much as the size of the PCR buffers. Without complex procedures of identifying the critical sequence or critical chain[12], therefore, the periodic PCR buffer allocation strategy is more intuitive, and has the advantage of procedural simplicity. Second, each project has a smaller delivery buffer than the project buffer, to protect commitment date that is located between periodic buffer zones. Unlike the project buffer pooling the entire buffers, the delivery buffer has similar (usually smaller) size to the normal periodic buffer (e.g., B at the end of P_1), and deals with disturbance occurred between the previous buffer zone (T_2) and the completion date of the project. The buffer strategy improves the manageability and predictability of the M/R program.



(a) Resource Schedule Chart

(b) Project Gantt Chart

Figure 5.7 Two Periodic Buffer Zones

One additional comment on the developed buffer strategy is that time scale of each activity is usually smaller than those of Figure 5.7. Above figures are only for conceptual description of the developed management strategy.

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[12] In the scheduling window B of Appendix B.1.1, there are two critical sequences or chains. In practice, it is often time-consuming process to identify them through the planning horizon of multiple projects

CHAPTER 6

SIMULATION EXPERIMENTS FOR BUFFER MANAGEMENT

Our company is in need of a profound transformation. We've read all the books. We know all the concepts and theories: transition management, frame-breaking, paradigms, empowerment, culture change, and so on. But we don't know how to implement the transition. We don't even know how to make the theories operational.

– Manager in a leading *Fortune* 100 company[1]

This chapter describes simulation models and environment of experiments. Implementation issues of Monte Carlo simulation and distribution models of activity durations are discussed. The chapter also explains used simulation variables, tested buffer allocation strategies, and their implementation in a spreadsheet package.

6.1. MONTE CARLO SIMULATION FOR STOCHASTIC[2] NETWORK ANALYSIS

Based on the master construction schedule (MCS) of multiple projects constructed at Section 3.5, the non-buffer allocation (NBA) strategy, the individual buffer allocation (IBA) strategy, and the PCR buffer allocation (PBA) strategy are modeled in a scheduling window.

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[1] It is quoted from Kanter et al. (1992, p. 369).

[2] "*A scheduler cannot observe the processing times in advance, but only has knowledge of a probability distribution for the various processing times, in which case the dynamic scheduling problem will be referred to as stochastic.*" (Wein and Ou, 1991, p. 1002)

For modeling buffer allocation process of the IBA and PBA strategies and evaluating two strategies against NBA strategy, a set of simulation templates is developed in a common spreadsheet package, Microsoft Excel.

Numerous researches argued that not only activity duration estimates but also their stochastic distribution types significantly affected results of network simulation (e.g., Van Slyke, 1963; Crandall, 1976; AbouRizk and Halpin, 1992; Back et al., 2000; Fente et al., 2000). A Monte Carlo approach is the *best* solution in reflecting the stochastic distribution of the activity duration and producing an "unbiased estimate" of project completion distribution (Van Slyke, 1963, p. 844). In this context, the research adopts a Monte Carlo simulation as an experimental technique. The Monte Carlo simulation generates random values for activity durations from a specified distribution profile. The major advantage of the Monte Carlo simulation was best described by Van Slyke (1963):

> *"The Monte Carlo approach has greater flexibility in that any distribution can be used for activity durations – beta, normal, triangular, uniform, or discrete in any sort of mix. This flexibility allows one, in particular, to try different distributions and observe the effect of neglecting or making highly arbitrary assumptions on the shape of these distributions."* (p. 844)

As a first step into the simulation analysis of construction operations, researchers have tried to model the duration distribution of construction activity using a standard statistical distribution (refer to Section 6.2). In contrast to their efforts, the purpose of the simulation experiments in this chapter is to characterize relative performance of buffer allocation strategies in terms of buffer sizes as well as underlying activity duration distributions. Therefore, the research modeled different distribution profiles of the duration estimates in the developed simulation templates, and investigated the effects of the distribution profiles on protection behaviors of the buffer management strategies in the context of the M/R environment.

6.2. MODELING STOCHASTIC DISTRIBUTIONS OF ACTIVITY DURATIONS

Even though several studies argued that the outputs of their simulation did not depend on the distribution types of activity durations (Fente et al., 2000), modeling stochastic distributions of the activity durations is essential to represent uncertainty of the activity durations and to investigate its effect on the program network of multiple projects. In this research, four types of distributions are used to model the uncertainty of an activity duration: (1) PERT (beta), (2) triangular, (3) uniform, and (4) normal distributions.

6.2.1. PERT (Beta) Distribution

Since Malcolm et al. (1959) introduced the Program Evaluation Research Task (PERT)[3] distribution as a simplified beta distribution, numerous researchers of project management have followed the time estimate model (e.g., Van Slyke, 1963; MacCrimmon and Rayvec, 1964; Badiru, 1991). PERT uses the three time estimates and the simplified equations to compute the mean and variance for an activity duration. The Beta distribution is defined by two end points (a and b) and two shape parameters (α and β). As depicted by AbouRizk et al. (1991), the generalized beta density is represented by the following equations:

[3] Later renamed "Program Evaluation and Review Technique" (Malcolm et al., 1959, p. 646).

$$f(x;\alpha,\beta,a,b) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \frac{(x-a)^{\alpha-1}(b-x)^{\beta-1}}{(b-a)^{\alpha+b-1}} \qquad \text{if } a \le x \le b, \qquad (6.1a)$$

$$f(x;\alpha,\beta,a,b) = 0 \qquad \text{otherwise}, \qquad (6.1b)$$

where $\Gamma(\,) =$ gamma function, $\Gamma(z) \equiv \int_0^\infty t^{z-1} e^{-t}\,dt$ for all $z > 0$, (6.2)

a = optimistic estimate (lower bound), b = pessimistic estimate (upper bound).

Based on the above Beta distribution, the PERT formulae for the mean and variance of activity time are, respectively,

$$t_e = \frac{(a+4m+b)}{6}, \qquad (6.3)$$

$$\sigma^2(t_e) = \frac{(b-a)^2}{36}, \qquad (6.4)$$

where t_e = expected time for the activity;

$\sigma^2(t_e)$ = variance of the activity duration; and

m = most likely estimate (mode parameter) $(a < m < b)$.

When α, $\beta > 0$, the beta distribution has a single mode that is

$$m = \frac{(\alpha b + \beta a)}{(\alpha+\beta)}, \qquad (6.5)$$

$$\mu = \frac{(a+b+km)}{(k+2)}, \text{ where } k = \alpha + \beta. \qquad (6.6)$$

Sasieni (1986) showed that assuming $\alpha \ne \beta$ and $a \ne b$, the PERT formula 6.3 is exact only when $k = 4$. (6.7)

Chae and Kim (1990) referred to Equation 6.7 as the "PERT assumption" on the mean activity time[4].

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[4] Equations 6.5 and 6.6 are quoted from Chae and Kim (1990).

The adopted spreadsheet package provides a built-in function, RAND() that can be used to generate random numbers based on the assumed stochastic distributions for an activity duration. While the beta distribution is supported by the package, a random number is not generated based on the PERT distribution. The simulation experiments, therefore, use 4 as the value of the constant k ($\alpha + \beta$), and the random number is generated according to Equations 6.4 and 6.5.

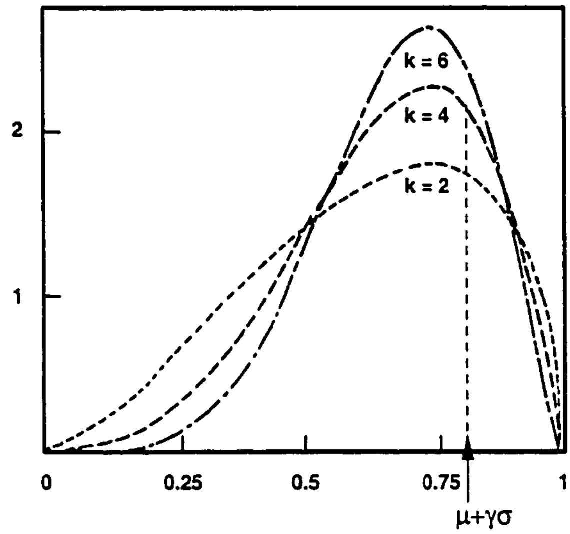

Figure 6.1 Beta (PERT) Distribution: m* = 0.75[5] (Chae and Kim, 1990, p. 200)

6.2.2. Triangular Distribution

The triangular distribution was used as an alternative to the PERT (beta) distribution (Keefer and Bodily, 1983; Chau, 1995; and Back and Boles, 2000). The triangular distribution density has three time estimates like the PERT distribution. Badiru (1996) presented the distribution mathematically as

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[5] m* is the standardized value of m, and equal to (m-a)/(b-a).

$$f(x) = \frac{2(x-a)}{(m-a)(b-a)} \qquad a \le x \le m, \tag{6.8a}$$

$$= \frac{2(b-x)}{(b-m)(b-a)} \qquad m \le x \le b, \tag{6.8b}$$

$$\mu = \frac{(a+m+b)}{3}, \tag{6.9}$$

$$\sigma^2 = \frac{\{a(a-m)+b(b-a)+m(m-b)\}}{18}. \tag{6.10}$$

Winston et al. (1997) provides a formula for generating the triangular random number in the spreadsheet package (p. 602), and the formula is used in the simulation templates:

= a +(b-a) * IF(RAND()<=m*, SQRT(RAND()*m*), 1- SQRT((1-m*)*(1-RAND()))). (6.11)

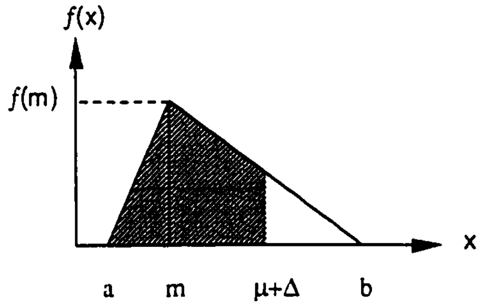

Figure 6.2 Triangular Distribution

6.2.3. Uniform Distribution

Touran (1992) suggests a uniform distribution, when the value of m is uncertain, or when the difference (b-a) is relatively small. The uniform distribution is defined mathematically as[6]

$$f(x) = \frac{1}{(b-a)} \qquad a \le x \le b, \tag{6.12a}$$

$$= 0 \qquad \text{otherwise}, \tag{6.12b}$$

[6] Equations 6.12 – 6.14 are quoted from Badiru (1996, p. 138).

with mean and variance defined, respectively, as

$$\mu = \frac{(a+b)}{2}, \tag{6.13}$$

$$\sigma^2 = \frac{(b-a)^2}{12}. \tag{6.14}$$

The formula used in the spreadsheet is

= a + (b-a)*RAND() (Winston et al., 1997). (6.15)

The advantage of the uniform distribution is that the estimation error can be reduced from the simpler assumption on activity duration that does not require the mode parameter m (Badiru, 1996).

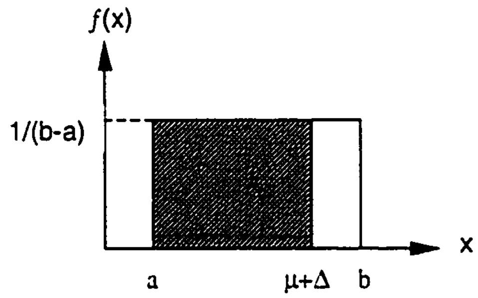

Figure 6.3 Uniform Distribution

6.2.4. Normal Distribution

The normal Monte Carlo process was used by Crandall and Woolery (1982), and a lognormal distribution was used by Touran and Wiser (1992). A random number with mean (μ) and standard deviation (σ) is generated in the spreadsheet according to the following formula:

= NORMINV(RAND(),μ,σ) (Winston et al., 1997). (6.16)

According to the normal probability theorem, if the mean (μ) is used to represent the duration of an activity, the probability of activity completion within the mean activity time is 50% (Moder, et al. 1983, p. 287; Meredith and Mantel, 1995, p. 351; Goldratt, 1997, p. 45), which means the possibility of completion delay of the activity is also 50%. To decrease the expected delay of the activity completion, if the estimate of the activity duration is increased up to ($\mu + \sigma$), the probability of activity completion within the increased estimate will be 84.13%. The similar inference can be made on the estimate of project duration through the central limit theorem. The determination of a duration safety factor (γ) and a periodic buffer ratio (β_P) is attributed to this inference (refer to section 6.3.2).

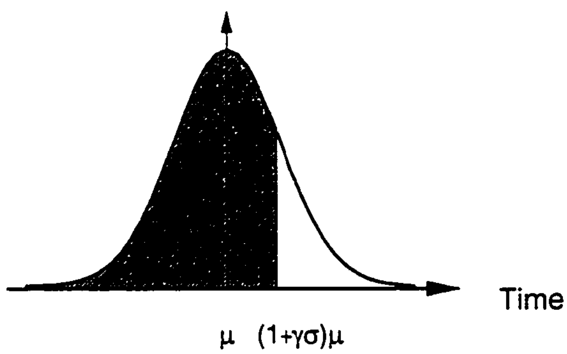

Figure 6.4 Normal Distribution

6.3. SIMULATION MODELS IN M/R PROGRAM ENVIRONMENT

This section describes a simulation models and their implementations on a spreadsheet package, Microsoft® Excel. The implemented spreadsheet models are used as templates for the simulation experiments. The dark cell/range with bold boundary contain inputs by the simulator, while the other cells of the template contain calculated values of each data entity according to developed formulas in the templates. A change in the input cell sequentially changes the values of linked cells, and the performance of buffer allocation strategies can be compared based on the repetitively recalculated simulation results.

6.3.1. Program Model and Simulation Environment

The program network used for the simulation experiments is the MCS constructed at the section 5 of Chapter 3 based on the PCR scheduling algorithm in a scheduling window. The program network was composed of four projects those were randomly selected from the overall project requests to the program organization, and each project was composed of three activities. Figure 6.5 presents a resource schedule chart and a project Gantt chart of the program model. While four delivery buffers of the M/R projects are shown only in the project Gantt chat, both charts contain the same size of two periodic PCR buffers (B_{22} in the resource flow of trade shop E and B_{32} in the resource flow of trade shop C).

The input variables for the simulation experiments are: a stochastic distribution type of activity durations, a duration safety factor (γ), a periodic buffer ratio (β_P), and a buffer allocation strategy. The distribution types of activity duration are the PERT (beta), triangular, uniform, and normal distributions. In the cases of the PERT, triangular, and uniform distributions, the values of a, b, and m are input into the developed spreadsheet-templates by the simulator depending on required distribution parameters.

Resource Schedule Chart

	DayNumber 1	2	3	4	5	6	7	8	9	10	11	12	13
E	P11	P11	P31	P31	P31	P22	P22	B[illegible]	P22	P43	P43	P43	P43
C	P21	P21	P42	P42	P42	P32	P32	B[illegible]	P32	P32	P13	P13	
M	P41	P41	P12	P12						P23	P23	P33	P33

Project Gantt Chart

	Day Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14
P1	P11	P11	P12	P12							P13	P13	B_{P1}	
P2	P21	P21				P22	P22	B[illegible]	P22	P23	P23	B_{P2}		
P3			P31	P31	P31	P32	P32	B[illegible]	P32	P32		P33	P33	B_{P3}
P4	P41	P41	P42	P42	P42					P43	P43	P43	P43	B_{P4}

8 DayNumbers = 1 month (4wks) = 20 work days (1 wk = 5 wds)

Figure 6.5 Simulation Models of Program Network and PCR Flows

The PERT templates automatically calculate the values of the shape parameters α and β based on the simulation inputs (a, m, and b) and Sasieni's PERT assumption on the constant k (refer to Section 6.2.1). In the case of the normal distribution, two parameters of the distribution are input into the Normal template by the simulator before the start of the simulation run: the mean (μ) of activity duration and a duration variance factor (α) to determine the standard deviation ($\sigma = \alpha \times \mu$).

To produce reliable results from the Monte Carlo simulation, the appropriate number of iterations needs to be determined. Among researchers of construction simulation, Crandall (1977) asserted that:

> *"The majority of information required by network analysis is available with sufficient accuracy with 1,000 iterations."* (p. 393)

Based on his research, each combination of input variables is simulated through 2000 iteration runs in each distribution template.

This experiment focuses on the effect of different buffer management strategy in terms of (1) various distribution types of activity durations, (2) amount of buffers, and (3) buffer allocation methods. Therefore, there is a need to fix the duration of each activity in a simulation run, which enables a simulator to compare the performance of buffer allocation strategy with the same value of activity duration. In this spreadsheet implementation, a data matrix of random numbers is generated for 12 network activities (3 activities × 4 projects) and 2000 iteration runs. The random number matrix is shared among 16 combinations of input variables (4 distribution profiles of the activity durations × 2 values of the duration safety factor × 2 values of the periodic buffer ratio). One advantage of the common data matrix is that the performance of buffer allocation strategies can be directly compared at each simulation run as well as statistical analysis of whole experiment. While the simulation experiment takes the benefit of the Monte Carlo simulation, use of randomness, it provides micro-level analysis through the common matrix. The values in the common matrix can be repetitively updated by newly generated random numbers, if further simulation runs are needed[7].

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[7] In the used spreadsheet package, the key *F9* triggers regeneration of the random number matrix, and recalculates the all associated values in the simulation templates.

6.3.2. Buffer Allocation Strategies

6.3.2.1. Individual Buffer Allocation Strategy

As described in Section 5.2 (Allocation of Time Buffer), the individual buffer allocation (IBA) is the way of distributing the time buffer to each activity. In this simulation experiment, the size of each activity buffer and the total amount of the time buffer allocated into the project are determined by an input variable, the duration safety factor (γ). In the case of the normal distribution, duration variance factor (α) is used as an additional input variable to determine the size of standard deviation (σ).

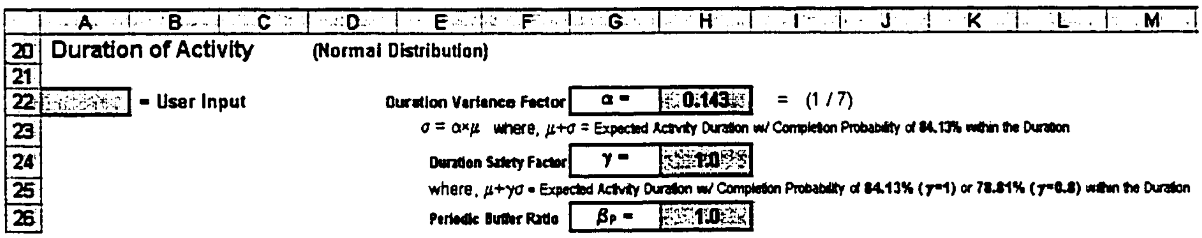


Figure 6.6 Simulation Template for User Inputs (α, β_P, and γ)

From the view of project scheduling, the mean (μ) of the normal distribution is interpreted as 50% probability of timely completion and 50% probability of completion delay. When a project coordinator adopts the IBA strategy, he/she increases the estimate of activity duration by adding the size of the individual time buffer. As a default value of the buffer size, the Normal template uses a standard deviation as an additional increase of the activity duration. The buffered activity duration of ($\mu+\sigma$) covers the completion probability of 84.13% calculated from the statistical density function of the normal distribution. The value of the duration safety factor (γ) determined by experiment design consequently decides the buffered duration ($\mu_i+\gamma\sigma_i$) of activity i. This experiment is simulated by using two values of γ: 1 and 0.8, where the value of ($\mu_i+0.8\sigma_i$) represents the expected activity duration with completion probability of 78.81%. Other value of γ[8], however, can be input into the simulation template by the project coordinator.

In the cases of other distribution templates, buffered activity durations are calculated according to completion probabilities of 84.13% and 78.81% based on the statistical density function of the assumed distribution. As an example of calculation procedures in other templates, the activity durations of PERT distribution (γ = 1) are presented in Figure 6.7.

	A	B	C	D	E	F	G	H	I	J	K	L	M
30	Duration of Activity				Note:	* μ (te) = (a+4m+b)/6: Activity Length of 50% Probability						* α: 4×(m-a) / (b-a)	
31						** $\mu+\gamma\sigma$: Expected Activity Duration w/ Completion Probability of 84.13%						** β: 4 - α	
32	unit: hours (1 work day = 8 work hours)					where, μ + α: Activity Length of 84.13% Probability						*** σ = (b-a) / 6	
33		P11	P12	P13	P21	P22	P23	P31	P32	P33	P41	P42	P43
34	a (min.)	30	22	34	24	27	33	50	65	25	18	50	41
35	m (most)	39	42	39	40	66	41	55	80	43	43	55	87
36	b (max.)	54	49	52	56	71	45	90	95	45	51	90	93
37	* α	1.67	2.67	1.33	2.00	3.00	2.33	1.00	2.00	3.00	2.67	1.00	3.00
38	** β	2.33	1.33	2.67	2.00	1.00	1.67	3.00	2.00	1.00	1.33	3.00	1.00
39	*** σ	4.80	5.40	3.60	6.40	8.80	2.40	8.00	6.00	4.00	6.60	8.00	10.40
40	* μ	40.0	40.0	40.0	40.0	60.0	40.0	60.0	80.0	40.0	40.0	60.0	80.0
41	** $\mu+\gamma\sigma$	44.80	45.40	43.60	46.40	68.80	42.40	68.00	86.00	44.00	46.60	68.00	90.40
42	Avg.	39.9351	39.9948	40.0508	39.5742	60.1277	39.9759	60.1326	79.8899	40.0225	40.1180	60.2164	79.8584
43	1	47.9275	44.2403	37.3120	43.8971	46.2426	39.0099	67.1164	88.7339	38.7891	38.6601	58.4159	92.4187
44	2	47.2180	48.2185	46.7169	50.8579	68.1264	37.8417	54.8399	80.2008	42.1518	34.6783	69.4641	52.9987
...					...								
2041	1999	46.1169	36.3970	37.6591	39.7236	61.4740	42.5971	58.9465	91.5332	33.1325	40.9256	56.8380	92.0926
2042	2000	30.8243	34.1700	39.0118	41.3924	46.0946	43.0942	70.2186	78.1223	40.4871	36.5383	56.7492	90.3572

Figure 6.7 Activity Durations of PERT (Beta) Distribution

[8] While the value of γ can be equal to or larger than 0, in practice the value larger than 3 (completion probability of 99.87%) seems to be too expensive to get the stability of the MCS. The decision about the size of γ is a trade-off between time-costs and manageability.

The value of $(\mu+\gamma\sigma)$[9] in the PERT template represents a buffered activity duration that covers completion probability of 84.13%. $(\mu+\Delta)$ shown in Figure 6.2 and 6.3 represent 84.13 % or 78.81% probabilities depending on the value of γ: 1.0 or 0.8, respectively. The four distribution templates are presented at Appendix D.

6.3.2.2. Periodic PCR Buffer Allocation Strategy

Section 5.3 described the concept of allocating periodic PCR buffers in a scheduling window. Under the periodic PCR buffer allocation (PBA) strategy, two kinds of buffers are used in the M/R program network: (1) the period buffer in PCR flows and (2) the delivery buffer at the end of construction and before project closeout of the project. When the individual buffer allocation (IBA) strategy is adopted, the expected completion days of a project construction is the sum of average activity durations plus the sum of time buffers:

$$\sum_{i=1}^{n}(\mu_i + \gamma\sigma_i)\,. \qquad (6.17)$$

Based on the principle of the "Management by Self-control," the PBA strategy periodically allocates pooled buffers in the middle of PCR flows, which makes two locations of periodic buffers in a scheduling window.

[9] The statistical position of $(\mu+\gamma\sigma)$ is graphically shown at Figure 6.1.

In addition to the duration safety factor, simulation of the PBA strategy needs another input variable called a periodic buffer ratio (β_P) that specifies the ratio of the sum of periodic PCR buffers and a delivery buffer[10] over the total amount of the individual buffers:

$$\beta_P = \frac{\sum_{j=1}^{m} B_{P_j}}{\sum_{i=1}^{n} \gamma\sigma_i} \qquad (6.18)$$

where, m: the number of the period buffers plus one for the delivery buffer, and n: the number of activities (or individual buffers) in a project. The value of periodic buffer ratio (β_P) is a input factor of the simulation experiment, which consequently determines the total size of periodic buffers in a scheduling window:

$$\sum_{j=1}^{m} B_{P_j} = \beta_P \times \sum_{i=1}^{n} \gamma\sigma_i\,. \qquad (6.19)$$

The experiment is simulated by using two values of β_P: 1.0 and 0.8. The value, 0.8, is arbitrarily decided by the research, and other value of β_P can be input into the simulation template by the project coordinator, like the input value of the duration safety factor (γ).

6.3.3. Project Models Implemented on a Spreadsheet

Based on the simulation model of the M/R program network in Figure 6.5, each project model is implemented on a spreadsheet. The implemented spreadsheet represents a template for a project simulation, with one row for each iteration (refer to Appendix E). To explain

[10] In the PBA strategy, the delivery buffer is a kind of the period buffer that protects the project components only between the last periodic PCR buffer and project completion.

how to construct the project templates, this section describes the implementation of project model 1 presented in Figure 6.8.

The project model is constructed based on the activity information of the PERT template in Figure 6.7: mean durations of 50% completion probability, buffered duration ($\mu_i+\gamma\sigma_i$) determined by the user input γ. These hourly durations are converted to daily duration (1 work day = 8 work hours), and plugged into the row 40 (μ&B) and row 41 ($\mu+\gamma\sigma$).

	O	P	Q	R	S	T	U	V	W
32	PROJECT 1								
33								$\beta_P\Sigma B = \beta_P(\Sigma(\mu+\gamma\sigma)-\Sigma\mu)$ =	2.80
34	* IDLE: due to Slack & resource (C) precedent (P32) of P13							$(B_{P32}) = B'_{P32}$ =	2.18
35	# (B_{P32}): @ PCR-B, Completion Time of P32							## $B_{P1} = \beta_P\Sigma B-(B_{P32})$ =	0.62
36								$\Sigma\mu$ =	27.50
37		cf.	$\Sigma(\mu+\gamma\sigma)$ =	24.85				$\Sigma\mu$+B =	30.30
38			$\Sigma\mu$+B =	22.50			30.53	$\Sigma(\mu+\gamma\sigma)$ =	30.30
39		P11	P12	*IDLE	#(B_{P32})	P13	##B_{P1}	Actual	IndivBuf
40	μ & B	5.00	5.00	12.50	2.18	5.00	0.62		
41	##$\mu+\gamma\sigma$	5.60	5.68	13.58		5.45			
42	CumAvg	4.992	10.432	24.819	24.819	29.826	30.396	28.451	31.004
43	1	5.9909	11.5210	25.4722	25.4722	30.1362	30.3000	30.1362	31.0327
44	2	5.9023	11.9296	25.0654	25.0654	30.9050	30.9050	30.9050	31.6299
...			...						
2041	1999	5.7646	10.1892	24.6795	24.6795	29.3869	30.3000	29.2820	31.2166
2042	2000	3.8530	8.8385	24.6795	24.6795	29.5560	30.3000	27.2721	30.5773

Figure 6.8 Project Model 1 Implemented on a Spreadsheet (γ = 1.0, β_B = 1.0)

Each activity duration is used to calculate the expected project duration depending on the buffer allocation strategies. Column V named as *Actual* represents the project completion days without any buffer allocation, i.e., non-buffer allocation (NBA) strategy. Column W designated as *IndivBuf* contains the project completion days, where the individual buffer allocation (IBA) strategy is applied into the project network model. Finally, the values of column U[11] under the header of BP1 represent the project completion days of the periodic PCR (PBA) buffer allocation. Simulated project completion days of 2,000 iterations are presented from row 43 to row 2042. The average value of each column is also included at a separate cell in row 42 of each project template. Appendix E presents the four project models simulated in the experiment, and shows the spreadsheet formula for each cell.

[11] This explanation is not applied to cell U40 that represents the size of delivery buffer for project 1 (B_{P1}).

CHAPTER 7

DISCUSSION OF SIMULATION RESULTS

To compare the performance of the buffer allocation strategies, it is necessary to establish the evaluation criteria. This chapter presents the performance criteria, and tests normality of the simulation results to know the possibility of standard statistical analysis on the results. The relative performance of buffer allocation strategies is analyzed in terms of the criteria, and a summary of the experiment is presented.

7.1. PERFORMANCE EVALUATION CRITERIA

The underlying hypothesis of the developed buffer management model is:

The propagation of the internal disturbance and timely completion of projects are affected by the proper placement of strategic buffers.

To test the hypothesis, the simulation experiment compared the three buffer management strategies: (1) non-buffer allocation (NBA), (2) individual buffer allocation (IBA), and (3) periodic PCR buffer allocation (PBA) strategies, in terms of two major evaluation criteria. The performance evaluation criteria are:

1. Average completion days of each M/R project that measures the expected degree of throughput performance and

2. Completion lateness of simulated project completion date against given buffered program schedule, which measures protection performance and predictability of buffer allocation strategies.

The second criterion is further divided into two sub-criteria:

1. Percentage late completion: percentage of projects completed after the scheduled completion date and

2. Average percentage lateness: average lateness as percentage of the scheduled project completion date.

These criteria were selected from the previous researches on multiple project management (Dumond, 1985; Walker, 1998)[1], and modified in the context of the M/R program environment.

The two sub-criteria for the second criterion represent protection performance of the buffer allocation strategies, and are used to compare on-time completion performance of them. A larger value of the completion lateness criteria means lower level of manageability of the M/R program schedule as well as lower level of completion predictability of a project. Therefore, the efficiently protected program schedule is secured by less frequency of project completions after the scheduled completion dates, and by small amount of the project

[1] Dumond (1985) used four performance measures (project mean completion time, project mean lateness, project standard deviation of lateness, and total tardiness), and Walker (1998) used four summary measures: (1) mean percent of early completions, (2) mean lateness as a percent of planned project duration, (3) mean earliness as a percent of planned project duration, and (4) mean resource utilization.

completion delays. The average percentage lateness was measured by the following formula that is applied to simulation runs where PCR-B > ($\Sigma\mu+\Sigma B$), or IndivB > $\Sigma(\mu+\Delta)$.

$$\frac{\sum(C_{Simulated} - C_{Scheduled})}{N_{runs}} \times 100\ \% \qquad (7.1)$$

where, $C_{Simulated}$: the realized completion days of a project resulted in each simulation run on a buffer allocation strategy;

$C_{Scheduled}$: the scheduled completion days of a project on a buffer allocation strategy; and

N_{runs}: the number of simulation runs (2000 times).

7.2. PRESENTATION AND ANALYSIS OF RESULTS

Based on the two primary criteria upon which the buffer allocation strategies were to be evaluated, the descriptive statistics for each measure and analyses are presented the following sub-sections.

7.2.1. Average Completion Days

Average completion days measure the degree of customer satisfaction on delivery time, which represent the throughput performance of buffer allocation strategies in the M/R program. The descriptive statistics for each experiment with a combination of experimental variables are presented in Appendix F.1. In this sub-section, two representative cases among 16 combinations of the variables and projects are discussed in detail (refer to section 6.3.1 for explanation about the factorial design of the experiments). These are Normal-84.13-Full, and

PERT-78.81-08, and showed in Tables 7.1 and 7.3, respectively. In each notation that identify the factorial combination of an experiment, the first component stands for the distribution type of activity durations, the second for the duration safety factor, and the third for the periodic buffer ratio.

Table 7.1 represents the summarized result of 2,000 experimental runs that are simulated under the condition of Normal-84.13-Full. In these simulations, probabilistic profile of activity duration is assumed as the normal distribution. The duration safety factor (γ) is 1.0, which means that each activity duration is buffered to secure the completion probability of 84.14 % within the duration. The periodic buffer ratio (β_P) is 1.0, which represents the aggregated size of periodic buffers is same as that of individual buffers. While the first row (μ & B) of column B_{Pl} represents the delivery buffer of project 1, other rows contain the completion time of the PBA strategy. The columns *Actual* and *IndivBuf* represent the completion time of the NBA and that of the IBA strategy, respectively.

Table 7.1 Average Completion Days of Normal-84.13-Full

Project No.	Expected Duration			Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(1+\gamma\alpha)\mu$	Actual	PCR-B	IndivBuf
1	27.50	31.43	31.43	28.43	31.48	31.93
2	25.00	28.57	28.57	25.02	28.61	28.93
3	30.00	34.29	34.29	30.35	34.31	34.70
4	30.00	34.29	34.29	30.00	34.37	34.81

An examination of Table 7.2 reveals that each run of project 1 executed on the individual buffer allocation (IBA) strategy has longer completion time than the corresponding run executed on the periodic PCR buffer (PBA) strategy. The examination of other projects shows the same result (refer to Appendix F.1). In the experiments of four projects, on average, the PBA strategy results in 13.2% increase of project duration against the actual project execution time, and the IBA strategy results in 14.6% increase of project duration.

Since the expected value of each project duration is same between two strategies ($\Sigma\mu+\Sigma B$ and $\Sigma(1+\gamma\alpha)\mu$), the difference of average completion days between them is interpreted as the performance difference to protect its planned project completion date. While the average completion time of the periodic PCR buffer strategy is, on average, 0.15% longer than the expected duration of each project ($\Sigma\mu+\Sigma B$), that of the individual buffer strategy is, on average, 1.40% longer than the expected value of each project ($\Sigma(1+\gamma\alpha)\mu$).

Table 7.2 Simulation Runs on Project 1 (Normal-84.13-Full)

	P11	P12	*IDLE	*(B_{P32})	P13	**B_{P1}	Actual	IndivBuf
μ & B	5.00	5.00	12.50	2.50	5.00	1.43		
$(1+\gamma\alpha)\mu$	5.71	5.71	14.29		5.71			
Cum.Avg.	4.989	10.390	25.171	25.171	30.188	31.48	28.43	31.93
1	5.9800	11.4010	26.1638	26.1638	30.7722	31.4286	30.7722	31.9979
2	5.8831	12.2377	25.0000	25.0000	31.1180	31.4286	30.8928	32.2854
3	5.3362	9.3720	25.4837	25.4837	30.3646	31.4286	30.3646	31.6681
...								
1999	5.7419	10.1951	25.8809	25.8809	30.5599	31.4286	30.5599	32.5804
2000	3.3833	8.9591	25.0000	25.0000	29.9251	31.4286	27.0036	31.6110

Table 7.3 shows the summarized result of 2,000 simulations executed under the condition of PERT-78.81-08. In these experimental iterations, probabilistic profile of activity

duration is assumed as a PERT (Beta) distribution. The duration safety factor (γ) is 0.8: each activity duration is buffered to secure the completion probability of 78.81%. The periodic buffer ratio (β_P) is 0.8, and the aggregated size of periodic buffers is 0.8 times that of individual buffers. Like the other cases of the experiments, any project executed on the IBA strategy has, on average, longer completion time than that of the PBA strategy. On average of the experiment results of four projects, the PBA strategy results in 7.2% increase of project duration against the actual project execution time, while the IBA strategy results in 10.8% increase of project duration.

Table 7.3 Average Completion Days of PERT-78.81-08

Project No.	Expected Duration				Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\gamma\sigma)$	Max.Path	Actual	PCR-B	IndivBuf
1	27.50	29.29	29.74	**29.92**	28.45	29.59	30.59
2	25.00	27.05	27.56	27.56	25.02	27.14	28.00
3	30.00	32.24	32.80	**32.96**	30.24	32.33	33.43
4	30.00	32.70	33.38	33.38	30.01	32.80	33.99

The values of column *Max.Path* are the maximum time length to complete a project whose activities are individually buffered by the IBA strategy. The difference between $\Sigma(\mu+\gamma\sigma)$ and Max.Path stems from the variance difference of activity durations. In Table 7.4, for example, activity P11, P21, P33, and P41 have the same expected duration (40 work-hours: 5 work-days). The buffered activity durations are, however, different because their input values (a, m, b) and the distribution profile of activity duration are different. These differences result in the difference of path lengths those affect the completion of a project based on constraints of activity precedence in the project and constraints of resource flows in the organization. The longest path dominates the completion time of the project. For example, the Max.Path of project 1 is the maximum value among the project completion days calculated by Formulas 7.2 and 7.3. Each activity duration is individually buffered according to the IBA strategy, and its value is respectively 29.74 and 29.92 work-days, respectively.

$$\text{SUM(P11,P12,IDLE(P32),P13)} = \Sigma(1+\gamma\alpha)\mu \qquad (7.2)$$

$$\text{MAX}((P_{11}+P_{12}),(\text{MAX}((\text{MAX}(P_{21},P_{41})+P_{42}),(P_{11}+P_{31}))+P_{32})) + P_{13} \qquad (7.3)$$

In the cases of Projects 1 and 3 (PERT-78.81-08), the values of Max.Path are different from those of $\Sigma(\mu+\gamma\sigma)$. Whereas, the path of expected project duration $\Sigma(\mu+\gamma\sigma)$ is the path of the maximum length in Projects 2 and 4.

Table 7.4 Activity Duration on PERT Distribution ($\gamma = 0.8$, $\beta_P = 0.8$)

	P11	P12	P13	P21	P22	P23	P31	P32	P33	P41	P42	P43
a (min.)	30	22	34	24	27	33	50	65	25	18	50	41
m (most)	39	42	39	40	66	41	55	80	43	43	55	87
b (max.)	54	49	52	56	71	45	90	95	45	51	90	93
*α	1.67	2.67	1.33	2.00	3.00	2.33	1.00	2.00	3.00	2.67	1.00	3.00
**β	2.33	1.33	2.67	2.00	1.00	1.67	3.00	2.00	1.00	1.33	3.00	1.00
***σ	4.80	5.40	3.60	6.40	8.80	2.40	8.00	6.00	4.00	6.60	8.00	10.40
#μ	40.0	40.0	40.0	40.0	60.0	40.0	60.0	80.0	40.0	40.0	60.0	80.0
##$\mu+\gamma\sigma$	43.84	44.32	42.88	45.12	67.04	41.92	66.40	84.80	43.20	45.28	66.40	88.32
Avg.	39.9351	39.9948	40.0508	39.5742	60.1277	39.9759	60.1326	79.8899	40.0225	40.1180	60.2164	79.8584
1	47.9275	44.2403	37.3120	43.8971	46.2426	39.0099	67.1164	88.7339	38.7891	38.6601	58.4159	92.4187
2	47.2180	48.2185	46.7169	50.8579	68.1264	37.8417	54.8399	80.2008	42.1518	34.6783	69.4641	52.9987
3	42.6338	31.2973	38.7534	42.8849	70.7664	41.9919	62.6121	87.4512	43.9543	43.1248	70.7678	56.2493
...												
1999	46.1169	35.3970	37.6591	39.7236	61.4740	42.5971	58.9465	91.5332	33.1325	40.9256	56.8380	92.0926
2000	30.8243	34.1700	39.0118	41.3924	46.0946	43.0942	70.2186	78.1223	40.4871	36.5383	56.7492	90.3572

As the measure to evaluate the protection performance for its expected project completion date, the average completion time of each strategy is compared. The average completion time of the PBA strategy results in, on average, 0.49% increases against the expected duration of each project ($\Sigma\mu+\Sigma B$). On the contrary, that of the IBA strategy results in, on average, 1.78% increases against the expected value of each project: $\Sigma(\mu+\gamma\sigma)$.

7.2.2. Completion Lateness

The descriptive statistics on the completion lateness are presented in terms of a combination of experimental factors in Appendices F.2 and F.3. In this sub-section, the results of representative simulation experiments are discussed in detail. These are Normal-84.13-Full and PERT-78.81-08, and subsets of their results are showed in (a) and (b) of Table 7.5.

5.2.2.1. Percentage (%) Late Completion

Based on the simulation results of completion lateness in Table 7.5, Table 7.6 summarizes completion time frequencies on 2,000 experiment runs. Each table was generated respectively under the condition of Project1-Normal-84.13-Full or Project4-PERT-78.81-08. Figure 7.1 is graphical representations on completion time frequencies of the project 1 (Normal-84.13-Full) and the project 4 (PERT-78.81-08). In the case of project 1, probabilistic profile of activity duration is assumed as the normal distribution. The duration safety factor (γ) is 1.0 (completion probability of 84.14 %), and the periodic buffer ratio (β_P) is 1.0.

Table 7.5 Simulation Results (subset) of Completion Lateness

(a) Project 1 (Normal-84.13-Full)

Note: $\Sigma(\mu+\Delta)$ represents $\Sigma(1+\gamma\alpha)\mu$.

$\Sigma\mu$	$\Sigma\mu$+B	$\Sigma(\mu+\Delta)$
27.5000	31.4286	31.4286

Simulation Runs	Completion Time			PCR > ($\Sigma\mu$+B)		IndivB > $\Sigma(\mu+\Delta)$	
	Actual	PCR-B	IndivBuf	Yes/No	Delays	Yes/No	Delays
1	30.7722	31.4286	31.9979			Y	0.5694
2	30.8928	31.4286	32.2854			Y	0.8568
3	30.3646	31.4286	31.6681			Y	0.2396
4	29.5890	31.4286	31.4286				
5	31.6854	31.6854	32.5408	Y	0.2569	Y	1.1122
6	26.3671	31.4286	31.4286				
7	29.3304	31.4286	32.3755			Y	0.9469
...		...			...		
1993	28.0797	31.4286	31.4286				
1994	27.6010	31.4286	32.1428			Y	0.7142
1995	31.7154	31.7154	32.7545	Y	0.2868	Y	1.3259
1996	28.6012	31.4286	31.6477			Y	0.2191
1997	26.5836	31.4286	31.4356			Y	0.0070
1998	28.8799	31.4286	32.8764			Y	1.4478
1999	30.5599	31.4286	32.5804			Y	1.1518
2000	27.0036	31.4286	31.6110			Y	0.1824

(b) Project 4 (PERT-7881-08)

Note: $\Sigma(\mu+\Delta)$ represents $\Sigma(\mu+\gamma\sigma)$.

$\Sigma\mu$	$\Sigma\mu$+B	$\Sigma(\mu+\Delta)$
30.0000	32.7040	33.3800

Simulation Runs	Completion Time			PCR > ($\Sigma\mu$+B)		IndivB > $\Sigma(\mu+\Delta)$	
	Actual	PCR-B	IndivBuf	Yes/No	Delays	Yes/No	Delays
1	31.7132	33.0043	34.3128	Y	0.3003	Y	0.9328
2	27.8979	32.7040	34.5960			Y	1.2160
3	29.0327	32.7040	34.3918			Y	1.0118
4	27.7535	32.7040	33.3800				
5	31.0671	32.7040	33.7726			Y	0.3926
6	29.8461	32.7040	33.3800				
7	33.3877	33.3877	35.0572	Y	0.6837	Y	1.6772
...		...			...		
1993	26.1622	32.7040	33.3800				
1994	29.9044	32.7040	34.3607			Y	0.9807
1995	27.8944	32.7040	33.8340			Y	0.4540
1996	28.9753	32.7040	34.1080			Y	0.7280
1997	30.8774	32.7040	33.7199			Y	0.3399
1998	33.1291	33.1291	35.3432	Y	0.4251	Y	1.9632
1999	32.3288	32.9635	33.9562	Y	0.2595	Y	0.5762
2000	29.6868	32.7466	33.9320	Y	0.0426	Y	0.5520

The central limit theorem claims that the sum of non-buffered activity duration, *Actual* completion time of project 1 in Table 7.6, is approximately normally distributed. As statistical descriptors on the project, the mean is 28.43 work-days, and the standard deviation is 1.87 work-days. This normal distribution of the *Actual* completion time is a general phenomenon across the all simulation experiments (refer to Appendix F.2).

The project 1 (Normal-84.13-Full) has 31.43 work-days as a value of both $\Sigma\mu+\Sigma B$ and $\Sigma(1+\gamma\alpha)\mu$. If the completion time of a simulation run is longer than 31.43, the run is evaluated as a case completed after the scheduled completion date (late completion). Since the row designated as *Value* shows the upper limit of each frequency category (Table 7.6-(a)), the PBA (periodic PCR buffer) strategy produces 1863 runs where project completion times fall under range between 31-31.5 work-days. On the contrary, the IBA (individual buffer allocation) strategy has only 685 simulation runs come under the same range, and shows a wide range of distribution profile (refer to Table 7.6-(a) and Figure 7.1). The project 4 (PERT-78.81-08) has 32.70 work-days as $\Sigma\mu+\Sigma B$, and 33.38 work-days as $\Sigma(1+\gamma\alpha)\mu$. Since the $\Sigma\mu+\Sigma B$ is determined according to formula, $\Sigma\mu + 0.8\times(\Sigma(1+\gamma\alpha)\mu-\Sigma\mu)$, its value is less than $\Sigma(1+\gamma\alpha)\mu$. While 1830 simulation runs fall under the category 32.5-33 work-days in the PBA strategy, 490 simulation runs come under the range 33-33.5 work-days when following the IBA strategy.

When the PBA strategy is applied into experiments of project 1 (Normal-84.13-Full), if the completion time of each simulation run, column *PCR-B* of Table 7.5-(a), is longer than the expected project completion time, $\Sigma\mu+\Sigma B$ (31.4286 work-days), it is the case of *PCR-B*

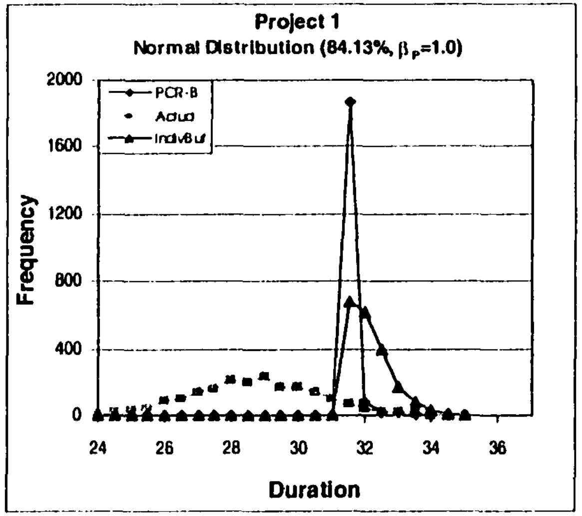
Table 7.6 Frequency Table of Completion Days

(a) Project 1 (Normal-84.13-Full)

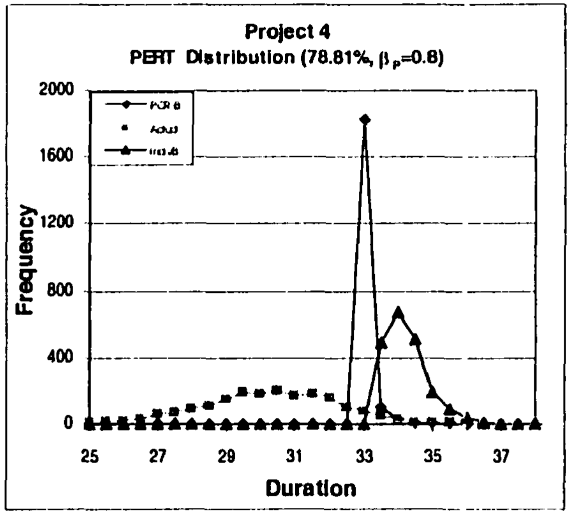
Value	21		22		23		24		25		26		27		28		29		30		31		32		33		34		35		36		37		38	SUM
PCR-B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1863	81	21	18	9	3	2	3	0	0	0	0	0	0	2000
Actual	0	0	1	0	1	4	12	17	34	42	88	103	143	165	209	205	233	170	168	143	98	69	44	17	17	9	3	2	3	0	0	0	0	0	0	2000
IndivBuf	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	685	619	396	174	79	28	12	4	1	0	1	1	0	0	2000

(b) Project 4 (PERT-78.81-08)

Value	21		22		23		24		25		26		27		28		29		30		31		32		33		34		35		36		37		38	SUM
PCR-B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1830	98	34	14	14	9	1	0	0	0	0	2000
Actual	0	0	0	1	1	3	3	4	11	19	22	35	59	68	96	112	148	197	179	205	177	187	168	104	77	52	34	14	14	9	1	0	0	0	0	2000
IndivBuf	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	490	669	509	192	89	39	9	3	0	0	2000



(a) Normal-84.13-Full



(b) PERT-78.81-08

Figure 7.1 Frequency Graph of Project Completion Days

> *($\Sigma\mu+\Sigma B$)* in Table 7.7. The 160 runs among 2000 experiment iterations are considered as the cases of late completion of the project 1, which comes to 8% late completion. In the case of the IBA (individual buffer allocation) strategy, 1405 simulation runs are the cases of *IndivB* > *$\Sigma(\mu+\Delta)$*. The frequency of 1405 is 70.25% of 2000 iterations, and significantly greater portion of the total simulation runs than that of the PBA strategy. The Table 7.7 compares the number of projects completed after the expected project duration, ($\Sigma\mu+\Sigma B$) and $\Sigma(\mu+\Delta)$, as a performance measure of on-time completion of PBA and IBA strategies. The developed PBA strategy results in only 11.39% of late completion against the IBA strategy in the simulations of project 1 under the condition of Normal-84.13-Full. The average percentage of *PCR-B/IndivB* is 13.43 across project 1 to project 4 under the same experiment condition.

Table 7.7 Comparison of Percentage Late Completion (Normal-84.13-Full)

Project No.	Evaluation Criteria	Freq.	Percent (2000)	PCR-B / IndivB
1	**PCR-B** > $\Sigma\mu+\Sigma B$	160	8.00	11.39 %
	IndivB > $\Sigma(\mu+\Delta)$	1405	70.25	
2	**PCR-B** > $\Sigma\mu+\Sigma B$	198	9.90	17.38 %
	IndivB > $\Sigma(\mu+\Delta)$	1139	56.95	
3	**PCR-B** > $\Sigma\mu+\Sigma B$	97	4.85	7.58 %
	IndivB > $\Sigma(\mu+\Delta)$	1279	63.95	
4	**PCR-B** > $\Sigma\mu+\Sigma B$	240	12.00	17.38 %
	IndivB > $\Sigma(\mu+\Delta)$	1381	69.05	

Note: $\Sigma(\mu+\Delta)$ represents $\Sigma(1+\gamma\alpha)\mu$.

In the experiments of project 4 (PERT-78.81-08), the frequency of *PCR-B* > *$\Sigma\mu+\Sigma B$* is 413 runs (refer to Table 7.8). The 413 runs among 200 experiment iterations are considered as the cases of late completion of the project, which comes to 20.65% late completion. In the case of the IBA strategy, 1661 simulation runs are the case of *IndivB* $> \Sigma(\mu+\Delta)$, and the frequency of 1661 is 83.05% of 2000 iterations. Even though 413 late completion of PBA strategy is only 24.86% of 1661 late completion of IBA strategy, which is a relatively high portion comparing to 11.39% of Normal-84.13-Full. The reason of higher percentage, 24.86%, is the smaller size of the total periodic PCR buffers (2.70 work-days: 7.57%) than the total individual buffers. The total buffer allocation of IBA strategy is 3.38 work-days, which is 11.27% of the non-buffered expected project duration, 30 work-days $\Sigma\mu$.

The developed PBA strategy allocates smaller amount of buffers into the M/R program schedule, and results in shorter expected project durations and realizes shorter completion time of each project. In the case of project 4, the difference of allocated buffer sizes between the two buffer strategies is 0.68 work-days, and the value is also the difference between the expected project durations of PBA and IBA strategies. The realized project completion time of the PBA strategy is, on average, 1.19 work-days shorter than that of IBA strategy (33.99-32.80). While the PBA strategy has the smaller amount of buffers, the frequency of late completion lower than that of IBA strategy.

Table 7.8 compares the number of projects completed after the expected duration, $(\Sigma\mu+\Sigma B)$ and $\Sigma(\mu+\Delta)$, as a performance measure of on-time completion on PBA and IBA strategies. The examination of the table shows that the developed PBA strategy has better performance of on-time completion with less expense of buffer allocation under the condition of PERT-78.81-08. The average percentage of *PCR-B/IndivB* is 27.36 across project 1 to project 4 under the same experiment condition. Appendix F.3 represents simulation results of other experiment conditions.

Table 7.8 Comparison of Percentage Late Completion (PERT-78.81-08)

Project No.	Evaluation Criteria	Freq.	Percent (2000)	PCR-B / IndivB
1	PCR-B > $\Sigma\mu+\Sigma B$	822	41.10	49.73
	IndivB > $\Sigma(\mu+\Delta)$	1653	82.65	
2	PCR-B > $\Sigma\mu+\Sigma B$	229	11.45	15.40
	IndivB > $\Sigma(\mu+\Delta)$	1487	74.35	
3	PCR-B > $\Sigma\mu+\Sigma B$	315	15.75	19.43
	IndivB > $\Sigma(\mu+\Delta)$	1621	81.05	
4	PCR-B > $\Sigma\mu+\Sigma B$	413	20.65	24.86
	IndivB > $\Sigma(\mu+\Delta)$	1661	83.05	

Note: $\Sigma(\mu+\Delta)$ represents $\Sigma(\mu+\gamma\sigma)$.

7.2.2.2. Average Percentage (%) Lateness

Average lateness as percentage of the scheduled project duration, as well as percentage late completion, was measured as the other evaluation criterion for completion lateness. As described earlier, the criteria of the completion lateness represent protection performance of the buffer allocation strategies, and were used to evaluate the extent to which a buffer allocation strategy deviated the completion date of a project beyond the scheduled completion time of the project. The small amount of average percentage lateness and narrow range (variance) of the completion delays secure higher manageability of the M/R program schedule and higher completion predictability of a project.

In Table 7.5, the columns named 'Delays' represent cumulative difference between realized completion time of each simulation run and the expected project completion time. When the PBA strategy is applied to experiments of project 1 under the condition of Normal-84.13-Full, the difference, PCR-B - ($\Sigma\mu+\Sigma B$), is the amount of project completion delay. Also IndivB - $\Sigma(\mu+\Delta)$ is the completion delay under the IBA strategy. The column 'Delays' in the Table 7.9 represents the cumulative amount of completion delays across 2000 iterations. The PBA strategy results in 101.9 work-days of delays on the project 1, and the average percentage lateness is 0.16%. In the case of the IBA strategy on project 1, the total 998.8 work-days is delayed beyond the scheduled project completion date, which comes to 0.16% of average percentage lateness. As a result, the total delayed work-days of the developed PBA strategy is 10.20% of IBA strategy's delays in the experiments of project 1. The average of *PCR-B/IndivB* is 10.81% across project 1 to project 4 under the same condition of experiment, Normal-84.13-Full.

Table 7.9 Comparison of Average Percentage Lateness (Normal-84.13-Full)

Project No.	Evaluation Criteria	Delays (work-days)	Percent (2000)	PCR-B / IndivB
1	**PCR-B** > $\Sigma\mu+\Sigma B$	101.9	0.16	10.20 %
	IndivB > $\Sigma(\mu+\Delta)$	998.8	1.59	
2	**PCR-B** > $\Sigma\mu+\Sigma B$	84.9	0.15	11.86 %
	IndivB > $\Sigma(\mu+\Delta)$	715.7	1.25	
3	**PCR-B** > $\Sigma\mu+\Sigma B$	50.2	0.07	6.04 %
	IndivB > $\Sigma(\mu+\Delta)$	831.1	1.21	
4	**PCR-B** > $\Sigma\mu+\Sigma B$	158.8	0.23	15.13 %
	IndivB > $\Sigma(\mu+\Delta)$	1049.5	1.53	

In the experiments of PERT-78.81-08, the PBA strategy on project 4 produces 192.3 work-day's delay and 0.29% of average percentage lateness. On the contrary, the total delays of the IBA strategy on the project are 1228.7 work-days, and the average percentage lateness is 1.84%. The total delays of the PBA strategy are 15.65% of the IBA strategy's. The average of *PCR-B/IndivB* is 25.12% across project 1 to project 4 under the condition of Normal-84.13-Full.

Table 7.10 Comparison of Average Percentage Lateness (PERT-78.81-08)

Project No.	Evaluation Criteria	Delays (work-days)	Percent (2000)	PCR-B / IndivB
1	PCR-B > $\Sigma\mu+\Sigma B$	605.2	1.03	44.87 %
	IndivB > $\Sigma(\mu+\Delta)$	1348.8	2.27	
2	PCR-B > $\Sigma\mu+\Sigma B$	183.1	0.34	20.84 %
	IndivB > $\Sigma(\mu+\Delta)$	878.5	1.59	
3	PCR-B > $\Sigma\mu+\Sigma B$	178.5	0.28	19.11 %
	IndivB > $\Sigma(\mu+\Delta)$	933.9	1.42	
4	PCR-B > $\Sigma\mu+\Sigma B$	192.3	0.29	15.65 %
	IndivB > $\Sigma(\mu+\Delta)$	1228.7	1.84	

Upon investigation of Table 7.6 and Figure 7.1, a projects coordinator finds different variance profile of completion dates between buffer allocation strategies. In the case of the PBA strategy on project 1 (Normal-84.13-Full), the frequency range of completion delays (31-35 workdays) is narrower than that of the IBA strategy (31-37 workdays). While 1863 simulation runs of the PBA strategy (93.15%), moreover, fall under a category, $31 < C_{realized} \leq 31.5$, 1700 runs of the IBA strategy (85.0%) fall under three categories, $31 < C_{realized} \leq 32.5$. In the experiments of project 4 under the condition of PERT-78.81-08, the completion range of the PBA strategy is 32.5-36 workdays, and that of the IBA strategy is 33-37 workdays. 91.5% of PBA simulation iterations (1830 runs) fall under $32.5 < C_{realized} \leq 33$, and 83.4% of IBA simulation iterations (1668 runs) come into the range 32.5-35 workdays. The developed PBA strategy secures narrower range of completion dates, and its variance profile is characterized as highly concentrated on the scheduled project duration. The benefits of the PBA strategy are, therefore, higher manageability of the M/R program schedule and higher completion predictability of a project.

7.3. SUMMARY

This chapter analyzed the simulation results on buffer allocation strategies in terms of two major evaluation criteria: (1) average completion days and (2) completion lateness. The first criterion represents the throughput performance (productivity) of buffer allocation strategies, and the second criterion evaluates the protection performance and predictability of the strategies. The completion lateness was further divided into two sub-criteria: (1) percentage late completion and (2) average percentage lateness.

In general, the periodic PCR buffer allocation (PBA) strategy performed better than the individual buffer allocation (IBA) strategy in all experiments. Regardless of which distribution type of activity duration was applied into the experiments, the PBA produced a smaller value of the average completion days than the IBA depending on used periodic buffer ratio (β_P). The most interesting result of these experiments was that the PBA produced considerably better performance on completion lateness criteria. Even though the total size of allocated PCR buffers was smaller than that of individual buffers ($\beta_P = 0.8$), for example, the PBA significantly decreased percentage late completion and average percentage lateness in all experiments.

CHAPTER 8: CONCLUSIONS

This chapter summarizes the developed M/R program management model and simulation experiments on scheduling algorithms and buffer management strategies. The results of simulation experiments indicate that the developed PCR Scheduling Algorithm and periodic PCR buffer allocation strategy outperform others in the M/R environments. The contributions of this research to the body of knowledge are discussed, followed by its practical implications for the construction industry. The limitations of the M/R program management model are indicated, and several suggestions are made for future research.

8.1. SUMMARY OF RESEARCH

As the first step of developing an effective and efficient management strategy for the M/R program, this research adopted the "philosophy of management"(Drucker, 1954, p. 136) as the theoretical basis. The first principle of the philosophy, management by objectives, motivated the research to construct a program master plan (PMP) in the long-time horizon and a master construction schedule in an operational scheduling window (MCS). While constructing PMP and MCS as the logical and time-based backbone of the program, the program manager could effectively plan/schedule the multi-resource constrained multiple projects, and achieve the long-term organizational objectives of the M/R program: (1) client satisfaction and (2) organizational efficiency and manageability.

To deal with the external uncertainty of dynamically arriving projects requests, a rolling horizon (RHZ) approach to the PMP was proposed based on the current negotiation process between a program manager and clients. By actively transforming the dynamic nature of continuous request arrivals into a series of static scheduling sub-problems, the RHZ approach improved predictability and manageability of the M/R program. A capacity-constrained scheduling algorithm was proposed to generate the MCS in a scheduling window, while resolving resource contentions among M/R projects. More emphasis was placed on long-term organizational resource continuity, especially flows management of the program constraint resources (PCRs) than ephemeral events of individual activity and project.

The simulation experiments of three scheduling windows were used to evaluate the relative performance of the proposed PCR scheduling heuristic against three popular scheduling heuristics for resource-constrained multiple projects: shortest-activity-from-shortest-project (SASP), shortest-after-chain (SAC), and longest-after-chain (LAC). One set of simulation conditions in each scheduling window assumed that program management could set the start-date of each projects by using the active contracting strategy, and that a deterministic integer value was assigned to an activity duration of each project at the initial MCS. The results of these experiments are reported in Chapter 4. The PCR scheduling heuristic and algorithm outperformed the others under the simulation conditions.

In Chapter 4, the resource-constrained scheduling heuristics are evaluated in terms of three major criteria of performance: (1) completion-time/project duration ratio (CDR), (2) shop utilization ratio (SUR), and (3) tardiness over windows (TOW). It was found that the

PCR Scheduling heuristic performed better on criteria CDR and TOW than heuristics SASP, SAC, and LAC. It was also found that PCR and LAC outperformed SASP and SAC on the criteria of SUR. The results of the simulation experiments, therefore, validated the proposed PCR scheduling heuristic could be adopted to construct the MCS of multi-resource constrained multiple projects in the M/R program environment.

The second principle of the philosophy, management by self-control, was implemented by the periodic PCR buffers in organizational PCR flows. This rhythm-based PCR flow management of the periodic PCR buffer allocation (PBA) strategy could stabilize the program by terminating propagation of an internal disturbance at the safety time-zones of periodic buffers. The PBA strategy also provided a cooperation mechanism for technicians and supervisors of trade shops to adjust the progress of M/R projects within the buffer periods of the MCS, when the internal uncertainty (unexpected delays of activities and projects) was developed. The PBA strategy improves flexibility of MCS based on the management by self-control, while preserving the productivity of the M/R program by smaller amount of the PCR buffers than individual activity buffers.

The Monte Carlo experiments were simulated to compare the performance of the developed PBA strategy to the individual buffer allocation (IBA) strategy proposed by previous researches (e.g., Ballard and Howell, 1998; Tommelein et al., 1999). The initial MCS of four projects constrained by resource flows of three trade shops was considered to simulate a M/R program network. The simulation variables of the experiments were the total size of buffers (duration safety factor γ and periodic buffer ratio β_P) and stochastic distribution types of activity duration (normal, PERT (beta), triangular, and uniform distribution). The simulation models and the results of these experiments are presented in Chapter 6 and Chapter 7.

The simulation results on buffer allocation strategies are analyzed in Chapter 7 based on two major evaluation criteria: (1) average completion days and (2) completion lateness. The first criterion represents the throughput performance, productivity, of buffer allocation strategies, and the second criterion evaluates the protection performance and predictability of the strategies. The completion lateness was further divided into two sub-criteria: percentage late completion and average percentage lateness.

In general, the PBA strategy performed better than the IBA strategy in all experiments. Regardless of which distribution type of activity duration was applied into the experiments, the PBA produced a smaller value of the average completion days than the IBA depending on used periodic buffer ratio (β_P). The most interesting result of these experiments was that the PBA produced considerably better performance on completion lateness criteria. Even though the total size of allocated PCR buffers was smaller than that of individual buffers ($\beta_P = 0.8$), for example, the PBA significantly decreased % late completion and average % lateness in all experiments. Based on the results of the simulation experiments, it was concluded that the period-based PCR buffer management improved the protection performance and predictability of the M/R program with better productivity than the IBA.

8.2. CONTRIBUTIONS OF RESEARCH

8.2.1. Contributions to Body of Knowledge

This research presented the organizational program management model to plan, schedule, and control multiple M/R projects under multi-trade resource constraints. During development process of the model, a significant amount of effort has been exerted to find out a theoretical framework[1], or basis for the construction engineering and management, and to apply the framework into the M/R program management. The following Halpin's questions motivated this effort:

> "*Do we have a unifying theory or set of paradigms that provide the theoretical underpinning of construction? What is the theoretical basis for our discipline and profession?*"[2] (Halpin, 1993, p. 419)

To seek and establish the theoretical foundation in construction, several researchers of construction have tried to apply production theories of the manufacturing industry, e.g., transformation, flow, and value concepts, to the construction environment. However, any production theory has been neither accepted by construction academia, nor realized by construction industry (Koskela, 1999b, p. 2). This research argues that a root cause of the failure is the environmental differences between the factory-based production industry and the site-oriented project industry. The concepts of "scientific management," e.g., "task

[1] Halpin (1993) defined the framework as "a set of proven conceptual models" (p. 418).

[2] These challenging questions were originally posed by Nam Suh: "*What is civil engineering? What is the theoretical framework, or basis, for civil engineering?*" (Halpin, 1993, p. 418).

management" of Tayor (1911, p. 26) and flow management of Gilbreths (1921), were developed and evolved in the environment of production, i.e., the manufacturing industry (Koskela, 1999a, p. 244). Despite the considerable endeavor of transplanting the scientific management to the construction, therefore, the progress of its propagation has been limited to specific operational processes or production activities of specialty-contractors.

The research applied the *philosophy of management*, "management by objectives and self-control" (Drucker, 1954, p. 136), into multiple project management of an owner organization as a new paradigm for developing a construction-oriented framework. Based on the philosophy, the research provided a framework of organizational program management in that a coordination and cooperation mechanism penetrated the underlying characteristics of construction, "interdependence and uncertainty" (Crichton, 1966). This research is the first experimental exploration that interprets and extends the management philosophy of organizational strategy to construction as well as the scientific management of the operational production.

In the environments of production and construction, two categories of management systems have been evolved based on their own theoretical backgrounds: (1) a centralized MRP/CPM system and (2) a decentralized JIT/Lean system. While the DBR and TOC provide a logistical combination of the two systems to production managements, this research presented a framework of total process management that logically integrates the conventional CPM/PERT and Lean construction. The new framework or model may be considered as a construction-based interpretation of the management philosophy that aims at stability and flexibility of the organizational program management.

8.2.2. Practical Implications for Construction Industry

The research modeled and implemented the program master plan (PMP), master construction schedule (MCS), and buffer management strategy in the dynamic M/R environment. This research results have implications for practitioners of multiple project management, e.g., program or system[3] managers in a large owner organization and a construction company.

Based on the impracticality of the mathematical optimization procedures, a heuristic procedure and algorithm for planning and scheduling multiple projects under multiple resource constraints has been developed. The PCR scheduling algorithm produces the PMP and the MCS from the perspective of organizational resource flows than ephemeral project events. Therefore the generated PMP and MCS provide the managers with better manageability on individual project on the lines of organizational continuity. To facilitate ease of the developed PCR scheduling procedure, scheduling templates are implemented in a common spreadsheet package, Microsoft® Excel, coded in Visual Basic® for Application (VBA) language. The scheduling templates also allow the program/system managers to apply

[3] A system is the "global realm" of project environment that a specific program is "associated with" (Badiru, 1996, p. 51).

other popular scheduling heuristics (SASP, SAC, and LAC rules) in multi-resource constrained multiple project management.

Another critical issues that the program/system managers in construction industry have been experienced are the 'internal' uncertainty, disturbance from the uncertainty, and claims for resultant delay damages. The new buffer management strategy provides a rhythmical stabilization mechanism for the MCS by periodically terminating propagation of an internal disturbance. This periodic PCR buffer allocation (PBA) strategy improved the flexibility of MCS preserving the productivity of the program/system with smaller protection premium than the individual buffer allocation strategy. Without complex procedures of identifying the critical sequences or chains, the PCR flows after a time-point of periodic buffers are simply right-shifted to allow allocation of the PCR buffers. The higher protection performance, less deteriorated productivity, and procedural simplicity of the PBA strategy increase the effectiveness and efficiency of program/system control, when it is adopted by the practitioners in the highly uncertain industry.

8.3. LIMITATIONS AND SUGGESTIONS FOR FUTURE RESEARCH

Since several assumptions were used to simplify the development process of the program management model (refer to section 1.4), the model does not reflect all conditions of the real construction environment.

First, subsets of the overall projects in the M/R program were used to simulate and evaluate scheduling heuristics and buffer allocation strategies. The simulation results based on relatively small size of a network problem might have limitations to be extended to the whole program scheduling problems. As a basis of justifying the results, however, this dissertation resorts to previous researches that emphasized the network characteristics as a more important determinant than network size. Pascoe (1965), for example, asserted that the most effective scheduling method for the smaller problems were also most effective for the larger problems, and verified this conclusion with an additional test on one large building-construction network taken from practice. Based on the studies, this dissertation advocates possibility of extending implications of the results to general program environment.

Second, the dissertation is based on the current condition that finite trade-shop resources are owned by the M/R program organization, and that the program manager has some authority over decision of project start/completion-date and negotiates with the clients for the final agreement. This dissertation also assumes that future projects will be managed based on currently available resources without any strategic adjustment of shop capacities. As a result, the scheduling procedure is dominated by capacity constraints of the trade shops. In practice of new construction, the resource constraints are relaxed by means of contractual outsourcing and operational overtime / multi-shifts, and due-date constraints may be more critical. The due-date constrained scheduling algorithm of multiple projects is left for future research. Interested researchers will refer to the previous studies: e.g., Dumond and Mabert (1988), Bock and Patterson (1990), and Yang and Sum (1997). Even though the procedure of generating the MCS is changed by imposed due-date constraints, however, the developed buffer management strategy will be still applicable to the due-date constrained MCS. Whether the MCS is scheduled by resource constraints or due-date constraints, the PBA strategy allocates periodic buffers in the MCS flows, and prevents the chain reactions of disturbance propagation.

From an internal coordination and cooperation view, the program management model focused on construction phase of multiple project and in-house human resources at multiple trade shops. Timely and pertinent supplies of material and system components during M/R services were not addressed. Even though timely procurement from outside vendors is essential to smooth flow of construction progress, it is still worthwhile to produce the stable PMP and the MCS based on organizational management strategy, because they are the backbone plan for scheduling the procurement process. The concept of "feeding buffers" (Newbold, 1998, p. 60) can be used to protect the PMP and the MCS against the uncertainty of the external chains.

Behavioral issues of worker and/or subcontractor with a given schedule and their implications for program management were not addressed in this dissertation. Early consumption behavior of internal float in Parkinson's Law (Parkinson, 1957) provides the theoretical foundation for a "super network"[4] in addition to "the basic network and time estimates which are openly displayed for all to see" (Wiest and Levy, 1969, p. 130). If a program manager use the super network, the relationship between the periodic buffers allocated in the MCS and his/her "private" super network should be defined (King and Wilson, 1967, p. 308), and the manager's *adjustment* process needs to be modeled in terms of "suprarlevel planning" (Badiru, 1996, p. 55) of the organizational strategy. The behavioral issues are challenging for future research. Gutierrez and Kouvelis (1991) and Krakowski (1974) presented initial researches, which provided some insights into behavioral issues for interested researchers.

Size of the periodic PCR buffers is another important issue. In the simulation experiments of Chapter 6 and 7, the buffer sizes were determined by the duration safety factor (γ) and the periodic buffer ratio (β_P), and two values (1.0 and 0.8) were plugged into the experiments to represent the two simulation variables. Since the main objective of the experiments was to evaluate relative performance of the two buffer allocation strategies, absolute sizes of the buffers were not considered. While the determination of actual buffer sizes depends on experience and intuition of a program/system scheduler as well as historical data of similar activities/projects, the formal procedure for the buffer sizing needs further researches.

[4] King and Wilson (1967) originally suggested the need of the "super network."

Another promising research area is concurrent construction by work-zoning. In the environment of multiple M/R projects, the program manager frequently needs to alleviate the future peak workforce loads by expediting on-going projects over the current scheduling window. Based on relatively small sizes of the M/R projects, the current practice of space utilization (one trade per space) is usually applied to the whole space of the remodeling project without discriminating space sizes and characteristics between maintenance and remodeling projects. The remodeling project often deals with changing and upgrading one or more spaces that are physically divided into sub-blocks: work-zones. This dissertation suggests investigating the potential of splitting an activity into more than one tasks and scheduling/executing the tasks in parallel with other tasks from other trades across the divided zones. By overlapping the tasks, the duration of a project could be shortened, and the M/R organization would be able to transfer workloads from a high-demand period to low-demand period. However, the concurrent construction by work-zoning does require operational-level information, which consequently needs the scientific time and motion studies. Classification and standardization of micro-level activity behaviors, e.g., space requirement and interference among them, are waiting for challenging researchers.

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APPENDIX A: VBA PROGRAMMING CODES

A.1. INPUTS AND DETERMINATION OF PCR

```
'***********************************************************************
   Option Explicit
   Public NoProjs As Integer, ProjNo As Integer
   Public NoDays As Integer, DayNo As Integer
   Public NoShops As Integer, ShopNo As Integer
   Public ShopNames As String

'***********************************************************************
Public Sub IsContinuedPeriod()

   Dim Result As Integer
   Dim PeriodStart As Integer
   Dim i As Integer, j As Integer, k As Integer, ShopIndex As Integer
   Dim ActName As String

   NoProjs = ActiveSheet.Cells(7, 9).Value
   NoShops = ActiveSheet.Cells(8, 9).Value
   Result = MsgBox("Do you want to Integrate following Projects into the Schedule of the Previous Period(s)?",_
            vbYesNoCancel, "Continuation")
   If Result = vbYes Then
      ActiveSheet.Cells(3, 20).Value = "Integrated Schedule"
      ActiveSheet.Cells(10, 42).Value = ActiveSheet.Cells(7, 9).Value      'Number of Projects in Previous Period
      ActiveSheet.Cells(11, 42).Value = ActiveSheet.Cells(8, 9).Value      'Number of Shops in Previous Period
      'Total # of Projects in Past Windows
      ActiveSheet.Cells(12, 42).Value = ActiveSheet.Cells(12, 42).Value + ActiveSheet.Cells(10, 42).Value
     'Copy InputTable
      ActiveSheet.Range("A15:AD26").Copy Range("AL29")
      ActiveSheet.Range("AE15:AE26").Copy Range("AK29")
     'Clear Contents of Gantt Chart
      Range("AK17:BE26").ClearContents
```

```
  ElseIf Result = vbNo Then
    ActiveSheet.Cells(3, 20).Value = "Separated Schedule"
    ActiveSheet.Cells(10, 42).Value = 0              'Previous # of Projects
    ActiveSheet.Cells(11, 42).Value = 0              'Previous # of Shops
    ActiveSheet.Cells(12, 42).Value = 0              'Total # of Projects during Past Windows
    ActiveSheet.Cells(15, 35).Value = 0              '# of Projects from Previous Window
    ActiveSheet.Cells(15, 61).Value = 0              '# of Activities from Previous Window
  'Clear Contents of Tables & Gantt Chart
    Range("AG17:AG26").ClearContents                 'Previous & Current Projects
    Range("AI17:AI26").ClearContents
    Range("BG17:BG26").ClearContents                 'Previous & Current Activities
    Range("BI17:BI26").ClearContents
    Range("AK17:BE26").ClearContents                 'Gantt of After-Schedule from Previous Sch. Window
    Range("AK31:AK40").ClearContents                 'Inputs of Previous Sch. Window
    Range("AM31:BO40").ClearContents
  'Clear Contents of Continuous Periods-Gantt Charts
    Worksheets("Heuristics").Range("B94:DQ99").ClearContents
    Worksheets("Heuristics").Range("B106:DQ125").ClearContents
  ElseIf Result = vbCancel Then
    End
  End If
  MsgBox "Please, Enter Information about Projects & Resources.", , "User Inputs" 'Ask User to Input New Data

End Sub

'*************************************************************************

Public Sub ExecuteProcedures()

  ESandEFtable
  InitialLayout
  ResDemandChart
  DetermMostPCR

End Sub
'*************************************************************************
```

```
'***************************************************************************
Public Sub ESandEFtable()

  Dim LastRow As Integer
  Dim CopyRange As String
  Dim i As Integer, j As Integer
  Dim NoActs As Integer, IntegNoActs As Integer
  Dim CurActName As String, CurProjNo As Integer, CurActNo As Integer
  Dim PreNoProjs As Integer, NewProjNo As Integer, NewCol As Integer, CountPreAct As Integer
  Dim PreActName As String, PreProjNo As Integer, PreNoActs As Integer, PreActNo As Integer, PreActDur As Integer

  NoProjs = ActiveSheet.Cells(7, 9).Value
  NoShops = ActiveSheet.Cells(8, 9).Value
'Clear Contents of Table
  Range("B33:AC42").ClearContents
'ES & EF of Act1 (All Projects)
  For i = 1 To NoProjs
    ActiveSheet.Cells(32 + i, 2).Value = ActiveSheet.Cells(16 + i, 3).Value
    If ActiveSheet.Cells(16 + i, 3).Value < 0 Then
      ActiveSheet.Cells(32 + i, 3).Value = ActiveSheet.Cells(16 + i, 4).Value
    Else
      ActiveSheet.Cells(32 + i, 3).Value = ActiveSheet.Cells(16 + i, 3).Value + ActiveSheet.Cells(16 + i, 4).Value
    End If
  Next i
  'ES & EF of Following Activities (Each Project)
  For i = 1 To NoProjs
    NoActs = ActiveSheet.Cells(16 + i, 31).Value
    For j = 2 To NoActs
      ActiveSheet.Cells(32 + i, 2 * j).Value = ActiveSheet.Cells(32 + i, 2 * j - 1).Value
      ActiveSheet.Cells(32 + i, 2 * j + 1).Value = ActiveSheet.Cells(32 + i, 2 * j).Value _
                                                   + ActiveSheet.Cells(16 + i, 2 + 2 * j).Value
    Next j
  Next i
'In Case of Integrating Current Input with Previous Schedule
If InStr(ActiveSheet.Cells(3, 20).Value, "Integrated Schedule") > 0 Then
  PreNoProjs = ActiveSheet.Cells(10, 42).Value
```

```
NewProjNo = 0
IntegNoActs = 0
For ProjNo = 1 To PreNoProjs
   PreNoActs = 0
   CurActNo = 0
   For DayNo = 37 To 57
      PreActName = ActiveSheet.Cells(16 + ProjNo, DayNo).Value
      If (InStr(PreActName, "P") > 0) And (StrComp(PreActName, ActiveSheet.Cells(16 + ProjNo, _
                                                            DayNo - 1).Value) <> 0) Then
         PreProjNo = CInt(Mid(PreActName, 2, 1))
         PreActNo = CInt(Mid(PreActName, 3, 1))
         IntegNoActs = IntegNoActs + 1
         ActiveSheet.Cells(15, 61).Value = IntegNoActs          'Total # of Acts From Previous Window
      'Previous Proj&Act Numbers
         ActiveSheet.Cells(16 + IntegNoActs, 61).Value = CStr(PreProjNo) & CStr(PreActNo)
         If (DayNo = 37) And (StrComp(PreActName, Worksheets("Heuristics").Cells(74 + ProjNo, 21).Value) = 0) Then
            ActiveSheet.Cells(33 + NoProjs + NewProjNo, 2).Value = -1
            If PreActNo = 1 Then
               ActiveSheet.Cells(17 + NoProjs + NewProjNo, 2).Value = ActiveSheet.Cells(30 + ProjNo, 39).Value
            Else
               ActiveSheet.Cells(17 + NoProjs + NewProjNo, 2).Value = _
                    ActiveSheet.Cells(30 + ProjNo, 40 + 2 * (PreActNo - 1)).Value
            End If
            ActiveSheet.Cells(17 + NoProjs + NewProjNo, 3).Value = -1
            PreActDur = 1
            For i = 1 To ActiveSheet.Cells(30 + ProjNo, 39 + 2 * PreActNo).Value
               If StrComp(PreActName, ActiveSheet.Cells(16 + ProjNo, 37 + i).Value) = 0 Then
                  PreActDur = PreActDur + 1
               End If
            Next i
            ActiveSheet.Cells(33 + NoProjs + NewProjNo, 3).Value = PreActDur
            ActiveSheet.Cells(17 + NoProjs + NewProjNo, 4).Value = PreActDur
            CurActNo = CurActNo + 1
            PreNoActs = PreNoActs + 1
         ElseIf (DayNo = 37) Or (CurActNo = 0) Then
            ActiveSheet.Cells(33 + NoProjs + NewProjNo, 2).Value = 0
```

```
            ActiveSheet.Cells(33 + NoProjs + NewProjNo, 3).Value = ActiveSheet.Cells(33 + NoProjs + _
                    NewProjNo, 2).Value + ActiveSheet.Cells(30 + ProjNo, 39 + 2 * PreActNo)
            If PreActNo = 1 Then
              ActiveSheet.Cells(17 + NoProjs + NewProjNo, 2).Value = ActiveSheet.Cells(30 + ProjNo, 39).Value
            Else
              ActiveSheet.Cells(17 + NoProjs + NewProjNo, 2).Value = ActiveSheet.Cells(30 + ProjNo, 40 +_
                    2 * (PreActNo - 1)).Value
            End If
            ActiveSheet.Cells(17 + NoProjs + NewProjNo, 3).Value = 0
            ActiveSheet.Cells(17 + NoProjs + NewProjNo, 4).Value = ActiveSheet.Cells(17 + NoProjs + NewProjNo,_
                    3).Value + ActiveSheet.Cells(30 + ProjNo, 39 + 2 * PreActNo)
            CurActNo = CurActNo + 1
            PreNoActs = PreNoActs + 1
          ElseIf (CurActNo > 0) Then
            ActiveSheet.Cells(33 + NoProjs + NewProjNo, 2 * (CurActNo) + 2).Value = ActiveSheet.Cells(33 + _
                    NoProjs + NewProjNo, 2 * (CurActNo) + 1).Value
            ActiveSheet.Cells(33 + NoProjs + NewProjNo, 2 * (CurActNo) + 3).Value = ActiveSheet.Cells(33 +_
                    NoProjs + NewProjNo, 2 * (CurActNo) + 2).Value + ActiveSheet.Cells(30 + ProjNo, 39 + 2 * PreActNo)
            ActiveSheet.Cells(17 + NoProjs + NewProjNo, 2 * (CurActNo) + 3).Value = ActiveSheet.Cells(30 +_
                    ProjNo, 38 + 2 * PreActNo)
            ActiveSheet.Cells(17 + NoProjs + NewProjNo, 2 * (CurActNo) + 4).Value = ActiveSheet.Cells(30_
                    + ProjNo, 39 + 2 * PreActNo)
            CurActNo = CurActNo + 1
            PreNoActs = PreNoActs + 1
          End If
      'Current Proj&Act Numbers
        ActiveSheet.Cells(30 + IntegNoActs, 35).Value = CStr(NoProjs + NewProjNo + 1) & CStr(CurActNo)
        End If
      Next DayNo
      If ActiveSheet.Cells(17 + NoProjs + NewProjNo, 4).Value > 0 Then               'If FirstAct exists
        ActiveSheet.Cells(17 + NoProjs + NewProjNo, 31).Value = PreNoActs
        NewProjNo = NewProjNo + 1
        ActiveSheet.Cells(16 + NewProjNo, 33).Value = PreProjNo                      'Previous ProjNo
        ActiveSheet.Cells(16 + NewProjNo, 35).Value = NoProjs + NewProjNo            'Current ProjNo
      End If
    Next ProjNo
```

```
'Number of Projects to be integrated into New Schedule from Previous Schedule
  ActiveSheet.Cells(15, 35).Value = NewProjNo
'Update StartTime of Scheduling Window' (20 = 1 month)
  ActiveSheet.Cells(7, 3).Value = ActiveSheet.Cells(7, 3).Value + 20
'Update NoShops & Enumeration of Shops
  For i = 1 To NewProjNo
    'For j = 1 To ActiveSheet.Cells(20 + i, 31).Value
    For j = 1 To ActiveSheet.Cells(20 + i, 31).Value
      If j = 1 Then
        NewCol = 2
      Else
        NewCol = 1 + 2 * j
      End If
      If InStr(ActiveSheet.Cells(8, 3).Value, ActiveSheet.Cells(20 + i, NewCol).Value) = 0 Then
        ActiveSheet.Cells(8, 9).Value = ActiveSheet.Cells(8, 9).Value + 1
        ActiveSheet.Cells(8, 3).Value = ActiveSheet.Cells(8, 3).Value & ActiveSheet.Cells(20 + i, NewCol).Value
      End If
    Next j
  Next i
  NoShops = ActiveSheet.Cells(8, 9).Value
'Update NoProjs
  ActiveSheet.Cells(7, 9) = ActiveSheet.Cells(7, 9).Value + NewProjNo
  NoProjs = ActiveSheet.Cells(7, 9).Value
End If

End Sub

'*************************************************************************
Public Sub InitialLayout()

  Dim NoActs As Integer, ActNo As Integer
  Dim ActEF As Integer, FirstActES As Integer
  Dim i As Integer

 'Clear Contents of Layout
  Range("B51:AD60").ClearContents
```

```
  For ProjNo = 1 To NoProjs
  'Activity 1
    FirstActES = ActiveSheet.Cells(ProjNo + 32, 2).Value
    If FirstActES < 1 Then                                  'For Act. (ES=0: Current Period) & (ES<=0: Previous Period)
      DayNo = 1
      For i = 1 To ActiveSheet.Cells(ProjNo + 32, 3).Value
        ActiveSheet.Cells(ProjNo + 50, 1 + i).Value = ActiveSheet.Cells(ProjNo + 16, 2).Value
        DayNo = DayNo + 1
      Next i
    Else
      DayNo = 1 + FirstActES
      For i = (FirstActES + 1) To ActiveSheet.Cells(ProjNo + 32, 3).Value
        ActiveSheet.Cells(ProjNo + 50, 1 + i).Value = ActiveSheet.Cells(ProjNo + 16, 2).Value
        DayNo = DayNo + 1
      Next i
    End If
  'Activity 2 & Following Activities
    NoActs = ActiveSheet.Cells(16 + ProjNo, 31)
    For ActNo = 2 To NoActs
      ActEF = ActiveSheet.Cells(ProjNo + 32, 1 + 2 * ActNo).Value
      Do
        ActiveSheet.Cells(ProjNo + 50, 1 + DayNo).Value = ActiveSheet.Cells(ProjNo + 16, 1 + 2 * ActNo).Value
        DayNo = DayNo + 1
      Loop While (DayNo <= ActEF)
    Next ActNo
    ActiveSheet.Cells(ProjNo + 50, 30).Value = DayNo – 1            'Project Duration
  Next ProjNo

End Sub

'*************************************************************************

Public Sub ResDemandChart()

  ShopNames = "EMCSP"
 'Clear Contents of Charts
  Range("B66:AC115").ClearContents
```

```
  For ProjNo = 1 To NoProjs
    For DayNo = 1 To ActiveSheet.Cells(ProjNo + 50, 30).Value
      For ShopNo = 0 To NoShops - 1
        If ActiveSheet.Cells(ProjNo + 50, DayNo + 1).Value = Mid(ShopNames, ShopNo + 1, 1) Then
          'Recursive Sub For moreThan 4 Projects
          Call DemandChart((75 + 10 * ShopNo), (DayNo + 1), ProjNo)
        End If
      Next ShopNo
    Next DayNo
  Next ProjNo

End Sub

'**************************************************************************

Private Sub DemandChart(Row As Integer, Col As Integer, Num As Integer)

  If InStr(ActiveSheet.Cells(Row, Col).Value, "P") > 0 Then
    Call DemandChart(Row - 1, Col, Num)
  Else
    ActiveSheet.Cells(Row, Col).Value = "P" & CStr(Num)
  End If

End Sub

'**************************************************************************

Public Sub DetermMostPCR()

  Dim NoResPerDay As Integer, ResUtilRatio As Integer          'Daily
  Dim NoUnderUtils As Integer, SumResUtils As Integer          'Period
  Dim LongProjDur As Integer                                   'Initial Required Duration of Longest Project
  Dim SortRange As String, LastRow As Integer
  Dim CopyShops As String, CopyValues As String
  Dim ShopCapa As Integer
  Dim i As Integer
```

```
'Clear Contents of Tables
  Range("C123:M128").ClearContents
'To find maximum of LongProjDur for scanning Initial Resource Demand Chart
  LastRow = 50 + NoProjs
  SortRange = "AD51:AD" & CStr(LastRow)
  LongProjDur = Application.WorksheetFunction.Max(ActiveSheet.Range(SortRange))
  For ShopNo = 0 To (NoShops - 1)
    NoResPerDay = 0
    NoUnderUtils = 0
    SumResUtils = 0
    For DayNo = 1 To LongProjDur
      For i = (66 + 10 * ShopNo) To (66 + 10 * ShopNo + 9)
        If InStr(ActiveSheet.Cells(i, DayNo + 1).Value, "P") > 0 Then
          NoResPerDay = NoResPerDay + 1
        End If
      Next i
      ShopCapa = ActiveSheet.Cells(123 + ShopNo, 2).Value
      ResUtilRatio = NoResPerDay / ShopCapa
      SumResUtils = SumResUtils + ResUtilRatio
      If ResUtilRatio < 1 Then
        NoUnderUtils = NoUnderUtils + 1
      End If
      NoResPerDay = 0
    Next DayNo
    ActiveSheet.Cells(123 + ShopNo, 4).Value = NoUnderUtils
    ActiveSheet.Cells(123 + ShopNo, 5).Value = SumResUtils
  Next ShopNo
'To determine Mostness of PCRs
  LastRow = 122 + NoShops
  CopyShops = "A122:A" & CStr(LastRow)
  CopyValues = "D122:F" & CStr(LastRow)
  SortRange = "J123:M" & CStr(LastRow)
'Copy
  ActiveSheet.Range(CopyShops).Copy Range("J122")
  ActiveSheet.Range(CopyValues).Copy Range("K122")
```

```
'Sort
  ActiveSheet.Range(SortRange).Sort _
    Key1:=ActiveSheet.Range("L123"), Order1:=xlDescending, _
    Key2:=ActiveSheet.Range("K123"), Order1:=xlAscending
  'Assign Mostness
  For i = 1 To NoShops
    ActiveSheet.Cells(122 + i, 13).Value = i
  Next i

End Sub
'**************************************************************************
```

A.2. APPLICATION OF HEURISTICS

```
'************************************************************************
   Option Explicit
   Public RuleName As String
   Public NoProjs As Integer, ProjNo As Integer
   Public NoDays As Integer, DayNo As Integer
   Public NoShops As Integer, ShopNo As Integer
   Dim SortRange As String, LastRow As Integer
   Dim Sentinel As Integer

'************************************************************************
Public Sub ExecuteProcedures()

   SelectHeuristics
   OrderBeforeHeuristics
   OrderAfterHeuristics
   GanttAfterHeuristics
   GanttAfterPrecSpace
   ConvertResToProject
   CopyToWindowsView

End Sub

'************************************************************************
Public Sub SelectHeuristics()

   dlgSelectHeuristic.Show
   RuleName = ActiveSheet.Cells(2, 26).Value
   'MsgBox "Again, Choice of Heuristic Rule is " & RuleName, , "Choice"

End Sub
'************************************************************************
```

```
'************************************************************************
Public Sub OrderBeforeHeuristics()

   Dim MaxNoActs As Integer, ActES As Integer
   Dim ColNo As Integer, Num As Integer
   Dim i As Integer, j As Integer

   NoProjs = Worksheets("Input&PCR").Cells(7, 9).Value
   NoShops = Worksheets("Input&PCR").Cells(8, 9).Value
   MaxNoActs = Application.WorksheetFunction.Max(Worksheets("Input&PCR").Range("AE17:AE20"))

 'Clear Contents of Tables
   Range("A5:Y20").ClearContents
   Num = 1
For ShopNo = 0 To NoShops - 1
 'Name of Shop
   ActiveSheet.Cells(5, 5 * ShopNo + 1).Value = Worksheets("Input&PCR").Cells(123 + ShopNo, 10).Value
 'Headers of Table
   ActiveSheet.Cells(6, 5 * ShopNo + 1).Value = "Act"          'Name of Act
   ActiveSheet.Cells(6, 5 * ShopNo + 2).Value = "P-D"          'Duration of Project
   ActiveSheet.Cells(6, 5 * ShopNo + 3).Value = "RAC"          'Remained After-Chain
   ActiveSheet.Cells(6, 5 * ShopNo + 4).Value = "ES"           'Early Start
   ActiveSheet.Cells(6, 5 * ShopNo + 5).Value = "A-D"          'Duration of Activity
   For j = 1 To MaxNoActs
      If j = 1 Then
         ColNo = 2
      Else
         ColNo = 2 * j + 1
      End If
      For i = 1 To NoProjs
         If Worksheets("Input&PCR").Cells(16 + i, ColNo).Value = Worksheets("Input&PCR").Cells(123 + _
                                                                   ShopNo, 10).Value Then
            ActiveSheet.Cells(6 + Num, 5 * ShopNo + 1).Value = "P" & CStr(i) & CStr(j)
            ActiveSheet.Cells(6 + Num, 5 * ShopNo + 2).Value = Worksheets("Input&PCR").Cells(50 + i, 30).Value
            ActES = Worksheets("Input&PCR").Cells(32 + i, 2 * j).Value
```

```
          'RemainAfterChain=ProjDur-ActES & Activity ES
           If ActES < 0 Then
              ActiveSheet.Cells(6 + Num, 5 * ShopNo + 3).Value = Worksheets("Input&PCR").Cells(50 + i, 30).Value
              ActiveSheet.Cells(6 + Num, 5 * ShopNo + 4).Value = -1            '<< Since for Priority, if < 0, Then All = Same
           Else
              ActiveSheet.Cells(6 + Num, 5 * ShopNo + 3).Value = Worksheets("Input&PCR").Cells(50 + i, 30).Value - ActES
              ActiveSheet.Cells(6 + Num, 5 * ShopNo + 4).Value = Worksheets("Input&PCR").Cells(32 + i, 2 * j).Value
           End If
           ActiveSheet.Cells(6 + Num, 5 * ShopNo + 5).Value = Worksheets("Input&PCR").Cells(16 + i, 2 * j + 2).Value
           Num = Num + 1
        End If
     Next i
  Next j
 'Number of Activities in Each Shop-flows
  ActiveSheet.Cells(5, 5 * ShopNo + 2).Value = Num - 1
  Num = 1
Next ShopNo

End Sub

'*********************************************************************

Public Sub OrderAfterHeuristics()

 'Application of Heuristics
  If InStr(ActiveSheet.Cells(2, 26).Value, "Period-PCR") > 0 Then     'InStr()  <- Since "  " was Used
     OrderPeriod_PCR
  Else
     OrderPeriod_Others
  End If

End Sub

'*********************************************************************
```

```
'*********************************************************************
Private Sub OrderPeriod_PCR()                                    'Period&FCFS-Based Heuristic

 'Clear Contents of Tables
   Range("AL18:AQ57").ClearContents                              'Different Heuristics (SASP)
   Range("A24:Y39").ClearContents                                'Erase before Filling
 'Copy for After-Heuristics
   ActiveSheet.Range("A5:Y20").Copy Range("A24")
   Sentinel = 0

Do
 '1'st Trade Sop
   LastRow = 25 + ActiveSheet.Cells(24, 2).Value
   SortRange = "A26:E" & CStr(LastRow)
 'Rule 0 (Continuing Act.) & Rule 0' (FCFS: Base Rule)
 'Rule 1 (Shortest After-Chain) & Rule 2 (Shortest Activity-Duration)
   ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("D26"), Order1:=xlAscending, _
     Key2:=ActiveSheet.Range("C26"), Order2:=xlAscending, Key3:=ActiveSheet.Range("E26"), Order3:=xlAscending
 '2'nd Trade Shop
   LastRow = 25 + ActiveSheet.Cells(24, 7).Value
   SortRange = "F26:J" & CStr(LastRow)
   ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("I26"), Order1:=xlAscending, _
     Key2:=ActiveSheet.Range("H26"), Order2:=xlAscending, Key3:=ActiveSheet.Range("J26"), Order3:=xlAscending
 '3'rd Trade Shop
   LastRow = 25 + ActiveSheet.Cells(24, 12).Value
   SortRange = "K26:O" & CStr(LastRow)
   ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("N26"), Order1:=xlAscending, _
     Key2:=ActiveSheet.Range("M26"), Order2:=xlAscending, Key3:=ActiveSheet.Range("O26"), Order3:=xlAscending
   If NoShops = 3 Then
     Exit Do
   End If
  '4'th Trade shop
   LastRow = 25 + ActiveSheet.Cells(24, 17).Value
   SortRange = "P26:T" & CStr(LastRow)
   ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("S26"), Order1:=xlAscending, _
```

```
    Key2:=ActiveSheet.Range("R26"), Order2:=xlAscending, Key3:=ActiveSheet.Range("T26"), Order3:=xlAscending
  If NoShops = 4 Then
    Exit Do
  End If
 '5'th Trade Shop
  LastRow = 25 + ActiveSheet.Cells(24, 22).Value
  SortRange = "U26:Y" & CStr(LastRow)
  ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("X26"), Order1:=xlAscending, _
    Key2:=ActiveSheet.Range("W26"), Order2:=xlAscending, Key3:=ActiveSheet.Range("Y26"), Order3:=xlAscending
  If NoShops = 5 Then
    Exit Do
  End If
Loop While (Sentinel <> 0)                    'Only Once Execution & Exit Based on NoShops

End Sub

'***********************************************************************
Private Sub OrderPeriod_Others()

  Dim CopyRange As String, RangeList As New Collection
  Dim NoRows As Integer, FirstRow As Integer, i As Integer
  Dim TargetCopyCell As String

  NoShops = Worksheets("Input&PCR").Cells(8, 9).Value
  RangeList.Add "A7:E", "1"
  RangeList.Add "F7:J", "2"
  RangeList.Add "K7:O", "3"
  RangeList.Add "P7:T", "4"
  RangeList.Add "U7:Y", "5"

 'Clear Contents of Tables
  Range("AL18:AQ57").ClearContents            'Erase before Filling
  Range("A24:Y39").ClearContents              'Clear Contents of PCR Table
 'Copy for After-Heuristics (Others)
  For ShopNo = 0 To NoShops - 1
```

```
    LastRow = 9 + ActiveSheet.Cells(5, 5 * ShopNo + 2).Value
   If LastRow > 9 Then
    CopyRange = RangeList.Item(CStr(ShopNo + 1)) & CStr(LastRow)
    If ShopNo = 0 Then
      FirstRow = 18
    Else
      NoRows = ActiveSheet.Cells(5, 5 * (ShopNo - 1) + 2).Value
      FirstRow = FirstRow + NoRows
    End If
    TargetCopyCell = "AL" & CStr(FirstRow)
    ActiveSheet.Range(CopyRange).Copy Range(TargetCopyCell)
    For i = FirstRow To (FirstRow + ActiveSheet.Cells(5, 5 * ShopNo + 2).Value - 1)    'For Shop-Name Col.
      ActiveSheet.Cells(i, 43).Value = ActiveSheet.Cells(5, 5 * ShopNo + 1).Value
    Next i
   End If
  Next ShopNo
  LastRow = FirstRow + NoRows
  SortRange = "AL18:AQ" & CStr(LastRow)

  If InStr(ActiveSheet.Cells(2, 26).Value, "FCFS-SASP") > 0 Then
   'Rule 0 (Earliest Start) & Rule 1 (Shortest Project-Duration) & Rule 2 (Shortest Activity-Duration)
    ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("AO18"), Order1:=xlAscending, _
      Key2:=ActiveSheet.Range("AM18"), Order2:=xlAscending, _
      Key3:=ActiveSheet.Range("AP18"), Order3:=xlAscending
  ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "Period-SASP") > 0 Then
   'Rule 1 (Shortest Project-Duration) & Rule 2 (Shortest Activity-Duration) & Other Rule (Earliest ES)
    ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("AM18"), Order1:=xlAscending, _
      Key2:=ActiveSheet.Range("AP18"), Order2:=xlAscending, _
      Key3:=ActiveSheet.Range("AO18"), Order3:=xlAscending
  ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "FCFS-SAC") > 0 Then
   'Rule 0 (Earliest Start) & Rule 1 (Shortest After-Chain) & Rule 2 (Shortest Activity-Duration)
    ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("AO18"), Order1:=xlAscending, _
      Key2:=ActiveSheet.Range("AN18"), Order2:=xlAscending, Key3:=ActiveSheet.Range("AP18"), Order3:=xlAscending
  ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "Period-SAC") > 0 Then
   'Rule 1 (Shortest After-Chain) & Rule 2 (Shortest Activity-Duration)
```

```
    ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("AN18"), Order1:=xlAscending, _
        Key2:=ActiveSheet.Range("AP18"), Order2:=xlAscending
  ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "FCFS-LAC") > 0 Then
   'Rule 0 (Earliest Start) & Rule 1 (Longest After-Chain) & Rule 2 (Longest Activity-Duration)
    ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("AO18"), Order1:=xlAscending, _
        Key2:=ActiveSheet.Range("AN18"), Order2:=xlDescending, _
        Key3:=ActiveSheet.Range("AP18"), Order3:=xlDescending
  ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "Period-LAC") > 0 Then
   'Rule 1 (Longest After-Chain) & Rule 2 (Longest Activity-Duration)
    ActiveSheet.Range(SortRange).Sort Key1:=ActiveSheet.Range("AN18"), Order1:=xlDescending, _
        Key2:=ActiveSheet.Range("AP18"), Order2:=xlDescending
  End If

End Sub

'**********************************************************************

Public Sub GanttAfterHeuristics()

  If InStr(ActiveSheet.Cells(2, 26).Value, "Period-PCR") > 0 Then
    GanttAfterHeuristics_PCR
  Else
    GanttAfterHeuristics_Others
  End If

End Sub

'**********************************************************************

Private Sub GanttAfterHeuristics_PCR()

  Dim ActName As String, NoActs As Integer, ActNo As Integer
  Dim i As Integer, j As Integer, k As Integer

 'Clear Contents of Chart
  Range("A48:AF53").ClearContents
```

```
For ShopNo = 0 To NoShops - 1
  ActiveSheet.Cells(48 + ShopNo, 1).Value = ActiveSheet.Cells(24, 5 * ShopNo + 1).Value        'Name of Shop
  k = 1
  For i = 1 To ActiveSheet.Cells(24, 5 * ShopNo + 2).Value
    ActName = ActiveSheet.Cells(25 + i, 5 * ShopNo + 1).Value
    ProjNo = CInt(Mid(ActName, 2, 1))
    ActNo = CInt(Mid(ActName, 3, 1))
    NoDays = Worksheets("Input&PCR").Cells(16 + ProjNo, 2 + 2 * ActNo).Value
    For j = 1 To NoDays
      ActiveSheet.Cells(48 + ShopNo, j + k).Value = ActName
    Next j
    k = k + NoDays
  Next i
 'Lengths of Resource Flows
  ActiveSheet.Cells(48 + ShopNo, 32).Value = (k - 1)
Next ShopNo

End Sub

'**************************************************************************

Private Sub GanttAfterHeuristics_Others()

  Dim ShopName As String, shopList As String
  Dim RowNo As Integer, ActName As String, ActNo As Integer
  Dim i As Integer, j As Integer, k As Integer
  Dim NoActsList As Integer, LastRowList As Integer
  Dim ActNameList As String, ProjNoList As Integer, ActNoList As Integer
  Dim ShopNameList As String, ShopNoList As Integer, DayNoList As Integer

 'Initialize openList
  Range("AV18:BA37").ClearContents                'Clear Contents of Open List
  ActiveSheet.Cells(16, 53).Value = 0             'NoActs of Open List
 'Clear Contents of Chart
  Range("A48:AF53").ClearContents
```

```
  NoShops = Worksheets("Input&PCR").Cells(8, 9).Value
  shopList = ""
  LastRow = 0
'Initialize shopList (String), and Row-Headers of Resource Chart
  For ShopNo = 0 To (NoShops - 1)                          'ShopNo starts from 0
    ShopName = ActiveSheet.Cells(5, 5 * ShopNo + 1).Value
    ActiveSheet.Cells(48 + ShopNo, 32).Value = 0           'Initial Length of Res.Flows
    shopList = shopList & ShopName
    ActiveSheet.Cells(48 + ShopNo, 1).Value = ShopName     'ShopName for Gantt
    ActiveSheet.Cells(59, 9 + ShopNo).Value = ShopName     'Header of Flow Length Table (ECMSP)
    LastRow = LastRow + ActiveSheet.Cells(5, 5 * ShopNo + 2).Value
  Next ShopNo
'Initialize Current ActNo of Each Project
  For i = 1 To NoProjs
    ActiveSheet.Cells(60, 20 + i).Value = 0
  Next i

  For RowNo = 1 To LastRow
    NoActsList = ActiveSheet.Cells(16, 53).Value       'To decide whether to check OpenList
    LastRowList = 16
    If NoActsList > 0 Then                             'Scan OpenList (List of Activities Those have not been scheduled
      k = 1
      For k = 1 To NoActsList                          'Because of Pecedence Constraints)
        NoActsList = ActiveSheet.Cells(16, 53).Value   'To Update LastRowList
        LastRowList = 17 + NoActsList
        ActNameList = ActiveSheet.Cells(17 + k, 48).Value
        ProjNoList = CInt(Mid(ActNameList, 2, 1))
        ActNoList = CInt(Mid(ActNameList, 3, 1))
        ShopNameList = ActiveSheet.Cells(17 + k, 53).Value
        ShopNoList = InStr(shopList, ShopNameList)
        DayNoList = ActiveSheet.Cells(47 + ShopNoList, 32).Value
        If ActNoList = (1 + ActiveSheet.Cells(60, 20 + ProjNoList).Value) Then      'If Succeeding Act exists
          For i = 1 To ActiveSheet.Cells(17 + k, 52).Value                          'For ActDuration
            ActiveSheet.Cells(47 + ShopNoList, 1 + DayNoList + i).Value = ActNameList
          Next i
```

```
ActiveSheet.Cells(47 + ShopNoList, 32).Value = DayNoList + ActiveSheet.Cells(17 + k, 52).Value
ActiveSheet.Cells(60, 20 + ProjNoList).Value = ActNoList            'Current ActNo
'Remove the Activity From OpenList
For j = 1 To 6
  ActiveSheet.Cells(17 + k, 47 + j).Value = ""
Next j
LastRowList = 17 + NoActsList

'Sort OpenList by Heuristic Rules
If InStr(ActiveSheet.Cells(2, 26).Value, "FCFS-SASP") > 0 Then
 'Rule 0 (Earliest Start) & Rule 1 (Shortest Project-Duration) & Rule 2 (Shortest Activity-Duration)
  Range("AV18:BA" & CStr(LastRowList)).Sort Key1:=ActiveSheet.Range("AY18"), Order1:=xlAscending, _
      Key2:=ActiveSheet.Range("AW18"), Order2:=xlAscending,_
      Key3:=ActiveSheet.Range("AZ18"), Order3:=xlAscending
ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "Period-SASP") > 0 Then
 'Rule 1 (Shortest Project-Duration) & Rule 2 (Shortest Activity-Duration) & Other Rule (Earliest ES)
  Range("AV18:BA" & CStr(LastRowList)).Sort Key1:=ActiveSheet.Range("AW18"), Order1:=xlAscending, _
      Key2:=ActiveSheet.Range("AZ18"), Order2:=xlAscending,_
      Key3:=ActiveSheet.Range("AY18"), Order3:=xlAscending
ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "FCFS-SAC") > 0 Then
 'Rule 0 (Earliest Start) & Rule 1 (Shortest After-Chain) & Rule 2 (Shortest Activity-Duration)
  Range("AV18:BA" & CStr(LastRowList)).Sort Key1:=ActiveSheet.Range("AY18"), Order1:=xlAscending, _
      Key2:=ActiveSheet.Range("AX18"), Order2:=xlAscending, _
      Key3:=ActiveSheet.Range("AZ18"), Order3:=xlAscending
ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "Period-SAC") > 0 Then
 'Rule 1 (Shortest After-Chain) & Rule 2 (Shortest Activity-Duration)
  Range("AV18:BA" & CStr(LastRowList)).Sort Key1:=ActiveSheet.Range("AX18"), Order1:=xlAscending, _
      Key2:=ActiveSheet.Range("AZ18"), Order2:=xlAscending
ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "FCFS-LAC") > 0 Then
 'Rule 0 (Earliest Start) & Rule 1 (Longest After-Chain) & Rule 2 (Longest Activity-Duration)
  Range("AV18:BA" & CStr(LastRowList)).Sort Key1:=ActiveSheet.Range("AY18"), Order1:=xlAscending, _
      Key2:=ActiveSheet.Range("AX18"), Order2:=xlDescending,_
      Key3:=ActiveSheet.Range("AZ18"), Order3:=xlDescending
```

```
        ElseIf InStr(ActiveSheet.Cells(2, 26).Value, "Period-LAC") > 0 Then
       'Rule 1 (Longest After-Chain) & Rule 2 (Longest Activity-Duration)
        Range("AV18:BA" & CStr(LastRowList)).Sort Key1:=ActiveSheet.Range("AX18"), Order1:=xlDescending,_
            Key2:=ActiveSheet.Range("AZ18"), Order2:=xlDescending
        End If
        k = k - 1
        ActiveSheet.Cells(16, 53).Value = NoActsList - 1              'Decrease NoActsList
      End If
      Next k
    Loop While (k <= ActiveSheet.Cells(16, 53).Value)
  End If
  ActName = ActiveSheet.Cells(17 + RowNo, 38).Value
  ProjNo = CInt(Mid(ActName, 2, 1))
  ActNo = CInt(Mid(ActName, 3, 1))
  ShopName = ActiveSheet.Cells(17 + RowNo, 43).Value
  ShopNo = InStr(shopList, ShopName)                                  'ShopNo starts from 1
  DayNo = ActiveSheet.Cells(47 + ShopNo, 32).Value                    'Current Length of Each ResFlow

  If ActNo = (1 + ActiveSheet.Cells(60, 20 + ProjNo).Value) Then
    If (ActNo = 1) And (DayNo < ActiveSheet.Cells(17 + RowNo, 41).Value) Then
      DayNo = ActiveSheet.Cells(17 + RowNo, 41).Value
    End If
    For i = 1 To ActiveSheet.Cells(17 + RowNo, 42).Value              'For ActDuration
      ActiveSheet.Cells(47 + ShopNo, 1 + DayNo + i).Value = ActName
    Next i
  ActiveSheet.Cells(47 + ShopNo, 32).Value = DayNo + ActiveSheet.Cells(17 + RowNo, 42).Value   'Flow Length
  ActiveSheet.Cells(60, 20 + ProjNo).Value = ActNo                    'Current ActNo
  Else                                                                'Add CurrentAct to Open List
    LastRowList = 17 + ActiveSheet.Cells(16, 53).Value + 1
    For j = 1 To 6
      ActiveSheet.Cells(LastRowList, 47 + j).Value = ActiveSheet.Cells(17 + RowNo, 37 + j).Value
    Next j
    ActiveSheet.Cells(16, 53).Value = ActiveSheet.Cells(16, 53).Value + 1   'Increase NoActsList
  End If
Next RowNo
```

```
If ActiveSheet.Cells(16, 53).Value > 0 Then                'Allocate Activities Remained in OpenList
  Do                                                       '(Because of Pecedence Constraints)
    k = 1
    For k = 1 To NoActsList
      NoActsList = ActiveSheet.Cells(16, 53).Value                              'To Update LastRowList
      LastRowList = 17 + NoActsList
      ActNameList = ActiveSheet.Cells(17 + k, 48).Value
      ProjNoList = CInt(Mid(ActNameList, 2, 1))
      ActNoList = CInt(Mid(ActNameList, 3, 1))
      ShopNameList = ActiveSheet.Cells(17 + k, 53).Value
      ShopNoList = InStr(shopList, ShopNameList)
      DayNoList = ActiveSheet.Cells(47 + ShopNoList, 32).Value
      If ActNoList = (1 + ActiveSheet.Cells(60, 20 + ProjNoList).Value) Then     'If Succeeding Act
        For i = 1 To ActiveSheet.Cells(17 + k, 52).Value                         'For ActDuration
          ActiveSheet.Cells(47 + ShopNoList, 1 + DayNoList + i).Value = ActNameList
        Next i
        ActiveSheet.Cells(47 + ShopNoList, 32).Value = DayNoList + ActiveSheet.Cells(17 + k, 52).Value  'Flow Length
        ActiveSheet.Cells(60, 20 + ProjNoList).Value = ActNoList                 'Current ActNo
       'Remove the Activity From OpenList
        For j = 1 To 6
          ActiveSheet.Cells(17 + k, 47 + j).Value = ""
        Next j
        LastRowList = 17 + NoActsList
        ActiveSheet.Cells(16, 53).Value = NoActsList - 1          'Decrease NoActsList
      End If
      Next k
    Loop While (k <= ActiveSheet.Cells(16, 53).Value)
  Loop While (ActiveSheet.Cells(16, 53).Value > 0)
End If

End Sub
'***************************************************************************
```

```
'************************************************************************
Public Sub GanttAfterPrecSpace()

  Dim ActName As String, NoActs As Integer, ActNo As Integer, ActDur As Integer
  Dim ScanActName As String, ScanProjNo As Integer, ScanActNo As Integer, ScanActDur As Integer
  Dim ActDelay As Integer, NoMoves As Integer, NoShifts As Integer
  Dim i As Integer, j As Integer, k As Integer, d As Integer, m As Integer
  Dim EndDay As Integer, DayNo As Integer, DayNo2 As Integer

 'Copy Heuristic Results
  ActiveSheet.Range("A48:AE53").Copy Range("A63")
  Range("AF63:CC68").ClearContents
  For i = 1 To NoShops
    ActiveSheet.Cells(59, 8 + i).Value = ActiveSheet.Cells(47 + i, 1).Value
    ActiveSheet.Cells(60, 8 + i).Value = ActiveSheet.Cells(47 + i, 32).Value
  Next i

Do  'Repeat Until no Right-Shift (Delay due to Res. Contention).
 'Initialize NoShift and Current ActNo of Each Project
  NoShifts = 0
  For i = 1 To NoProjs
    ActiveSheet.Cells(60, 20 + i).Value = 0
  Next i
  For ShopNo = 0 To NoShops - 1
    i = 1
    For i = 1 To ActiveSheet.Cells(X, Y).Value
      ActName = ActiveSheet.Cells(63 + ShopNo, 1 + i).Value
     If StrComp(ActName, "") <> 0 Then                        'When ""(idleTime), Skip
      ProjNo = CInt(Mid(ActName, 2, 1))
      ActNo = CInt(Mid(ActName, 3, 1))
      If ActNo = 1 Then                                       'Just Skip
        ActiveSheet.Cells(60, 20 + ProjNo).Value = ActNo
    'Look for Precedent Activity in This Project That can Delay This Activity
      ElseIf ActNo <> ActiveSheet.Cells(60, 20 + ProjNo).Value Then        'Only 1'st Day of Activity
        ActiveSheet.Cells(60, 20 + ProjNo).Value = ActNo
```

```
For j = 0 To NoShops - 1
 If ShopNo <> j Then                                    'Currently, NOT scan the shop of Act
  For k = 1 To ActiveSheet.Cells(60, 9 + j).Value
    ScanActName = ActiveSheet.Cells(63 + j, 1 + k).Value
   If StrComp(ScanActName, "") <> 0 Then                'When ""(idleTime), Skip
    ScanProjNo = CInt(Mid(ScanActName, 2, 1))
    ScanActNo = CInt(Mid(ScanActName, 3, 1))
    ScanActDur = Worksheets("Input&PCR").Cells(16 + ScanProjNo, 2 + 2 * ScanActNo).Value
   'When conflict, Right-Shift(delay) the current activity
    If (ScanProjNo = ProjNo And ScanActNo < ActNo And k >= i) Or _
      (ScanProjNo = ProjNo And ScanActNo < ActNo And (k < i And (k + ScanActDur - 1) >= i) And _
      (StrComp(ScanActName, ActiveSheet.Cells(63 + j, k).Value) <> 0)) Then
      ActDelay = ((1 + k) + ScanActDur) - (i + 1)
    'Copy from End for Delay
      NoMoves = ActiveSheet.Cells(60, 9 + ShopNo).Value - i + 1
      For d = 0 To NoMoves - 1
        ActiveSheet.Cells(63 + ShopNo, 1 + ActiveSheet.Cells(60, 9 + ShopNo).Value + ActDelay - d).Value _
         = ActiveSheet.Cells(63 + ShopNo, 1 + ActiveSheet.Cells(60, 9 + ShopNo).Value - d).Value
        NoShifts = NoShifts + 1
      Next d
      ActiveSheet.Cells(60, 9 + ShopNo).Value = ActiveSheet.Cells(60, 9 + ShopNo).Value + ActDelay
      For d = 0 To ActDelay - 1
        ActiveSheet.Cells(63 + ShopNo, 1 + i + d).Value = ""
      Next d
    'Jump to the Next Act of Scanned Shop.
      k = k + ScanActDur - 1
    'New Delayed DayNo of Act.
      i = i + ActDelay
      EndDay = ActiveSheet.Cells(60, 9 + ShopNo).Value
      DayNo = i
      For DayNo = i To EndDay
        If StrComp(ActiveSheet.Cells(63 + ShopNo, DayNo + 1).Value, "") = 0 Then
          For DayNo2 = DayNo To EndDay - 1
            ActiveSheet.Cells(63 + ShopNo, DayNo2 + 1).Value = ActiveSheet.Cells(63 + ShopNo, _
                                                                DayNo2 + 2).Value
```

```
                    Next DayNo2
                    ActiveSheet.Cells(63 + ShopNo, EndDay + 1).Value = ""
                    ActiveSheet.Cells(60, 9 + ShopNo).Value = ActiveSheet.Cells(60, 9 + ShopNo).Value - 1
                  End If
                Next DayNo
              End If   'If ScanProjNo...
             End If   'If StrComp(ScanActName...
            Next k
           End If   'If ShopNo...
          Next j
        'Else   'Case: Not 1'st Day of Activity = Leave as it is.
        End If
       End If      'If StrComp(ActName...
       NoDays = ActiveSheet.Cells(60, 9 + ShopNo).Value
      Next i
    Next ShopNo
  Loop While (NoShifts > 0)

  End Sub

  '*******************************************************************************
  Public Sub ConvertResToProject()

    Dim ActName As String

   'Clear Contents of Tables
    Range("B75: AO84").ClearContents

    For ShopNo = 0 To NoShops - 1
      NoDays = ActiveSheet.Cells(60, 9 + ShopNo).Value
      For DayNo = 1 To NoDays
        ActName = ActiveSheet.Cells(63 + ShopNo, 1 + DayNo).Value
        If StrComp(ActName, "") <> 0 Then                    'When ""(idleTime), Skip
          ProjNo = CInt(Mid(ActName, 2, 1))
          ActiveSheet.Cells(74 + ProjNo, 1 + DayNo).Value = ActName
```

```
      End If
    Next DayNo
  Next ShopNo

End Sub

'*******************************************************************************
Public Sub CopyToWindowsView()

  Dim PeriodStart As Integer, PrevNoProjs As Integer, PrevTotalNoProjs As Integer
  Dim i As Integer, j As Integer, k As Integer, a As Integer
  Dim ShopIndex As Integer
  Dim ActName As String, NewActName As String

  PeriodStart = Worksheets("Input&PCR").Cells(7, 3).Value

'Integrate (Copy) Current Schedule into Existing Multiple Periods
'Resource View
  For ShopNo = 0 To 5
    For DayNo = 1 To 40
      ActiveSheet.Cells(94 + ShopNo, PeriodStart + DayNo).Value = ""
    Next DayNo
  Next ShopNo
  For i = 1 To NoShops
    ShopIndex = InStr(ActiveSheet.Cells(91, 6).Value, ActiveSheet.Cells(62 + i, 1).Value)
    For j = 1 To 40
      ActName = ActiveSheet.Cells(62 + i, 1 + j).Value
      If StrComp(ActName, "") <> 0 Then
        If Worksheets("Input&PCR").Cells(15, 35).Value = 0 Then
          ActiveSheet.Cells(93 + ShopIndex, PeriodStart + j).Value = ActName
        Else
          If CInt(Mid(ActName, 2, 1)) < Worksheets("Input&PCR").Cells(17, 35).Value Then
            ActiveSheet.Cells(93 + ShopIndex, PeriodStart + j).Value = ActName
          Else
            For k = 1 To Worksheets("Input&PCR").Cells(15, 35).Value        'PreNoProjs
```

```
              If CInt(Mid(ActName, 2, 1)) = Worksheets("Input&PCR").Cells(16 + k, 35).Value Then
                For a = 1 To Worksheets("Input&PCR").Cells(29, 35).Value   'PreNoActs
                  If StrComp(Mid(ActName, 2, 2), CStr(Worksheets("Input&PCR").Cells(30 + a, 35).Value)) = 0 Then
                  NewActName = CStr(Worksheets("Input&PCR").Cells(30 + a, 33).Value)
                  End If
                Next a
                ActiveSheet.Cells(93 + ShopIndex, PeriodStart + j).Value = "P" & NewActName
              End If
            Next k
          End If     'CInt
        End If     'Worksheets
      End If     'StrComp
    Next j
  Next i

'Project View
  For ProjNo = 1 To 10
    For DayNo = 1 To 40
      ActiveSheet.Cells(105 + ProjNo, PeriodStart + DayNo).Value = ""
    Next DayNo
  Next ProjNo
  PrevNoProjs = Worksheets("Input&PCR").Cells(10, 42).Value
  PrevTotalNoProjs = Worksheets("Input&PCR").Cells(12, 42).Value
  For i = 1 To NoProjs
    For j = 1 To 40
      ActName = ActiveSheet.Cells(74 + i, 1 + j).Value
      If StrComp(ActName, "") <> 0 Then
        If Worksheets("Input&PCR").Cells(15, 35).Value = 0 Then
          ActiveSheet.Cells(105 + PrevTotalNoProjs + i, PeriodStart + j).Value = ActName
        Else
          If CInt(Mid(ActName, 2, 1)) < Worksheets("Input&PCR").Cells(17, 35).Value Then
            ActiveSheet.Cells(105 + PrevTotalNoProjs + i, PeriodStart + j).Value = ActName
          Else
            For k = 1 To Worksheets("Input&PCR").Cells(15, 35).Value                    'PreNoProjs
              If CInt(Mid(ActName, 2, 1)) = Worksheets("Input&PCR").Cells(16 + k, 35).Value Then
```

```
            For a = 1 To Worksheets("Input&PCR").Cells(15, 61).Value              'PreNoActs
              If StrComp(Mid(ActName, 2, 2), CStr(Worksheets("Input&PCR").Cells(30 + a, 35).Value)) = 0 Then
                NewActName = CStr(Worksheets("Input&PCR").Cells(16 + a, 61).Value)
              End If
            Next a
            ActiveSheet.Cells((105 + PrevTotalNoProjs - PrevNoProjs + _
                Worksheets("Input&PCR").Cells(16 + k, 33).Value), (PeriodStart + j)).Value = "P" & NewActName
          End If
        Next k
      End If
    End If
  End If
 Next j
Next i

End Sub
'************************************************************************
```

A.3. SELECTION OF HEURISTICS

```
'*************************************************************************
Option Explicit
Public RuleName As String

'*************************************************************************
Private Sub UserForm_Initialize()
   lstHeuristics.AddItem "(P-1)  Period-Based PCR"
   lstHeuristics.AddItem "(P-2)  Period-Based SASP"
   lstHeuristics.AddItem "(P-3)  Period-Based SAC"
   lstHeuristics.AddItem "(P-4)  Period-Based LAC"
   lstHeuristics.AddItem "(F-1)  FCFS-Based SASP"
   lstHeuristics.AddItem "(F-2)  FCFS-Based SAC"
   lstHeuristics.AddItem "(F-3)  FCFS-Based LAC"
End Sub

'*************************************************************************
Private Sub cmdCancel_Click()
   Unload Me
End Sub

'*************************************************************************
Private Sub cmdSelect_Click()
   ActivateSelectedHeuristic
End Sub

'*************************************************************************
Private Sub ActivateSelectedHeuristic()
   If lstHeuristics.ListIndex = 0 Then
      RuleName = "Period-PCR"
   ElseIf lstHeuristics.ListIndex = 1 Then
      RuleName = "Period-SASP"
   ElseIf lstHeuristics.ListIndex = 2 Then
      RuleName = "Period-SAC"
   ElseIf lstHeuristics.ListIndex = 3 Then
```

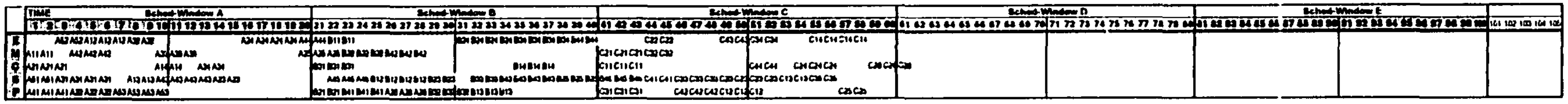
```
      RuleName = "Period-LAC"
    ElseIf lstHeuristics.ListIndex = 4 Then
      RuleName = "FCFS-SASP"
    ElseIf lstHeuristics.ListIndex = 5 Then
      RuleName = "FCFS-SAC"
    ElseIf lstHeuristics.ListIndex = 6 Then
      RuleName = "FCFS-LAC"
    End If
    Worksheets("Heuristics").Cells(2, 26).Value = "  " & RuleName   '2 Spaces: not to left-justified
    Unload Me
End Sub
'***************************************************************************
```

APPENDIX B: SAMPLE OUTPUTS OF SIMULATION RUNS

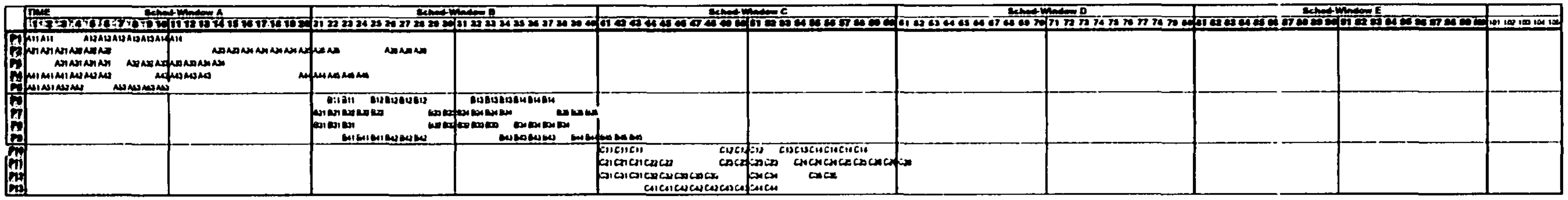
B.1. SIMULATION RUN 16

B.1.1. Period-PCR

(a) Resource Schedule Chart

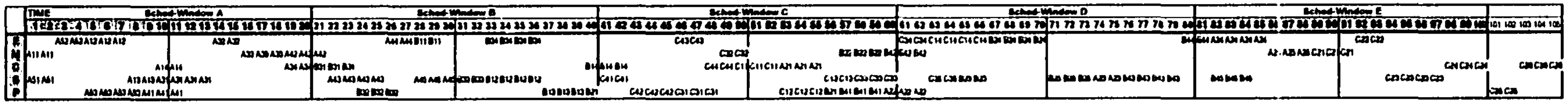


(b) Project Gantt Chart

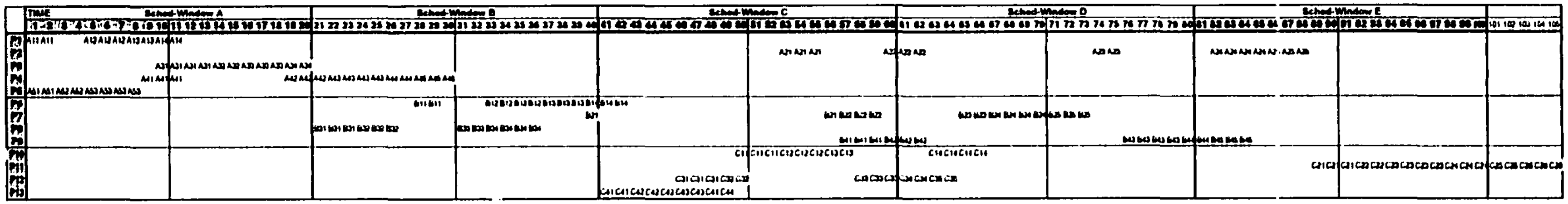


B.1.2. Period-SASP

(a) Resource Schedule Chart

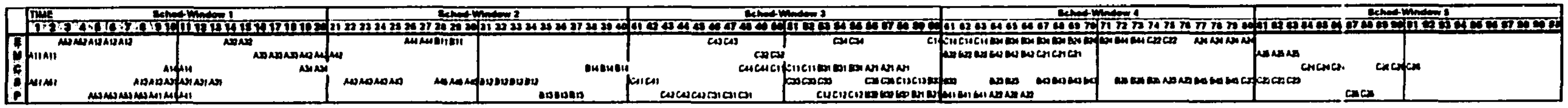


(b) Project Gantt Chart

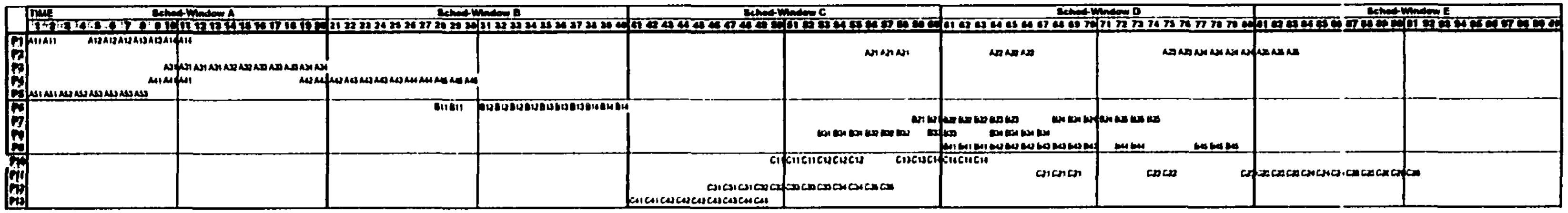


B.1.3. Period-SAC

(a) Resource Schedule Chart

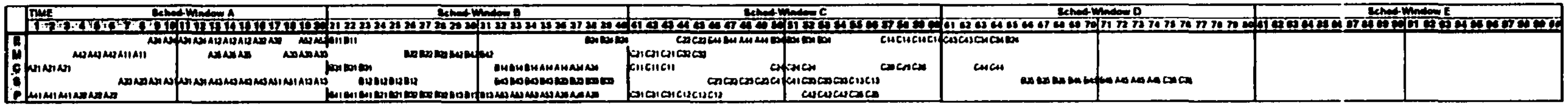


(b) Project Gantt Chart

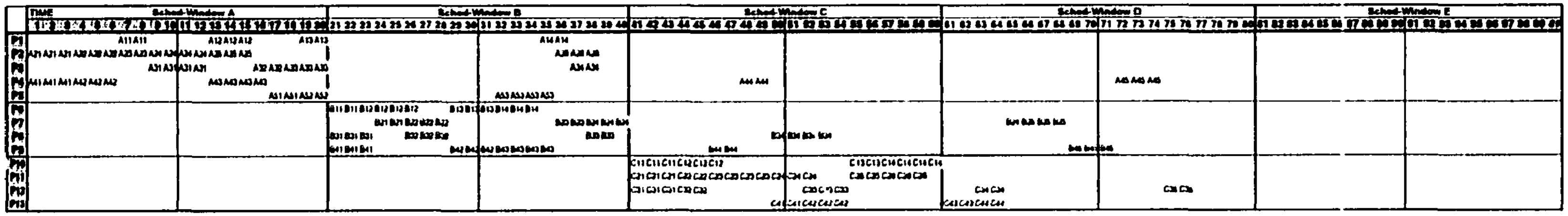


B.1.4. Period-LAC

(a) Resource Schedule Chart



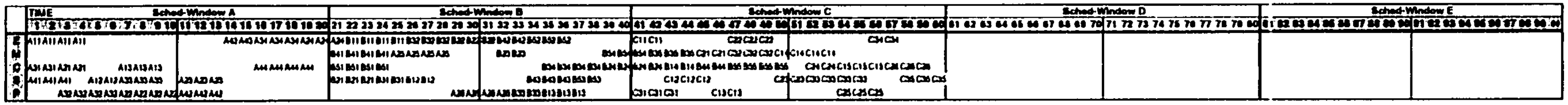
(b) Project Gantt Chart



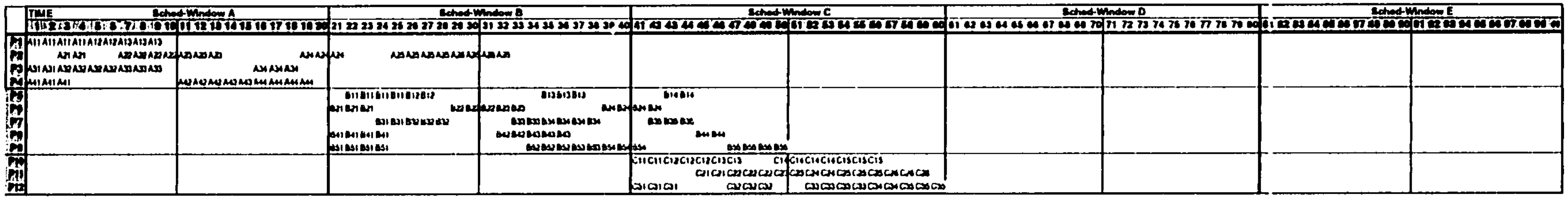
B.2. SIMULATION RUN 35

B.2.1. Period-PCR

(a) Resource Schedule Chart

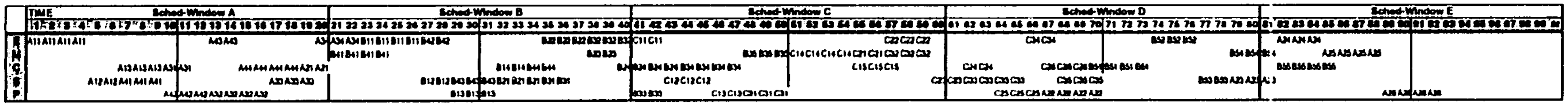


(b) Project Gantt Chart

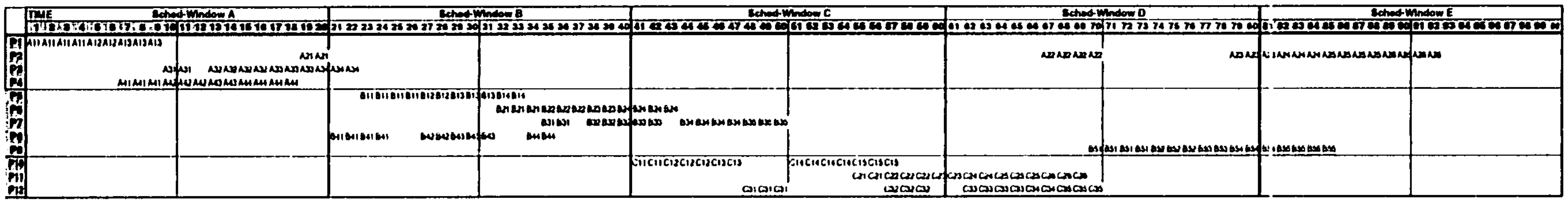


B.2.2. Period-SASP

(a) Resource Schedule Chart

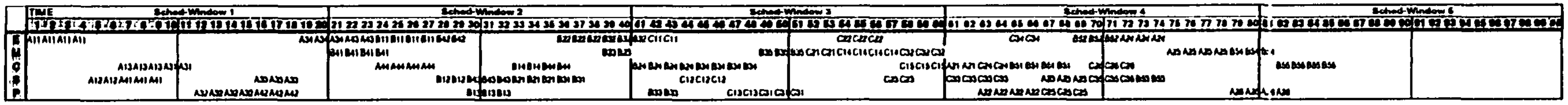


(b) Project Gantt Chart

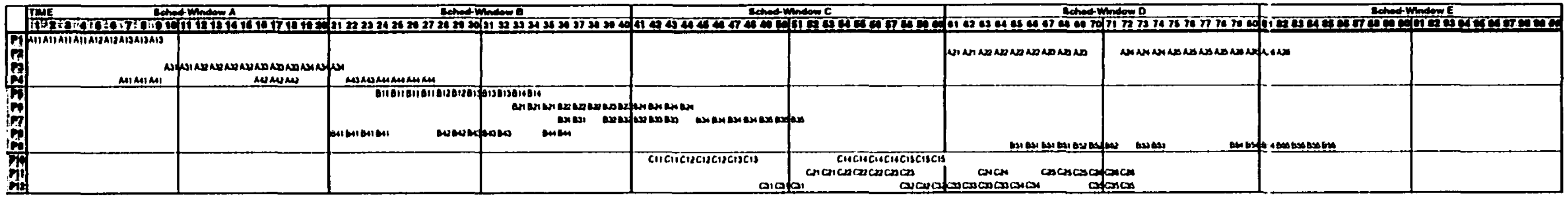


B.2.3. Period-SAC

(a) Resource Schedule Chart

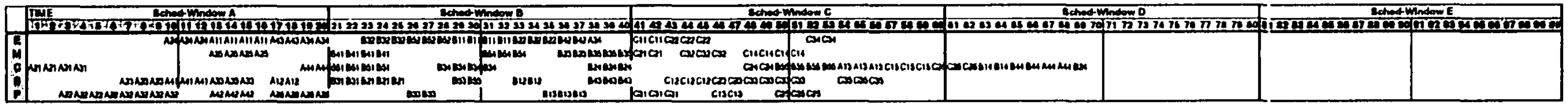


(b) Project Gantt Chart

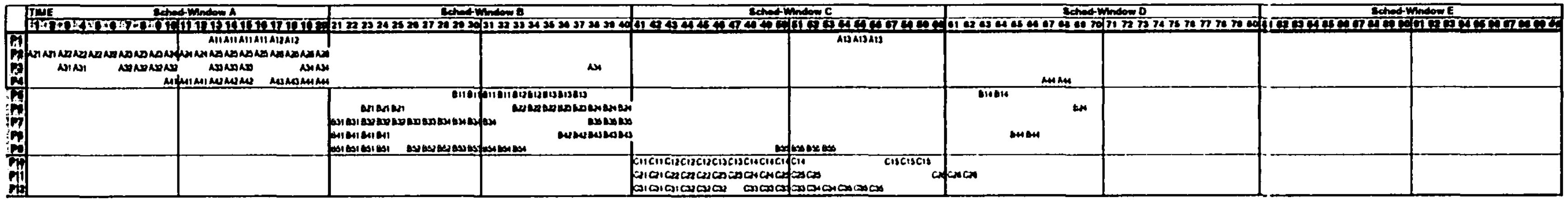


B.2.4. Period-LAC

(a) Resource Schedule Chart



(b) Project Gantt Chart



APPENDIX C: SIMULATION RESULTS OF SCHEDULING HEURISTICS

C.1. PROJECT DURATION AND COMPLETION-TIME

C.1.1. Scheduling Window 1

Run	P1					P2					P3				
	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC
Avg.	12.175	17.025	24.35	21.1	29.25	12.825	18.95	31.45	26.9	30.25	12.775	18.175	34.75	27.75	32.725
1	8	11	18	18	40	9	10	9	9	39	15	21	77	72	36
2	13	18	25	25	15	12	21	35	40	20	15	26	94	86	33
3	15	22	27	24	19	13	20	13	13	70	16	22	104	28	38
4	16	19	22	22	16	16	19	24	24	18	12	12	12	12	18
5	12	13	12	14	16	16	20	28	22	16	12	13	12	12	18
6	8	11	8	8	17	15	22	30	35	18	9	19	13	18	55
7	12	20	47	33	20	11	17	16	16	63	16	27	85	81	35
8	12	16	16	16	12	11	12	11	11	18	14	19	30	25	16
9	16	22	24	24	20	10	13	14	14	17	6	8	6	6	64
10	9	15	9	9	18	10	20	13	13	20	12	21	20	20	20
11	12	25	24	24	74	14	26	71	68	19	14	32	48	59	17
12	12	20	28	17	12	12	23	31	20	37	12	26	34	12	40
13	17	22	89	27	73	14	20	14	14	20	15	18	26	23	18
14	12	17	20	27	16	9	17	11	11	16	8	9	8	8	15
15	12	17	12	12	13	15	19	33	25	17	13	18	23	13	16
16	9	11	11	11	36	18	28	88	83	38	11	14	20	20	38
17	9	11	9	9	18	12	15	21	16	14	17	19	74	34	19
18	15	29	61	36	68	15	27	88	80	40	12	15	12	12	17
19	6	6	6	6	18	12	16	78	40	15	14	17	24	24	19
20	12	20	24	39	18	9	11	15	16	17	16	22	73	90	63
21	16	19	49	49	20	16	23	40	40	39	6	7	6	6	64
22	12	18	25	23	54	11	14	13	14	16	13	24	47	38	19
23	16	19	24	24	39	14	19	17	17	40	11	14	11	11	38
24	10	16	21	21	16	15	20	50	50	56	9	17	9	9	55
25	13	16	35	21	19	12	19	14	16	20	15	21	52	25	39
26	14	17	27	26	62	12	16	17	19	68	15	21	62	40	24
27	12	15	17	12	67	12	17	15	18	74	18	23	100	50	18
28	15	18	21	22	19	17	21	71	29	17	12	14	12	12	16
29	12	18	13	15	19	13	16	23	19	18	12	15	17	12	16
30	12	16	33	17	18	15	19	42	42	64	12	15	23	21	57
31	12	13	12	12	13	15	16	23	23	16	16	18	42	27	18
32	14	23	26	29	34	12	19	12	19	18	12	17	12	12	64
33	13	33	51	53	40	11	28	17	17	66	12	22	38	35	64
34	12	15	17	18	39	9	14	9	9	19	9	12	13	13	17
35	9	9	9	9	56	16	32	92	78	20	12	18	22	21	38
36	12	17	17	25	39	12	27	17	32	35	12	21	21	17	35
37	6	6	6	6	29	20	28	80	25	20	16	18	16	16	39
38	17	18	41	27	19	9	12	9	9	40	15	19	22	22	62
39	12	17	27	23	16	6	7	6	6	17	12	15	30	41	13
40	11	13	11	11	13	13	15	48	24	15	13	18	40	27	18

Run	P4					P5					P6				
	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC
Avg.	12.6	19.433	29.6	23.4	35.633	11.824	19.294	29.412	30.059	31.588	10.571	17.571	17.857	18.857	32.857
1	12	15	47	21	19	12	16	29	25	19					
2	9	13	9	9	38	12	18	35	35	34	11	15	18	18	40
3	14	23	18	21	19										
4															
5	16	17	28	22	61										
6	9	11	17	13	17	12	23	21	26	56					
7	11	19	22	22	65	12	29	27	29	45	9	15	9	9	67
8															
9	16	33	37	37	31										
10	13	27	40	24	33										
11	9	17	9	9	17	12	27	27	27	16	9	19	12	12	19
12	12	18	23	26	36										
13															
14	12	19	19	19	18	15	22	32	49	16					
15															
16	15	24	30	30	16	8	10	8	8	35					
17															
18	12	19	16	16	69	14	24	30	30	58					
19	12	14	14	14	13										
20	9	15	9	9	60	13	20	43	45	19	12	17	28	25	15
21	15	18	25	25	18	12	15	16	16	60					
22	12	23	40	33	38	12	16	33	26	20	9	12	9	9	18
23															
24	15	25	36	36	20	9	15	14	14	18					
25	12	17	18	12	20										
26	9	13	9	9	73	15	24	68	62	17					
27	15	20	24	29	20										
28															
29	15	24	45	21	69										
30	12	17	25	23	36	8	10	8	8	40					
31															
32	17	25	107	49	36										
33	9	23	9	9	59	14	36	77	77	14	11	22	22	22	36
34	18	29	88	31	38										
35	12	19	18	27	38										
36	15	19	77	73	67	9	10	9	9	58	13	23	27	37	35
37															
38															
39	9	12	11	11	10	12	13	23	25	12					
40	12	15	18	22	15										

C.1.2. Scheduling Window 2

Run	P1					P2					P3					P4					P5					P6				
	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC
Avg.	12.675	18.9	33.475	29.775	30.4	12.475	19.15	32.25	28.325	27.75	12.95	19.625	35.925	36.125	26.25	12.12	21.12	33.24	29.16	37.52	12.286	20.357	33.286	30.286	33.643	14.667	27.333	54.667	48.333	30
1	9	12	17	17	13	11	17	38	38	17	9	15	13	13	19	6	7	6	6	15										
2	12	13	28	31	16	12	18	24	26	15	14	19	65	66	16															
3	11	17	18	16	20	15	20	74	60	18	12	18	28	23	15															
4	11	18	11	12	50	15	25	56	28	33	12	21	23	16	17	13	23	38	26	52	12	26	26	19	20					
5	9	14	17	15	39	12	22	33	27	43	12	20	37	36	20	12	25	40	23	37	9	14	20	11	41					
6	12	25	25	25	19	12	22	22	54	29	13	22	43	66	18	12	23	27	48	19	8	12	8	8	17	13	22	59	62	15
7	10	13	14	20	29	13	16	48	37	41	12	16	23	29	17															
8	11	16	14	11	20	12	19	31	21	18	12	21	28	26	30	12	18	24	16	46	16	23	50	31	20					
9	16	24	79	58	16	8	14	8	8	17	12	18	35	20	19	12	18	29	23	18										
10	12	16	45	40	14	9	16	9	9	15	12	17	30	19	14	12	20	45	26	17										
11	9	17	12	12	47	12	23	26	23	12	15	26	57	54	20	11	20	18	18	49										
12	13	25	64	40	45	12	20	32	22	18	11	19	16	11	47	12	22	36	17	42	12	24	28	26	49					
13	9	13	15	16	47	16	24	46	40	43	14	23	27	28	37	9	9	15	13	43	12	16	37	31	20					
14	15	20	85	23	47	14	17	44	17	45	15	22	84	38	49															
15	16	37	39	34	50	12	16	17	14	18	12	20	21	18	15	20	38	65	73	47	9	12	9	9	55	14	23	38	27	45
16	12	17	22	20	14	14	20	53	54	48	12	18	16	47	33	15	23	64	59	51										
17	14	18	34	52	40	12	20	23	26	35	11	17	15	18	37	20	41	71	79	20	8	12	8	8	42					
18	12	16	19	20	16	12	14	22	26	13	17	27	87	84	15															
19	11	14	18	28	54	14	19	28	48	49	14	20	27	60	26	9	15	13	13	49	16	23	86	67	16					
20	17	17	87	78	17	10	11	10	10	40	16	18	53	50	43															
21	15	20	25	25	34	9	14	12	12	42	18	32	52	52	18	9	12	16	16	37										
22	15	20	67	61	15	13	19	49	27	20	12	14	33	24	16															
23	9	14	11	11	20	9	12	13	18	18	16	27	31	61	20	11	20	17	22	38	15	23	56	57	16					
24	15	21	63	40	17	15	20	68	53	20	9	17	9	9	33	13	22	23	23	28										
25	15	21	64	25	19	12	37	25	18	20	8	8	8	11	17															
26	12	15	27	26	54	9	9	23	15	18	17	23	71	57	46	9	12	19	19	51										
27	17	24	42	68	43	14	19	14	18	49	17	23	57	76	46															
28	12	23	17	40	43	18	40	105	62	19	13	22	28	27	40	10	22	10	10	34	12	30	21	17	54	17	37	67	56	30
29	12	17	17	17	18	15	19	52	23	20	9	12	9	9	15															
30	16	16	54	31	20	13	13	26	16	20	18	18	89	46	18															
31	14	24	57	61	51	12	15	12	16	42	17	30	81	72	39	15	27	72	66	45	12	18	15	22	48					
32	11	15	11	14	16	15	21	61	56	20	12	19	23	21	18															
33	8	15	8	8	19	12	20	20	23	17	18	32	86	78	18															
34	12	19	12	20	49	13	19	20	28	20	14	18	36	54	16	15	28	68	39	48										
35	11	24	13	14	44	12	22	23	24	49	14	24	30	31	20	11	26	15	16	46	16	30	65	65	33					
36	14	20	28	48	15	11	18	12	22	43	13	20	21	36	45															
37	13	17	25	26	47	9	13	14	15	43	9	15	9	10	48	14	22	59	39	17	15	22	37	53	40					
38	15	20	36	27	44	20	30	69	70	30	9	9	9	21	39	9	15	9	16	43										
39	14	20	45	26	17	12	17	19	18	14	9	11	13	12	14															
40	16	29	54	35	18	9	16	9	11	19	9	14	14	16	17	12	20	32	23	46										

C.1.3. Scheduling Window 3

Run	P1 Dur	P1 PCR	P1 SASP	P1 SAC	P1 LAC	P2 Dur	P2 PCR	P2 SASP	P2 SAC	P2 LAC
Avg.	12.625	19.55	31.875	25.925	22.7	13.375	20.725	34.475	29.475	23.875
1	12	21	35	24	12	12	19	39	28	29
2	12	17	33	39	15	9	9	17	20	20
3	9	14	21	16	21	12	27	42	25	24
4	14	18	23	23	25	16	25	45	31	32
5	13	21	34	34	27	11	19	24	20	25
6	9	14	14	11	12	9	16	14	20	12
7	12	20	19	25	29	12	18	22	20	16
8	15	23	59	36	28	11	15	17	22	26
9	12	26	47	26	18	12	31	43	33	21
10	16	20	53	33	19	14	19	39	24	19
11	12	16	22	14	25	9	11	17	9	33
12	13	23	41	34	27	11	18	23	15	31
13	16	27	56	37	17	12	19	23	17	27
14	14	28	71	36	24	9	17	33	17	22
15	14	25	30	18	48	20	34	48	46	50
16	12	18	46	23	20	17	21	85	51	19
17	11	23	25	23	19	20	34	54	52	21
18	8	12	30	14	22	17	27	85	57	25
19	11	13	19	12	36	15	22	50	43	30
20	9	9	10	12	24	15	18	50	56	19
21	15	21	44	40	21	9	15	9	9	18
22	9	10	12	16	21	12	14	39	24	18
23	12	16	22	21	20	16	22	48	43	20
24	14	18	21	27	17	15	20	34	39	19
25	16	26	56	32	22	12	20	29	12	25
26	20	31	62	49	23	12	20	17	13	29
27	14	20	34	33	32	12	17	20	19	29
28	9	21	17	16	19	16	31	38	33	32
29	11	19	11	11	26	15	24	40	32	28
30	17	24	51	45	23	12	19	18	16	18
31	11	18	11	11	36	12	16	23	23	16
32	16	25	55	50	25	12	18	21	25	25
33	12	15	23	25	19	15	23	49	43	22
34	11	17	11	20	24	12	16	26	27	23
35	14	16	17	20	19	15	19	29	32	22
36	9	15	9	9	15	16	25	47	41	21
37	9	11	9	10	21	12	16	20	30	25
38	16	29	32	35	19	16	29	37	40	19
39	16	23	75	56	19	12	16	12	32	26
40	10	19	15	21	19	19	30	53	40	19

Run	P3 Dur	P3 PCR	P3 SASP	P3 SAC	P3 LAC	P4 Dur	P4 PCR	P4 SASP	P4 SAC	P4 LAC
Avg.	13.125	20.2	36.8	31.525	23.675	12.455	20.273	33.636	27.97	23.091
1	14	25	51	43	33	14	27	54	46	20
2	12	17	35	33	17	11	19	23	26	22
3	12	18	35	31	17	9	16	15	10	17
4	9	15	9	13	34	14	21	27	27	28
5	13	22	37	37	23	8	10	8	11	18
6	12	22	30	37	14	9	18	17	24	15
7	14	23	36	34	19					
8	12	18	28	39	27	16	27	47	40	23
9	12	23	35	21	18	11	28	23	14	23
10	10	11	13	10	18	16	22	51	31	18
11	16	20	47	40	22	16	20	50	43	21
12	12	15	33	27	19	14	26	53	39	23
13	14	23	34	29	21	17	29	65	46	35
14	12	23	39	25	22	14	28	64	43	26
15	9	21	14	19	53					
16	12	15	44	17	36	9	12	29	9	24
17	9	15	11	9	22	9	17	9	14	24
18	18	27	103	68	24	9	10	35	19	21
19	11	15	28	21	39	11	17	23	16	41
20	11	17	21	23	22	13	17	40	37	25
21	12	19	24	24	14	11	20	17	17	26
22	15	15	62	41	23	16	18	78	46	17
23	12	13	25	12	16	12	15	21	26	20
24	15	19	33	45	18					
25	18	31	66	42	28	11	18	19	12	23
26	15	22	37	28	25					
27	16	24	50	53	32	12	21	14	23	34
28	12	24	20	19	29					
29	13	24	23	19	26	20	32	51	43	23
30	16	22	34	36	21					
31	12	21	19	18	34	12	17	24	31	23
32	19	28	80	61	19	9	16	9	13	23
33	15	24	50	52	21	12	17	29	19	19
34	17	25	79	49	26	16	24	62	46	21
35	15	20	30	32	16					
36	15	21	31	36	16	12	20	16	23	17
37	15	24	55	45	15	12	21	24	24	17
38	9	14	9	21	23	9	20	11	16	25
39	14	20	56	46	22	16	26	82	63	25
40	6	13	6	6	23	11	20	20	26	25

Run	P5 Dur	P5 PCR	P5 SASP	P5 SAC	P5 LAC	P6 Dur	P6 PCR	P6 SASP	P6 SAC	P6 LAC
Avg.	12.0	19.625	35.875	25.75	25.5	12.5	28	55.5	33	30
3	11	24	23	18	29	12	30	39	35	27
12	9	11	13	9	25					
14	6	7	26	10	31	13	26	72	31	33
18	12	18	53	31	19					
25	15	28	45	24	25					
29	12	21	16	16	28					
32	15	21	29	47	24					
39	16	27	82	51	23					

Runs 1–40 with no P5 or P6 entries are not listed in this last table; their P5 and P6 cells are empty.

C.2. COMPLETION-TIME / PROJECT DURATION RATIO (CDR)

C.2.1. Scheduling Window 1

Run	P1 Dur	P1 PCR	P1 SASP	P1 SAC	P1 LAC	P2 Dur	P2 PCR	P2 SASP	P2 SAC	P2 LAC	P3 Dur	P3 PCR	P3 SASP	P3 SAC	P3 LAC
Avg.	12.175	1.39	1.90	1.69	2.50	12.825	1.48	2.27	1.99	2.46	12.775	1.43	2.49	2.04	2.87
1	8	1.38	2.25	2.25	5.00	9	1.11	1.00	1.00	4.33	15	1.40	5.13	4.80	2.40
2	13	1.38	1.92	1.92	1.15	12	1.75	2.92	3.33	1.67	15	1.73	6.27	5.73	2.20
3	15	1.47	1.80	1.60	1.27	13	1.54	1.00	1.00	5.38	16	1.38	6.50	1.75	2.38
4	16	1.19	1.38	1.38	1.00	16	1.19	1.50	1.50	1.13	12	1.00	1.00	1.00	1.50
5	12	1.08	1.00	1.17	1.33	16	1.25	1.75	1.38	1.00	12	1.08	1.00	1.00	1.50
6	8	1.38	1.00	1.00	2.13	15	1.47	2.00	2.33	1.20	9	2.11	1.44	2.00	6.11
7	12	1.67	3.92	2.75	1.67	11	1.55	1.45	1.45	5.73	16	1.69	5.31	5.06	2.19
8	12	1.33	1.33	1.33	1.00	11	1.09	1.00	1.00	1.64	14	1.36	2.14	1.79	1.14
9	16	1.38	1.50	1.50	1.25	10	1.30	1.40	1.40	1.70	6	1.33	1.00	1.00	1.07
10	9	1.67	1.00	1.00	2.00	10	2.00	1.30	1.30	2.00	12	1.75	1.67	1.67	1.67
11	12	2.08	2.00	2.00	6.17	14	1.86	5.07	4.86	1.36	14	2.29	3.43	4.21	1.21
12	12	1.67	2.33	1.42	1.00	12	1.92	2.58	1.67	3.08	12	2.17	2.83	1.00	3.33
13	17	1.29	5.24	1.59	4.29	14	1.43	1.00	1.00	1.43	15	1.20	1.73	1.53	1.20
14	12	1.42	1.67	2.25	1.33	9	1.89	1.22	1.22	1.78	8	1.13	1.00	1.00	1.88
15	12	1.42	1.00	1.00	1.08	15	1.27	2.20	1.67	1.13	13	1.38	1.77	1.00	1.23
16	9	1.22	1.22	1.22	4.00	18	1.56	4.89	4.61	2.11	11	1.27	1.82	1.82	3.45
17	9	1.22	1.00	1.00	2.00	12	1.25	1.75	1.33	1.17	17	1.12	4.35	2.00	1.12
18	15	1.93	4.07	2.40	4.53	15	1.80	5.87	5.33	2.67	12	1.25	1.00	1.00	1.42
19	6	1.00	1.00	1.00	3.00	12	1.33	6.50	3.33	1.25	14	1.21	1.71	1.71	1.36
20	12	1.67	2.00	3.25	1.50	9	1.22	1.67	1.78	1.89	16	1.38	4.56	5.63	3.94
21	16	1.19	3.06	3.06	1.25	16	1.44	2.50	2.50	2.44	6	1.17	1.00	1.00	1.07
22	12	1.50	2.08	1.92	4.50	11	1.27	1.18	1.27	1.45	13	1.85	3.62	2.92	1.46
23	16	1.19	1.50	1.50	2.44	14	1.36	1.21	1.21	2.86	11	1.27	1.00	1.00	3.45
24	10	1.60	2.10	2.10	1.60	15	1.33	3.33	3.33	3.73	9	1.89	1.00	1.00	6.11
25	13	1.23	2.69	1.62	1.46	12	1.58	1.17	1.33	1.67	15	1.40	3.47	1.67	2.60
26	14	1.21	1.93	1.86	4.43	12	1.33	1.42	1.58	5.67	15	1.40	4.13	2.67	1.60
27	12	1.25	1.42	1.00	5.58	12	1.42	1.25	1.50	6.17	18	1.28	5.56	2.78	1.00
28	15	1.20	1.40	1.47	1.27	17	1.24	4.18	1.71	1.00	12	1.17	1.00	1.00	1.33
29	12	1.50	1.08	1.25	1.58	13	1.23	1.77	1.46	1.38	12	1.25	1.42	1.00	1.33
30	12	1.33	2.75	1.42	1.50	15	1.27	2.80	2.80	4.27	12	1.25	1.92	1.75	4.75
31	12	1.08	1.00	1.00	1.08	15	1.07	1.53	1.53	1.07	16	1.13	2.63	1.69	1.13
32	14	1.64	1.86	2.07	2.43	12	1.58	1.00	1.58	1.50	12	1.42	1.00	1.00	5.33
33	13	2.54	3.92	4.08	3.08	11	2.55	1.55	1.55	6.00	12	1.83	3.17	2.92	5.33
34	12	1.25	1.42	1.50	3.25	9	1.56	1.00	1.00	2.11	9	1.33	1.44	1.44	1.89
35	9	1.00	1.00	1.00	6.22	16	2.00	5.75	4.88	1.25	12	1.50	1.83	1.75	3.17
36	12	1.42	1.42	2.08	3.25	12	2.25	1.42	2.67	2.92	12	1.75	1.75	1.42	2.92
37	6	1.00	1.00	1.00	4.83	20	1.40	4.00	1.25	1.00	16	1.13	1.00	1.00	2.44
38	17	1.06	2.41	1.59	1.12	9	1.33	1.00	1.00	4.44	15	1.27	1.47	1.47	4.13
39	12	1.42	2.25	1.92	1.33	6	1.17	1.00	1.00	2.83	12	1.25	2.50	3.42	1.08
40	11	1.18	1.00	1.00	1.18	13	1.15	3.69	1.85	1.15	13	1.38	3.08	2.08	1.38

Run	P4 Dur	P4 PCR	P4 SASP	P4 SAC	P4 LAC	P5 Dur	P5 PCR	P5 SASP	P5 SAC	P5 LAC	P6 Dur	P6 PCR	P6 SASP	P6 SAC	P6 LAC
Avg.	12.6	1.55	2.18	1.78	2.9798	11.824	1.60	2.34	2.32	2.85	10.571	1.67	1.63	1.70	3.20
1	12	1.25	3.92	1.75	1.5833	12	1.33	2.42	2.08	1.58					
2	9	1.44	1.00	1.00	4.2222	12	1.50	2.92	2.92	2.83	11	1.36	1.64	1.64	3.64
3	14	1.64	1.29	1.50	1.3571										
4															
5	16	1.06	1.75	1.38	3.8125										
6	9	1.22	1.89	1.44	1.8889	12	1.92	1.75	2.17	4.67					
7	11	1.73	2.00	2.00	5.9091	12	2.42	2.25	2.42	3.75	9	1.67	1.00	1.00	7.44
8															
9	16	2.06	2.31	2.31	1.9375										
10	13	2.08	3.08	1.85	2.5385										
11	9	1.89	1.00	1.00	1.8889	12	2.25	2.25	2.25	1.33	9	2.11	1.33	1.33	2.11
12	12	1.50	1.92	2.17	3										
13															
14	12	1.58	1.58	1.58	1.5	15	1.47	2.13	3.27	1.07					
15															
16	15	1.60	2.00	2.00	1.0667	8	1.25	1.00	1.00	4.38					
17															
18	12	1.58	1.33	1.33	5.75	14	1.71	2.14	2.14	4.14					
19	12	1.17	1.17	1.17	1.0833										
20	9	1.67	1.00	1.00	6.6667	13	1.54	3.31	3.46	1.46	12	1.42	2.33	2.08	1.25
21	15	1.20	1.67	1.67	1.2	12	1.25	1.33	1.33	5.00					
22	12	1.92	3.33	2.75	3.1667	12	1.33	2.75	2.17	1.67	9	1.33	1.00	1.00	2.00
23															
24	15	1.67	2.40	2.40	1.3333	9	1.67	1.56	1.56	2.00					
25	12	1.42	1.50	1.00	1.6667										
26	9	1.44	1.00	1.00	8.1111	15	1.60	4.53	4.13	1.13					
27	15	1.33	1.60	1.93	1.3333										
28															
29	15	1.60	3.00	1.40	4.6										
30	12	1.42	2.08	1.92	3	8	1.25	1.00	1.00	5.00					
31															
32	17	1.47	6.29	2.88	2.1176										
33	9	2.56	1.00	1.00	6.5556	14	2.57	5.50	5.50	1.00	11	2.00	2.00	2.00	3.27
34	18	1.61	4.89	1.72	2.1111										
35	12	1.58	1.50	2.25	3.1667										
36	15	1.27	5.13	4.87	4.4667	9	1.11	1.00	1.00	6.44	13	1.77	2.08	2.85	2.69
37															
38															
39	9	1.33	1.22	1.22	1.1111	12	1.08	1.92	2.08	1.00					
40	12	1.25	1.50	1.83	1.25										

C.2.2. Scheduling Window 2

Run	P1					P2					P3				
	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC
Avg.	12.775	1.50	2.44	2.22	2.50	12.475	1.54	2.42	2.17	2.29	13.0	1.51	2.55	2.60	2.11
1	9	1.33	1.89	1.89	1.44	11	1.55	3.45	3.45	1.55	9	1.67	1.44	1.44	2.11
2	12	1.08	2.33	2.58	1.33	12	1.50	2.00	2.17	1.25	14	1.36	4.64	4.71	1.14
3	11	1.55	1.64	1.45	1.82	15	1.33	4.93	4.00	1.20	12	1.50	2.33	1.92	1.25
4	11	1.64	1.00	1.09	4.55	15	1.67	3.73	1.87	2.20	12	1.75	1.92	1.33	1.42
5	9	1.56	1.89	1.67	4.33	12	1.83	2.75	2.25	3.58	12	1.67	3.08	3.00	1.67
6	12	2.08	2.08	2.08	1.58	12	1.83	1.83	4.50	2.42	13	1.69	3.31	5.08	1.38
7	10	1.30	1.40	2.00	2.90	13	1.23	3.69	2.85	3.15	12	1.33	1.92	2.42	1.42
8	11	1.45	1.27	1.00	1.82	12	1.58	2.58	1.75	1.50	12	1.75	2.33	2.17	2.50
9	16	1.50	4.94	3.63	1.00	8	1.75	1.00	1.00	2.13	12	1.50	2.92	1.67	1.58
10	12	1.33	3.75	3.33	1.17	9	1.78	1.00	1.00	1.67	12	1.42	2.50	1.58	1.17
11	9	1.89	1.33	1.33	5.22	12	1.92	2.17	1.92	1.00	15	1.73	3.80	3.60	1.33
12	13	1.92	4.92	3.08	3.46	12	1.67	2.67	1.83	1.50	11	1.73	1.45	1.00	4.27
13	9	1.44	1.67	1.78	5.22	16	1.50	2.88	2.50	2.69	14	1.64	1.93	2.00	2.64
14	15	1.33	5.67	1.53	3.13	14	1.21	3.14	1.21	3.21	15	1.47	5.60	2.53	3.27
15	16	2.31	2.44	2.13	3.13	12	1.33	1.42	1.17	1.50	12	1.67	1.75	1.50	1.25
16	12	1.42	1.83	1.67	1.17	14	1.43	3.79	3.86	3.43	12	1.50	1.33	3.92	2.75
17	14	1.29	2.43	3.71	2.86	12	1.67	1.92	2.17	2.92	11	1.55	1.36	1.64	3.36
18	12	1.33	1.58	1.67	1.33	12	1.17	1.83	2.17	1.08	17	1.59	5.12	4.94	0.88
19	11	1.27	1.64	2.55	4.91	14	1.36	2.00	3.43	3.50	14	1.43	1.93	4.29	1.86
20	17	1.00	5.12	4.59	1.00	10	1.10	1.00	1.00	4.00	16	1.13	3.31	3.13	2.69
21	15	1.33	1.67	1.67	2.27	9	1.56	1.33	1.33	4.67	18	1.78	2.89	2.89	1.00
22	15	1.33	4.47	4.07	1.00	13	1.46	3.77	2.08	1.54	12	1.17	2.75	2.00	1.33
23	9	1.56	1.22	1.22	2.22	9	1.33	1.44	2.00	2.00	16	1.69	1.94	3.81	1.25
24	15	1.40	4.20	2.67	1.13	15	1.33	4.53	3.53	1.33	9	1.89	1.00	1.00	3.67
25	15	1.40	4.27	1.67	1.27	12	3.08	2.08	1.50	1.67	8	1.00	1.00	1.38	2.13
26	12	1.25	2.25	2.17	4.50	9	1.00	2.56	1.67	2.00	17	1.35	4.18	3.35	2.71
27	17	1.41	2.47	4.00	2.53	14	1.36	1.00	1.29	3.50	17	1.35	3.35	4.47	2.71
28	12	1.92	1.42	3.33	3.58	18	2.22	5.83	3.44	1.06	13	1.69	2.15	2.08	3.08
29	12	1.42	1.42	1.42	1.50	15	1.27	3.47	1.53	1.33	9	1.33	1.00	1.00	1.67
30	16	1.00	3.38	1.94	1.25	13	1.00	2.00	1.23	1.54	18	1.00	4.94	2.56	1.01
31	14	1.71	4.07	4.36	3.64	12	1.25	1.00	1.33	3.50	17	1.76	4.76	4.24	2.29
32	11	1.36	1.00	1.27	1.45	15	1.40	4.07	3.73	1.33	12	1.58	1.92	1.75	1.50
33	8	1.88	1.00	1.00	2.38	12	1.67	1.67	1.92	1.42	18	1.78	4.78	4.33	1.00
34	12	1.58	1.00	1.67	4.08	13	1.46	1.54	2.15	1.54	14	1.29	2.57	3.86	1.14
35	11	2.18	1.18	1.27	4.00	12	1.83	1.92	2.00	4.08	14	1.71	2.14	2.21	1.43
36	14	1.43	2.00	3.43	1.07	11	1.64	1.09	2.00	3.91	13	1.54	1.62	2.77	3.46
37	13	1.31	1.92	2.00	3.62	9	1.44	1.56	1.67	4.78	9	1.67	1.00	1.11	5.33
38	15	1.33	2.40	1.80	2.93	20	1.50	3.45	3.50	1.50	9	1.00	1.00	2.33	4.33
39	14	1.43	3.21	1.86	1.21	12	1.42	1.58	1.50	1.17	9	1.22	1.44	1.33	1.56
40	16	1.81	3.38	2.19	1.13	9	1.78	1.00	1.22	2.11	9	1.56	1.56	1.78	1.89

Run	P4					P5					P6				
	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC
Avg.	12.12	1.71	2.53	2.22	3.27	12.286	1.65	2.47	2.24	2.87	14.667	1.84	3.73	3.33	2.04
1	6	1.17	1.00	1.00	2.50										
2															
3															
4	13	1.77	2.92	2.00	4.00	12	2.17	2.17	1.58	1.67					
5	12	2.08	3.33	1.92	3.08	9	1.56	2.22	1.22	4.56					
6	12	1.92	2.25	4.00	1.58	8	1.50	1.00	1.00	2.13	13	1.69	4.54	4.77	1.15
7															
8	12	1.50	2.00	1.33	3.83	16	1.44	3.13	1.94	1.25					
9	12	1.50	2.42	1.92	1.50										
10	12	1.67	3.75	2.17	1.42										
11	11	1.82	1.64	1.64	4.45										
12	12	1.83	3.00	1.42	3.50	12	2.00	2.33	2.17	4.08					
13	9	1.00	1.67	1.44	4.78	12	1.33	3.08	2.58	1.67					
14															
15	20	1.90	3.25	3.65	2.35	9	1.33	1.00	1.00	6.11	14	1.64	2.71	1.93	3.21
16	15	1.53	4.27	3.93	3.40										
17	20	2.05	3.55	3.95	1.00	8	1.50	1.00	1.00	5.25					
18															
19	9	1.67	1.44	1.44	5.44	16	1.44	5.38	4.19	1.00					
20															
21	9	1.33	1.78	1.78	4.11										
22															
23	11	1.82	1.55	2.00	3.45	15	1.53	3.73	3.80	1.07					
24	13	1.69	1.77	1.77	2.15										
25															
26	9	1.33	2.11	2.11	5.67										
27															
28	10	2.20	1.00	1.00	3.40	12	2.50	1.75	1.42	4.50	17	2.18	3.94	3.29	1.76
29															
30															
31	15	1.80	4.80	4.40	3.00	12	1.50	1.25	1.83	4.00					
32															
33															
34	15	1.87	4.53	2.60	3.20										
35	11	2.36	1.36	1.45	4.18	16	1.88	4.06	4.06	2.06					
36															
37	14	1.57	4.21	2.79	1.21	15	1.47	2.47	3.53	0.87					
38	9	1.67	1.00	1.78	4.78										
39															
40	12	1.67	2.67	1.92	3.83										

C.2.3. Scheduling Window 3

Run	P1					P2					P3					P4					P5					P6				
	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC
Avg.	12.625	1.54	2.41	1.98	1.87	13.375	1.55	2.49	2.13	1.85	13.125	1.56	2.64	2.30	1.92	12.455	1.64	2.53	2.15	1.94	12.0	1.60	2.96	2.02	2.40	12.5	2.25	4.39	2.65	2.39
1	12	1.75	2.92	2.00	1.00	12	1.58	3.25	2.33	2.42	14	1.79	3.64	3.07	2.36	14	1.93	3.86	3.29	1.43										
2	12	1.42	2.75	3.25	1.25	9	1.00	1.89	2.22	2.22	12	1.42	2.92	2.75	1.42	11	1.73	2.09	2.36	2.00										
3	9	1.56	2.33	1.78	2.33	12	2.25	3.50	2.08	2.00	12	1.50	2.92	2.58	1.42	9	1.78	1.67	1.11	1.89	11	2.18	2.09	1.64	2.64	12	2.50	3.25	2.92	2.25
4	14	1.29	1.64	1.64	1.79	16	1.56	2.81	1.94	2.00	9	1.67	1.00	1.44	3.78	14	1.50	1.93	1.93	2.00										
5	13	1.62	2.62	2.62	2.08	11	1.73	2.18	1.82	2.27	13	1.69	2.85	2.85	1.77	8	1.25	1.00	1.38	2.25										
6	9	1.56	1.56	1.22	1.33	9	1.78	1.56	2.22	1.33	12	1.83	2.50	3.08	1.17	9	2.00	1.89	2.67	1.67										
7	12	1.67	1.58	2.08	2.42	12	1.50	1.83	1.67	1.33	14	1.64	2.57	2.43	1.36															
8	15	1.53	3.93	2.40	1.87	11	1.36	1.55	2.00	2.36	12	1.50	2.33	3.25	2.25	16	1.69	2.94	2.50	1.44										
9	12	2.17	3.92	2.17	1.50	12	2.58	3.58	2.75	1.75	12	1.92	2.92	1.75	1.50	11	2.55	2.09	1.27	2.09										
10	16	1.25	3.31	2.06	1.19	14	1.36	2.79	1.71	1.36	10	1.10	1.30	1.00	1.80	16	1.38	3.19	1.94	1.13										
11	12	1.33	1.83	1.17	2.08	9	1.22	1.89	1.00	3.67	16	1.25	2.94	2.50	1.38	16	1.25	3.13	2.69	1.31										
12	13	1.77	3.15	2.62	2.08	11	1.64	2.09	1.36	2.82	12	1.25	2.75	2.25	1.58	14	1.86	3.79	2.79	1.64	9	1.22	1.44	1.00	2.78					
13	16	1.69	3.50	2.31	1.06	12	1.58	1.92	1.42	2.25	14	1.64	2.43	2.07	1.50	17	1.71	3.82	2.71	2.06										
14	14	2.00	5.07	2.57	1.71	9	1.89	3.67	1.89	2.44	12	1.92	3.25	2.08	1.83	14	2.00	4.57	3.07	1.86	6	1.17	4.33	1.67	5.17	13	2.00	5.54	2.38	2.54
15	14	1.79	2.14	1.29	3.43	20	1.70	2.40	2.30	2.50	9	2.33	1.56	2.11	5.89															
16	12	1.50	3.83	1.92	1.67	17	1.24	5.00	3.00	1.12	12	1.25	3.67	1.42	3.00	9	1.33	3.22	1.00	2.67										
17	11	2.09	2.27	2.09	1.73	20	1.70	2.70	2.60	1.05	9	1.67	1.22	1.00	2.44	9	1.89	1.00	1.56	2.67										
18	8	1.50	3.75	1.75	2.75	17	1.59	5.00	3.35	1.47	18	1.50	5.72	3.78	1.33	9	1.11	3.89	2.11	2.33	12	1.50	4.42	2.58	1.58					
19	11	1.18	1.73	1.09	3.27	15	1.47	3.33	2.87	2.00	11	1.36	2.55	1.91	3.55	11	1.55	2.09	1.45	3.73										
20	9	1.00	1.11	1.33	2.67	15	1.20	3.33	3.73	1.27	11	1.55	1.91	2.09	2.00	13	1.31	3.08	2.85	1.92										
21	15	1.40	2.93	2.67	1.40	9	1.67	1.00	1.00	2.00	12	1.58	2.00	2.00	1.17	11	1.82	1.55	1.55	2.36										
22	9	1.11	1.33	1.78	2.33	12	1.17	3.25	2.00	1.50	15	1.00	4.13	2.73	1.53	16	1.13	4.88	2.88	1.06										
23	12	1.33	1.83	1.75	1.67	16	1.38	3.00	2.69	1.25	12	1.08	2.08	1.00	1.33	12	1.25	1.75	2.17	1.67										
24	14	1.29	1.50	1.93	1.21	15	1.33	2.27	2.60	1.27	15	1.27	2.20	3.00	1.20															
25	16	1.63	3.50	2.00	1.38	12	1.67	2.42	1.00	2.08	18	1.72	3.67	2.33	1.56	11	1.64	1.73	1.09	2.09	15	1.87	3.00	1.60	1.67					
26	20	1.55	3.10	2.45	1.15	12	1.67	1.42	1.08	2.42	15	1.47	2.47	1.87	1.67															
27	14	1.43	2.43	2.36	2.29	12	1.42	1.67	1.58	2.42	16	1.50	3.13	3.31	2.00	12	1.75	1.17	1.92	2.83										
28	9	2.33	1.89	1.78	2.11	16	1.94	2.38	2.06	2.00	12	2.00	1.67	1.58	2.42															
29	11	1.73	1.00	1.00	2.36	15	1.60	2.67	2.13	1.87	13	1.85	1.77	1.46	2.00	20	1.60	2.55	2.15	1.15	12	1.75	1.33	1.33	2.33					
30	17	1.41	3.00	2.65	1.35	12	1.58	1.50	1.33	1.50	16	1.38	2.13	2.25	1.31															
31	11	1.64	1.00	1.00	3.27	12	1.33	1.92	1.92	1.33	12	1.75	1.58	1.50	2.83	12	1.42	2.00	2.58	1.92										
32	16	1.56	3.44	3.13	1.56	12	1.50	1.75	2.08	2.08	19	1.47	4.21	3.21	1.00	9	1.78	1.00	1.44	2.56	15	1.40	1.93	3.13	1.60					
33	12	1.25	1.92	2.08	1.58	15	1.53	3.27	2.87	1.47	15	1.60	3.33	3.47	1.40	12	1.42	2.42	1.58	1.58										
34	11	1.55	1.00	1.82	2.18	12	1.33	2.17	2.25	1.92	17	1.47	4.65	2.88	1.53	16	1.50	3.88	2.88	1.31										
35	14	1.14	1.21	1.43	1.36	15	1.27	1.93	2.13	1.47	15	1.33	2.00	2.13	1.07															
36	9	1.67	1.00	1.00	1.67	16	1.56	2.94	2.56	1.31	15	1.40	2.07	2.40	1.07	12	1.67	1.33	1.92	1.42										
37	9	1.22	1.00	1.11	2.33	12	1.33	1.67	2.50	2.08	15	1.60	3.67	3.00	1.00	12	1.75	2.00	2.00	1.42										
38	16	1.81	2.00	2.19	1.19	16	1.81	2.31	2.50	1.19	9	1.56	1.00	2.33	2.56	9	2.22	1.22	1.78	2.78										
39	16	1.44	4.69	3.50	1.19	12	1.33	1.00	2.67	2.17	14	1.43	4.00	3.29	1.57	16	1.63	5.13	3.94	1.56	16	1.69	5.13	3.19	1.44					
40	10	1.90	1.50	2.10	1.90	19	1.58	2.79	2.11	1.00	6	2.17	1.00	1.00	3.83	11	1.82	1.82	2.36	2.27										

C.3. DIFFERENCE BETWEEN COMPLETION-TIME AND PROJECT DURATION (DCD)

C.3.1. Scheduling Window 1

Run	P1					P2					P3					P4					P5					P6				
	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC
Avg.	12.175	4.85	12.175	8.925	17.075	12.825	6.125	18.625	14.075	17.425	12.775	5.4	21.975	14.975	19.95	12.6	6.8333	17	10.8	23.033	11.824	7.4706	17.588	18.235	19.765	10.571	7	7.2857	8.2857	22.286
1	8	3	10	10	32	9	1	0	0	30	15	6	62	57	21	12	3	35	9	7	12	4	17	13	7					
2	13	5	12	12	2	12	9	23	28	8	15	11	79	71	18	9	4	0	0	29	12	6	23	23	22	11	4	7	7	29
3	15	7	12	9	4	13	7	0	0	57	16	6	88	12	22	14	9	4	7	5										
4	16	3	6	6	0	16	3	8	8	2	12	0	0	0	6															
5	12	1	0	2	4	16	4	12	6	0	12	1	0	0	6	16	1	12	6	45										
6	8	3	0	0	9	15	7	15	20	3	9	10	4	9	46	9	2	8	4	8	12	11	9	14	44					
7	12	8	35	21	8	11	6	5	5	52	16	11	69	65	19	11	8	11	11	54	12	17	15	17	33	9	6	0	0	58
8	12	4	4	4	0	11	1	0	0	7	14	5	16	11	2															
9	16	6	8	8	4	10	3	4	4	7	6	2	0	0	58	16	17	21	21	15										
10	9	6	0	0	9	10	10	3	3	10	12	9	8	8	8	13	14	27	11	20										
11	12	13	12	12	62	14	12	57	54	5	14	18	34	45	3	9	8	0	0	8	12	15	15	15	4	9	10	3	3	10
12	12	8	16	5	0	12	11	19	8	25	12	14	22	0	28	12	6	11	14	24										
13	17	5	72	10	56	14	6	0	0	6	15	3	11	8	3															
14	12	5	8	15	4	9	8	2	2	7	8	1	0	0	7	12	7	7	7	6	15	7	17	34	1					
15	12	5	0	0	1	15	4	18	10	2	13	5	10	0	3															
16	9	2	2	2	27	18	10	70	65	20	11	3	9	9	27	15	9	15	15	1	8	2	0	0	27					
17	9	2	0	0	9	12	3	9	4	2	17	2	57	17	2															
18	15	14	46	21	53	15	12	73	65	25	12	3	0	0	5	12	7	4	4	57	14	10	16	16	44					
19	6	0	0	0	12	12	4	66	28	3	14	3	10	10	5	12	2	2	2	1										
20	12	8	12	27	6	9	2	6	7	8	16	6	57	74	47	9	6	0	0	51	13	7	30	32	6	12	5	16	13	3
21	16	3	33	33	4	16	7	24	24	23	6	1	0	0	58	15	3	10	10	3	12	3	4	4	48					
22	12	6	13	11	42	11	3	2	3	5	13	11	34	25	6	12	11	28	21	26	12	4	21	14	8	9	3	0	0	9
23	16	3	8	8	23	14	5	3	3	26	11	3	0	0	27															
24	10	6	11	11	6	15	5	35	35	41	9	8	0	0	46	15	10	21	21	5	9	6	5	5	9					
25	13	3	22	8	6	12	7	2	4	8	15	6	37	10	24	12	5	6	0	8										
26	14	3	13	12	48	12	4	5	7	56	15	6	47	25	9	9	4	0	0	64	15	9	53	47	2					
27	12	3	5	0	55	12	5	3	6	62	18	5	82	32	0	15	5	9	14	5										
28	15	3	6	7	4	17	4	54	12	0	12	2	0	0	4															
29	12	6	1	3	7	13	3	10	6	5	12	3	5	0	4	15	9	30	6	54										
30	12	4	21	5	6	15	4	27	27	49	12	3	11	9	45	12	5	13	11	24	8	2	0	0	32					
31	12	1	0	0	1	15	1	8	8	1	16	2	26	11	2															
32	14	9	12	15	20	12	7	0	7	6	12	5	0	0	52	17	8	90	32	19										
33	13	20	38	40	27	11	17	6	6	55	12	10	26	23	52	9	14	0	0	50	14	22	63	63	0	11	11	11	11	25
34	12	3	5	6	27	9	5	0	0	10	9	3	4	4	8	18	11	70	13	20										
35	9	0	0	0	47	16	16	76	62	4	12	6	10	9	26	12	7	6	15	26										
36	12	5	5	13	27	12	15	5	20	23	12	9	9	5	23	15	4	62	58	52	9	1	0	0	49	13	10	14	24	22
37	6	0	0	0	23	20	8	60	5	0	16	2	0	0	23															
38	17	1	24	10	2	9	3	0	0	31	15	4	7	7	47															
39	12	5	15	11	4	6	1	0	0	11	12	3	18	29	1	9	3	2	2	1	12	1	11	13	0					
40	11	2	0	0	2	13	2	35	11	2	13	5	27	14	5	12	3	6	10	3										

C.3.2. Scheduling Window 2

Run	P1					P2					P3					P4					P5					P6				
	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC	Dur	PCR	SASP	SAC	LAC
Avg.	12.775	6.225	20.8	17.1	17.725	12.475	6.675	19.775	15.85	15.275	12.95	6.675	22.975	23.175	13.3	12.12	9	21.12	17.04	25.4	12.286	8.0714	21	18	21.357	14.667	12.667	40	33.667	15.333
1	9	3	8	8	4	11	6	27	27	6	9	6	4	4	10	6	1	0	0	9										
2	12	1	16	19	4	12	6	12	14	3	14	5	51	52	2															
3	11	6	7	5	9	15	5	59	45	3	12	6	16	11	3															
4	11	7	0	1	39	15	10	41	13	18	12	9	11	4	5	13	10	25	13	39	12	14	14	7	8					
5	9	5	8	6	30	12	10	21	15	31	12	8	25	24	8	12	13	28	11	25	9	5	11	2	32					
6	12	13	13	13	7	12	10	10	42	17	13	9	30	53	5	12	11	15	36	7	8	4	0	0	9	13	9	46	49	2
7	10	3	4	10	19	13	3	35	24	28	12	4	11	17	5															
8	11	5	3	0	9	12	7	19	9	6	12	9	16	14	18	12	6	12	4	34	16	7	34	15	4					
9	16	8	63	42	0	8	6	0	0	9	12	6	23	8	7	12	6	17	11	6										
10	16	4	33	28	2	9	7	0	0	6	12	5	18	7	2	12	8	33	14	5										
11	9	8	3	3	38	12	11	14	11	0	15	11	42	39	5	11	9	7	7	38										
12	13	12	51	27	32	12	8	20	10	6	11	8	5	0	36	12	10	24	5	30	12	12	16	14	37					
13	9	4	6	7	38	16	8	30	24	27	14	9	13	14	23	9	0	6	4	34	12	4	25	19	8					
14	15	5	70	8	32	14	3	30	3	31	15	7	69	23	34															
15	16	21	23	18	34	12	4	5	2	6	12	8	9	6	3	20	18	45	53	27	9	3	0	0	46	14	9	24	13	31
16	12	5	10	8	2	14	6	39	40	34	12	6	4	35	21	15	8	49	44	36										
17	14	4	20	38	26	12	8	11	14	23	11	6	4	7	26	20	21	51	59	0	8	4	0	0	34					
18	12	4	7	8	4	12	2	10	14	1	17	10	70	67	-2															
19	11	3	7	17	43	14	5	14	34	35	14	6	13	46	12	9	6	4	4	40	16	7	70	51	0					
20	17	0	70	61	0	10	1	0	0	30	16	2	37	34	27															
21	15	5	10	10	19	9	5	3	3	33	18	14	34	34	0	9	3	7	7	28										
22	15	5	52	46	0	13	6	36	14	7	12	2	21	12	4															
23	9	5	2	2	11	9	3	4	9	9	16	11	15	45	4	11	9	6	11	27	15	8	41	42	1					
24	15	6	48	25	2	15	5	53	38	5	9	8	0	0	24	13	9	10	10	15										
25	15	6	49	10	4	12	25	13	6	8	8	0	0	3	9															
26	12	3	15	14	42	9	0	14	6	9	17	6	54	40	29	9	3	10	10	42										
27	17	7	25	51	26	14	5	0	4	35	17	6	40	59	29															
28	12	11	5	28	31	18	22	87	44	1	13	9	15	14	27	10	12	0	0	24	12	18	9	5	42	17	20	50	39	13
29	12	5	5	5	6	15	4	37	8	5	9	3	0	0	6															
30	16	0	38	15	4	13	0	13	3	7	18	0	71	28	0															
31	14	10	43	47	37	12	3	0	4	30	17	13	64	55	22	15	12	57	51	30	12	6	3	10	36					
32	11	4	0	3	5	15	6	46	41	5	12	7	11	9	6															
33	8	7	0	0	11	12	8	8	11	5	18	14	68	60	0															
34	12	7	0	8	37	13	6	7	15	7	14	4	22	40	2	15	13	53	24	33										
35	11	13	2	3	33	12	10	11	12	37	14	10	16	17	6	11	15	4	5	35	16	14	49	49	17					
36	14	6	14	34	1	11	7	1	11	32	13	7	8	23	32															
37	13	4	12	13	34	9	4	5	6	34	9	6	0	1	39	14	8	45	25	3	15	7	22	38	25					
38	15	5	21	12	29	20	10	49	50	10	9	0	0	12	30	9	6	0	7	34										
39	14	6	31	12	3	12	5	7	6	2	9	2	4	3	5															
40	16	13	38	19	2	9	7	0	2	10	9	5	5	7	8	12	8	20	11	34										

C.3.3. Scheduling Window 3

Run	P1 Dur	P1 PCR	P1 SASP	P1 SAC	P1 LAC	P2 Dur	P2 PCR	P2 SASP	P2 SAC	P2 LAC	P3 Dur	P3 PCR	P3 SASP	P3 SAC	P3 LAC
Avg.	12.625	6.825	19.25	13.3	10.075	13.375	7.35	21.1	16.1	10.5	13.125	7.075	23.675	18.4	10.55
1	12	9	23	12	0	12	7	27	16	17	14	11	37	29	19
2	12	5	21	27	3	9	0	8	11	11	12	5	23	21	5
3	9	5	12	7	12	12	15	30	13	12	12	6	23	19	5
4	14	4	9	9	11	16	9	29	15	16	9	6	0	4	25
5	13	8	21	21	14	11	8	13	9	14	13	9	24	24	10
6	9	5	5	2	3	9	7	5	11	3	12	10	18	25	2
7	12	8	7	13	17	12	6	10	8	4	14	9	22	20	5
8	15	8	44	21	13	11	4	6	11	15	12	6	16	27	15
9	12	14	35	14	6	12	19	31	21	9	12	11	23	9	6
10	16	4	37	17	3	14	5	25	10	5	10	1	3	0	8
11	12	4	10	2	13	9	2	8	0	24	16	4	31	24	6
12	13	10	28	21	14	11	7	12	4	20	12	3	21	15	7
13	16	11	40	21	1	12	7	11	5	15	14	9	20	15	7
14	14	14	57	22	10	9	8	24	8	13	12	11	27	13	10
15	14	11	16	4	34	20	14	28	26	30	9	12	5	10	44
16	12	6	34	11	8	17	4	68	34	2	12	3	32	5	24
17	11	12	14	12	8	20	14	34	32	1	9	6	2	0	13
18	8	4	22	6	14	17	10	68	40	8	18	9	85	50	6
19	11	2	8	1	25	15	7	35	28	15	11	4	17	10	28
20	9	0	1	3	15	15	3	35	41	4	11	6	10	12	11
21	15	6	29	25	6	9	6	0	0	9	12	7	12	12	2
22	9	1	3	7	12	12	2	27	12	6	15	0	47	26	8
23	12	4	10	9	8	16	6	32	27	4	12	1	13	0	4
24	14	4	7	13	3	15	5	19	24	4	15	4	18	30	3
25	16	10	40	16	6	12	8	17	0	13	18	13	48	24	10
26	20	11	42	29	3	12	8	5	1	17	15	7	22	13	10
27	14	6	20	19	18	12	5	8	7	17	16	8	34	37	16
28	9	12	8	7	10	16	15	22	17	16	12	12	8	7	17
29	11	8	0	0	15	15	9	25	17	13	13	11	10	6	13
30	17	7	34	28	6	12	7	6	4	6	16	6	18	20	5
31	11	7	0	0	25	12	4	11	11	4	12	9	7	6	22
32	16	9	39	34	9	12	6	9	13	13	19	9	61	42	0
33	12	3	11	13	7	15	8	34	28	7	15	9	35	37	6
34	11	6	0	9	13	12	4	14	15	11	17	8	62	32	9
35	14	2	3	6	5	15	4	14	17	7	15	5	15	17	1
36	9	6	0	0	6	16	9	31	25	5	15	6	16	21	1
37	9	2	0	1	12	12	4	8	18	13	15	9	40	30	0
38	16	13	16	19	3	16	13	21	24	3	9	5	0	12	14
39	16	7	59	40	3	12	4	0	20	14	14	6	42	32	8
40	10	9	5	11	9	19	11	34	21	0	6	7	0	0	17

Run	P4 Dur	P4 PCR	P4 SASP	P4 SAC	P4 LAC	P5 Dur	P5 PCR	P5 SASP	P5 SAC	P5 LAC	P6 Dur	P6 PCR	P6 SASP	P6 SAC	P6 LAC
Avg.	12.455	7.5882	20.559	15.059	10.324	12.0	7.625	23.875	13.75	13.5	12.5	15.5	43	20.5	17.5
1	14	13	40	32	6										
2	11	8	12	15	11										
3	9	7	6	1	8	11	13	12	7	18	12	18	27	23	15
4	14	7	13	13	14										
5	8	2	0	3	10										
6	9	9	8	15	6										
7															
8	16	11	31	24	7										
9	11	17	12	3	12										
10	16	6	35	15	2										
11	16	4	34	27	5										
12	14	12	39	25	9	9	2	4	0	16					
13	17	12	48	29	18										
14	14	14	50	29	12	6	1	20	4	25	13	13	59	18	20
15															
16	9	3	20	0	15										
17	9	8	0	5	15										
18	9	1	26	10	12	12	6	41	19	7					
19	11	6	12	5	30										
20	13	4	27	24	12										
21	11	9	6	6	15										
22	16	2	62	30	1										
23	12	3	9	14	8										
24															
25	11	7	8	1	12	15	13	30	9	10					
26															
27	12	9	2	11	22										
28															
29	20	12	31	23	3	12	9	4	4	16					
30		0	0	0	0										
31	12	5	12	19	11										
32	9	7	0	4	14	15	6	14	32	9					
33	12	5	17	7	7										
34	16	8	46	30	5										
35															
36	12	8	4	11	5										
37	12	9	12	12	5										
38	9	11	2	7	16										
39	16	10	66	47	9	16	11	66	35	7					
40	11	9	9	15	14										

C.4. SHOP UTILIZATION

C.4.1. Workdays in Resource Demand during 3 Scheduling-Windows (60 workdays)

Run	P-PCR					P-SASP					P-SAC					P-LAC				
	E	M	C	S	P	E	M	C	S	P	E	M	C	S	P	E	M	C	S	P
Avg.	37.4	22.4	30.1	37.9	22.4	25.9	14.6	20.0	26.8	16.1	28.5	15.7	22.8	28.5	16.9	36.5	22.7	26.4	36.7	22.3
stdev.	4.3	5.3	5.1	4.1	5.9	4.8	5.9	4.8	4.3	4.8	5.5	5.8	4.4	4.8	4.7	5.2	5.2	4.8	3.7	5.8
1	35	18	30	36	15	21	9	22	21	15	26	8	23	24	15	38	16	25	35	15
2	37	22	30	42	22	28	11	21	26	13	28	11	21	23	11	37	22	28	42	22
3	38	29	29	41	14	26	23	16	24	6	32	27	25	31	10	38	29	27	43	14
4	30	37	27	42	18	25	28	18	33	16	30	31	22	40	18	30	38	18	42	18
5	40	20	33	37	22	32	17	26	32	21	32	17	28	32	22	39	20	27	37	22
6	44	19	34	38	25	37	15	31	31	23	28	9	29	22	17	44	19	36	38	25
7	35	21	29	40	16	29	10	20	33	12	29	11	22	36	13	35	21	23	40	16
8	31	32	27	41	16	21	25	24	27	16	24	26	22	33	16	26	27	25	40	16
9	35	9	31	30	24	29	6	20	21	16	34	6	25	26	20	38	9	36	30	26
10	46	19	21	37	20	34	6	10	25	16	40	13	19	28	19	46	19	23	37	20
11	41	28	39	39	23	25	16	24	30	15	28	20	26	30	16	40	28	25	39	23
12	39	23	33	39	27	28	12	27	27	18	31	16	29	35	22	40	23	22	37	27
13	43	21	32	35	18	28	16	20	18	12	37	19	30	25	14	43	25	26	30	18
14	41	26	30	32	19	27	16	20	22	15	31	23	27	28	19	41	29	22	35	17
15	41	16	28	36	25	33	12	25	29	17	34	12	26	29	17	40	19	23	28	22
16	35	22	23	48	35	17	14	18	28	28	16	10	18	29	24	30	22	22	37	35
17	39	15	23	34	26	24	6	14	29	21	25	7	17	26	22	39	18	25	38	24
18	34	29	39	37	21	20	21	21	22	9	23	21	23	22	9	35	31	34	37	22
19	35	29	25	48	20	24	19	13	33	13	23	19	15	34	14	26	22	16	42	17
20	42	21	26	46	27	24	13	16	25	22	23	9	16	23	22	39	21	23	41	27
21	37	22	35	39	29	32	15	28	37	20	32	15	28	37	20	37	22	29	39	29
22	45	22	35	39	20	29	13	18	22	12	36	15	22	30	12	46	20	31	34	24
23	41	25	26	35	24	34	19	17	28	18	31	15	18	22	16	41	25	26	37	24
24	41	21	25	44	23	27	19	19	24	21	30	19	19	25	21	41	21	25	44	23
25	34	16	28	40	27	20	10	17	26	14	32	15	24	31	22	32	15	29	39	27
26	37	21	31	35	22	27	7	18	27	20	32	16	22	27	20	36	21	24	33	22
27	39	23	25	43	24	23	11	11	33	21	23	11	13	30	18	32	21	18	35	23
28	38	24	31	39	20	30	14	20	32	9	30	17	27	36	13	38	26	26	39	20
29	30	29	24	34	25	24	25	17	27	17	29	25	21	33	19	27	30	23	33	25
30	36	19	26	33	32	20	11	15	22	22	29	11	20	27	25	36	20	26	33	32
31	35	27	41	36	20	23	17	22	25	20	23	15	22	22	18	34	25	26	34	20
32	31	24	32	32	31	18	12	23	21	14	18	18	26	22	17	28	27	34	31	28
33	35	15	31	37	37	21	7	13	24	23	20	7	16	26	26	35	17	28	37	38
34	33	21	33	37	25	21	4	15	26	16	25	11	23	34	18	31	21	27	40	25
35	34	25	39	35	28	26	18	26	22	17	26	18	24	23	17	34	25	30	35	28
36	39	29	37	37	15	28	27	28	29	12	28	22	23	29	12	40	31	33	37	15
37	42	17	34	37	15	28	15	23	30	12	36	15	28	24	10	41	18	26	36	18
38	28	18	23	37	22	19	14	20	31	16	19	14	19	28	16	29	20	24	36	22
39	40	22	36	36	11	24	14	23	23	7	31	18	32	25	7	38	23	37	36	11
40	41	20	24	33	13	31	18	22	28	9	37	17	22	31	8	41	23	26	32	13

C.4.2. Shop Utilization Percentage during 3 Scheduling-Windows (SUP)

(unit: %)

Run	P-PCR					P-SASP					P-SAC					P-LAC				
	E	M	C	S	P	E	M	C	S	P	E	M	C	S	P	E	M	C	S	P
Avg.	62.4	37.3	50.2	63.2	37.3	43.2	24	33.4	44.7	26.8	47.5	26.2	38.0	47.4	28.1	60.9	37.9	43.9	61.2	37.2
stdev.	7.2	8.9	8.5	6.9	9.8	8.0	9.8	8.0	7.2	8.0	9.2	9.7	7.4	8.0	7.8	8.7	8.7	8.0	6.2	9.7
1	58.3	30.0	50.0	60.0	25.0	35.0	15.0	36.7	35.0	25.0	43.3	13.3	38.3	40.0	25.0	63.3	26.7	41.7	58.3	25.0
2	61.7	36.7	50.0	70.0	36.7	46.7	18.3	35.0	43.3	21.7	46.7	18.3	35.0	38.3	18.3	61.7	36.7	46.7	70.0	36.7
3	63.3	48.3	48.3	68.3	23.3	43.3	38.3	26.7	40.0	10.0	53.3	45.0	41.7	51.7	16.7	63.3	48.3	45.0	71.7	23.3
4	50.0	61.7	45.0	70.0	30.0	41.7	46.7	30.0	55.0	26.7	50.0	51.7	36.7	66.7	30.0	50.0	63.3	30.0	70.0	30.0
5	66.7	33.3	55.0	61.7	36.7	53.3	28.3	43.3	53.3	35.0	53.3	28.3	46.7	53.3	36.7	65.0	33.3	45.0	61.7	36.7
6	73.3	31.7	56.7	63.3	41.7	61.7	25.0	51.7	51.7	38.3	46.7	15.0	48.3	36.7	28.3	73.3	31.7	60.0	63.3	41.7
7	58.3	35.0	48.3	66.7	26.7	48.3	16.7	33.3	55.0	20.0	48.3	18.3	36.7	60.0	21.7	58.3	35.0	38.3	66.7	26.7
8	51.7	53.3	45.0	68.3	26.7	35.0	41.7	40.0	45.0	26.7	40.0	43.3	36.7	55.0	26.7	43.3	45.0	41.7	66.7	26.7
9	58.3	15.0	51.7	50.0	40.0	48.3	10.0	33.3	35.0	26.7	56.7	10.0	41.7	43.3	33.3	63.3	15.0	60.0	50.0	43.3
10	76.7	31.7	35.0	61.7	33.3	56.7	10.0	16.7	41.7	26.7	66.7	21.7	31.7	46.7	31.7	76.7	31.7	38.3	61.7	33.3
11	68.3	46.7	65.0	65.0	38.3	41.7	26.7	40.0	50.0	25.0	46.7	33.3	43.3	50.0	26.7	66.7	46.7	41.7	65.0	38.3
12	65.0	38.3	55.0	65.0	45.0	46.7	20.0	45.0	45.0	30.0	51.7	26.7	48.3	58.3	36.7	66.7	38.3	36.7	61.7	45.0
13	71.7	35.0	53.3	58.3	30.0	46.7	26.7	33.3	30.0	20.0	61.7	31.7	50.0	41.7	23.3	71.7	41.7	43.3	50.0	30.0
14	68.3	43.3	50.0	53.3	31.7	45.0	26.7	33.3	36.7	25.0	51.7	38.3	45.0	46.7	31.7	68.3	48.3	36.7	58.3	28.3
15	68.3	26.7	46.7	60.0	41.7	55.0	20.0	41.7	48.3	28.3	56.7	20.0	43.3	48.3	28.3	66.7	31.7	38.3	46.7	36.7
16	58.3	36.7	38.3	80.0	58.3	28.3	23.3	30.0	46.7	46.7	26.7	16.7	30.0	48.3	40.0	50.0	36.7	36.7	61.7	58.3
17	65.0	25.0	38.3	56.7	43.3	40.0	10.0	23.3	48.3	35.0	41.7	11.7	28.3	43.3	36.7	65.0	30.0	41.7	63.3	40.0
18	56.7	48.3	65.0	61.7	35.0	33.3	35.0	35.0	36.7	15.0	38.3	35.0	38.3	36.7	15.0	58.3	51.7	56.7	61.7	36.7
19	58.3	48.3	41.7	80.0	33.3	40.0	31.7	21.7	55.0	21.7	38.3	31.7	25.0	56.7	23.3	43.3	36.7	26.7	70.0	28.3
20	70.0	35.0	43.3	76.7	45.0	40.0	21.7	26.7	41.7	36.7	38.3	15.0	26.7	38.3	36.7	65.0	35.0	38.3	68.3	45.0
21	61.7	36.7	58.3	65.0	48.3	53.3	25.0	46.7	61.7	33.3	53.3	25.0	46.7	61.7	33.3	61.7	36.7	48.3	65.0	48.3
22	75.0	36.7	58.3	65.0	33.3	48.3	21.7	30.0	36.7	20.0	60.0	25.0	36.7	50.0	20.0	76.7	33.3	51.7	56.7	40.0
23	68.3	41.7	43.3	58.3	40.0	56.7	31.7	28.3	46.7	30.0	51.7	25.0	30.0	36.7	26.7	68.3	41.7	43.3	61.7	40.0
24	68.3	35.0	41.7	73.3	38.3	45.0	31.7	31.7	40.0	35.0	50.0	31.7	31.7	41.7	35.0	68.3	35.0	41.7	73.3	38.3
25	56.7	26.7	46.7	66.7	45.0	33.3	16.7	28.3	43.3	23.3	53.3	25.0	40.0	51.7	36.7	53.3	25.0	48.3	65.0	45.0
26	61.7	35.0	51.7	58.3	36.7	45.0	11.7	30.0	45.0	33.3	53.3	26.7	36.7	45.0	33.3	60.0	35.0	40.0	55.0	36.7
27	65.0	38.3	41.7	71.7	40.0	38.3	18.3	18.3	55.0	35.0	38.3	18.3	21.7	50.0	30.0	53.3	35.0	30.0	58.3	38.3
28	63.3	40.0	51.7	65.0	33.3	50.0	23.3	33.3	53.3	15.0	50.0	28.3	45.0	60.0	21.7	63.3	43.3	43.3	65.0	33.3
29	50.0	48.3	40.0	56.7	41.7	40.0	41.7	28.3	45.0	28.3	48.3	41.7	35.0	55.0	31.7	45.0	50.0	38.3	55.0	41.7
30	60.0	31.7	43.3	55.0	53.3	33.3	18.3	25.0	36.7	36.7	48.3	18.3	33.3	45.0	41.7	60.0	33.3	43.3	55.0	53.3
31	58.3	45.0	68.3	60.0	33.3	38.3	28.3	36.7	41.7	33.3	38.3	25.0	36.7	36.7	30.0	56.7	41.7	43.3	56.7	33.3
32	51.7	40.0	53.3	53.3	51.7	30.0	20.0	38.3	35.0	23.3	30.0	30.0	43.3	36.7	28.3	46.7	45.0	56.7	51.7	46.7
33	58.3	25.0	51.7	61.7	61.7	35.0	11.7	21.7	40.0	38.3	33.3	11.7	26.7	43.3	43.3	58.3	28.3	46.7	61.7	63.3
34	55.0	35.0	55.0	61.7	41.7	35.0	6.7	25.0	43.3	26.7	41.7	18.3	38.3	56.7	30.0	51.7	35.0	45.0	66.7	41.7
35	56.7	41.7	65.0	58.3	46.7	43.3	30.0	43.3	36.7	28.3	43.3	30.0	40.0	38.3	28.3	56.7	41.7	50.0	58.3	46.7
36	65.0	48.3	61.7	61.7	25.0	46.7	45.0	46.7	48.3	20.0	46.7	36.7	38.3	48.3	20.0	66.7	51.7	55.0	61.7	25.0
37	70.0	28.3	56.7	61.7	25.0	46.7	25.0	38.3	50.0	20.0	60.0	25.0	46.7	40.0	16.7	68.3	30.0	43.3	60.0	30.0
38	46.7	30.0	38.3	61.7	36.7	31.7	23.3	33.3	51.7	26.7	31.7	23.3	31.7	46.7	26.7	48.3	33.3	40.0	60.0	36.7
39	66.7	36.7	60.0	60.0	18.3	40.0	23.3	38.3	38.3	11.7	51.7	30.0	53.3	41.7	11.7	63.3	38.3	61.7	60.0	18.3
40	68.3	33.3	40.0	55.0	21.7	51.7	30.0	36.7	46.7	15.0	61.7	28.3	36.7	51.7	13.3	68.3	38.3	43.3	53.3	21.7

C.4.3. Shop Utilization Ratio against P-PCR (SUR)

Run	P-PCR					P-SASP					P-SAC					P-LAC				
	E	M	C	S	P	E	M	C	S	P	E	M	C	S	P	E	M	C	S	P
Avg.	1.0	1.0	1.0	1.0	1.0	69.2	64.3	66.7	71.1	72.5	76.2	69.3	76.3	75.5	76.0	97.4	102.1	88.4	97.2	99.9
stdev.	0.0	0.0	0.0	0.0	0.0	9.6	17.2	13.2	10.7	15.6	12.2	15.7	12.0	12.5	14.3	6.7	9.1	14.2	7.5	6.3
1	1	1	1	1	1	60	50	73.3	58.3	100	74.3	44.4	76.7	66.7	100	109	88.9	83.3	97.2	100
2	1	1	1	1	1	75.7	50	70	61.9	59.1	75.7	50	70	54.8	50	100	100	93.3	100	100
3	1	1	1	1	1	68.4	79.3	55.2	58.5	42.9	84.2	93.1	86.2	75.6	71.4	100	100	93.1	105	100
4	1	1	1	1	1	83.3	75.7	66.7	78.6	88.9	100	83.8	81.5	95.2	100	100	103	66.7	100	100
5	1	1	1	1	1	80	85	78.8	86.5	95.5	80	85	84.8	86.5	100	97.5	100	81.8	100	100
6	1	1	1	1	1	84.1	78.9	91.2	81.6	92	63.6	47.4	85.3	57.9	68	100	100	106	100	100
7	1	1	1	1	1	82.9	47.6	69	82.5	75	82.9	52.4	75.9	90	81.3	100	100	79.3	100	100
8	1	1	1	1	1	67.7	78.1	88.9	65.9	100	77.4	81.3	81.5	80.5	100	83.9	84.4	92.6	97.6	100
9	1	1	1	1	1	82.9	66.7	64.5	70	66.7	97.1	66.7	80.6	86.7	83.3	109	100	116	100	108
10	1	1	1	1	1	73.9	31.6	47.6	67.6	80	87	68.4	90.5	75.7	95	100	100	110	100	100
11	1	1	1	1	1	61	57.1	61.5	76.9	65.2	68.3	71.4	66.7	76.9	69.6	97.6	100	64.1	100	100
12	1	1	1	1	1	71.8	52.2	81.8	69.2	66.7	79.5	69.6	87.9	89.7	81.5	103	100	66.7	94.9	100
13	1	1	1	1	1	65.1	76.2	62.5	51.4	66.7	86	90.5	93.8	71.4	77.8	100	119	81.3	85.7	100
14	1	1	1	1	1	65.9	61.5	66.7	68.8	78.9	75.6	88.5	90	87.5	100	100	112	73.3	109	89.5
15	1	1	1	1	1	80.5	75	89.3	80.6	68	82.9	75	92.9	80.6	68	97.6	119	82.1	77.8	88
16	1	1	1	1	1	48.6	63.6	78.3	58.3	80	45.7	45.5	78.3	60.4	68.6	85.7	100	95.7	77.1	100
17	1	1	1	1	1	61.5	40	60.9	85.3	80.8	64.1	46.7	73.9	76.5	84.6	100	120	109	112	92.3
18	1	1	1	1	1	58.8	72.4	53.8	59.5	42.9	67.6	72.4	59	59.5	42.9	103	107	87.2	100	105
19	1	1	1	1	1	68.6	65.5	52	68.8	65	65.7	65.5	60	70.8	70	74.3	75.9	64	87.5	85
20	1	1	1	1	1	57.1	61.9	61.5	54.3	81.5	54.8	42.9	61.5	50	81.5	92.9	100	88.5	89.1	100
21	1	1	1	1	1	86.5	68.2	80	94.9	69	86.5	68.2	80	94.9	69	100	100	82.9	100	100
22	1	1	1	1	1	64.4	59.1	51.4	56.4	60	80	68.2	62.9	76.9	60	102	90.9	88.6	87.2	120
23	1	1	1	1	1	82.9	76	65.4	80	75	75.6	60	69.2	62.9	66.7	100	100	100	106	100
24	1	1	1	1	1	65.9	90.5	76	54.5	91.3	73.2	90.5	76	56.8	91.3	100	100	100	100	100
25	1	1	1	1	1	58.8	62.5	60.7	65	51.9	94.1	93.8	85.7	77.5	81.5	94.1	93.8	104	97.5	100
26	1	1	1	1	1	73	33.3	58.1	77.1	90.9	86.5	76.2	71	77.1	90.9	97.3	100	77.4	94.3	100
27	1	1	1	1	1	59	47.8	44	76.7	87.5	59	47.8	52	69.8	75	82.1	91.3	72	81.4	95.8
28	1	1	1	1	1	78.9	58.3	64.5	82.1	45	78.9	70.8	87.1	92.3	65	100	108	83.9	100	100
29	1	1	1	1	1	80	86.2	70.8	79.4	68	96.7	86.2	87.5	97.1	76	90	103	95.8	97.1	100
30	1	1	1	1	1	55.6	57.9	57.7	66.7	68.8	80.6	57.9	76.9	81.8	78.1	100	105	100	100	100
31	1	1	1	1	1	65.7	63	53.7	69.4	100	65.7	55.6	53.7	61.1	90	97.1	92.6	63.4	94.4	100
32	1	1	1	1	1	58.1	50	71.9	65.6	45.2	58.1	75	81.3	68.8	54.8	90.3	113	106	96.9	90.3
33	1	1	1	1	1	60	46.7	41.9	64.9	62.2	57.1	46.7	51.6	70.3	70.3	100	113	90.3	100	103
34	1	1	1	1	1	63.6	19	45.5	70.3	64	75.8	52.4	69.7	91.9	72	93.9	100	81.8	108	100
35	1	1	1	1	1	76.5	72	66.7	62.9	60.7	76.5	72	61.5	65.7	60.7	100	100	76.9	100	100
36	1	1	1	1	1	71.8	93.1	75.7	78.4	80	71.8	75.9	62.2	78.4	80	103	107	89.2	100	100
37	1	1	1	1	1	66.7	88.2	67.6	81.1	80	85.7	88.2	82.4	64.9	66.7	97.6	106	76.5	97.3	120
38	1	1	1	1	1	67.9	77.8	87	83.8	72.7	67.9	77.8	82.6	75.7	72.7	104	111	104	97.3	100
39	1	1	1	1	1	60	63.6	63.9	63.9	63.6	77.5	81.8	88.9	69.4	63.6	95	105	103	100	100
40	1	1	1	1	1	75.6	90	91.7	84.8	69.2	90.2	85	91.7	93.9	61.5	100	115	108	97	100

C.5. TARDINESS OVER WINDOWS (TOW)

Run	P-PCR			P-SASP			P-SAC			P-LAC		
	NOP	NWD	WCE	NOP	NWD	WCE	NOP	NWD	WCE	NOP	NWD	WCE
Avg.	1.88	7.65	10.43	4.68	53.53	101.60	4.03	44.98	67.43	4.85	13.15	32.45
1	3	12	13	5	55	116	5	47	73	3	17	37
2	0	0	0	5	54	90	5	59	92	1	2	2
3	3	10	21	7	59	138	4	33	51	5	10	31
4	2	6	6	4	40	51	3	19	21	6	14	51
5	2	3	3	3	27	35	2	24	31	6	10	20
6	1	2	2	3	25	32	6	57	91	0	0	0
7	1	3	3	4	40	51	3	33	40	5	9	25
8	2	7	10	4	45	101	4	33	47	5	20	30
9	4	14	28	5	47	107	4	28	38	3	4	8
10	1	2	2	5	54	93	3	26	28	0	0	0
11	0	0	0	5	60	87	4	50	65	8	15	62
12	2	6	9	5	55	94	3	34	40	8	18	49
13	3	16	19	6	69	133	3	40	52	8	23	60
14	4	20	25	5	66	156	4	40	55	9	24	59
15	3	20	20	3	50	63	3	48	67	8	34	74
16	1	1	1	6	56	120	6	64	97	5	18	53
17	3	14	18	4	57	84	4	54	86	4	7	9
18	2	13	14	7	80	304	5	75	160	7	14	35
19	1	2	2	5	54	105	5	54	79	7	36	98
20	0	0	0	6	62	124	6	69	134	5	11	17
21	1	1	1	3	31	40	3	31	36	4	7	13
22	0	0	0	6	67	157	4	46	72	1	1	1
23	1	2	2	5	37	52	5	51	68	0	0	0
24	0	0	0	5	44	79	4	40	64	0	0	0
25	4	20	71	5	72	140	3	41	63	6	23	75
26	2	13	13	5	59	100	4	44	69	9	23	71
27	2	5	5	5	60	103	5	64	113	9	30	86
28	3	11	16	4	58	101	3	40	51	5	14	44
29	4	17	21	4	49	66	2	32	35	6	21	40
30	2	5	6	4	61	108	3	39	47	3	4	8
31	1	1	1	5	50	97	5	57	93	7	21	59
32	3	14	14	6	75	173	5	63	119	5	16	21
33	2	7	7	6	74	134	5	67	115	4	7	13
34	2	9	9	6	76	176	4	47	76	6	14	31
35	0	0	0	4	52	76	4	49	67	5	9	29
36	2	6	6	3	39	55	5	49	61	4	7	16
37	2	5	5	4	42	78	4	37	52	5	11	24
38	2	16	18	3	40	58	4	44	66	5	13	17
39	3	13	16	5	67	140	4	45	56	4	13	16
40	1	10	10	2	33	47	3	26	27	3	6	14

APPENDIX D:

INPUT VARIABLES AND RANDOM VALUES FOR ACTIVITY DURATION

D.1. NORMAL DISTRIBUTION

	A	B	C	D	E	F	G	H	I	J	K	L	M
21													
22		= User Input				Duration Variance Factor	α =	0.143	= (1 / 7)				
23						$\sigma = \alpha \times \mu$	where, $\mu+\sigma$ = Expected Activity Duration w/ Completion Probability of 84.13% within the Duration						
24						Duration Safety Factor	γ =	1.0					
25							where, $\mu+\gamma\sigma$ = Expected Activity Duration w/ Completion Probability of 84.13% within the D						
26						Periodic Buffer Ratio	β_P =	1.0					
27													
28		P11	P12	P13	P21	P22	P23	P31	P32	P33	P41	P42	P43
29	μ	5.0	5.0	5.0	5.0	7.5	5.0	7.5	10.0	5.0	5.0	7.5	10.0
30	$(1+\gamma\alpha)\mu$	5.71	5.71	5.71	5.71	8.57	5.71	8.57	11.43	5.71	5.71	8.57	11.43
31	Avg.	4.989	4.997	5.017	4.954	7.519	4.997	7.516	9.972	5.001	5.012	7.537	9.972
32	1	5.9800	5.4210	4.6084	5.3322	6.0204	4.7368	8.4516	11.7322	4.6813	4.8005	7.5207	12.6231
33	2	5.8831	6.3546	6.1180	6.0586	8.4669	4.4729	7.0014	10.0360	5.2384	4.4776	8.6803	6.7884

...

Examples of Spreadsheet Formulas:

B32: =NORMINV([RANDforALL.xls]Sheet1!B11,$B$29,$B$29*$H$22)

...

M32: =NORMINV([RANDforALL.xls]Sheet1!M11,$M$29,$M$29*$H$22)

D.2. PERT (BETA) DISTRIBUTION

	A	B	C	D	E	F	G	H	I	J	K	L	M
26													
27		= User Input				Periodic Buffer Ratio	β_P =	1.0					
28						Duration Safety Factor	γ =	1.0					
29													
30					Note:	* μ (te) = (a+4m+b)/6. Activity Length of 50% Probability					* α: 4×(m-a) / (b-a)		
31						** $\mu+\gamma\sigma$ Expected Activity Duration w/ Completion Probability of 84.13%					** β: 4 - α		
32	unit: hours (1 work day = 8 work hours)					where, $\mu + \sigma$: Activity Length of 84.13% Probability					*** σ = (b-a) / 6		
33		P11	P12	P13	P21	P22	P23	P31	P32	P33	P41	P42	P43
34	a (min.)	30	22	34	24	27	33	50	65	25	18	50	41
35	m (most)	39	42	39	40	66	41	55	80	43	43	55	87
36	b (max.)	54	49	52	56	71	45	90	95	45	51	90	93
37	* α	1.67	2.67	1.33	2.00	3.00	2.33	1.00	2.00	3.00	2.67	1.00	3.00
38	** β	2.33	1.33	2.67	2.00	1.00	1.67	3.00	2.00	1.00	1.33	3.00	1.00
39	*** σ	4.80	5.40	3.60	6.40	8.80	2.40	8.00	6.00	4.00	6.60	8.00	10.40
40	* μ	40.0	40.0	40.0	40.0	60.0	40.0	60.0	80.0	40.0	40.0	60.0	80.0
41	** $\mu+\gamma\sigma$	44.80	45.40	43.60	46.40	68.80	42.40	68.00	86.00	44.00	46.60	68.00	90.40
42	Avg.	39.9351	39.9948	40.0508	39.5742	60.1277	39.9759	60.1326	79.8899	40.0225	40.1180	60.2164	79.8584
43	1	47.9275	44.2403	37.3120	43.8971	46.2426	39.0099	67.1164	88.7339	38.7891	38.6601	58.4159	92.4187
44	2	47.2180	48.2185	46.7169	50.8579	68.1264	37.8417	54.8399	80.2008	42.1518	34.6783	69.4641	52.9987

...

Examples of Spreadsheet Formulas:

B43: =BETAINV([RANDforALL.xls]Sheet1!B11,$B$37,$B$38,$B$34,$B$36)

...

M43: =BETAINV([RANDforALL.xls]Sheet1!M11,$M$37,$M$38,$M$34,$M$36)

D.3. TRIANGULAR DISTRIBUTION

	A	B	C	D	E	F	G	H	I	J	K	L	M
50					(A Factor for Expected Activity Duration w/ Completion Probability of 84.13% within the Duration)								
51		= User Input				Duration Safety Factor	α_1 =	0.8413			Periodic Buffer Ratio	β_P =	1.0
52							$\alpha_2 = 1 - \alpha_1$	0.1587					
53													
54				Note:	* μ: Activity Length of 50% Probability						# std m: standardized value of m = (m-a)/(b-a)		
55	unit: hours (1 work day = 8 work hours)				** Δ ($\mu + \Delta$): Activity Length of 84.13% Probability								
56		P11	P12	P13	P21	P22	P23	P31	P32	P33	P41	P42	P43
57	a (min.)	29	24	34	24	39	34	50	65	28	23	46	55
58	m (most)	39	43	36	40	67	40	55	80	42	43	53	87
59	b (max.)	53	51	52	56	71	46	90	95	46	52	85	94
60	*μ	40.0	40.0	40.0	40.0	60.0	40.0	60.0	80.0	40.00	40.0	60.0	80.0
61	**Δ	45.70	45.15	45.24	46.99	66.46	42.62	75.09	86.55	42.62	45.56	70.93	87.42
62	#std m	0.42	0.70	0.11	0.50	0.88	0.50	0.13	0.50	0.78	0.69	0.18	0.82
63	Avg.	40.2661	39.3199	40.7130	39.5973	58.9602	39.9878	66.1317	79.8980	38.6853	39.4364	61.5875	78.5189
64	1	47.6552	43.2537	37.7182	43.1813	47.3020	39.0647	73.8095	87.8799	37.0878	38.0398	60.2132	90.9911
65	2	46.9716	48.4994	47.8857	50.0492	66.0021	38.0719	59.1647	80.1514	40.6072	34.6075	72.0046	58.9156

...

Examples of Spreadsheet Formulas:

B64: =$B$57+($B$59-$B$57)*IF([RANDforALL.xls]Sheet1!B11<=$B$62,SQRT ([RANDforALL.xls]Sheet1!B11*$B$62), 1-SQRT((1-$B$62)*(1-[RANDforALL.xls]Sheet1!B11)))

...

M64: =$M$57+($M$59-$M$57)*IF([RANDforALL.xls]Sheet1!M11<=$M$62,SQRT ([RANDforALL.xls]Sheet1!M11*$M$62), 1-SQRT((1-$M$62)*(1-[RANDforALL.xls]Sheet1!M11)))

D.4. UNIFORM DISTRIBUTION

	A	B	C	D	E	F	G	H	I	J	K	L	M
28													
29		= User Input			Duration Safety Factor	γ =	0.8413			Periodic Buffer Ratio	β_P =	1.0	
30				(A Factor for Expected Activity Duration w/ Completion Probability of 84.13% within the Duration)									
31													
32					Note:	# μ: Activity Length of 50% Probability						γ - 0.5 =	0.3413
33	unit: hours (1 work day = 8 work hours)					## $\mu+\Delta$: Expected Activity Duration w/ Completion Probability of 84.13%						* Δ =	(γ-0.5)×(b-a)
34		P11	P12	P13	P21	P22	P23	P31	P32	P33	P41	P42	P43
35	a (min.)	26	31	28	24	49	35	35	65	33	28	40	65
36	b (max.)	54	49	52	56	71	45	85	95	47	52	80	95
37	*Δ	9.56	6.14	8.19	10.92	7.51	3.41	17.07	10.24	4.78	8.19	13.65	10.24
38	#μ	40.0	40.0	40.0	40.0	60.0	40.0	60.0	80.0	40.0	40.0	60.0	80.0
39	##$\mu+\Delta$	49.56	46.14	48.19	50.92	67.51	43.41	77.07	90.24	44.78	48.19	73.65	90.24
40	Avg.	39.8984	39.9715	40.0846	39.4909	60.1343	39.9687	60.1143	79.8689	40.0249	40.1301	60.3652	79.8218
41	1	51.6194	43.9996	35.0026	45.7300	50.8402	38.5626	75.6381	91.6203	37.5883	37.3598	60.3082	94.0051
42	2	50.9715	48.4789	50.5894	53.7867	66.9650	37.3028	51.0423	80.3012	41.8301	33.5752	74.5872	65.3686

...

Examples of Spreadsheet Formulas:

B41: =$B$35+($B$36-$B$35)*[RANDforALL.xls]Sheet1!B11

...

M41: =$M$35+($M$36-$M$35)*[RANDforALL.xls]Sheet1!M11

APPENDIX E: PROJECT MODELS IMPLEMENTED ON SPREADSHEET[1]

E.1. PROJECT 1

	O	P	Q	R	S	T	U	V	W
22	PROJECT 1		* IDLE: due to Slack & resource (C) precedent (P32) of P13						
23			# B_{P32} = 20wds × (1 - 1/(1+αβγ) 2.50				X =Σμ - (20-B_{P32}) =		10.00
24			(@ PCR-B, Completion Time of P32)				## B_{P1}= αβγX =		1.43
25								Σμ =	27.50
26		cf.	Σ(1+α)μ =	25.71				Σμ+B =	31.43
27			Σμ =	22.50			31.43	Σ(1+γα)μ=	31.43
28		**P11**	**P12**	***IDLE**	**#(B_{P32})**	**P13**	**###B_{P1}**	**Actual**	**IndivBuf**
29	μ & B	5.00	5.00	12.50	2.50	5.00	1.43		
30	(1+γα)μ	5.71	5.71	14.29		5.71			
31	CumAvg	4.989	10.390	25.171	25.171	30.188	31.480	28.431	31.928
32	1	5.9800	11.4010	26.1638	26.1638	30.7722	31.4286	30.7722	31.9979
33	2	5.8831	12.2377	25.0000	25.0000	31.1180	31.4286	30.8928	32.2854

...

Spreadsheet Formulas for Cells:

P32 =B32

Q32 =MAX(B32,K32)+C32

R32 =MAX(Q32,AM32)

S32 =MAX(R32,SUM($P$29:$S$29))

T32 =MAX(Q32,S32)+D32

U32 =MAX(T32,SUM($P$29:$U$29))

V32 =MAX(AL32,Q32)+D32

W32 =MAX((MAX($P$30,B32)+MAX($Q$30,C32)),(MAX((MAX($Z$30,E32,$AU$30,K32)
+MAX($AV$30,L32)),(MAX($P$30,B32)+MAX($AK$30,H32)))+MAX($AL$30,I32)))
+MAX($T$30,D32)

E.2. PROJECT 2

	Y	Z	AA	AB	AC	AD	AE	AF	AG
22	PROJECT 2		* IDLE: due to resource (E) precedent (P31) of P32						
23			# B_{P22} = 20wds × (1 - 1/(1+αβγ) 2.50				X =Σμ - (20-B_{P22}) =		7.50
24			(@ PCR-B, Completion Time of P22)				## B_{P2}= αβγX =		1.07
25								Σμ =	25.00
26			cf.	Σ(1+α)μ = 22.86				Σμ+B =	28.57
27				Σμ = 20.00			28.57	Σ(1+γα)μ=	28.57
28		**P21**	***IDLE**	**P22**	**#B_{P22}**	**P23**	**###B_{P2}**	**Actual**	**IndivBuf**
29	μ & B	5.00	7.50	7.50	2.50	5.00	1.07		
30	(1+γα)μ	5.71	8.57	8.57		5.71			
31	CumAvg	4.954	12.505	20.024	22.562	27.559	28.614	25.021	28.929
32	1	5.3322	14.4316	20.4520	22.5000	27.2368	28.5714	25.1888	28.8372
33	2	6.0586	12.8845	21.3514	22.5000	26.9729	28.5714	25.8244	28.9157

...

[1] These models are based on input variables and random values for Normal Distribution. Models of other distribution types are same as these models except row numbers.

Spreadsheet Formulas for Cells:

Z32 =E32 AA32 =AK32

AB32 =MAX(E32,AA32)+F32 AC32 =MAX(AB32,SUM($Z$29:$AC$29))

AD32 =MAX(AC32,Q32)+G32 AE32 =MAX(AD32,SUM($Z$29:$AE$29))

AF32 =MAX(AB32,Q32)+G32

AG32 =MAX((MAX($Z$30,E32,$P$30,B32)+MAX($AK$30,H32)+MAX($AB$30,F32)),
(MAX($AU$30,K32,$P$30,B32)+MAX($Q$30,C32)))+MAX($AD$30,G32)

E.3. PROJECT 3

	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR
22	PROJECT 3		* IDLE: due to resource (E) precedent (P11) of P31							
23			** IDLE: Slack = (P22+P23)-P32					$X = \Sigma\mu - (20 - B_{P32}) =$		12.50
24			# B_{P32} = 20wds × (1 - 1/(1+αβγ) 2.50					## $B_{P3} = \alpha\beta\gamma X =$		1.79
25			(@ PCR-B, Completion Time of P32)						$\Sigma\mu =$	30.00
26			cf.	$\Sigma(1+\alpha)\mu$ = 25.71					$\Sigma\mu+B =$	34.29
27				$\Sigma\mu$ = 22.50				34.29	$\Sigma(1+\gamma\alpha)\mu=$	34.29
28		*IDLE	P31	P32	# B_{P32}	**IDLE	P33	### B_{P3}	Actual	IndivBuf
29	μ & B	5.00	7.50	10.00	2.50	2.50	5.00	1.79		
30	$(1+\gamma\alpha)\mu$	5.71	8.57	11.43		2.86	5.71			
31	CumAvg	4.989	12.505	23.415	25.171	27.571	32.571	34.311	30.348	34.701
32	1	5.9800	14.4316	26.1638	26.1638	27.2368	31.9181	34.2857	30.8451	34.5515
33	2	5.883'	12.8845	24.7748	25.0000	26.9729	32.2113	34.2857	31.0628	34.6300

...

Spreadsheet Formulas for Cells:

AJ32 =B32 AK32 =B32+H32

AL32 =MAX(AK32,AV32)+I32 AM32 =MAX(AL32,SUM($AJ$29:$AM$29))

AN32 =MAX(AD32,AM32) AO32 =AN32+J32

AP32 =MAX(AO32,SUM($AJ$29:$AP$29)) AQ32 =MAX(AF32,AL32)+J32

AR32 =MAX(AG32,(MAX((MAX($P$30,B32)+MAX($AK$30,H32)),(MAX($Z$30,E32,$AU$30,K32)
+MAX($AV$30,L32)))+MAX($AL$30,I32)))+MAX($AO$30,J32)

E.4. PROJECT 4

	AT	AU	AV	AW	AX	AY	AZ	BA	BB
22	PROJECT 4		* IDLE: due to resource (E) precedent (P22) of P43						
23			# B_{P22} = 20wds × (1 - 1/(1+αβγ) 2.50				X =Σμ - (20-B_{P22}) =		12.50
24			(@ PCR-B, Completion Time of P22)				** B_{P4}= αβγX =		1.79
25								Σμ =	30.00
26			cf.	Σ(1+α)μ = 22.86				Σμ+B =	34.29
27				Σμ = 22.50			34.29	Σ(1+γα)μ=	34.29
28		P41	P42	*IDLE	#(B_{P22})	P43	**B_{P4}	Actual	IndivBuf
29	μ & B	5.00	7.50	7.50	2.50	10.00	1.79		
30	(1+γα)μ	5.71	8.57	8.57		11.43			
31	CumAvg	5.012	12.918	20.024	22.562	32.534	34.365	29.996	34.810
32	1	4.8005	12.8529	20.4520	22.5000	35.1231	35.1231	33.0751	35.7460
33	2	4.4776	14.7389	21.3514	22.5000	29.2884	34.2857	28.1399	34.7389

...

Spreadsheet Formulas for Cells:

AU32 =K32

AV32 =MAX(E32,K32)+L32

AW32=MAX(E32,B32+H32)+F32

AX32 =MAX(AW32,SUM($AU$29:$AX$29))

AY32 =MAX(AV32,AX32)+M32

AZ32 =MAX(AY32,SUM($AU$29:$AZ$29))

BA32 =MAX(AB32,AV32)+M32

BB32 =MAX((MAX($AU$30,K32,$Z$30,E32)+MAX($AV$30,L32)+MAX($AB$30,F32)),(MAX(MAX($Z$30,E32),MAX($P$30,B32)+MAX($AK$30,H32))+MAX($AB$30,F32)))+MAX($AY$30,M32)

APPENDIX F: SIMULATION RESULTS OF BUFFER MANAGEMENT STRATEGIES

F.1. AVERAGE COMPLETION-DAYS

F.1.1. Normal Distribution

Full-84.13

Project No.	Expected Duration			Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(1+\gamma\alpha)\mu$	Actual	PCR-B	IndivBuf
1	27.50	31.43	31.43	28.43	31.48	31.93
2	25.00	28.57	28.57	25.02	28.61	28.93
3	30.00	34.29	34.29	30.35	34.31	34.70
4	30.00	34.29	34.29	30.00	34.37	34.81

Full-78.81

Project No.	Expected Duration			Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(1+\gamma\alpha)\mu$	Actual	PCR-B	IndivBuf
1	27.50	30.64	30.64	28.43	30.77	31.35
2	25.00	27.86	27.86	25.02	27.95	28.37
3	30.00	33.43	33.43	30.35	33.50	34.02
4	30.00	33.43	33.43	30.00	33.58	34.17

0.8-84.13

Project No.	Expected Duration			Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(1+\gamma\alpha)\mu$	Actual	PCR-B	IndivBuf
1	27.50	30.64	31.43	28.43	30.77	31.93
2	25.00	27.86	28.57	25.02	27.95	28.93
3	30.00	33.43	34.29	30.35	33.50	34.70
4	30.00	33.43	34.29	30.00	33.58	34.81

0.8-78.81

Project No.	Expected Duration			Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(1+\gamma\alpha)\mu$	Actual	PCR-B	IndivBuf
1	27.50	30.01	30.64	28.43	30.25	31.35
2	25.00	27.29	27.86	25.02	27.45	28.37
3	30.00	32.74	33.43	30.35	32.88	34.02
4	30.00	32.74	33.43	30.00	32.98	34.17

F.1.2. PERT (Beta) Distribution

Full-84.13

Project No.	Expected Duration				Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\gamma\sigma)$	Max.Path	Actual	PCR-B	IndivBuf
1	27.50	30.30	30.30	**30.53**	30.40	28.45	31.00
2	25.00	28.20	28.20	28.20	28.22	25.02	28.49
3	30.00	33.50	33.50	**33.70**	33.51	30.24	34.00
4	30.00	34.23	34.23	34.23	34.24	30.01	34.60

Full-78.81

Project No.	Expected Duration				Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\gamma\sigma)$	Max.Path	Actual	PCR-B	IndivBuf
1	27.50	29.74	29.74	**29.92**	28.45	29.93	30.59
2	25.00	27.56	27.56	27.56	25.02	27.61	28.00
3	30.00	32.80	32.80	**32.96**	30.24	32.84	33.43
4	30.00	33.38	33.38	33.38	30.01	33.41	33.99

0.8-84.13

Project No.	Expected Duration				Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\gamma\sigma)$	Max.Path	Actual	PCR-B	IndivBuf
1	27.50	29.74	30.30	**30.53**	28.45	29.93	31.00
2	25.00	27.56	28.20	28.20	25.02	27.61	28.49
3	30.00	32.80	33.50	**33.70**	30.24	32.84	34.00
4	30.00	33.38	34.23	34.23	30.01	33.41	34.60

0.8-78.81

Project No.	Expected Duration				Avg.Completion Days (2000 runs)		
	$\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\gamma\sigma)$	Max.Path	Actual	PCR-B	IndivBuf
1	27.50	29.29	29.74	**29.92**	28.45	29.59	30.59
2	25.00	27.05	27.56	27.56	25.02	27.14	28.00
3	30.00	32.24	32.80	**32.96**	30.24	32.33	33.43
4	30.00	32.70	33.38	33.38	30.01	32.80	33.99

F.1.3. Triangular Distribution

Full-84.13

Project No.	Expected Duration $\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma\Delta$	Max.Path	Avg.Completion Days (2000 runs) Actual	PCR-B	IndivBuf
1	27.50	31.57	31.57	31.57	28.92	31.59	31.89
2	25.00	28.89	28.89	28.89	25.54	28.91	29.13
3	30.01	34.06	34.06	**34.22**	30.51	34.07	34.48
4	30.01	33.80	33.80	**34.33**	30.36	33.83	34.62

Full-78.81

Project No.	Expected Duration $\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma\Delta$	Max.Path	Avg.Completion Days (2000 runs) Actual	PCR-B	IndivBuf
1	27.50	30.85	30.85	30.85	28.92	30.91	31.33
2	25.00	28.28	28.28	28.28	25.54	28.31	28.64
3	30.01	33.41	33.41	**33.54**	30.51	33.43	33.94
4	30.01	33.18	33.18	**33.69**	30.36	33.26	34.13

0.8-84.13

Project No.	Expected Duration $\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma\Delta$	Max.Path	Avg.Completion Days (2000 runs) Actual	PCR-B	IndivBuf
1	27.50	30.76	31.57	31.57	28.925	30.830	31.885
2	25.00	28.12	28.89	28.89	25.543	28.161	29.129
3	30.01	33.25	34.06	**34.22**	30.514	33.283	34.477
4	30.01	33.04	33.80	**34.33**	30.360	33.135	34.617

0.8-78.81

Project No.	Expected Duration $\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma\Delta$	Max.Path	Avg.Completion Days (2000 runs) Actual	PCR-B	IndivBuf
1	27.50	30.18	30.85	30.85	28.92	30.34	31.33
2	25.00	27.62	28.28	28.28	25.54	27.71	28.64
3	30.01	32.73	33.41	**33.54**	30.51	32.80	33.94
4	30.01	32.55	33.18	**33.69**	30.36	32.72	34.13

F.1.4. Uniform Distribution

Full-84.13

Project No.	Expected Duration $\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\Delta)$	Max.Path	Avg.Completion Days (2000 runs) Actual	PCR-B	IndivBuf
1	27.50	33.13	33.13	33.13	28.92	33.14	33.38
2	25.00	29.86	29.86	29.86	25.01	29.87	30.06
3	30.00	35.29	35.29	**35.46**	30.50	35.29	35.68
4	30.00	34.95	34.95	**35.55**	30.00	34.96	35.79

Full-78.81

Project No.	Expected Duration $\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\Delta)$	Max.Path	Avg.Completion Days (2000 runs) Actual	PCR-B	IndivBuf
1	27.50	32.25	32.25	32.25	28.92179	32.28019	32.72191
2	25.00	29.11	29.11	29.11	25.01446	29.12837	29.46485
3	30.00	34.47	34.47	**34.61**	30.49936	34.47891	35.00693
4	30.00	34.18	34.18	**34.68**	29.99712	34.23654	35.14507

0.8-84.13

Project No.	Expected Duration $\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\Delta)$	Max.Path	Avg.Completion Days (2000 runs) Actual	PCR-B	IndivBuf
1	27.50	32.01	33.13	33.13	28.92	32.05	33.38
2	25.00	28.89	29.86	29.86	25.01	28.92	30.06
3	30.00	34.23	35.29	**35.46**	30.50	34.25	35.68
4	30.00	33.96	34.95	**35.55**	30.00	34.04	35.79

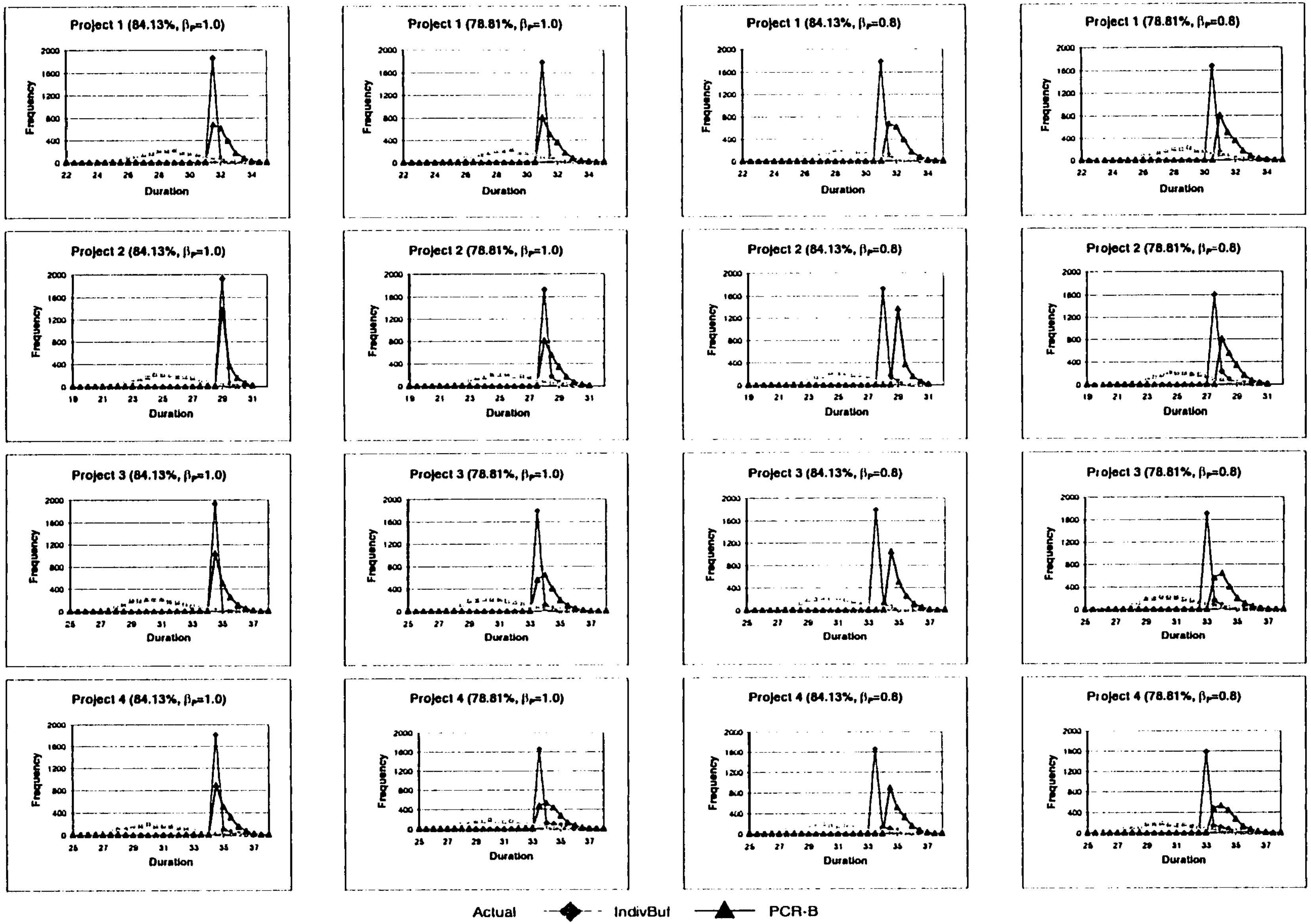
0.8-78.81

Project No.	Expected Duration $\Sigma\mu$	$\Sigma\mu+\Sigma B$	$\Sigma(\mu+\Delta)$	Max.Path	Avg.Completion Days (2000 runs) Actual	PCR-B	IndivBuf
1	27.50	31.30	32.25	32.25	28.92	31.41	32.72
2	25.00	28.28	29.11	29.11	25.01	28.35	29.46
3	30.00	33.57	34.47	**34.61**	30.50	33.63	35.01
4	30.00	33.34	34.18	**34.68**	30.00	33.50	35.15

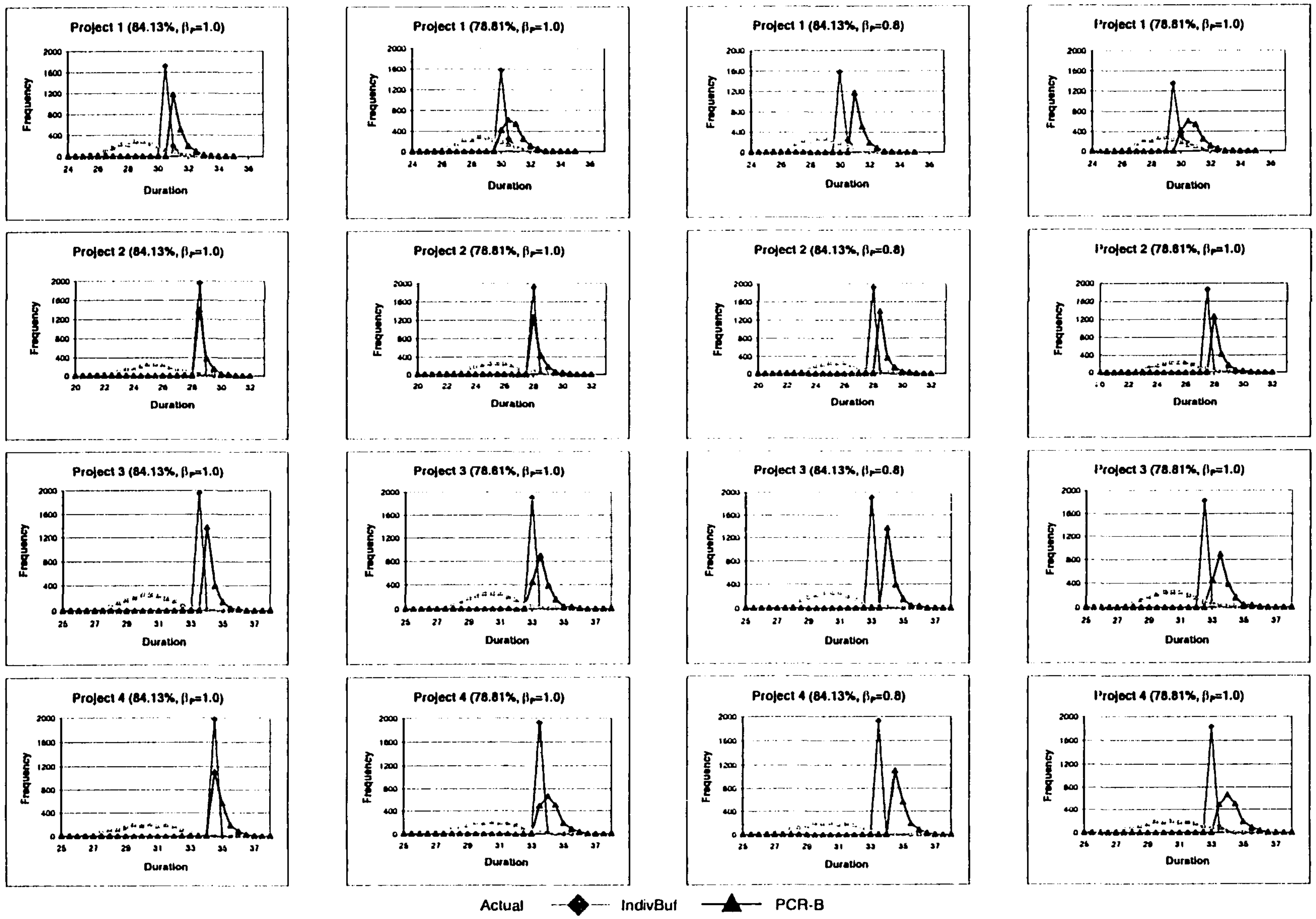
Note: Max.Path $\geq \Sigma(\mu+\gamma\sigma)$, Due to different variance (distribution profile) bet. activities those have the same expected values.

F.2. FREQUENCY GRAPHS OF COMPLETION-DAYS

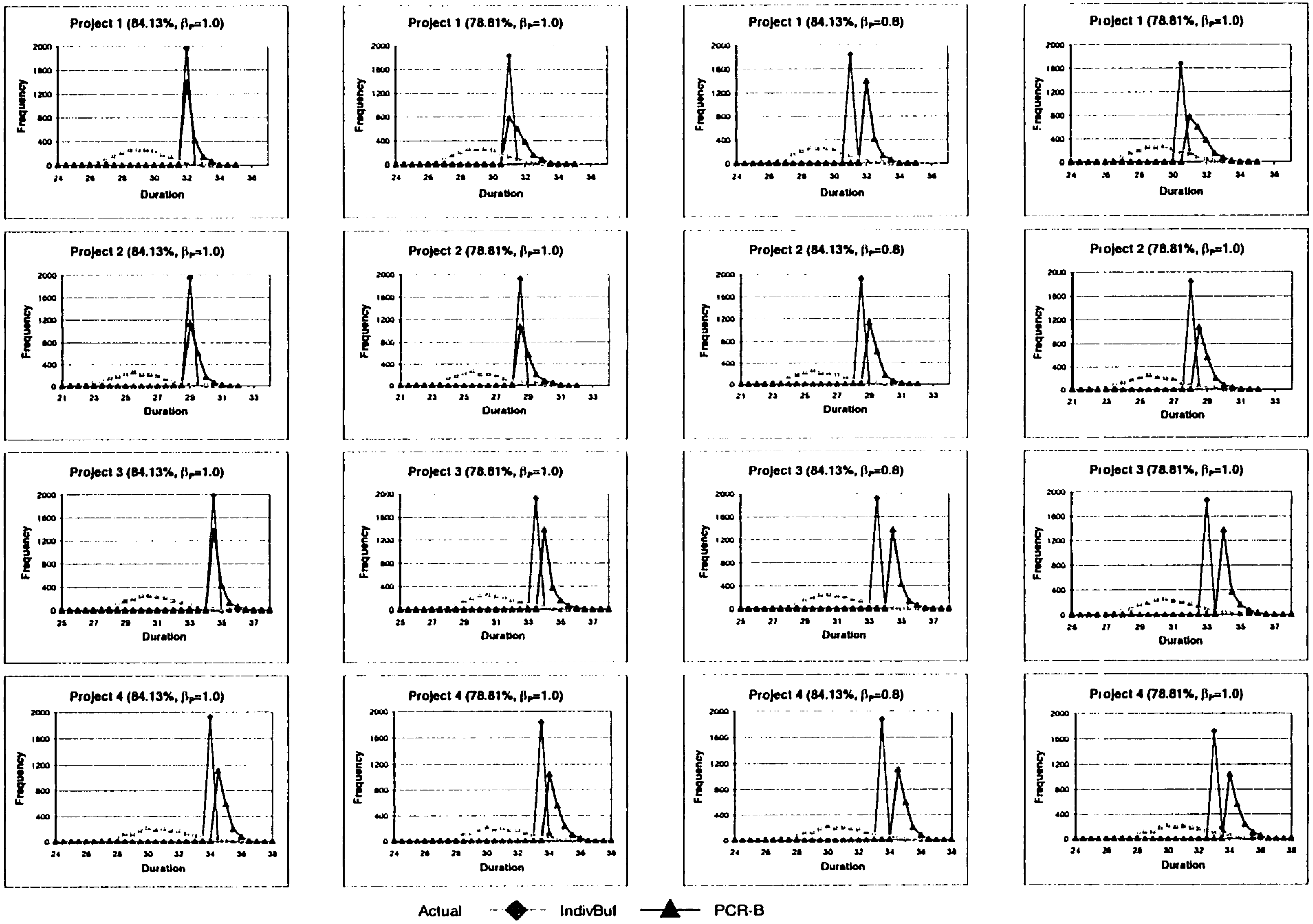
F.2.1. Normal Distribution



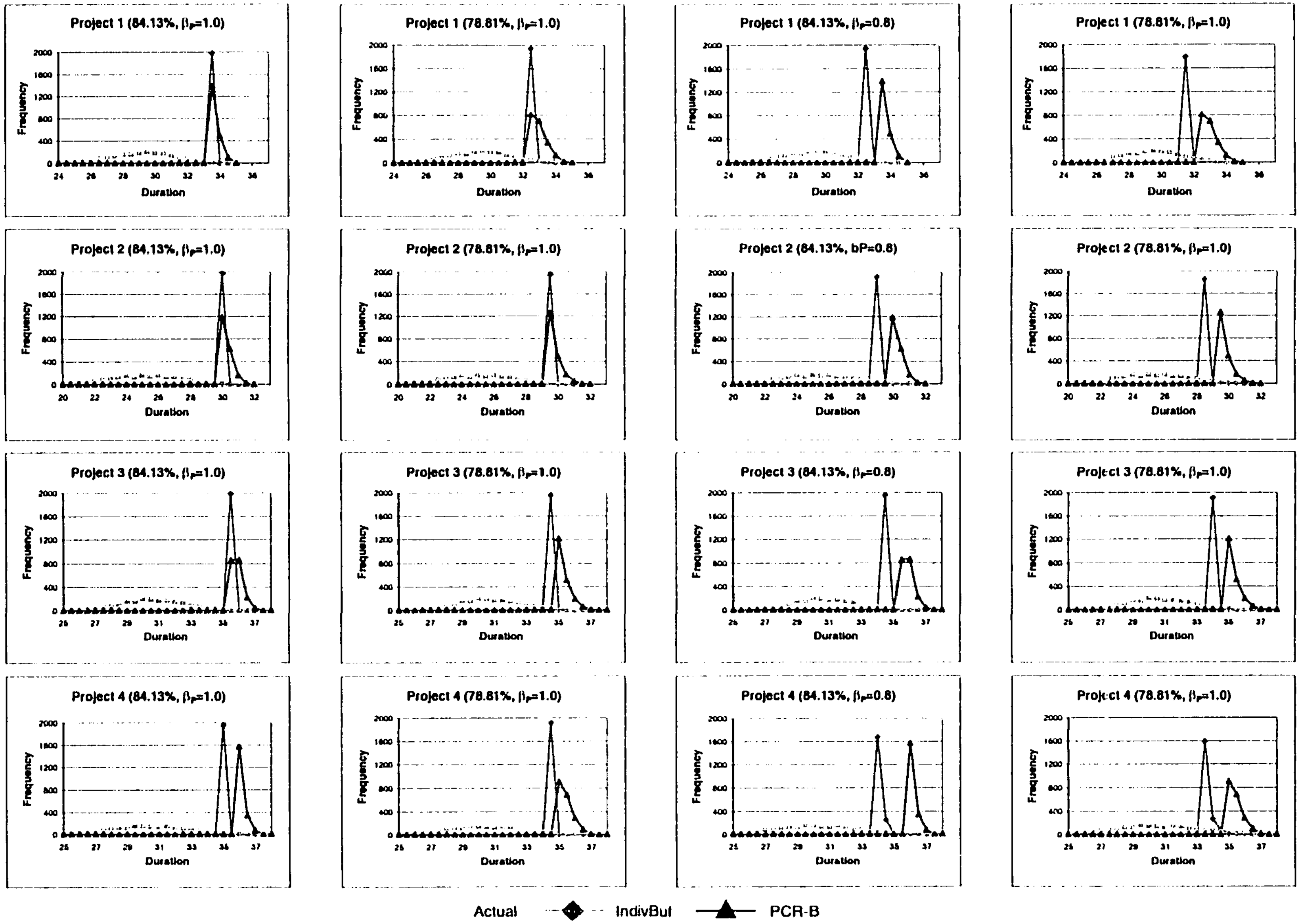
F.2.2. PERT (Beta) Distribution



F.2.3. Triangular Distribution



F.2.4. Uniform Distribution



F.3. COMPLETION LATENESS

F.3.1. Normal Distribution

Project No.	Evaluation Criteria	Full-8413				Full-7881				08-8413				08-7881			
		Freq	%	Delays	%	Freq	%	Delays	%	Freq	%	Delays	%	Freq	%	Delays	%
1	PCR-B > Σμ+ΣB	160	8.00	101.9	0.16	335	16 75	253 6	0 41	335	16.75	253.6	0 41	547	27 35	472 5	0 79
	IndivB > Σ(μ+Δ)	1405	70 25	998 8	1.59	1606	16 06	1404 9	2 29	1405	70 25	998 8	1 59	1606	80 30	1404 9	2 29
2	PCR-B > Σμ+ΣB	198	9.90	84.9	0.15	356	17 80	190 9	0 34	356	17.80	190.9	0 34	542	27 10	334 4	0 61
	IndivB > Σ(μ+Δ)	1139	56.95	715.7	1.25	1373	68 65	1020 9	1 83	1139	56.95	715.7	1.25	1373	68 65	1020 9	1 83
3	PCR-B > Σμ+ΣB	97	4.85	50.2	0.07	229	11 45	134 2	0 20	229	11.45	134.2	0 20	4 4	20 20	275 0	0 42
	IndivB > Σ(μ+Δ)	1279	63.95	831.1	1.21	1517	78 85	1191 8	1 78	1279	63.95	831.1	1.21	1517	75 85	1191 8	1 78
4	PCR-B > Σμ+ΣB	240	12.00	158.8	0.23	366	18 30	308 0	0 46	366	18.30	308 0	0.46	508	25 40	481 0	0 73
	IndivB > Σ(μ+Δ)	1381	69.05	1049.5	1.53	1591	79 55	1485 1	2 22	1381	69.05	1049 5	1.53	1591	79 55	1485 1	2 22

(Unit: %)

Project No.	Full-8413		Full-7881		08-8413		08-7881	
	Freq	Delays	Freq	Delays	Freq	Delays	Freq	Delays
1	11.388	10.203	20 85[illegible]	18 048	23.843	25.386	34 06	33 634
2	17.384	11.857	25 92[illegible]	18 697	31.255	26.67	39 476	32 756
3	7.5841	6 0415	15 09[illegible]	11 264	17.905	16.152	0 29	23 078
4	17.379	15.128	23 00[illegible]	20 739	26.503	29.347	31 93	32.389

F.3.2. PERT (Beta) Distribution

Project No.	Evaluation Criteria	Full-8413				Full-7881				08-8413				08-7881			
		Freq	%	Delays	%	Freq	%	Delays	%	Freq	%	Delays	%	Freq	%	Delays	%
1	PCR-B > Σμ+ΣB	402	20.10	192.6	0.32	620	31.00	379 5	0 64	620	31.00	379.5	0 64	822	41 10	605 2	1 03
	IndivB > Σ(μ+Δ)	1479	73.95	957.1	1.58	1653	82 65	1348 8	2 27	1479	73 95	957.1	1.58	1653	82 65	1348 8	2 27
2	PCR-B > Σμ+ΣB	64	3.20	36 6	0.06	128	6 40	94 9	0 17	128	6.40	94 9	0.17	229	11 45	183 1	0 34
	IndivB > Σ(μ+Δ)	1225	61.25	573.8	1.02	1487	74.35	878 5	1 59	1225	61.25	573 8	1.02	1487	74 35	878 5	1 59
3	PCR-B > Σμ+ΣB	46	2.30	23.5	0.04	136	6 80	78 8	0 12	136	6 80	78 8	0 12	315	15 75	178 5	0 28
	IndivB > Σ(μ+Δ)	1329	66.45	590.8	0.88	1621	81 05	933 9	1 42	1329	66 45	590 8	0 88	1621	81 05	933 9	1 42
4	PCR-B > Σμ+ΣB	31	1.55	20.1	0.03	94	4 70	63 0	0 09	94	4.70	63 0	0 09	413	20 65	192 3	0 29
	IndivB > Σ(μ+Δ)	1383	69.15	759.1	1.11	1661	83 05	1228 7	1 84	1383	69 15	759 1	1.11	1661	83 05	1228 7	1 84

(Unit: %)

Project No.	Full-8413		Full-7881		08-8413		08-7881	
	Freq	Delays	Freq	Delays	Freq	Delays	Freq	Delays
1	27.181	20.125	37 50[illegible]	28 137	41.92	39 654	49 728	44 867
2	5.2245	6.3821	8 607[illegible]	10 805	10.449	16 543	15.4	20 843
3	3.4612	3.9791	8 389[illegible]	8 4367	10.233	13 335	19 432	19.113
4	2.2415	2.6428	5 659[illegible]	5 1284	6.7968	8.3012	24 865	15 654

F.3+A62.3. Triangular Distribution

Project No.	Evaluation Criteria	Full-8413				Full-7881				08-8413				08-7881			
		Freq	%	Delays	%	Freq	%	Delays	%	Freq	%	Delays	%	Freq	%	Delays	%
1	PCR-B > Σμ+ΣB	68	3.40	32.9	0.05	247	12 35	123 9	0 20	267	13.35	141.1	0.23	481	24 05	333 7	0 55
	IndivB > Σ(μ+Δ)	1180	59.00	625.7	0.99	1426	71 30	973 9	1 58	1180	59.00	625.7	0.99	1425	71 30	973 9	1 58
2	PCR-B > Σμ+ΣB	51	2.55	24.1	0.04	109	5 45	70 5	0 12	130	6.50	89.6	0.16	214	10 70	173 3	0 31
	IndivB > Σ(μ+Δ)	1083	54.15	468.1	0.81	1332	66 60	730 8	1 29	1083	54.15	468.1	0.81	1332	66 60	730 8	1 29
3	PCR-B > Σμ+ΣB	30	1.50	13.9	0.02	85	4 30	49 5	0 07	102	5.10	64.3	0.10	195	9 75	137 7	0 21
	IndivB > Σ(μ+Δ)	1229	61.45	510.3	0.75	1481	74 05	796 9	1 19	1229	61.45	510.3	0.75	1481	74 05	796 9	1 19
4	PCR-B > Σμ+ΣB	173	8.65	63.3	0.09	357	17 85	163 6	0 25	397	19.85	184.7	0.29	560	28 00	339 7	0 52
	IndivB > Σ(μ+Δ)	1179	58.95	567.3	0.84	1414	70 70	887 8	1 34	1179	58.95	567.3	0.84	1414	70 70	887 8	1 34

(Unit: %)

Project No.	Full-8413		Full-7881		08-8413		08-7881	
	Freq	Delays	Freq	Delays	Freq	Delays	Freq	Delays
1	5.7627	5.2647	17 321	12 722	22.627	22.543	33 731	34.268
2	4.7091	5.1525	8 183[illegible]	9 6531	12.004	19.138	16 066	23.71
3	2.441	2.7298	5 739[illegible]	6 2101	8.2994	12.599	13.167	17 275
4	14.673	11.156	25 24[illegible]	18 424	33.673	34.323	39 604	38 262

F.3.4. Uniform Distribution

Project No.	Evaluation Criteria	Full-8413				Full-7881				08-8413				08-7881			
		Freq	%	Delays	%	Freq	%	Delays	%	Freq	%	Delays	%	Freq	%	Delays	%
1	PCR-B > Σμ+ΣB	25	1.25	9.3	0.01	94	4 70	53 1	0 08	124	6.20	80.3	0.13	244	12 20	207 9	0 33
	IndivB > Σ(μ+Δ)	1186	59.30	498 8	0.75	1467	73 35	936 5	1 45	1186	59.30	498.8	0.75	1467	73 35	936 5	1 45
2	PCR-B > Σμ+ΣB	25	1.25	11.4	0.02	69	3 45	45 9	0 08	88	4.40	62.7	0.11	168	8 40	139 9	0 25
	IndivB > Σ(μ+Δ)	1089	54.45	393.0	0.66	1346	67 30	718 9	1 23	1089	54.45	393 0	0 66	1346	67 30	718 9	1 23
3	PCR-B > Σμ+ΣB	11	0.55	6.5	0.01	49	2 45	26 7	0 04	65	3.25	40 2	0.06	155	7 75	107 4	0 16
	IndivB > Σ(μ+Δ)	1235	61.75	434.6	0.62	1492	74 60	794 7	1 15	1235	61.75	434.6	0 62	1492	74 60	794 7	1 15
4	PCR-B > Σμ+ΣB	58	2.90	32.0	0.05	284	14 20	118 2	0 17	338	16.90	159.3	0.23	483	24 15	315 3	0 47
	IndivB > Σ(μ+Δ)	1178	58.90	490.9	0.70	1465	73 25	926 9	1 36	1178	58 90	490 9	0.70	1465	73 25	926 9	1 36

(Unit: %)

Project No.	Full-8413		Full-7881		08-8413		08-7881	
	Freq	Delays	Freq	Delays	Freq	Delays	Freq	Delays
1	2.1079	1.8665	6 407[illegible]	5 6657	10.455	16.093	16 633	22 195
2	2.2957	2 896	5 126[illegible]	6 3852	8.0808	15.949	12 481	19 466
3	0.8907	1.4955	3 284[illegible]	3 3637	5.2632	9.2515	10 389	13.518
4	4.9236	6 5207	19 386	12 749	28 693	32.447	32.969	34 013

Note: Delays = PCR-delays/Indiv-delays*100