A Development of Performance Metrics for Forecasting Schedule Slippage

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(ABSTRACT)

Project schedules should mirror the project, as the project takes place. Accurate project schedules, when updated and revised, reflect the actual progress of construction as performed in the field. Various methods for monitoring progress of construction are successful in their representation of actual construction as it takes place. Progress monitoring techniques clearly identify when we *are* behind schedule, yet it is less obvious to recognize when we are going to slip behind schedule.

This research explores how schedule performance measurement mechanisms are used to recognize construction projects that may potentially slip behind schedule, as well as what type of early warning they provide in order to take corrective action. Such early warning systems help prevent situations where the contractor and/or owner are in denial for a number of months that a possible catastrophe of a project is going to finish on time.

This research develops the intellectual framework for schedule control systems, based on a review of control systems in the construction industry. The framework forms the foundation for the development of a schedule control technique for forecasting schedule slippage – the Required Performance Method (RPM). The RPM forecasts the required performance needed for timely project completion, and is based on the contractor's ability to expand future work. The RPM is a paradigm shift from control based on scheduled completion date to control based on required performance. This shift enables forecasts to express concern in terms that are more tangible. Furthermore, the shift represents a focus on what *needs to be done* to achieve a target completion date, as opposed to the traditional focus on what *has been done*. The RPM is demonstrated through a case study, revealing its ability to forecast impending schedule slippage.

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Chapter 1 – Introduction

1.1 Overview – The Need for Forecasting Schedule Slippage

Project schedules should mirror the project, as the project takes place. Accurate project schedules, when updated and revised, reflect the actual progress of construction as performed in the field. Various methods for monitoring the progress of construction are successful in their representation of actual construction as it takes place. These methods include the tracking of money, commodities, activities, float, milestones, as well as others. Progress monitoring tools, when all work goes smoothly and in accordance with plans, may seem merely a formality; confirmation that the contractor will complete on time. Ideally, this situation would be commonplace. However, when the contractor is not on time, these tools gain major importance.

Progress monitoring techniques clearly identify when we *are* behind schedule, yet it is less obvious to recognize when we are going to slip behind schedule; for example, if our final destination is point A, and we finish at point B, it is clear that we are in the wrong place. Here in lies the problem – not recognizing that we were going to point B, and not point A, before we arrived at point B. In the construction industry, contractors and owners face this same dilemma, of properly identifying that the project is headed towards that “point B”, before it gets there.

The challenge is to effectively analyze performance measurement data in order to predict where the project is headed. Doing so would make it possible to detect an impending schedule slippage. As noted above, it is straightforward to take a snapshot of the project and detect that a project is behind schedule; however, an analysis of preceding indicators in this snapshot could have provided an early warning of the approaching schedule slippage.

An early warning indicator would be of great benefit to both the contractor and owner, allowing to distinguish the difference between projects where progress monitoring is a formality, and projects where progress monitoring could possibly recognize crucial schedule slippage. In the latter case, raising a level of concern may lead to the opportunity for taking timely, corrective action. The result of such a system would allow ample time for adjustments to be made, in order to complete the project on time.

This research explores how schedule performance measurement mechanisms can be used to recognize construction projects that may potentially slip behind schedule, as well as what type of early warning they provide in order to take corrective action. Such an early warning system helps prevent situations where the contractor and/or owner are in denial for a number of months that a possible catastrophe of a project is going to finish on time. To review and recommend such a system or systems, a better comprehension is needed of the intellectual framework of performance measurement mechanisms, as well as their potential use as a tool for providing an early warning of schedule slippage.

This research develops the intellectual framework for schedule control systems, based on a review of control systems in the construction industry. The framework forms the foundation for the development of a schedule control technique for forecasting schedule slippage – the Required Performance Method (RPM). The RPM forecasts the required performance needed for timely project completion, and is based on the contractor’s ability to expand future work. The theory behind this method is developed in Chapter 4, followed by a demonstration of its use as presented by a case study in Chapter 5.

1.2 Problem Statement

This research addresses the two major problems that arise when considering the use of performance measurement mechanisms to provide an early warning of schedule slippage: 1) the construction industry does not have a good understanding and intellectual framework for "schedule control", and 2) there is no ready access to systems that can be used to maintain schedule control. The subsequent sections break down schedule control into components, followed by a discussion of the limitations of these components.

1.2.1 Poor Comprehension Of and Intellectual Framework for "Schedule Control"

Academic development of control systems in the construction industry appears to have reached a plateau in terms of the advancement of literature. Barrie and Paulson [1984] summarize familiar knowledge on the subject:

> Throughout the project, the control system quantitatively measures actual performance against the plan and acts as an early warning system to diagnose major problems while management action can still be effective in achieving solutions. Development and application of a practical control system to measure progress and costs are among the most important contributions of the professional construction manager.

It is clear that there is a need for a control system, and that the function of a control system is to compare the actual versus planned, which should in turn give a warning of future problems. Too often is this casual link made – that an uncomplicated comparison of actual and planned work provides the most efficient and effective early warning system; there is no mention of a forecast or prediction that provides the early warning. A dissection of construction control systems into base components is not readily available. Control systems in general can be broken down into five stages, used to maintain a desired output, which are:

1. Define
2. Measure
3. Compare
4. Predict
5. Act

The first three stages (*define*, *measure*, and *compare*) form a subset that are the basis for *progress monitoring*. From this grouping, the three major stages of control systems are:

1. Monitor Progress to Determine Current State
2. Predict Possible Future States
3. Act to Achieve a Desired Future State

These minor and major stages are directly applicable to the construction industry, and more specifically for this research, to project scheduling. To explain the need for a "control system" as opposed to a "monitoring system", the following sections discuss how monitoring systems are only a piece, albeit an integral one, of control systems.

1.2.1.1 Monitor Progress to Determine Current State

Forming the foundation of a control system is a progress monitoring system, which as stated before, consists of the steps of *define, measure*, and *compare*. Progress monitoring is essential in the control process in that you need to know where you are before you know where you are going. Knowing "where you are" is the practice of defining where you want to be, measuring where you are, and making a comparison between the two to determine where you are with respect to where you planned to be. The following diagram depicts progress monitoring in scheduling.

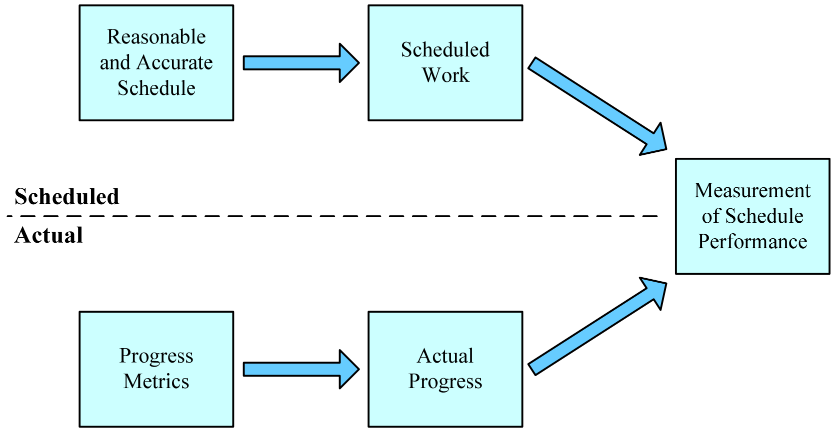


Figure 1.1: Progress Monitoring System

The diagram is divided vertically into scheduled work and actual work performed. On the *Scheduled* half of the diagram, once a reasonable and accurate schedule is approved (the schedule of record), there is a plan of attack for how construction will take place, comprised of scheduled work. This scheduled work serves as a datum or baseline of the actual work as it takes place. Examples of standards for measurement include CPM schedules, control budgets, procurement schedules, quality control specifications, and construction working drawings [Paulson 1976]. On the *Actual* half of the diagram, predefined progress metrics are used to track actual progress of construction. The *Measurement of Schedule Performance* takes place when *Scheduled Work* is compared with *Actual Progress*. With the measurement of schedule performance, it can be determined how close to, or how far off, actual construction is to the schedule. This quantifiable measurement provides information for the following steps of schedule control systems – predicting and acting, which in terms of project scheduling, need further understanding and definition.

1.2.1.2 Predict Possible Future States

A *prediction* is synonymous with a *forecast*, which serves as a necessary step in bridging the gap between monitoring progress, and taking action. According to Barrie and Paulson [1984], a *forecast* defined: "based on the best knowledge at hand, what is expected to happen to the project and its elements in the future." Forecasts require reliable progress measurement in order to project the future, for you cannot properly initiate action without valid predictions. Improving the validity of projections will provide strong grounds for improving actions. This being said, what actually *is* a "forecast" – what is it based on. Are forecasts based on tracking data (trends in current project data), historical data (trends in data from previous projects, applied to the current project), or both? Is forecasting taking the production to date and superimposing on the future? In reference to the definition above, what is the "best knowledge at hand" – the construction industry has clearly defined its concept of what a forecast is, but it is difficult to define what that "best knowledge" is.

1.2.1.3 Act to Achieve a Desired Future State

The final stage in a schedule control system is *acting*, which relies on predictions to produce actionable information in a format that allows action to be taken, if needed, in order to end up where you want to be. This stage shifts predictions into the "so what?" area – what does the forecast mean. It is documented that ominous forecasts necessitate that a decision must be made concerning what corrective action, if any, is required [Clough et al. 2000]. However, lacking is a good understanding of what the middle ground is between a poor forecast and corrective action – what type of indicator signals action to be taken. To further analyze problems associated with *acting*, the indicator is symbolized using a smoke alarm analogy.

Smoke alarms ring when they detect smoke, or in scheduling terms, an alarm to take action occurs when a forecast warrants action. A smoke alarm, when ringing, grabs your attention – which is exactly what is needed in construction scheduling, an alarm that raises awareness of a situation with the potential to cause schedule slippage. There are two different types of smoke alarms: 1) an alarm that requires you to check things out and inspect if all is OK, and 2) an alarm that warns that things are wrong. The second alarm differs in that it has detected something is definitely wrong and there is a need for corrective action. Associating a smoke alarm with forecasts puts the urgency on acting, which may be a change in method, sequence or other corrective action of the dismal prediction.

1.2.1.4 Structure of Control Systems

There is a clear understanding of progress monitoring systems, which are comprised of defining a plan or schedule, measuring actual work as it occurs, and tracking and reporting a comparison between planned and actual work. The same cannot be said, however, for intellectual framework that encompasses the *predict* and *act* stages of schedule controls systems. While it is known that a reliable forecast is needed for control systems, the links between progress monitoring and forecasts, and forecasts and control, are not thoroughly developed. As mentioned above, a prediction that causes action is what is described as an early warning system. Early warning systems that utilize a “smoke alarm” serve as the major component of schedule control systems, signaling an alarm to call attention and possibly take corrective action. The following diagram attempts to structure schedule control systems:

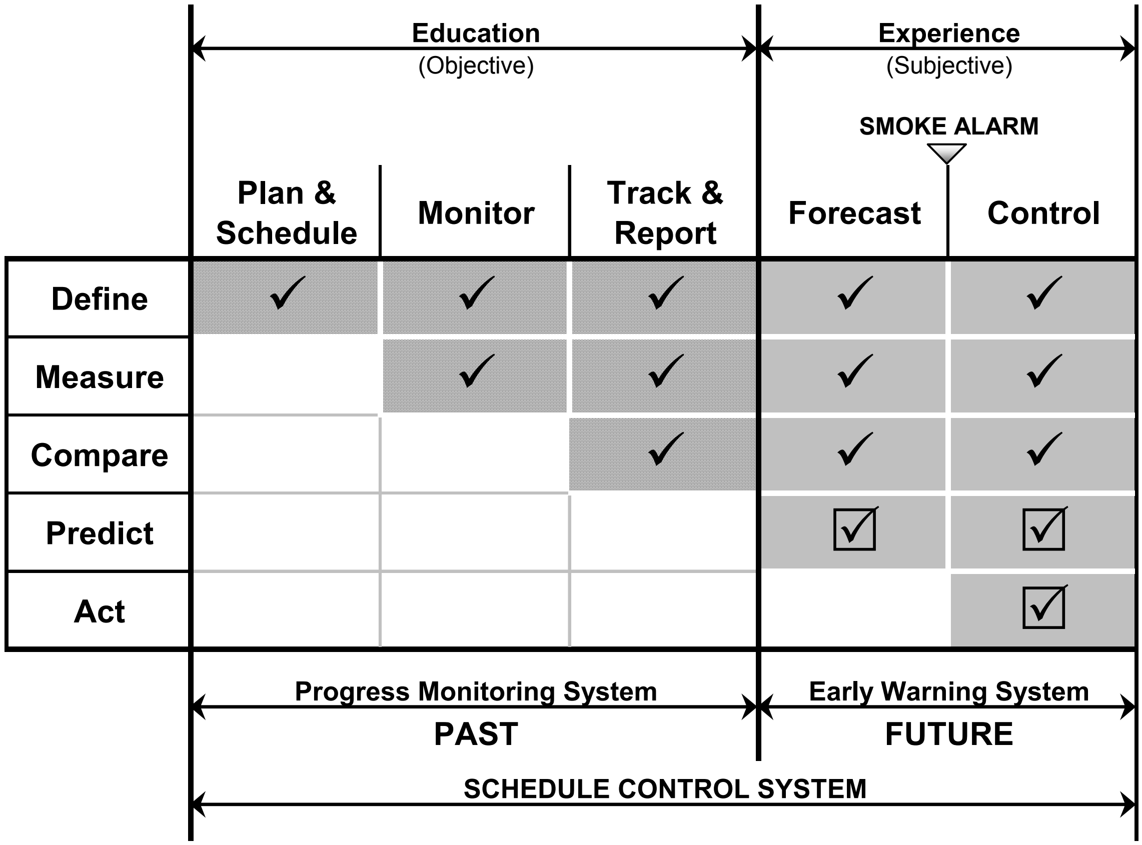


Figure 1.2: Structure of a Schedule Control System

Schedule control systems, as shown in the diagram, are divided into two major components: 1) a *Progress Monitoring System* that is a historical representation of the first three stages (*define, measure, compare*), and 2) an *Early Warning System* that looks towards the future by using the final two stages (*predict, act*). Bordering the top of the diagram, the five stages are matched with their project scheduling counterpart. Each project scheduling component has checkmarks across from the stages included in that component, e.g. *Track & Report* requires the stages of *define, measure, and compare*. These project scheduling components are the intellectual framework for schedule control that needs further development, as is described in Chapter 3.

Further distinguishing between progress monitoring and early warning, progress monitoring is generally of objective matter – tracking and reporting measurements of actual versus planned, which can be learned through an education of progress monitoring. On the other hand, early warning systems are more of subjective matter, where experience is required to determine what type of smoke alarm is needed, as well as how to fine-tune the smoke alarm to go off when it should go off. To develop an alarm, there must be a valid prediction of where the project is headed.

Given the information above on "schedule control," there is an understandable distinction between progress monitoring systems and schedule control systems. Based on the notion that schedule control requires reliable forecasts that produce an action, there is not readily available information on quantitative indicators that say when the smoke alarm should go off. For example, remedial stages are suggested when project activities are "appreciably behind", there are "substantial delays", or durations have been "materially underestimated" [Clough et al. 2000]. All of these terms are laced with subjectivity and require experience for quantification.

With the clear need for a good understanding and intellectual framework for schedule control, the following section communicates the need for actual forms of schedule control systems.

1.2.2 Lack of Systems to Use to Maintain Schedule Control

Construction scheduling does not have universal, used-by-all methods for effective schedule control systems that alert an early warning of slippage. Many techniques are extremely effective as progress monitoring systems, yet these systems do not have pronounced forecasting methods and smoke alarms that result in knowing when to take action.

1.2.2.1 Limitation of Progress Monitoring Systems

Progress monitoring systems are well documented in their ability to accurately represent both the past and the present – defining where you have been and where you are, to determine where you are going. Given that the historical representation of the project is a major step in schedule control systems, the need is for the development of systems that are forward-looking. Right now, the construction industry is very accurate in its monitoring and reporting, yet these systems do not necessarily have the ability to forecast and find triggers that warrant action.

This research addresses the problem that there are not well-documented procedures that look forward and say when exactly there should be alarm that the project is in danger. The question of *when* to call attention is an essential part of an early warning system. If the warning is too late, which is often the case, the contractor must *react* to the problem. Rather than reacting to problems recognized by progress monitoring systems, schedule control systems will predict the problem before it becomes one. Doing so allows preventative measures and corrective action to minimize the potential damage. Consider the following diagram:

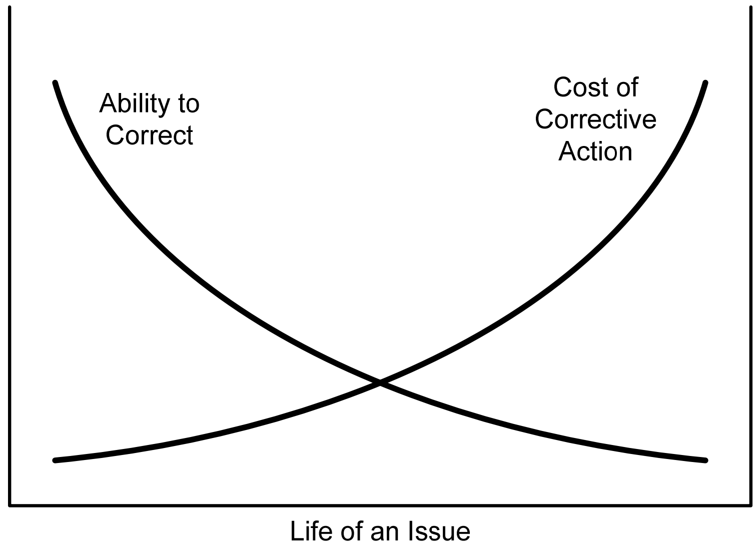


Figure 1.3: Ability to Correct vs. Cost of Corrective Action

There must be an issue before it can be detected and action taken. The trick is to identify the issue early while action can be taken at a reasonable cost; waiting until later to take action on the issue increases the cost of corrective action and increases the chances of the issue having a detrimental effect on the schedule.

1.2.2.2 Limitations of Forecasting and Acting Tools

A prediction is only as reliable as the information used to make the prediction. In the case of project scheduling, a forecast is only as reliable as the progress monitoring system that developed the information used in the forecast. Therefore, forecasts are limited when progress monitoring systems are not regularly updated and accurate. Assuming that tracking and reporting is up-to-date and correct, a problem lies in that while there are forecasting tools available to use this information, there are no smoke alarms that trigger actions; no scientific means of saying that when a forecasting tool shows "this", action should be taken.

Forecasting tools commonly rely on an extrapolation of recent trends in data; mechanistically applying the past to the future and making a prediction of what *will* happen, based on what *has* happened. In retrospect, this is a limitation of predicting the future; the only information available for construction forecasting is what you planned to happen, what actually happened, and the rate or means in which it has been happening. Computerized scheduling, such as P3, monitors progress very well, yet is less dependable in its ability to produce forecasts that cause action. P3 relies on duration information that you provide it, making predictions and sequencing of future work based on original durations for these future activities. Consequently, if a forecast based on this information shows a projection that the project will finish late, there is a need for an indicator to take the subjectivity out of the forecast and make the smoke alarm ring, a need for a system that causes action. Furthermore, what types of acts are produced – a call for attention, a need for a recovery plan, or quite possibly grounds for suspension or termination? With the objective of delivering a reliable schedule control system, these are problems that this research addresses.

1.2.3 Schedule Control Systems: An Analogy

To better understand the need for a schedule control system, consider an analogy. Barrie and Paulson [1984] expressed the need for a schedule control system as a car driving down the highway with the windshield painted over. The driver is unable to look down the road, into the future, for information that will keep the car on the right path (forecasting). The only information available to the driver is that observed by looking out the side and rear windows – looking at where you are and where you have been, respectively (monitoring progress). It is possible to drive successfully like this by 1) driving *very* slow, 2) continually monitoring progress, and 3) taking action to immediately correct small deviations. However, in construction scheduling, it is unrealistic to update schedules and take action at this rate, which would equate to an hourly or daily basis. This analogy clearly expresses the need for forward-looking control systems, in order to prevent a "crash".

Consider another automobile analogy, yet this time it expresses schedule control systems using quantitative measures. In this analogy, two friends embark on a ten-day road trip with $100 between them, leaving a budget of $10/day. Figure 1.4 is a graphical representation of the friends' budget, in terms of budgeted expenses, actual expenses, and money remaining that they can spend.

After two days, they have spent $20 – great, they are precisely on budget! Another couple days pass, and at the end of day 4, the friends check their wallets and determine that they have spent a total of $46. Although spending to date is slightly more than planned, there are no worries, for they believe they shall easily be able to get by on the remaining $56, at $9/day.

Yet another two days pass, and after leaving the tip for dinner at the end of day 6, they count their remaining funds to be $32. They have spent a total of $68 in six days, a rate of $11.33/day – moderately over the budgeted $10/day – leaving only $8/day for the remaining four days. One friend is worried that at the rate they are spending, they will not have sufficient funds to finish their trip. To this, the other friend responds, "Don't worry, we'll be just fine. We can make it on $8/day." The first friend shrugs his shoulders, sighs, and gives a nod of approval.

Two more days pass and because of the one friend's calming reassurance that there was nothing to worry about, the pair fails to pay as close attention to their budget as they probably should have. On days 7 and 8, they spent $12 each day, which did not seem too far over budget after spending at a previous clip of $11.33/day. The wallets come out, and the friends count their remaining funds – *"Eight dollars left for two days!"* It does not appear that the dynamic duo will have enough money to finish their trip.

This analogy clearly illustrates the importance of knowing when you are no longer on budget. In this case, any rate over $10/day is over budget, however real projects reflect this critical "on budget" value through progress monitoring tools such as cost and commodity curves that may have varying values of where you should be at each point in time. At the end of day 8, the friends reached a point where there was no way they could finish their journey – $4/day was completely unrealistic funds for completion. Once realized that their spending rate was over budget, their "smoke alarm" should have been going off, indicating that they need to take corrective action, otherwise they are in danger of running out of money. They *did* recognize early on that they were over budget, yet continued spending without worries, confident with their budget situation.

Another factor to consider is how the schedule analysts (in this case, the two friends) view any type of early warning indicators, in terms of a pessimistic, realistic, or optimistic approach. Often, optimism rules supreme, as was the case in this example where one friend continually reassured, "Don't worry, we're okay, we'll finish within our budget." If a realistic approach to early warning indicators is not taken, there are only so many "don't worry's" before there's an "uh-oh." In this regard, if reliable early-warning tools are developed and are quantitative, they will serve as a powerful instrument to help prevent the "uh-oh's" of the construction industry – interpreted as "behind schedule, over budget."

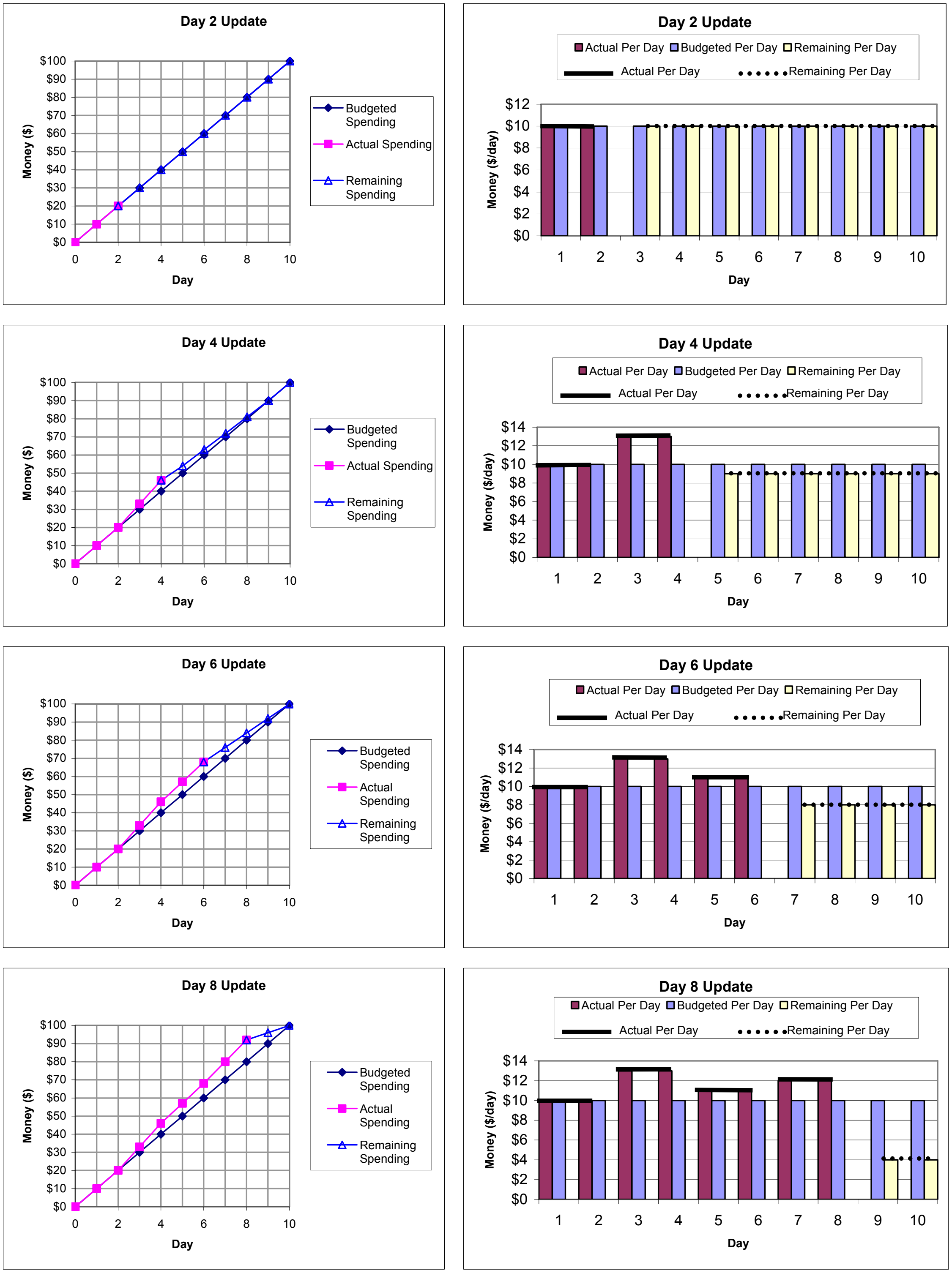


Figure 1.4: Car Analogy Updates

1.3 Objectives

This research examines, organizes, and presents how the industry applies progress-monitoring techniques to detect an early warning of impending schedule slippage; to know when the schedule will slip *before* it slips into a crisis. The primary objectives are to:

1. Develop intellectual framework for schedule control
2. Develop and describe a schedule control system that can be used
3. Demonstrate the schedule control system

A review of mechanisms used in the construction industry to measure schedule performance and provide an early warning for schedule slippage presents the background needed to develop a new means for using performance metrics to forecast impending schedule slippage. These forecasts serve as an extremely valuable tool to contractors and owners, transforming historical data and trends into projected future information that may prevent a project from slipping behind schedule. This research takes the status of where we have been and where we are, along with predictions, to develop triggers that will say when to take action.

1.3.1 Develop Intellectual Framework for Schedule Control

In the domain of project scheduling, the intellectual framework for predictions and taking action are not as prevalent as those for progress measurement. Routinely making reliable predictions that provide an early warning of schedule slippage, in turn supporting taking action, provide a control system to help minimize projects being delivered late. This is excellent reason to further develop the intellectual framework for schedule control.

Researching and developing schedule control builds the philosophical and intellectual differences between progress monitoring systems and early warning systems. The research seeks valuable insight on the concept of triggers and their relation to warranting action, in terms of how quantifiable, if at all, these triggers are. Given that the concepts of progress monitoring are well known and accepted, the focus is on the relationships between progress monitoring, predicting, and taking action.

1.3.2 Develop and Describe a Schedule Control System that Can Be Used

This objective is to determine if the predict/act components of a schedule control system can be developed, based on established progress monitoring systems. When considering the development of control systems, the following items need addressing:

- What performance metrics does the construction industry use
- Can historical project performance data (such as experiences on previous projects) be combined with current project tracking data to accurately predict schedule slippage
- How does the construction industry predict based on variance and trends
- What are the characteristics of a good system for predicting
    - Is it based on historical data and tendencies from previous projects
    - Is it based on tracking data exclusively from the current project
    - Does it consider future limitations, such as resources
- Does anyone have an early warning system that produces an act
- Are there quantitative tools for developing smoke alarms
    - What performance metrics make up the smoke alarm
- Based on the prediction, when does the industry react – does the smoke alarm:
    - Call for attention / reason for concern
    - Warrant / take timely action

- How much do agencies rely on smoke alarms
- What threshold is allowable for the smoke alarm – how often must the ring be correct to be used

The goal is to develop and describe a valuable schedule control system, which will consist of useful means of progress measurement and early warning that detect schedule slippage and predict before it happens. Using all information gathered, recommendations are made regarding the most effective use of the schedule control system, accompanied by the appropriate conditions under which the system is applicable.

1.3.3 Demonstrate the Schedule Control System

Once the control system is developed, it is demonstrated using real project data, attempting to confirm a quantifiable means for an early warning system of impending schedule slippage. This research utilizes a case study project to demonstrate the schedule control system developed. Application of the control system on real project data highlights the ability of the control system to recognize early warnings of impending schedule slippage. Furthermore, a successful demonstration of the control system on a case study recognizes that it *is* a method with potential for implementation in the real world.

1.4 Scope and Limitations

The scope of this research is to determine the *predict* and *act* stages of a construction schedule control system. Referring back to Figure 1.2, the scope is graphically displayed as the boxed checkmarks on the diagram – developing an early warning system that will use forecasts and smoke alarm type indicators to warrant taking action. Within this scope, the following limitations apply.

1.4.1 Construction Project Scheduling

Only control system techniques that apply to construction project scheduling are considered for future implementation. However, these schedule control techniques are developed with an understanding of other construction control systems. The objective of the research is limited to the domain of real-world construction scheduling control systems developed for use within the construction scheduling industry.

Further defining limitations, the only methods reviewed are those applicable to schedule performance measurement. The term *performance,* as used in this research, is defined as the relationship between quantifiable progress metrics and the project schedule. Performance measurements must be scientific and of objective matter – those typically monitored on major construction projects. This research focuses on metrics that are based on quantity, and not quality. The assumption is that if a quantifiable metric is "counted", the field inspection staff has used their judgment to determine that the metric meets satisfactory quality.

1.4.2 Based on Existing Progress Monitoring Tools

The final recommendation is based on progress metrics that are or have been successfully implemented in the construction industry. Only effective techniques that have withstood the test of time are considered in this research; approaches not proven in the industry are not considered in the process of making a recommendation. While new progress metrics for defining, measuring, and comparing are not developed, the research develops an innovative application of existing metrics for use in the early warning/ schedule control system.

1.4.3 Based on Metrics Produced or Able to Be Produced in Normal Schedule Processes

The construction project schedule control system is only to be considered if it is based on metrics produced or able to be produced in normal schedule processes. It is unreasonable to recommend a control system that requires new, difficult techniques or an unrealistic number of resources. This limitation, in conjunction with the others, provide a control system recommendation with potential for immediate use in the construction industry.

1.5 Benefits of Research

There are multiple benefits of this research, the first being the contribution to the construction industry body of knowledge. While there is an abundance of current knowledge on progress monitoring systems, this research develops the intellectual framework for complete schedule control systems, bridging the gaps between progress monitoring, forecasting and acting. Guidelines developed for schedule control systems will serve as principles for developing future early warning systems.

The second benefit of this research is the development of a schedule control system that can be used, based on existing progress monitoring tools, and based on metrics produced in normal schedule processes. Effective scheduling early warning systems are scarce, and the Required Performance Method developed in this research has potential for immediate real world application. The RPM is a tool for the contractor to forecast their work slipping behind schedule, while the owner may potentially apply the tool as a schedule requirement in the contract, to ensure the contractor fulfills their duties in a proper and appropriate manner.

1.6 Document Format

This document is configured in a logical manner to fulfill the objectives of this research. Below is a document map, followed by a description of the remainder of this document.

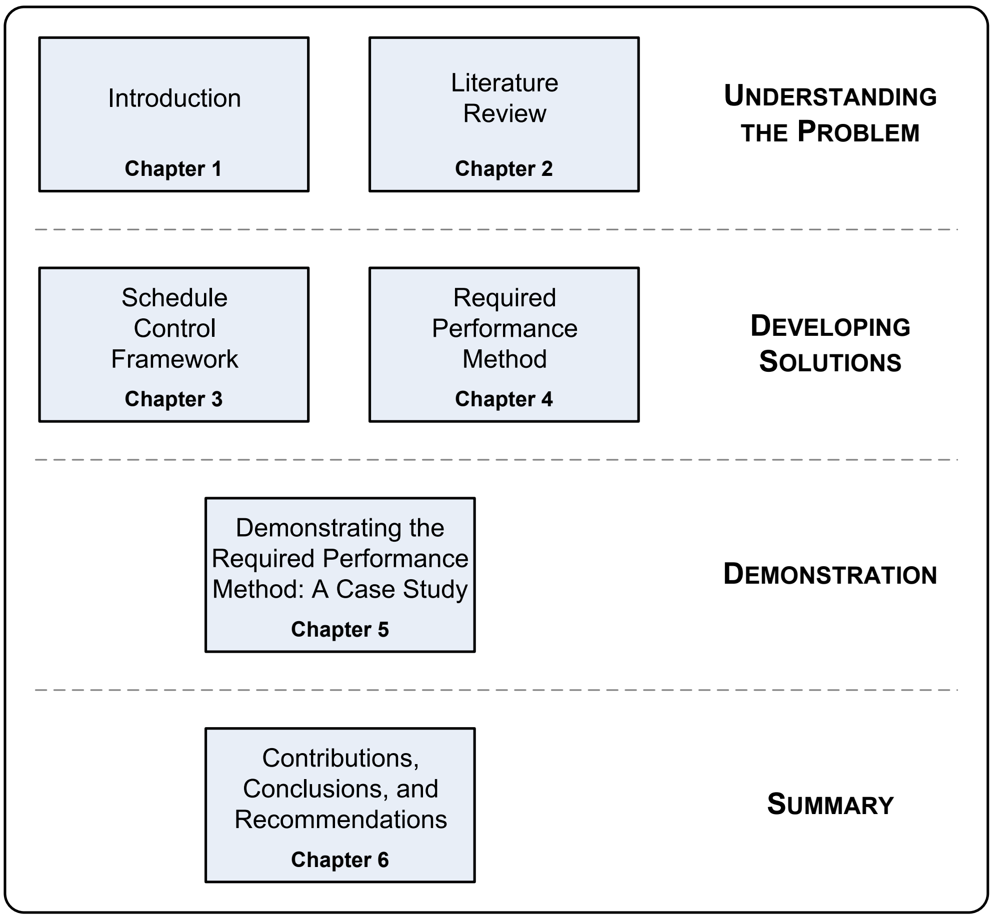


Figure 1.5: Document Map

Chapter 2 – Literature Review: A review of three major construction control systems – safety control, quality control, and cost control – aids the development of the intellectual framework for the fourth major construction control system, schedule control.

Chapter 3 – Schedule Control Framework: The intellectual framework for schedule control is developed for each of the five stages of a control system (*define*, *measure*, *compare*, *predict*, and *act*).

Chapter 4 – Required Performance Method: The conceptual framework for the Required Performance Method is developed, as well as a description of how it fulfills the requirements of schedule control systems. Finally, the chapter offers help interpreting monthly RPM reports.

Chapter 5 – Demonstrating the Required Performance Method: A Case Study: The RPM is applied on a case study construction project, analyzing the reports for early warning indicators of schedule slippage.

Chapter 6 – Contributions, Conclusions, and Recommendations: The contributions and results of the research are discussed, along with suggestions for real world application of the RPM and future research.

Bibliography and References: A list of literature studied for the preparation of this document.

Appendix: Two appendices conclude this document.

> **Appendix A – Case Study:** A gathering of information and monthly report data used in the case study.
>
> **Appendix B – Supplemental Graphics:** Graphics summarizing the contributions of the intellectual framework for schedule control.

Chapter 2 – Literature Review

A review of current literature searched for documentation on early warning systems, within the construction schedule control domain, as acknowledged in today's academic world. Sources of literature include construction management textbooks, journal articles, various other reports and professional industry insight. The result of the review is that while a significant amount of material exists on monitoring progress and recognizing when a schedule *is* behind, the academic construction industry has failed to develop documentation on a means for early recognition of impending schedule slippage, in terms of an alarm or indicator of when to take action when a forecast warrants action. Before developing such an early warning system, the intellectual framework for schedule control systems needs further development.

To develop the intellectual framework for schedule control, the research considers other control systems prominent in the construction industry. These other control systems analyzed in this chapter are safety control, quality control, and cost control. Examining the components of other construction control systems exposes common traits of all control systems, aiding the development of the intellectual framework for schedule control.

In all construction projects, the goal is to *safely* construct a project *on time*, *within budget*, to a specified *quality* level. This statement describes integrated project performance that includes the four main elements of a construction project: safety, schedule, cost, and quality, respectively [Barraza et al. 2004]. To develop the intellectual framework for the schedule element, this chapter explores control systems in the other three elements and how they define, measure, compare, predict, and act. The choice of these elements is based on their presence on all construction projects, as well as their documented and accepted concepts of the *predict* and *act* stages of control.

Safety, quality, and cost control systems are now analyzed. While all three contain the *predict* and *act* stages, there is a fundamental difference in the type of control systems that they belong to. Safety and quality control systems are considered *absolute control systems*, whereas cost and schedule control systems are regarded as *cyclic control systems* – the difference is that the later two have a substantial amount of feedback used from the *act* stage to redefine the *define* stage.

2.1 Absolute Control Systems

Absolute control systems follow the general framework of control systems, yet are distinct in that the control system is not a circular process; there is no feedback loop that always links the *act* stage back to the *define* stage. This is very important to note, for in construction safety and construction quality the standards are constant and absolute. Whatever happens during the control process, it will not affect the goals of these elements. For example, the safety objective is to have no future injuries or accidents on the project. Yet, should an injury or accident occur, the safety objective is not changed – the goal is still to have no future mishaps on the project. The same goes for quality control: the goal is to produce an acceptable product. If substandard work should occur, there is no compromise in the established standard of acceptability.

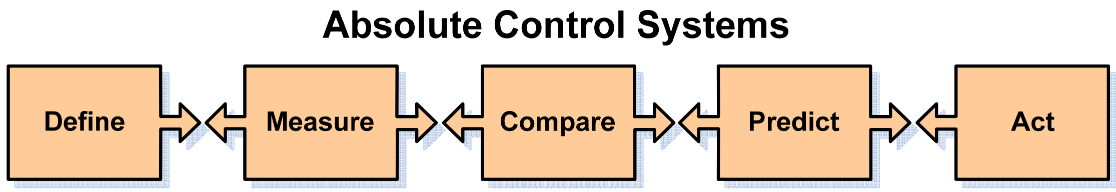


Figure 2.1: Absolute Control Systems

Safety and quality control systems lacking the feedback loop is attributed to the high-risk nature of the construction industry. If safety or quality are negotiated and a less regimented standard of acceptance is developed, lives are at risk – both those on site during construction, as well as civilians that will use these facilities.

While absolute controls systems are not one-in-the-same as cyclic control systems, there is great value in analyzing the components of how they define, measure, compare, predict, and act. Absolute control systems provide a strong emphasis on the *define* stage, which is demonstrated in the following sections on safety and cost control.

2.1.1 Safety Control

"Safety control is a person's perception of the ability or opportunity to manage work situations to avoid injuries and accidents" [Huang et al. 2006], a tool used for controlling the wellbeing of a project, free of risk or dangers. There has been added emphasis on how project management can improve site safety [Cheng et al. 2004], leading to a development of advanced safety control systems. This section details how each stage of general control systems is unique to safety control, as will be developed later for quality control, cost control, and ultimately schedule control.

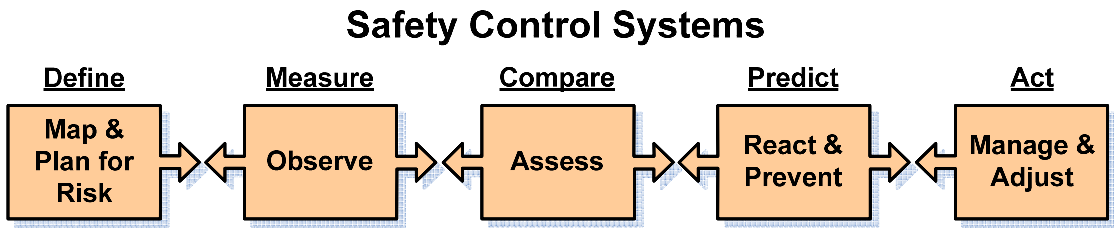


Figure 2.2: Safety Control Systems

Define: As noted before, the objective of every project is to be injury and accident-free. To achieve this, there is a strong emphasis on the initial stage of control, the *define* stage. Theoretically, an unlimited number of safety precautions, using an unlimited number of safety equipment, prepared by an unlimited amount of safety planning, eliminates any possible dangers in construction. This very well may be true. However, doing so puts construction costs at unreasonable and undesirable levels. Therefore, while "injury and accident-free" is the goal, efficient safety control should only cost a small (slightly over 1%) portion of total contract costs – this factoring in the cost of injuries and accident to an organization [Son and Melchers, 2000]. Based on this, limits are established for the cost of prevention, as well as the assumed damages for potential shortcomings. There are both direct and indirect costs, but the ultimate goal is to minimize the overall expected total cost for safety [Son and Melchers, 2000]. Statistical data of accident rates, the direct costs of damage and loss per worker, and the number of workers per accident provide a formula that helps management determine what safety expenditures they have to properly plan [Terrero and Yates 1997].

When considering the appropriate allocations for safety planning, keep in mind of the three stages of planning: 1) long-term planning, 2) medium-term (look-ahead), and 3) short-term. Throughout all stages, define proactive metrics that eventually provide feedback to safety planning of future tasks [Saurin et al. 2005]. Safety metrics tracked include number of accidents per man-hours worked, percentage of total project cost, hours lost to accidents per hours worked, unsafe acts, and near misses. Safety managers use this feedback to coordinate with schedulers to prevent hazardous environments and ensure that risk is spread over the entirety of the project [Yi and Langford, 2006]. Additional details defined during the initial planning stage include mandatory safety standards set by government regulations [Kerridge 1994], new employee orientation to safety standards, training, and the development of incentive programs [Huang and Hinze, 2006].

Measure: The importance of defining limits, regulations, and risks in safety control raises the question of how to measure all this. Safety management is a dynamic process operating in a constant state of change [Wilson and Koehn 2000], in which some safety problems can be only identified through careful and frequent observations of site activities [Saurin et al. 2005]. Because the slightest mishap in safety procedures can result in immediate injury or accident, reliable and continuing feedback is made through observation [Ai Lin Teo and Yean Yng Ling 2006]. Through constant observation, the aforementioned safety metrics are documented and reported to safety managers.

Watching the "action" of construction is not the only observations that need to be made – equipment should be inspected for repairs and preventative maintenance [Terrero and Yates 1997]. Just as important, work-in-place also requires thorough inspection to ensure safety.

Compare: The *compare* stage weighs the planned safety system against the actual safety system as it took place. One common source for black-and-white comparisons are through hazard logs and safety reports, such as the percentage of safe work packages that checks the written safety plans against the actual work performed [Saurin et al. 2005]. Assessing the climate is taking a "snapshot" comparison of the state of safety at a discreet point in time [Huang et al. 2006]. If the planned does not match up with the actual, there is recognition of a high-risk atmosphere. While constant observation is needed to prevent possible accidents, reporting and feedback are not as frequent.

Seeking feedback through scheduled safety meetings and interviews with supervisors, project managers, foremen, and workers is another source of comparison [Terrero et al. 1997, Saurin et al. 2005]. This communication ensures that all potential hazards and concern are known throughout all levels of command on a project. Weekly meetings provide management with the feedback needed to make changes, although "open door" policies allow for constant communication of potential hazardous environments.

Predict: The power of predicting in construction safety control systems saves lives every day. A useful predicting tool is the "near miss", or "unplanned events that could potentially cause human injury or property damage," which are "valuable, but inexpensive, warnings of unsafe trends on site" [Huang and Hinze 2006]. Near misses recognize an unsafe environment that may be a precursor of an accident; the near misses forecast potential harm. Also used for predicting are all warning signs that arise during the comparison stage, whether from data comparison or through communication and hazard recognition.

Beyond current project data and near misses, the most important predicting tool is that which takes place during the planning stage – taking preventative measures based on accident history and statistics [Mohan and Zech 2005, Terrero and Yates 1997]. Visualizing and predicting unsafe environments at the beginning of the project is the best predictor that the construction industry has, preventing accidents, rather than reacting to them.

Act: As previously noted, there generally is not redefinition of safety objectives – the goal is to be injury and accident-free from "this point forward". That said, evaluation of safety performance provides opportunity to check the status of safety boundaries (crossed, not crossed, or not defined) and to reinforce the respect for them. If boundaries are crossed and there have been near misses, action can be taken by eliminating the root cause of the near miss [Saurin et al. 2005]. The action represents a "time-out" in the work, recognition of an accident or hazardous environment, analysis of the root cause of the accident, and the formulation and execution of remedial action. Failure to take action and adjust in response to a constraint in the environment is a potential work hazard [Huang and Hinze 2006].

A summary of the main components of safety control systems, as well as quality and cost control systems is provided in Table 2.1, presented after these three controls systems have been developed.

2.1.2 Quality Control

The second absolute control system in construction covered is quality control. A quality control system defined is "that system by which an organization achieves and maintains the fitness for use of its products or services" [Bishop 1974]. "By doing it right the first time, competitors add value to their products/services and exceed customers' expectations, under budget and ahead of schedule." [Calder 1997] This section discusses how quality control systems attempt to achieve and maintain a quality product the first time around.

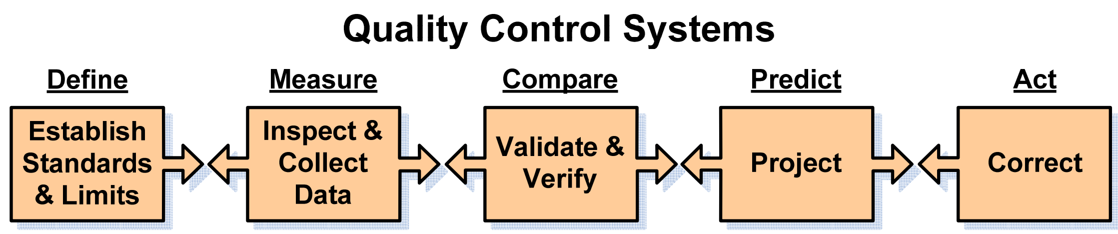


Figure 2.3: Quality Control Systems

Define: As an absolute control system, quality control is also very reliant on the *define* stage. The first step in a quality control system is to determine what metrics will be used to measure quality (performance, features, reliability, etc.) [Schniederjans and Karuppan 1995], followed by the establishment of standards for what is "acceptable" for these metrics – in terms of raw material, work in progress, and finished product [Bishop 1974]. Acceptability can be further defined into establishing limits for what is deemed acceptable – a control chart with a center (optimum) line and two surrounding lines that define the limits [Kuo and Mital 1993]. Also to be determined is the sample size and sample frequency.

The plan for quality control is done in a manner that minimizes the total cost overall for the product or service, cost of inspection, and cost of reworking a defective product or service [Bishop 1974].

Measure: The second stage of quality control systems is to perform an acceptance inspection on the product or service [Bishop 1974]. Inspection records the actual construction as it takes place, in terms of the metrics defined in the *define* stage of the control system, at the time of construction. As daily activities are completed, construction inspectors analyze work in place for acceptability.

Compare: Comparing actual to planned quality provides feedback on the accuracy of the work in place. The acceptability of a sample is weighed by its plot on the quality control chart, whether it lies between the two "acceptable" lines; a control point inside the lines is considered to be statistically in control, whereas an outlier is interpreted as out of control [Kuo and Mital 1993]. In construction, the control lines are a measurement tolerance of what is acceptable. This acceptability assessment contains two parts: validation and verification [Katasonov and Sakkinen 2006]. Validation is ensuring the right product is in place and verification is ensuring the product in place is right.

Predict: The main prediction tool in quality control systems are patterns in quality, as recognized on control charts. A change in a process is indicated by the following common signals: cycles; freaks; plotted points falling outside the control limits; gradual change in level; systematic variations; trends; mixtures; abnormal fluctuations [Kuo and Mital 1993]. This interpretation of the control chart provides grounds for the next stage of the control system.

Act: Upon investigating trends and patterns in quality and control charts, corrective action may be taken to eliminate assignable causes responsible for the behavior [Kuo and Mital 1993]. A *root cause analysis* determines what the source of defective products or services are. If defective products or services are found, it is at this stage they are eliminated and a plan for remedial action is taken. Unless there is a change in scope of the objective that affects the acceptability, the original standards and limits remain. "Quality control is generally composed of three successive actions: measuring, comparing, and correcting" [Yaseen and El-Marashly 1989]. There is no redefining, rather just assuring that the original quality standards are met.

2.2 Cyclic Control Systems

What distinguishes construction cost and schedule control systems from safety and quality control systems is that following defining, measuring, comparing, predicting, and acting, it is routine to reassess and possibly redefine the definition of the baseline cost or schedule. The closed loop system for cyclic control systems, as shown below, takes action that may include revising the original plan.

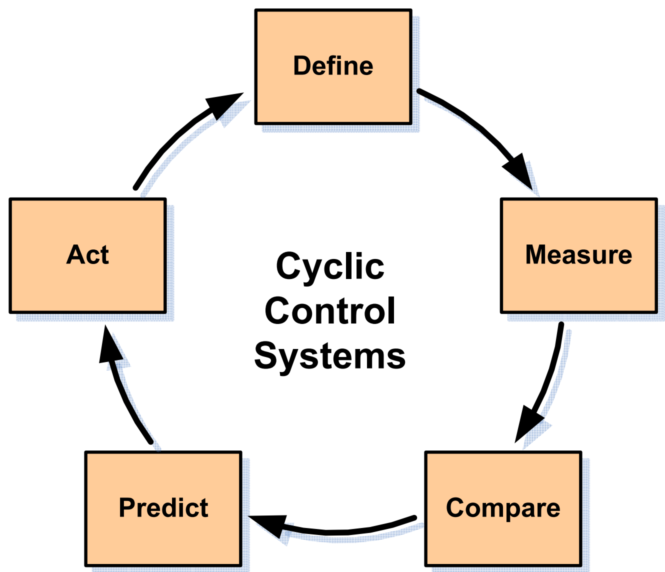


Figure 2.4: Cyclic Control Systems

2.2.1 Cost Control

Stevenson and Wilson's "Cost Control Program to Meet Your Needs" [1989] provide the following definitions: The Project Management Institute defines a cost control program as "to provide a mechanism that reacts to the current project status in order to ensure accomplishments of project budget/cost objectives." The American Association of Cost Engineers [Stevenson and Wilson 1989] elaborates further:

> The application of procedures to follow the progress of design and construction projects in order to minimize cost with the objective of

> increasing profitability and assuring efficient operations. There are three essential elements of control. The first is to establish the optimum condition, the second is to measure variation from the optimum and the third is to take corrective action in order to minimize this variation. The application of these procedures attempts to limit costs to those authorized for capital projects or cost standards, focuses control efforts where they will be most effective, and achieves maximum control at minimum operating cost.

And finally, Stevenson and Wilson [1989] summarize the elements of control to coincide closely with the five stages of control:

1. *Define*: Baseline Budget
2. *Measure*: Monitor the Progress
3. *Compare*: Variance Analysis
4. *Predict*: Re-Forecasting
5. *Act*: Corrective Action

Through continuous recording, reporting, and forecasting of both obligations and expenditures, the project cost control system provides the information needed for decision making [Stevens 1986, Eldin 1989].

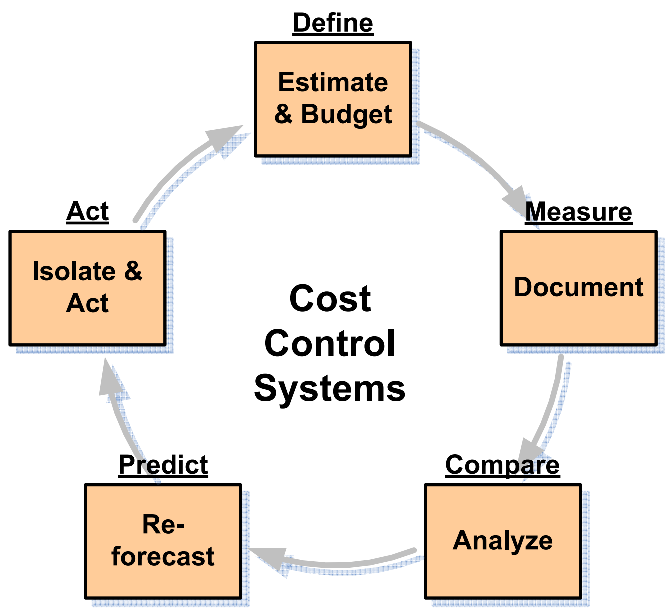


Figure 2.5: Cost Control Systems

Define: The first stage of cost control is to establish the optimum condition for cash flow on the project by inputting data such as planned earned values and budgeted cost for each month [Stevenson and Wilson 1989, Park et al. 2005]. These inputs create a level of expected accuracy and flexibility to uncertain factors such as time delay, cost overrun, and variation of cost [Park et al. 2005]. By the end of the *define* stage, there shall be clear guidelines for the cost control process, product, precision, and metrics to be used.

Measure: The second stage of cost control is to measure the actual costs though continuous recording, reporting, gathering, and accumulating project cost data [Stevens 1986, Stevenson and Wilson 1989]. The main variable in recording actual costs is the frequency with which it is performed; while data collection may be performed on routine, sufficient intervals, it is important to have the most pertinent, up-to-date information. Project accountants and those in charge of cost control shall have the same current knowledge to provide for the next stage of cost control.

Compare: Periodic comparisons between previous estimates and incremental costs form the basis for the *Compare* stage of cost control [Stevens 1986]. Budgeted costs and actual costs are weighed against each other to determine the current status of the project, quantifying any variation from the optimum (budgeted) values [Stevenson and Wilson 1989]. The frequency of measurements allows for realizing variations in cost information – transparency that is needed to make forecasts or predictions of the project's future [Peeples 1985]. How fast deviations are recognized are a product of how frequent measurements are made. In order to properly monitor and control sizable construction projects, a huge volume of information needs processing rapidly and accurately [Eldin 1989].

Predict: Data collected through cost progress monitoring systems, if current and accurate, provide a snapshot of the budgeted versus actual conditions. It is through the interpretation of this data that trends, patterns, and tendencies allow for predicting the path that the project is headed. Throughout the project, McMullan [1996] defines two objectives of forecasting: "1) to provide a forecast final cost for the project based on current status and trends, and 2) at the same, to highlight trends or potential budget deviations that require management control." Predicting the future and recognizing deviations that need attention prevent potential letdowns that cannot be fixed once money and time has been spent; "surprises" on projects can be avoided by forecasting with the same frequency that costs are measured and compared [McMullan 1996]. McMullan also provides a set of general rules for business cost forecasting:

- A good forecast is more than a single number (a range).
- Aggregate forecasts are more accurate.
- The longer the forecast horizon, the less accurate.
- Forecasts should not be used to the exclusion of known information.

Cost progress monitoring often results in actual values that vary from the budgeted values, resulting in amounts either above or below planned. Whichever the case, the value of this variation is a moving weight, which is distributed over the remaining duration of the item being controlled [Park et al. 2005]. An automatic redistribution of remaining cost for each item provides a rolling forecast of money to be earned over the time remaining to earn it [Park et al. 2005]. It is becoming more apparent that forecasts and cost control have a strong interrelationship with time control and schedule [Stevens 1986].

Act: Taking (or not taking) action is product of managing predictions and forecasts provided. Corrective action assures efficient operation and minimization of variation [Stevenson and Wilson 1989]. This stage of control is that which completes the cycle of the cyclic control system – acting to redefine the goals. Once the cost controller has sufficient information on current project status and projected project status, remedial actions are needed to control the cost system. Stevenson and Wilson [1989] offer the following process for the *Act* stage of cost control:

1. Isolate the deviation
2. Estimate the cost impact if not corrected
3. Identify and estimate alternative corrective action
4. Choose and implement corrective action
5. Monitor the correction

The process clearly shows the steps needed to close the cycle loop, redefining the cost control system and continue monitoring the costs of the corrected plan.

2.3 A Summary of Safety, Quality, and Cost Control Systems

Safety, quality and cost control systems have definitive stages for defining, measuring, comparing, predicting and acting. Table 2.1 summarizes the literature review for each of these control systems, broken down into the five stages. The literature review material presented in this chapter and the following figure provide valuable information on three of the four main construction control systems, which guide the development of the intellectual framework for the fourth construction control system, schedule control, in Chapter 4.

STRUCTURE OF CONTROL SYSTEMS

	DEFINE	MEASURE	COMPARE	PREDICT	ACT
SAFETY CONTROL	• Spread out risk • Abide by regulations • Select metrics • Establish limits for cost (based on prevention and potential damages)	• Observation and recording • Immediate reporting of accidents • Inspection • Maintenance • Hazard analysis	• Communication between workers & supervisors • Assess the climate • Recognizing high-risk atmospheres • Seek feedback • Hazard logs and safety reports	• Preventative action, followed by reaction • Consider accident histories • Near misses • Heavy reliance on planning	• Manage situation to avoid injuries and accidents • Evaluate safety performance • Adjustments for desired goals • Root cause analysis
QUALITY CONTROL	• Determine metrics • Establish standards Determine acceptability • Establish limits • Sample size • Sample frequency	• Acceptance inspection • Data collection	• Pass judgment on acceptability • Validation (sound, logical) and Verification (correct) • Interpret control charts	• Project cycles • Gradual changes • Trends • Fluctuations	• Eliminate defective products • Diagnose assignable causes • Corrections
COST CONTROL	• Baseline estimate • Budget • Establish optimum conditions • Project details: process, product, precision, metrics	• Monitor actual earning and spending • Data collection • Frequency of measurement	• Variance analysis • Transparency of progress • Recognize costs' interrelationship with time • Isolate deviation	• Forecast planned monthly earned values with results of variance analysis • Highlight trends and potential deviations • Re-forecasting	• Corrective action • Budget revisions • Maximize profit while ensuring efficiency • Control risk • Minimize detrimental variation

Table 2.1: Structure of Safety, Quality, and Cost Control Systems

Chapter 3– Schedule Control Framework

The second type of cyclic control system, which comprises the first major objective of this research, is the schedule control system. The objective is to develop the intellectual framework for “schedule control”, done by applying what has been learned in the three previous control systems. Both of the absolute control systems, safety and quality, as well as the cyclic control system, cost, have components in each stage that are standardized and applied to schedule control.

What is needed for schedule control is a clear understanding of all five stages that are *define, measure, compare, predict,* and *act.* Existing literature contains an abundance of pertinent literature on the first three stages, comprising progress monitoring systems, but the goal is to further develop what is needed to predict and act in a schedule environment. The following sections borrow concepts and ideas from safety, quality, and cost control systems to expand the intellectual knowledge base for “schedule control.”

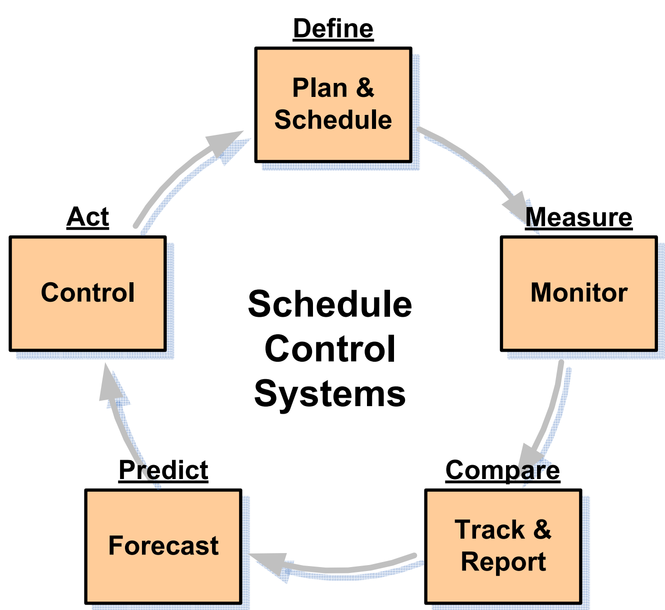


Figure 3.1: Schedule Control Systems

3.1 Plan and Schedule Optimum Outcomes

Absolute and cyclic control systems differ in that the latter involve regularly scheduled feedback to the *define* stage. While schedule control is categorized as a cyclic control system, this does not dismiss the strong presence of absolute control system characteristics within schedule control. The most prominent feature of absolute control systems incorporated in schedule control is the emphasis on the *define* stage.

Project planning involves setting the project scope and determining the means and methods. Upon developing a plan of attack for how construction will take place, quantities of work and rates of production add a time component to the plan, which are then used to build a project schedule. A reasonable and accurate schedule is approved and becomes the schedule of record. This scheduled work serves as a datum or baseline of the actual work as it takes place. Examples of standards for measurement include CPM schedules, control budgets, procurement schedules, quality control specifications, and construction working drawings [Paulson 1976]. As in absolute control systems, the initial schedule, the "baseline", establishes the planned conditions – a historic reference of where you want to be. It is at this time that the initial long-term, medium-term (look-ahead), and short-term plans are developed. Because schedule control is a closed-loop system, all three of these plans (and schedules) may be revised in the future.

Built into the schedule are proactive metrics, designed to provide feedback. Reliable data is needed for reliable feedback, to make reliable predictions. Metrics measure the most relevant project data to reveal quantities and production rates, used to measure the performance of the schedule. Performance metrics are defined with a level of acceptability – establishing a standard for what is deemed "acceptable". In CPM scheduling, a safe operating range for performance metrics represents this. The range denotes the expected accuracy of schedule performance. By the end of the *define* stage, there shall be clear guidelines for the schedule control process, product, precision, and metrics to be used.

3.2 Monitor Progress to Determine Current State

While the *define* stage outlines where you want to be, the *measure* stage determines where you are. Actual schedule progress is recorded through continuous observation, recording, reporting, gathering, and accumulating project schedule data. Data gathered coincides with the data outlined for measurement in the project *define* stage. These quantities, production rates, and other figures serve as historical project data, for later use in making forecasts based on actual project performance. Schedule performance is used to produce a current and up-to-date schedule, representative of the actual sequence of construction.

Construction is in a constant stage of change, and the updated project schedule represents this through careful and frequent observation of site activities. The frequency with which data is recorded directly correlates with the most precise rates and trends in performance. While data is recorded on a near instantaneous basis through construction inspection, ideally, the project schedule is updated the same. However often the updates, the most pertinent, up-to-date information is most useful when making comparisons between the planned and actual project performance.

3.3 Track and Report Current State and Variation

The *compare* stage completes the progress monitoring sequence through comparing the planned schedule with actual schedule performance, quantifying the deviation of where you are with respect to where you wanted to be. A "snapshot" of the actual schedule at a discreet point in time serves as the most defined approach for comparison.

While the frequency of measuring schedule performance is defined in the previous section, the frequency of comparison is considered separate. Measurements tell what is actually happening, yet comparisons tell if that *should* be happening. As with data collection, schedule comparisons are done at regular intervals, to make the construction performance as transparent as possible. The frequency with which comparisons are made determines how aware project parties are of any possible schedule deviations.

Comparing hard data is not the only means for determining project status; also beneficial is seeking feedback from individuals involved in the project (supervisors, project managers, foremen, workers) by arranging scheduled meetings and interviews. Communication throughout project parties aims to ensure that all pertinent schedule performance information is put to best use.

Updated project performance evaluations provide feedback on how accurate the "actual" is to the "planned". The current status allows for quantifying variation from the optimum schedule set in the baseline. Any variation in schedule performance metrics is a call for attention. Whether or not there is variation, the "snapshot" comparisons are used in the following stage to make predictions of the future, based on the past and present.

3.4 Predict Possible Future States

A *prediction* is synonymous with a *forecast*, which serves as a necessary step in bridging the gap between monitoring progress, and taking action. According to Barrie and Paulson [1984], a *forecast* defined: "based on the best knowledge at hand, what is expected to happen to the project and its elements in the future." Forecasts require reliable progress measurement in order to project the future, for you cannot initiate action without valid predictions. Improving the validity of projections provides strong grounds for improving actions.

There are two objectives of schedule forecasting: 1) to determine a project completion date based on current status and trends, and 2) at the same time, highlight trends or schedule deviations that require management control [McMullan 1996]. In other words, the goal is to ensure the project is going to finish on time, and to recognize any sign that it might not happen. The following rules of forecasting by McMullan [1996] are presented in the cost control system, yet are also highly applicable to schedule control:

- Quality forecasts provide best and worst case scenarios.
- Aggregate forecasts best represent project progress.
- Forecasts lose accuracy with increased project duration.
- Forecasts shall consider all known project information.

The *define* stage notes that reliable predictions are based on reliable data. Assuming project data is current and correct, forecasts are crucial for recognizing if the schedule may slip. The frequency of forecasts should be performed with the frequency of comparisons, as with the frequency of measurements – ideally, as often and current as possible. Doing so avoids surprises in status and trends that result from lagging behind on updates.

Forecasting data is often performed by extrapolation – taking the production rate to date, lining it up with where you are, and superimposing that rate on the future. This interpretation of data produces trends, patterns, and tendencies that identify where the project is heading. Variations between planned and actual result in the value of this variation being a moving weight, distributed over the remaining duration of that activity or the project.

Another important predicting tool is that which takes place during the planning stage. Often, there are signs of project distress before the project gets started. A poorly developed plan or incomprehensive understandings of the project may be early indications that the project will be in future distress. Such an early warning sign accelerates through the control system and requires action immediately.

3.5 Act to Achieve a Desired Future State

The final stage of schedule control systems is to act to achieve a desired future state. Acting is a product of predicting, which relies on reliable forecasts and warning signs to produce actionable information in a format that allows action to be taken, if needed, in order to end up where you want to be. The objective of predictions is to allow ample time for adjustments to be made in order to complete the project on time. Unfavorable trends in schedule performance metrics and other signs of project distress are the "smoke alarms" in schedule control that call for attention and require investigating if all is okay or something is wrong on the project.

To investigate the situation that may lead to project distress, call a "time-out" and perform a root cause analysis – a determination of what the root cause of the problem is, in an attempt to correct or eliminate it, as opposed to merely addressing the immediately obvious symptoms. The investigation determines if any metrics have crossed their predefined boundaries for acceptability, as well as identifies any other possible causes for the mishap. Failing to take action on a sign of distress may lead to the untimely completion of the project. Once sufficient information is known on the project status, remedial corrective action needs to be taken. As described by Stevenson and Wilson [1989], the process for acting in cost control is applied here for schedule control:

1. Isolate the conflict
2. Determine the schedule impact if not corrected
3. Develop corrective actions
4. Do nothing or implement corrective action
5. Evaluate action taken

The schedule conflict is isolated and quantified, remedial action identified and implemented, and the correction monitored. This process closes the cycle of the control system – reassessing, rescheduling, and redefining. The conflict is part of the new definition that is now monitored.

The following chart is a summary of the intellectual framework for schedule control, as well as the three control systems used to develop the intellectual framework for schedule control – safety control, quality control, and cost control. For each control system, the chart is broken down into the five stages of *define*, *measure*, *compare*, *predict*, and *act*.

Structure of Control Systems

	DEFINE	MEASURE	COMPARE	PREDICT	ACT
SAFETY CONTROL	• Spread out risk • Abide by regulations • Select metrics • Establish limits for cost (based on prevention and potential damages)	• Observation and recording • Immediate reporting of accidents • Inspection • Maintenance • Hazard analysis	• Communication between workers & supervisors • Assess the climate • Recognizing high-risk atmospheres • Seek feedback • Hazard logs and safety reports	• Preventative action, followed by reaction • Consider accident histories • Near misses • Heavy reliance on planning	• Manage situation to avoid injuries and accidents • Evaluate safety performance • Adjustments for desired goals • Root cause analysis
QUALITY CONTROL	• Determine metrics • Establish standards Determine acceptability • Establish limits • Sample size • Sample frequency	• Acceptance inspection • Data collection	• Pass judgment on acceptability • Validation (sound, logical) and Verification (correct) • Interpret control charts	• Project cycles • Gradual changes • Trends • Fluctuations	• Eliminate defective products • Diagnose assignable causes • Corrections
COST CONTROL	• Baseline estimate • Budget • Establish optimum conditions • Project details: process, product, precision, metrics	• Monitor actual earning and spending • Data collection • Frequency of measurement	• Variance analysis • Transparency of progress • Recognize costs' interrelationship with time • Isolate deviation	• Forecast planned monthly earned values with results of variance analysis • Highlight trends and potential deviations • Re-forecasting	• Corrective action • Budget revisions • Maximize profit while ensuring efficiency • Control risk • Minimize detrimental variation
SCHEDULE CONTROL	Plan & Schedule • Project plan • Means and methods • Scope • Quantities • Rate of production • Progress metrics • Reasonable and accurate schedule (schedule of record) • Long, medium, short-term planning	Monitor • Observe construction • Record, gather, report, accumulate project data • Represent actual progress • Current and up-to-date schedule	Track & Report • Actual versus planned • Quantify deviation • Feedback and communication • Performance transparency • Snapshot at discreet point in time • Determines current status	Forecast • Valid predictions needed to initiate action • Find completion date • Highlight trends or deviations • Best and worst case scenarios • Aggregate forecasts best represent progress • Forecasts lose accuracy with increased project duration • Avoid surprises • Distribute variations • Reliance on planning	Control • Recognize "smoke alarms" • Allow time for adjustments • "Time-out", root cause analysis • Isolate the conflict • Determine impact • Develop corrective actions • Do nothing or implement corrective action • Evaluate action taken

Table 3.1: Structure of Control Systems

Chapter 4 – Required Performance Method

The intellectual framework for schedule control serves as a guide for the second objective of this research, which is to develop and describe a schedule control system that can be used to detect an early warning of schedule slippage. The schedule control system developed by this research is the Required Performance Method (RPM), a technique that utilizes the tracking of commodities to predict what performance is required for the remainder of the project.

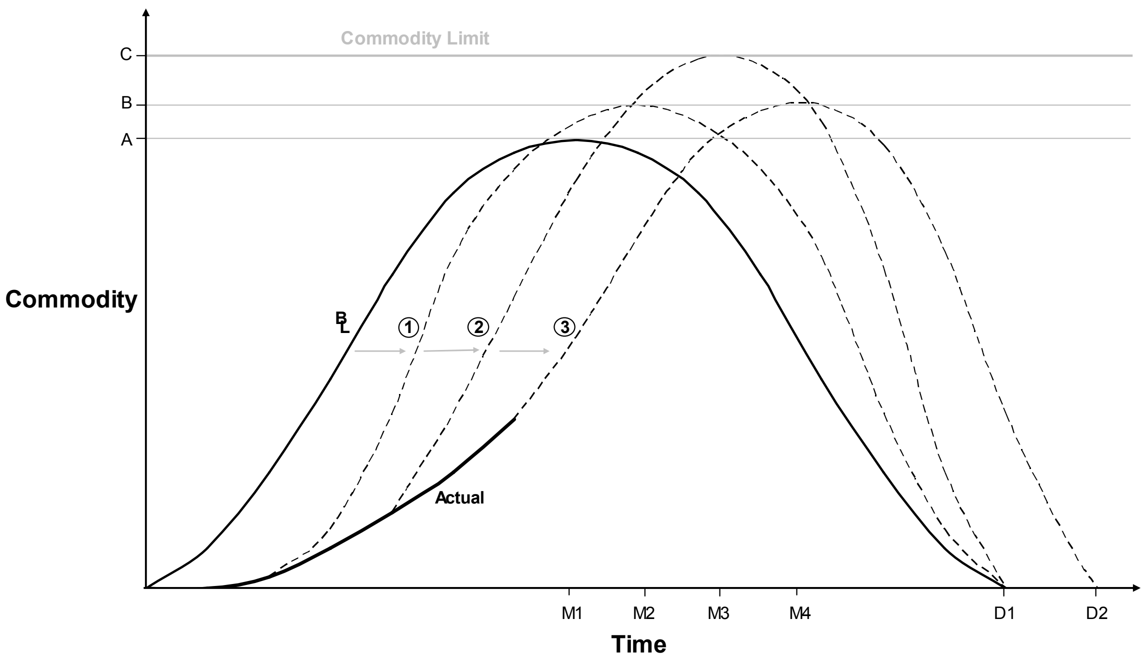
This chapter first discusses the conceptual framework for the RPM, followed by how the RPM fulfills the requirements outlined by the intellectual framework for schedule control. Finally, there is a discussion on how to interpret values and trends presented by the RPM, in order to recognize an early warning for schedule slippage.

4.1 RPM Conceptual Framework

The innovative component of the Required Performance Method is its application of a quantitative means for defining the degree to which the amount of work planned for any one month can be expanded, and using this means to distribute any deviation from the planned values. The subsequent sections discuss how the tracking of commodities is used by the RPM to forecast required performance, as well as what type of commodities are tracked.

4.1.1 Concept of Expansion: An Analogy

The purpose of this research is to forecast schedule slippage – a warning of potential failure to finish on time. To begin explaining the concept of expansion, let us first look at a graphical representation of a schedule that is slipping, represented by the following commodity versus time curves:



Schedule	Complete By	Max Commodity	In Month
BL	D1	A	M1
		Increase	
①	D1	B	M2
		Increase	
②	D1	C	M3
	Shift	Decrease	
③	D2	B	M4

Figure 4.1: Toothpaste Expansion Analogy

Consider the analogy of a toothpaste tube, where the toothpaste represents the commodity (whether it is money, tons of asphalt, crew-hours, etc.), and the length of the tube represents the project duration, with completion date *D1* being the end of the tube. The idea is that the amount of toothpaste in the tube remains constant, as will the area under the curve (cumulative planned earned values for the commodity).

The baseline (BL) schedule is set to complete on *D1*, with the maximum monthly commodity *A* scheduled for month *M1*. As time progresses, the *Actual* progress of the commodity has underperformed, squeezing the toothpaste in the tube (remaining commodity) to curve *1*. The planned schedule has shifted to the right, and because of the underperformance, in order to complete by *D1*, the maximum monthly commodity increases to value *B* in month *M2*; the toothpaste is squeezed further towards the end of the tube, requiring an increased diameter to accommodate the full volume of toothpaste.

After another sub-par period of work, failing to perform in accordance with adjusted curve *1*, the schedule is further behind, reflected in curve *2*. The toothpaste is still restricted by the end of the tube (*D1*), consequently stretching further the diameter of the tube in order to fit the constant amount of toothpaste. The production rate of the commodity increases to complete the project on time, approaching value *C* in month *M3*, the *Commodity Limit*. This commodity limit represents the maximum production rate of this project; for example, maximum production rate restrictions may include availability of resources or equipment.

Again, the failure to perform to the adjusted curve *B* results in an updated schedule of curve *C*. However, the production rate has reached the maximum for that commodity. The only option to perform the remaining work is to extend the contract completion date to *D2*, decreasing the maximum commodity value within the limits, to value *B*.

As the commodity maximum increased and shifted to the right, the project was under increased danger of finishing late. Ultimately, the schedule completion date needed to be shifted to accommodate the underperformance. In our toothpaste analogy, there was no longer room for the toothpaste in the tube. The tube had expanded to its limits, and it was time to get a longer toothpaste tube.

4.1.2 RPM: Expanding the Proper Months

The toothpaste analogy illustrates that when there is underperformance and deviation from the planned schedule, the remainder of the project compensates for this by expanding the production of each subsequent period. While the expanded schedule appears to balance the variance evenly, it may expect unreasonable production rates for particular periods.

The key to the Required Performance Method is that it distributes the expanded work to the months with work that is most likely to expand, rather than evenly distributing expansion among all remaining months. There are restrictions that limit the relative expansion of certain periods of the project, discussed in the following section. Relative work expansion for each month is considered by assigning all months of the project an Expansion Factor (EF). The EF measures the degree to which the amount of work planned for any one month can be expanded, relative to all other months on the project. By expanding certain months more than others, the peaks and valleys of forecasted work are exaggerated.

Forecasting required performance on a monthly basis produces trends whose purpose is provide an early warning before the monthly expansion reaches an undesirable and unattainable level. Further discussion on the indicators for alarms and the RPM conformance with the schedule control framework are found later in this chapter. First, however, is a better understanding of what considerations determine the expansion factor for each month.

4.1.3 The Expansion Factor

When the actual cumulative value of a commodity deviates from the planned value, the expansion factor has the important role of allocating this deviation to the appropriate months. For this reason, numerous factors are considered to establish the contractor's ability to expand the work in each month. It is the contractor's role to determine the expansion factors, for it is *their* ability to expand the work. The required performance of each month is determined by the following:

$$\text{Required Performance}_{\text{month}} = \text{Planned Performance}_{\text{month}} + \left(\frac{\text{EF}_{\text{month}}}{\Sigma\text{EF}_{\text{remaining}}}\right) * \left(\begin{matrix}\text{Cumulative Planned to Date} - \\ \text{Cumulative Actual to Date}\end{matrix}\right)$$

Equation 4.1: Monthly Required Performance

The expansion of each month is relative to the other months on the project. Considering this, each EF is defined as a number from 0-10. A month with an EF of 10 is allocated twice as much of the deviation (cumulative planned to date minus cumulative actual to date) as a month with an EF of 5, and ten times as much as a month with an EF of 1. Should the contractor assign every month a value of 10, or any other uniform number, all months expand the same amount – expansion is relative. Months with an EF of zero are not allocated any of the deviation, for they are regarded as lacking the ability to expand the work.

To define expansion factors, various considerations are taken into account. These limitations on ability to expand the work include but are not limited to the following.

- **Type of Work**: The expansion factors define the ability of the contractor to expand the work; therefore, the type of work scheduled has a major influence on how much expansion can take place. For instance, consider the development of a high-rise building facility on a plot of untouched land. The earthwork phase of the project may be more welcoming to expansion than the building phase. More dozers and scrapers may be added to expand the earthwork, while pouring concrete for many successive floors requires a minimum amount of time to allow for curing. The latter work may have a lower expansion factor than the earthwork, for it may be tougher to expand the linear work. Linear work, or work performed in sequence (Activity A must be completed before activity B, which must be completed before Activity C) limits the amount of expansion. Whichever months these activities are scheduled for, the expansion factors reflect this.

- **Amount of Float**: The amount of work in a month on the critical path may influence the amount of expansion in that month. Periods with more work on the critical path, and less activities with float, may be more restricted to expansion than periods with less critical activities and more float.
- **Weather**: Seasonal weather patterns influence the degree to which the amount of work planned can be expanded, whether they be cold harsh winters, rainy seasons, excessive heat, or even a moderate climate that has very little effect on the ability to expand. Furthermore, the weather affects certain work more than other. For example, it is difficult to expand outdoor painting during rainy seasons, or laying underground pipe during winter in a cold climate.
- **Physical space limitations**: A lack of physical space on the job site may restrict the amount of additional resources a contractor can bring on site, in hand restricting their ability to increase production and expand the work. For

instance, the small amount of space on a metropolitan block may restrict the number of tower cranes that can fit on the limited space.

- **Resource availability**: Limits on available labor, equipment, and raw materials bound the contractor's ability to expand the work. Such a restriction may be found on a roadway construction project, where the only asphalt plant within range is capable of producing a maximum amount of tons per day.
- **Other work**: The current project may not be the only project the contractor has going on. This may tie into the point above, in that the contractor may need labor and equipment resources on other projects. During these periods, expansion of work may be limited.
- **Where in the project duration**: Often, project have a learning curve, where it may be difficult to expand work at the beginning of the job. Once past this initial period, the middle of the project may be more allowing to expanding the work. Furthermore, the end of the project may be a period that the contractor will not want to rely on for expanding the work – pushing work onto the end of the project is dangerous for timely completion.
- **History of expansion**: The contractor's history of expansion on current and similar projects affects the definition of expansion factors. This knowledge aids in forecasting the contractor's ability to expand certain work, under certain conditions. On the current project, the history of ability to expand work to date may influence their opinion of their ability to expand future work, so as not to exclude good and known information.

The above list is not inclusive of all considerations for defining the expansion factors. Whatever the dynamics in defining the expansion factors, the goal is for the contractor to make all considerations necessary to best predict their ability to expand the work over the life of the project.

4.1.4 Tracking of Commodities

One of the main reasons for tracking and reporting project commodities is that they reflect project performance; in regards to time, how close actual schedule performance is with respect to where it needs to be. Commodity-loaded schedules form the basis for the RPM, allowing for a control system that effectively mirrors the advancement of the project.

Driving commodities are those commodities essential to the completion of the project, a handful of resources that reflect the project progress. The most common driving commodity is money, whether it is money earned or money spent. Cash flow is aggregate, in that it may encompass all aspects of the project – resources, labor, indirect costs, etc. Linear feet of pipe cannot be converted to cubic yards of concrete, yet both can be converted to cash values. Another advantage of tracking cash flow is that nearly all projects budget payments for work completed, and in turn, cost-load the schedule.

While cash flow is the most common commodity loaded on schedules, there are varieties of other driving commodities that reflect project progress. Inputs such as man-hours, crew-hours, and raw materials are consumed throughout the construction process. Conversely, outputs may also tracked be tracked for specific items, including cubic yards, tons, and linear feet. The driving commodities of each project vary in accordance with the type of project, yet the goal stays the same: reflect project progress through tracking a manageable component of the project. Performance of the project comes from the comparison of where we are with respect to where we planned to be, or actual versus planned. This *compare* stage of schedule control reflects the current status of the project; yet to forecast required performance, the RPM employs the projects ability to expand future work.

4.2 RPM as a Schedule Control System

The guidelines set by the intellectual framework for schedule control built a foundation for what is needed to develop the Required Performance Method. This section breaks down the RPM into its schedule control system components, detailing how it effectively bridges the gap between progress monitoring and schedule control.

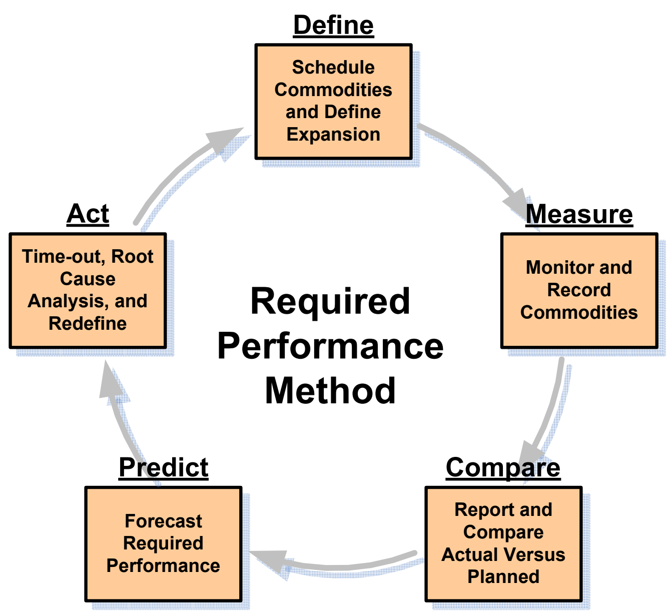


Figure 4.2: RPM as a Schedule Control System

In the following sections, accompanying the conceptual framework of the RPM is a brief narrative example that describes the mechanics of the control system. The example is a fictional 17-month, 10-mile highway realignment project whose driving activity is the movement of earthwork (tracked in cubic yards). A sample RPM graphic, as applied to this example, is shown in the following figure:

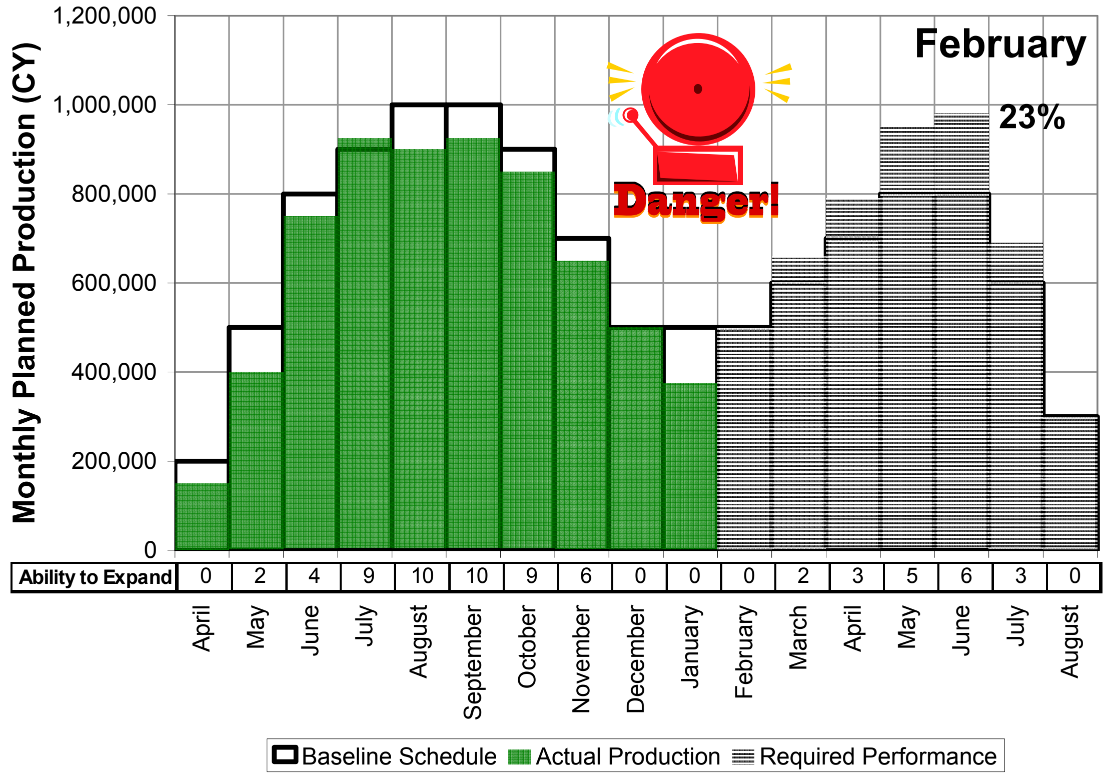


Figure 4.3: Expanding Work in the Proper Months

Referring to the figure, the actual performance for seven of the eight months from April through January are below the planned values in the baseline schedule. Outstanding earthwork is distributed over the remaining duration of the project, and is done using the concept of expansion. Shown along the bottom of the figure is the contractor's ability to expand the work for each month. Notice that expansion is greatest during the first August and September, and lowest during the beginning, the middle, and the end of the project (all for various reasons, which are discussed later). Expansion for the remainder of the project is greatest in May and June, and this is when most of the required recovery work will occur. As shown in June, the required work is expanded

23% more than planned, resulting in an expected performance higher than any actual performance on this job. This is a reason for concern, and the "alarm" indicating a warning of possible late project completion should definitely be ringing. Accompanying the figure above would be additional figures, data, and graphs, tracking the expansion on a month-to-month basis. These are described in following sections.

4.2.1 Schedule Commodities and Define Expansion

The first stage of the RPM schedule control system is to schedule commodities and define expansion. Chosen commodities must meet the requirement of representing project progress. Commodities are scheduled along the duration of the project, defining how much of each commodity is to be assigned to each month. A contractor defines this data the same way they always: from a commodity-loaded schedule. If there are early and late schedules, commodities are defined for both schedules. When using early schedule RPM techniques, float months are considered planned zero-production months at the end of the early-calculated schedule. Should the contractor aim to meet the early-calculated completion date, any float months are removed from the end of the early schedule, resulting in a shorter target early schedule completion date than the contract completion date.

Monthly planned values for commodities in the original schedule have a built in design capacity, or the contractor's definition for what they anticipate their maximum monthly production can be. Whether considering the early, late, or another target schedule, the maximum monthly value may be used as a control limit for comparison of required monthly performance. That is, this planned maximum value may be a number that when approached by forecasted required monthly performance, is reason for concern and a signal for alarm. Considering the late schedule as the worst-case scenario for timely project completion, the commodities defined in this schedule assume the latest possible plan for work. Whatever the target schedule is, the monthly values for commodities form a baseline for monitoring progress and forecasting required performance to perform to this target schedule.

In the highway realignment example, tracking earthwork as a commodity is directly representative of the project progress. Over the 17-month duration, a total of 11.3 million cubic yards of earth is planned to be moved. The following graphics represent the baseline schedule planned value for the commodity, shown in the forms of a data table, cumulative production curve, and monthly planned production chart.

Month	Baseline Schedule (CY) Monthly	Cumulative
		0
April	200,000	200,000
May	500,000	700,000
June	800,000	1,500,000
July	900,000	2,400,000
August	1,000,000	3,400,000
September	1,000,000	4,400,000
October	900,000	5,300,000
November	700,000	6,000,000
December	500,000	6,500,000
January	500,000	7,000,000
February	500,000	7,500,000
March	600,000	8,100,000
April	700,000	8,800,000
May	800,000	9,600,000
June	800,000	10,400,000
July	600,000	11,000,000
August	300,000	11,300,000

Table 4.1: Baseline Schedule Data

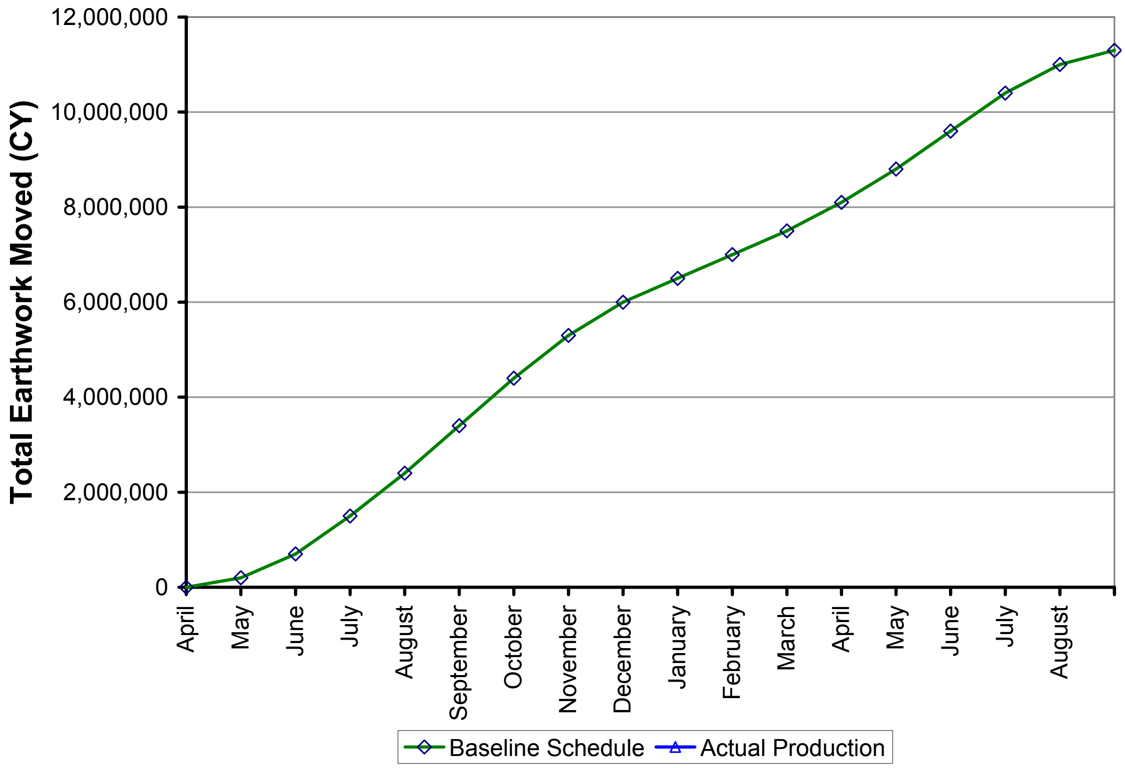


Figure 4.4: Cumulative Production Curve

The cumulative production curve may take the form of planned early and planned late cumulative production curves, if there are early and late project schedules. Whichever the case, the cumulative production curve chart also displays an actual cumulative project production curve. These curves provide an overall snapshot of where the commodity is, compared to where it needs to be. It is a common graph for tracking the status of commodities.

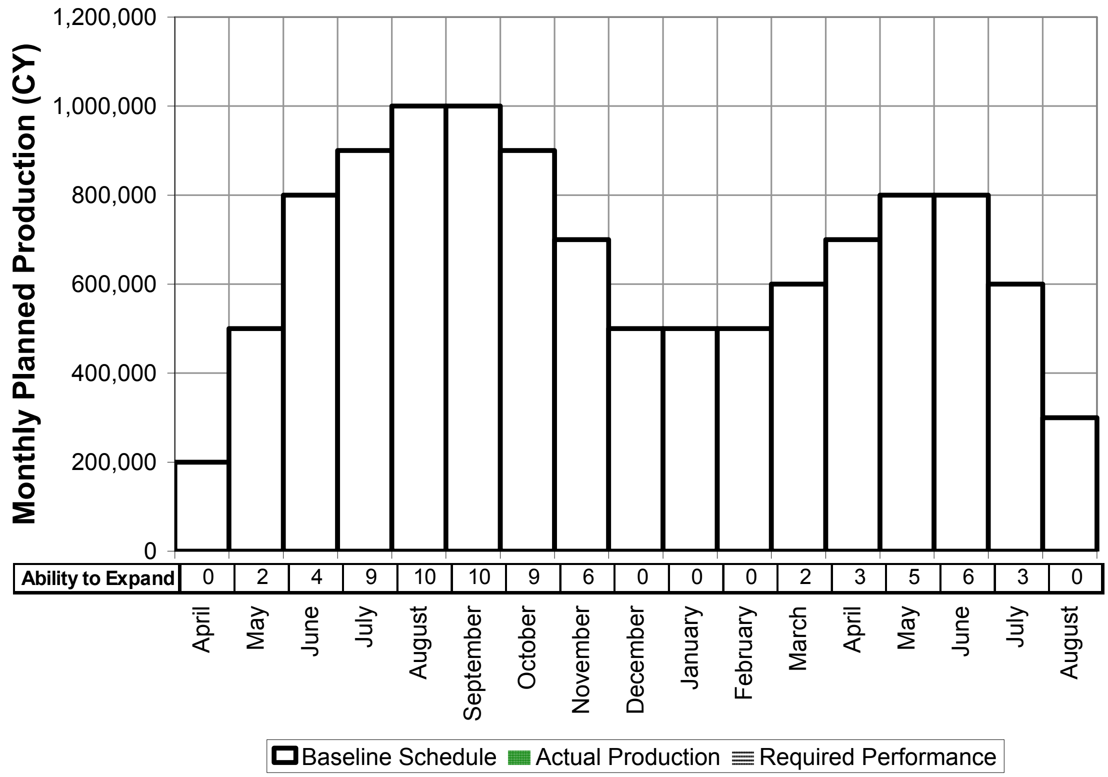


Figure 4.5: Monthly Planned Production

The monthly planned production chart tracks monthly planned, actual, and required performance. If there are early and late schedules, there are both early and late monthly planned production charts. Individual required monthly performances are compared with actual and planned performance.

The contractor's ability to expand work in each month is defined according to all considerations described in *4.1.3 The Expansion Factor*. Because schedule control systems are cyclic, the expansion factors may be redefined as the project progresses. While expansion factors may change to include good and known information, the concept remains the same: using all available information and knowledge, the contractor defines their ability to expand work for the remainder of the project. The expansion factors for the example project are defined in the following figure:

Month	EF
April	0
May	2
June	4
July	9
August	10
September	10
October	9
November	6
December	0
January	0
February	0
March	2
April	3
May	5
June	6
July	3
August	0

Table 4.2: Monthly Expansion Factors

The project's driving commodity throughout the project duration is the cut and fill of earth. The project is set in a cold weather, U.S climate, having winters with moderate snowfall and ground freezing. In this climate, for the type of work performed, the ability to expand work in summer months is much greater than the ability to expand in winter months, when conditions are far from ideal. While earthwork is the commodity tracked, other driving activities such as paving and pavement marking are restricted to the paving season, which ends starts in March and ends in November. Seasonal weather patterns restrict the contractor's ability to expand work throughout the project, decreasing expansion to zero for the months of December through February.

Also considered is the contractor's limited ability to expand work at the beginning and end of the project. For the first three months of the project, the contractor is wrapping up another project, waning resources away from the other project onto this one. After three months, the contractor's fleet is at full strength. At the end of the project, the contractor is hesitant to depend on these months for a large amount of expansion, weary of relying on this period to catch up on work, should they be behind.

4.2.2 Monitor and Record Commodities

To produce the most reliable and up-to-date forecasts of required performance, commodities need daily monitoring and recording. While complete RPM reports may not be updated with such frequency, thorough knowledge of project-driving commodities is necessary in knowing the current health of the project. Remediation plans need daily attention, rather than waiting until the end of each month for the new RPM report to disclose what has or has not been accomplished. Monitoring and recording progress on a daily basis allow for the next step in the control system, reporting and comparing actual versus planned. The data and conditions monitored in this phase aid in possible revisions of expansion factors, providing the "known information" for future adjustments. In our example project, earthwork is monitored and recorded on a daily basis, which supplies the necessary data to report and compare in monthly RPM reports.

4.2.3 Report and Compare Actual Versus Planned

Monthly RPM reports provide the facts of the project – how much of the commodity has actually been produced/performed versus how much was planned to be produced/performed. The reports are a comparison of monthly and cumulative values, both in tabular and graphical form. Included in the reports are a history of actual versus planned expansion, supplying the contractor information to make any necessary changes to expansion factors for the remainder of the project. The actual ability to expand the work on the project is reported, and may influence the predicted ability to expand work in future months. Reports constitute a summary of the progress monitoring system, providing the early warning system with the data necessary to forecast required performance.

The example project is now in the month of February, having just received production figures for January work. The data and cumulative production curve for the February are shown below. Comparing actual versus planned production, a few months that did not earn as much as planned have resulted in a schedule that is currently 575,000 cubic yards behind schedule.

Month	EF	Baseline Schedule (CY)		Actual Production (CY)		Δ Cumulative (CY)
		Monthly	Cumulative	Monthly	Cumulative	
			0		0	
April	0	200,000	200,000	150,000	150,000	50,000
May	2	500,000	700,000	400,000	550,000	150,000
June	4	800,000	1,500,000	750,000	1,300,000	200,000
July	9	900,000	2,400,000	925,000	2,225,000	175,000
August	10	1,000,000	3,400,000	900,000	3,125,000	275,000
September	10	1,000,000	4,400,000	925,000	4,050,000	350,000
October	9	900,000	5,300,000	850,000	4,900,000	400,000
November	6	700,000	6,000,000	650,000	5,550,000	450,000
December	0	500,000	6,500,000	500,000	6,050,000	450,000
January	0	500,000	7,000,000	375,000	6,425,000	575,000
February	0	500,000	7,500,000			
March	2	600,000	8,100,000			
April	3	700,000	8,800,000			
May	5	800,000	9,600,000			
June	6	800,000	10,400,000			
July	3	600,000	11,000,000			
August	0	300,000	11,300,000			

Table 4.3: February Update - Project Data

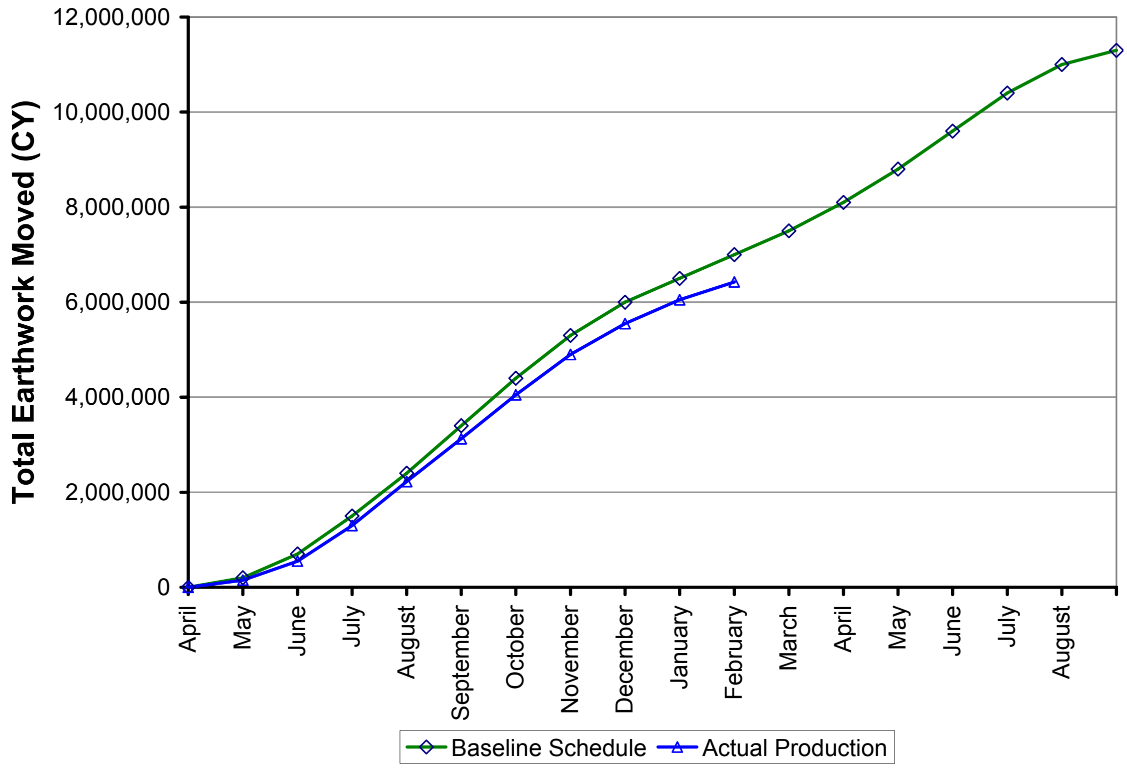


Figure 4.6: February Update – Cumulative Production

4.2.4 Forecast Required Performance

The detail with which you forecast is dependent upon the detail with which you monitor progress. This statement holds true with the Required Performance Method – the quality of predicting required performance depends on how accurate the commodity reports are in representing project progress. All data collected from planned and actual performance is converted into information that predicts performance that is necessary to finish on time. The following charts show the data as converted to required performance for the February update, as well as a chart tracking maximum and monthly expansion for each month.

Month	EF	Baseline Schedule (CY) Monthly	Baseline Schedule (CY) Cumulative	Actual Production (CY) Monthly	Actual Production (CY) Cumulative	Δ Cumulative (CY)	February Required Performance	February Percentage Expansion
			0		0			
April	0	200,000	200,000	150,000	150,000	50,000		
May	2	500,000	700,000	400,000	550,000	150,000		
June	4	800,000	1,500,000	750,000	1,300,000	200,000		
July	9	900,000	2,400,000	925,000	2,225,000	175,000		
August	10	1,000,000	3,400,000	900,000	3,125,000	275,000		
September	10	1,000,000	4,400,000	925,000	4,050,000	350,000		
October	9	900,000	5,300,000	850,000	4,900,000	400,000		
November	6	700,000	6,000,000	650,000	5,550,000	450,000		
December	0	500,000	6,500,000	500,000	6,050,000	450,000		
January	0	500,000	7,000,000	375,000	6,425,000	575,000		
February	0	500,000	7,500,000				500,000	0.0%
March	2	600,000	8,100,000				660,526	10.1%
April	3	700,000	8,800,000				790,789	13.0%
May	5	800,000	9,600,000				951,316	18.9%
June	6	800,000	10,400,000				981,579	22.7%
July	3	600,000	11,000,000				690,789	15.1%
August	0	300,000	11,300,000				300,000	0.0%
							Max Expansion	22.7%
							Avg Expansion	13.4%

Table 4.4: February Update – Monthly Data Report

	Data Date	Max Expansion	Δ1-Mo Max	Δ3-Mo Max	Average Expansion	Δ1-Mo Max	Δ3-Mo Max
Start	**April**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	May	0.7%	0.7%	0.7%	0.5%	0.5%	0.5%
	June	2.2%	1.5%	2.2%	1.4%	1.0%	1.4%
	July	3.2%	0.9%	3.2%	2.0%	0.6%	2.0%
	August	3.2%	0.1%	2.5%	2.0%	-0.1%	1.5%
	September	6.3%	3.0%	4.0%	3.5%	1.5%	2.1%
	October	10.3%	4.0%	7.1%	5.1%	1.6%	3.0%
	November	13.7%	3.4%	10.5%	6.7%	1.6%	4.7%
	December	17.8%	4.0%	11.5%	8.5%	1.8%	5.0%
	January	17.8%	0.0%	7.5%	9.4%	0.9%	4.3%
	February	22.7%	4.9%	9.0%	13.4%	4.0%	6.7%
	March						
	April						
	May						
	June						
	July						
Completion	**August**						

Table 4.5: February Update – Tracking Monthly Expansion

In the first table above, *Max Expansion* is the maximum monthly expansion for forecasted required performance, which in the case of the February Update, is 22.7%, required in the month of June. This number is tracked on a monthly basis in the bottom table. The *Avg Expansion* is the remaining required performance divided by the planned performance over the same remaining duration; in other words, if all expansion factors were equal, this would be the value for expansion. For the February Update, the average expansion is 13.4%. This value is tracked month-by-month, the same as the *Max Expansion*. In the bottom table, both the maximum and average expansions are evaluated in terms of their deviation from the last month (*Δ 1-Mo*), as well as their total change over the last three months (*Δ 3-Mo*).

Information for predictions is presented in the following forms (Note that not all projects have both early and late schedules. In the case of our example, where there is only one schedule, there will be only one figure each for numbers 1, 2, and 3 below.):

1. Early/late monthly production – a production chart of monthly planned, actual, and required performance. Individual forecasted, required monthly performances are easily compared with actual and planned performance. The maximum actual monthly production is labeled, as well as the maximum required performance.

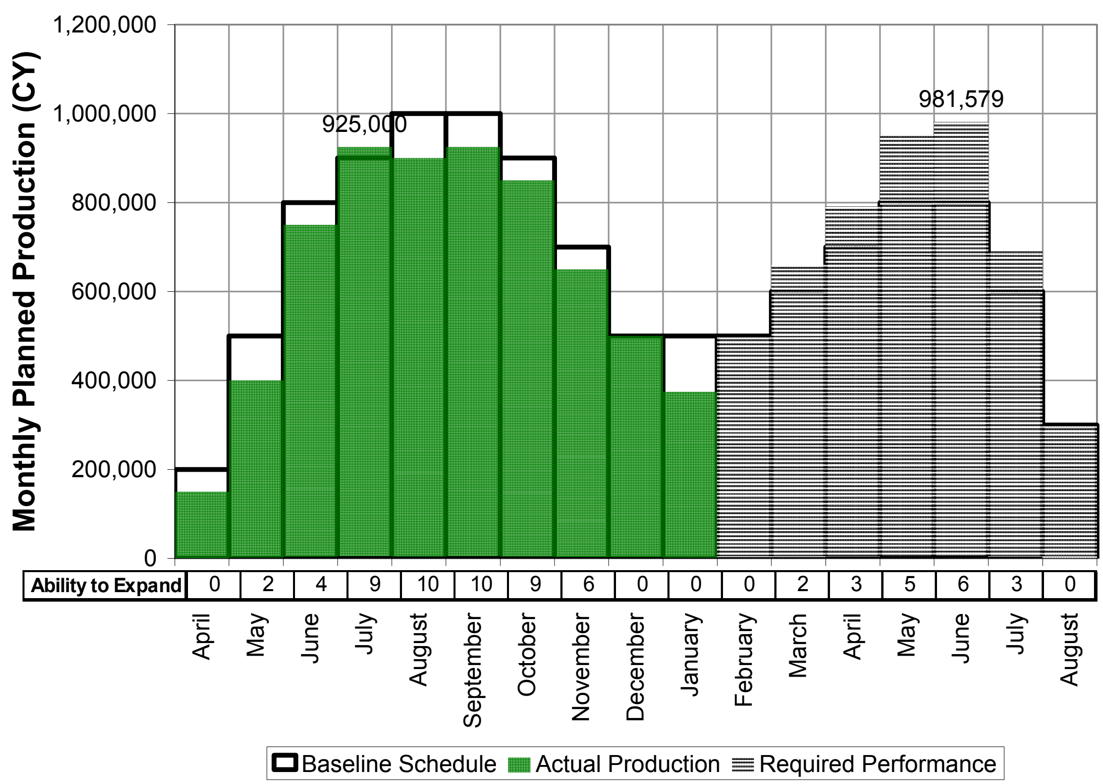


Figure 4.7: February Update – Monthly Production

2. Maximum and average early/late expansion – a chart tracking the maximum monthly expansion of projected required performance, as well as the overall average expansion (cumulative required performance divided by cumulative remaining planned performance).

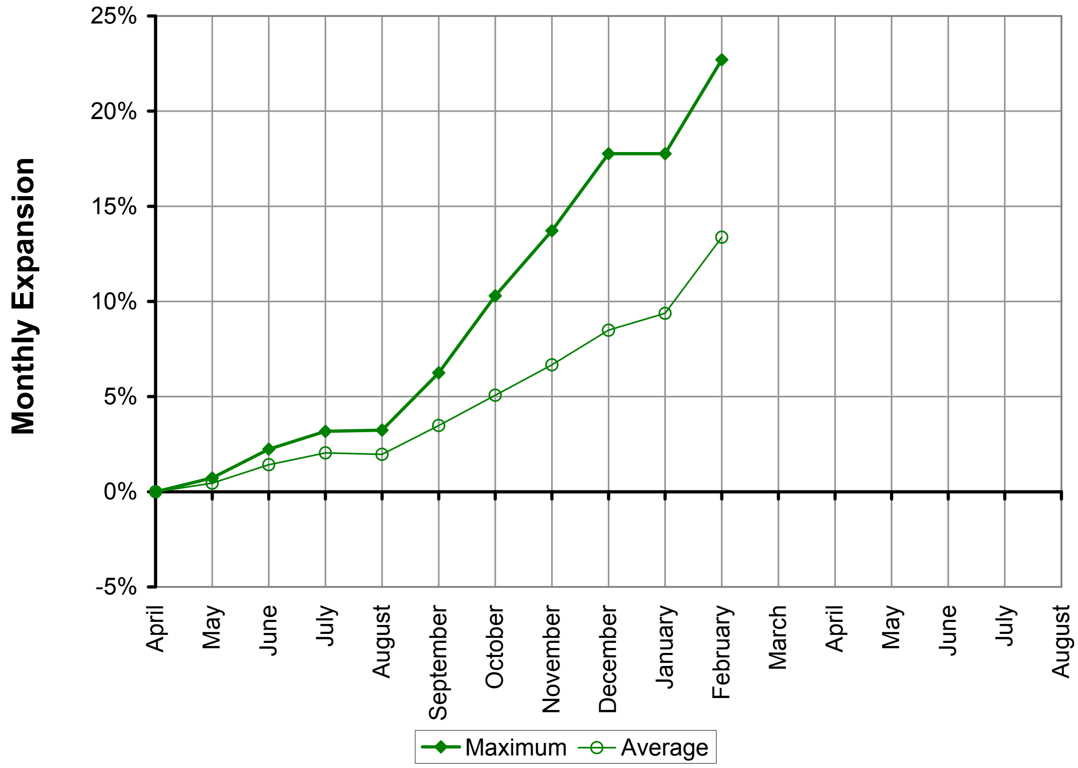


Figure 4.8: February Update – Monthly Expansion

3. Change in maximum early/late expansion – a chart tracking the 1-month and 3-month changes in maximum expansion. This chart shows the direction the project is headed, whether it is recovering or slipping further behind schedule.

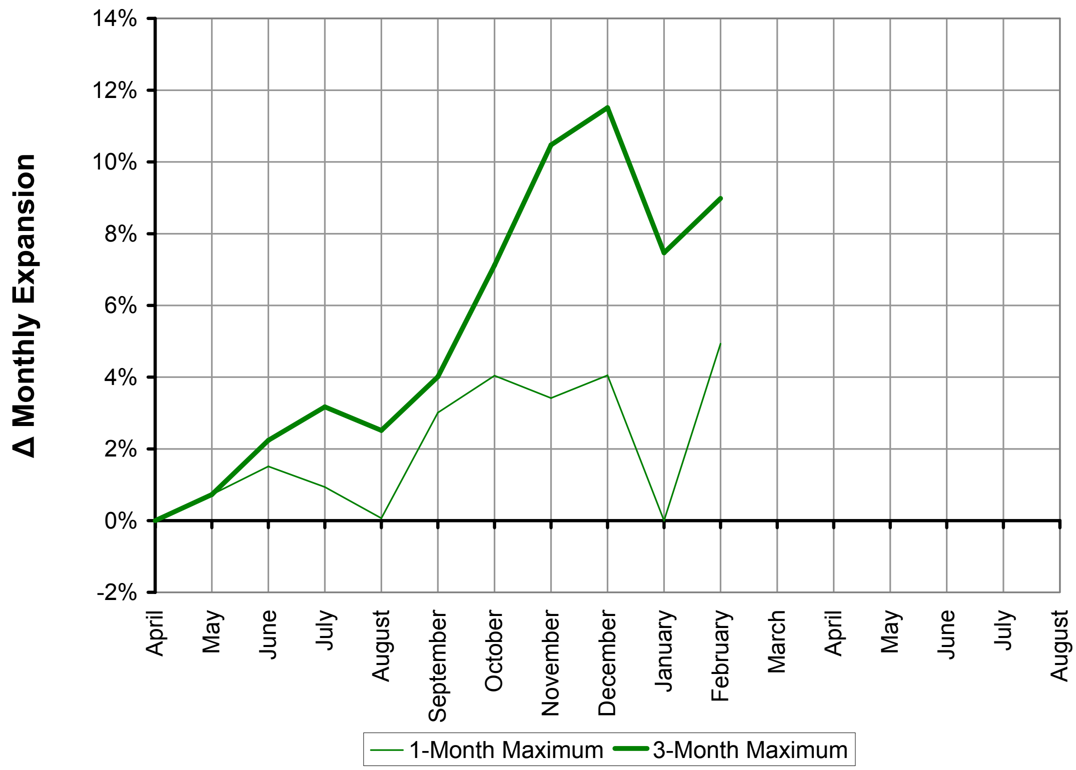


Figure 4.9: February Update - Change in Monthly Expansion

The forecasts provide the necessary information that may set off a "smoke alarm" and call for attention. While recognizing when the alarm should be going off is not discussed until section 4.3, the following section discusses what happens when an alarm is going off.

4.2.5 Time-out, Root Cause Analysis, and Redefine

The final step of the Required Performance method is the *act* stage that is present in all schedule control systems. At this point, the contractor defined a schedule of production, measured and compared actual production to the planned, and forecasted what required performance is needed to complete the project on time.

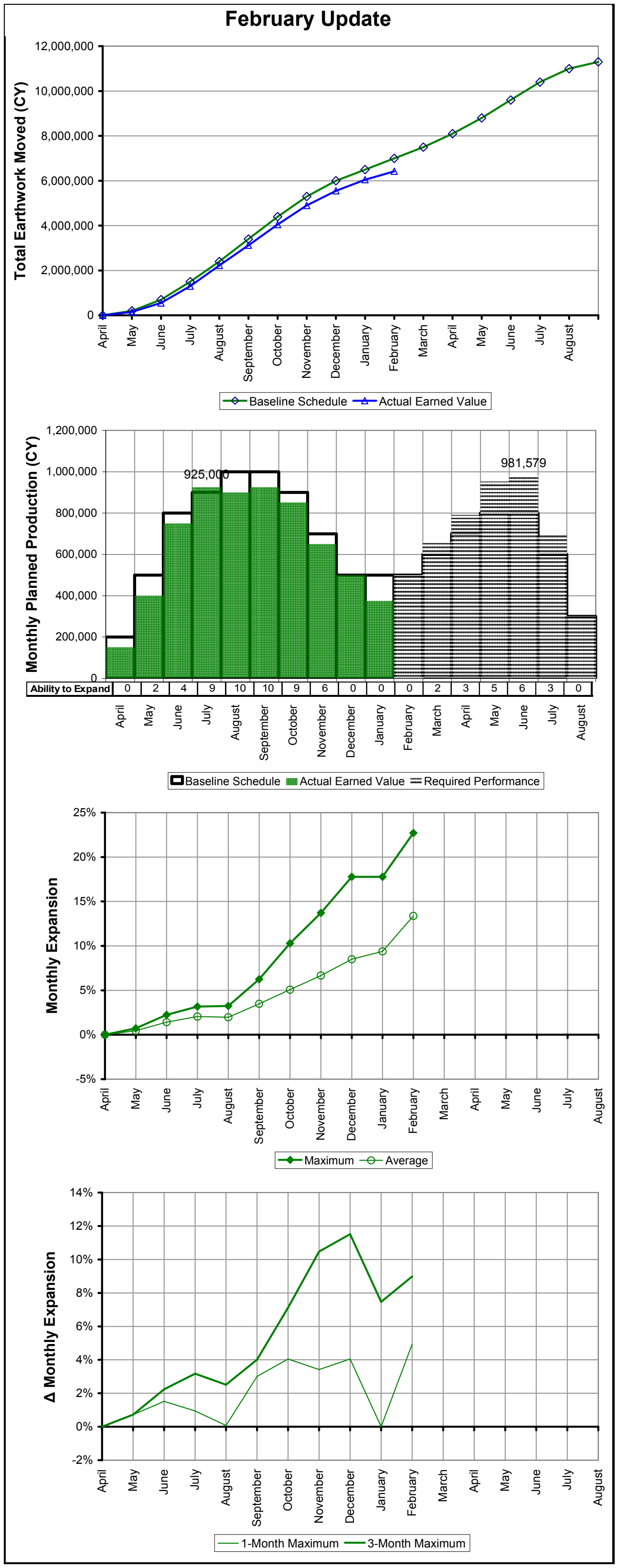
The RPM charts present information that predict values and show trends that potentially are cause for concern when the project is not going according to plan – indicators that set off the "smoke alarm" and call for attention. These trends, values, limits, and thresholds are discussed in section *4.3 Interpreting Monthly RPM Reports.* When there is evidence that the project is not progressing according to plan, it is time to call a "time-out" and recognize that whatever the plan was, it is not working. At this time, the contractor performs a root cause analysis to determine the source of deviation from the plan. Should this deviation reflect an ominous prediction for required performance, a recovery plan is needed. The source and impact are isolated, and a plan for corrective action is developed. The plan may include a redefinition of expansion factors to reflect the contractor's actual ability to expand work on the project to date. To recover, the contractor may need to accelerate work, alter resources, change the logic, or take any other remedial action needed to finish the project on time. Whatever the action taken, the Required Performance Method succeeded as an early warning system by calling for attention and indicating that the project is in danger of timely completion.

Concluding our example project, Figure 4.7 clearly shows that actual earthwork production has been at or below planned production for nine of the ten months, resulting in a required performance that expands in May and June to and beyond a level that has yet to be achieved on the project. This is obvious cause for alarm – requiring performance that has not been done before. Figure 4.8 and Figure 4.9 show that maximum expansion was on a manageable level through August, followed by a steady increase from 3% to 23% over the next six months. This increase was not because of a steady decline in performance, but a steady running out of time. The months of August and September were pivotal in the project, requiring the greatest production. By underachieving in these months, the earthwork would need to be made up over winter months and towards the end of the project – both periods that are regarded as not ideal in their ability to expand work. Although it is clear that as of February, the project needs an immediate recovery plan, the gradual increases in required performance, as well required performance late in the project beyond that achieved in any previous month, were early warning indicators that the schedule was slipping.

While the example assisted in narrating the Required Performance Method, the following section will help interpret reports that show different patterns and trends in the charts.

4.3 Interpreting Monthly RPM Reports

With an understanding of the logistics of the Required Performance Method, this section discusses how to interpret the information presented in monthly reports. The following figure is a sample monthly report for our previous example, which would be accompanied by numerical data on planned, actual, and required performance. Each of the four charts is examined for the type of information they provide.



(a) Cumulative Production Curve

(b) Monthly Planned Production

(c) Monthly Expansion

(d) Change in Monthly Expansion

Figure 4.10: Sample Monthly Report

4.3.1 Cumulative Production

The cumulative production curves (Figure 4.10(a)) allow for a snapshot of cumulative actual versus cumulative planned project performance. The chart is a summary of the commodity, which shows how close to or how far away from, the planned production the project is. On projects with early and late schedules, to assure timely completion, the safest path for the actual production curve is somewhere between the early and late schedule curves. In this case, actual production has been somewhere between the best and worst-case scenarios. While early and late schedule have the same completion date, working towards the early schedule provides an opportunity to finish the project early, quite possibly allowing the contractor to get ahead or pull resources off the project. When working towards the late schedule, as the actual production curve inches closer to the late curve, there is greater potential for untimely completion. Once the actual curve crosses the late curve, the project is in recovery mode, a situation where required performance is expanded beyond planned performance.

4.3.2 Monthly Planned Production

While cumulative production curves provide a good summary of total production, the monthly planned production charts (Figure 4.10(b)) offer a more detailed, monthly reporting of what was planned to be done, what has been done, and what needs to be done. When the project is behind schedule and required performance is expanded, the height of the columns for future monthly production are clearly weighed against historical performance. Projecting a monthly value beyond the planned, and beyond any value previously achieved, is a cause for alarm. There needs to be analysis to see if that level of production is attainable. Quite possibly, there may be a limit to how much production is possible in a month, e.g., if the commodity is concrete, how much concrete is the only accessible local plant capable of producing per day, and per month. Alternatively, consider man-hours: is limited management personnel capable of managing only a certain number of man-hours per day, and per month.

Should the project be ahead of the late schedule, and possibly ahead of the early schedule, the monthly performance bars may still provide an early warning. For instance, actual performance at the beginning of the project may have been beyond planned performance, yet in the last few months, the actual production has been less than planned. This is a call for attention, an early warning that while the project is still ahead of schedule, in recent months it has not been performing according to plan.

4.3.3 Monthly Expansion

As the RPM report for each month calculates the maximum expansion for required performance, as well as the average expansion, these values are tracked on the monthly expansion chart (Figure 4.10(c)). On this chart, there are two major components: the sign of the expansion (positive or negative) and the magnitude of the expansion.

The sign of expansion indicates if the project is ahead or behind of the cumulative planned schedule. Whether it is the early or late schedule, positive values for expansion show the project requires expansion and is behind schedule. Alternatively, negative values show the project is ahead of the early or late schedule. While positive values for late schedules (or if there is only one schedule) recognize that the project is currently behind schedule, positive values for early schedule RPM are not dangerous, but rather an opportunity. Positive expansion may allow the contractor to get ahead of schedule or ease things up, possibly taking off some resources.

The magnitude specifies how far ahead or behind the project is, in terms of expansion. The greater the positive value, the more behind the project is, while the lower the negative value, the further ahead. This chart highlights the innovation of the RPM by plotting the milder value for average expansion against the more extreme values for maximum expansion. For example, a project may be only 10% behind in total project expansion (average expansion), yet required monthly performance indicates that a certain month may need to be expanded by 25%, a substantial difference in projected required monthly performance.

The monthly expansion charts are susceptible to extreme and/or scattered values of expansion. Extremely large or small magnitudes for expansion occur when projecting required performance for months whose planned performance is minimal or zero – the reason being that expanding any amount of work over minimal or zero planned work produces an extremely large number for expansion, with infinite expansion in zero-months. In this case, the monthly planned production charts show these values, and an early warning is still available through their analysis.

4.3.4 Change in Monthly Expansion

As was the case with the monthly expansion chart, the two major components of the change in monthly expansion chart (Figure 4.10(d)) is the sign (positive or negative) and the magnitude of change in expansion. Positive changes in maximum expansion represent a project that is falling behind the respective schedule, whereas negative changes in maximum expansion represent a project that is reducing the monthly expansion – an indication that actual performance has been better than planned, or that a project behind schedule is recovering.

Tracking the change in maximum expansion over the previous one month and previous three months provide insight on how you have performed in the immediate past as well as a more general trend of performance. Peaks and valleys in the monthly expansion charts are represented here by values crossing the zero-axis. On the change in monthly expansion charts, these situations indicate a change for the better (positive to negative) or turn for the worse (negative to positive).

Changes in monthly expansion values, percentage expansion, and trends in these charts call attention to the project, serving their purpose in the Required Performance Method as an early warning indictor for schedule slippage. To demonstrate further the RPM as an applicable control system, Chapter 5 applies the method to a case study.

Chapter 5 – Demonstrating the Required Performance Method: A Case Study

The third objective of this research is to demonstrate the Required Performance Method using real project data, exhibiting its potential use an early warning system for recognizing schedule slippage. While the example in the previous chapter provided an understanding of the concept, demonstrating the RPM using real project data exhibits its real world application as an early warning system. This chapter applies the RPM to a building construction project that failed to complete on time, highlighting early warning indicators that forecasted the project finishing late.

5.1 Project Background

The demonstration project is a $157 million, six-floor building project. Contract start date was February 1, 1997 and contract completion date was set for July 1, 2000 – a 41-month contract term. The original CPM calculated early completion date was March 1, 2000 (37-month duration), and the original CPM calculated late completion date was March 31, 2000 (38-month duration). With the contract term having an additional three months of project float beyond the CPM calculated late completion duration, the late schedule is shifted these three months, representing the latest late schedule possible that will result in timely project completion (Figure 5.1) – a duration of 41 months. This scenario assumes that no contract value is earned in the first three months of the shifted late schedule. In the demonstration RPM, this shifted late schedule is considered the *Baseline Late Schedule*, while the 37-month early CPM schedule is the *Baseline Early Schedule.*

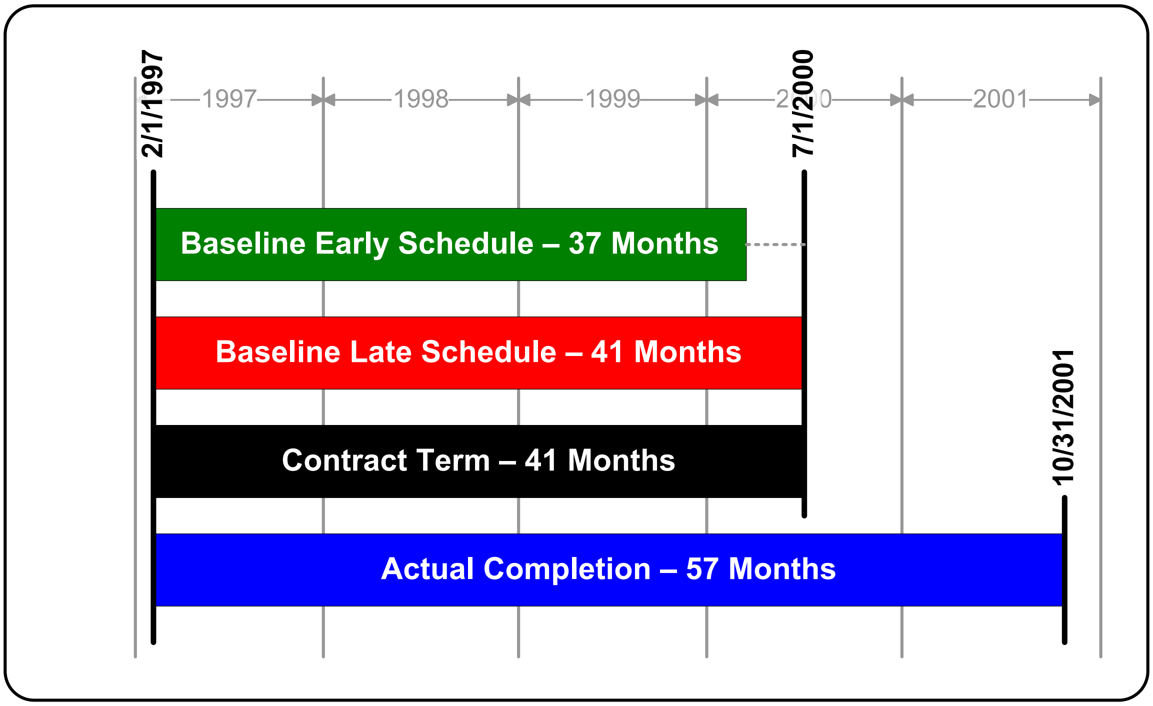


Figure 5.1: Case Study Schedule

The project concluded on October 31, 2001, completing in 57 months – 16 months beyond the contract term. To determine when the "smoke alarm" should have been ringing for this project, the RPM is applied to the planned and actual project data.

5.2 Progress Monitoring in the Case Study

Although the demonstration project did not apply the Required Performance Method in real-time, it did however fulfill the requirements of the first three stages of a RPM schedule control system:

1. **Schedule Commodities and Define Expansion**: The commodity scheduled in this project is earned value. Both the original early schedule and original late schedule are cost-loaded, planning the monthly and cumulative earnings for each month, for the duration of the project. However, the expansion factors are defined for this project retrospectively, shown in section 5.3.

2. **Monitor and Record Commodities**: In compliance with the standards of a schedule control system, earned value was monitored and recorded on a monthly basis. This assures that the most up-to-date, relevant information on actual performance, needed for accurate representations of project progress, was collected.
3. **Report and Compare Actual Versus Planned**: Monthly progress reports provide side-by-side comparisons of actual performance versus planned performance. These "snapshots" track the health of the project, with regards to both the early and late schedules.

The project data provides the necessary information to apply the Required Performance Method and look for early indicators of impending schedule slippage. While the monitoring of progress clearly shows when the project was behind schedule, the RPM predicts when it was *going to be* behind schedule.

5.3 Establishing Expansion Factors

Expansion factors are defined based on the commodity you are expanding and how it is affected by considerations outlined in *4.1.3 The Expansion Factor.* To establish the expansion factors for the case study project, there were five major considerations, described below. However, the contractor of this project best knows *their* ability to expand the work under these conditions. Lacking the personal familiarity with the contractor's ability to perform work, that only this contractor has, five assumptions for expansion are described using the best knowledge at hand.

1. The project is built in a moderate four-season climate with cool, damp winters and a small amount of snowfall. While the project is the construction of a

building that has indoor activities in the later stages of the schedule, the weather still has an impact. Because the building is not completely enclosed until later in the project, and because there are external activities on the roof and outside the building, seasonal climate changes influence the expansion of work. The type of work performed, as influenced by the weather, developed the expansion factors below.

EF for Type of Work and Weather	
Jan	5
Feb	5
Mar	7
Apr	8
May	8
Jun	9
Jul	9
Aug	10
Sep	10
Oct	9
Nov	7
Dec	5

Table 5.1: Case Study: Expansion Factors – Type of Work and Weather

2. The only activity scheduled for the first two months is the removal of surcharge, followed by four months of driving piles. The limited job site space restricted the possibility additional pile driving equipment and storage of raw materials. These two linear activities result in there being expansion factors of zero for the first six months of construction.

3. Following the pile-driving is a five-month sequence of strictly linear work – form/rebar/pour the floor slabs for the six floors. Because this work is performed one at a time, one after the other, there is limited expansion through the month of December 1997.

4. For approximately the middle 50-percent of the project (January 1998 – October 1999), the major influence on expansion how the type of work performed is affected by the weather. As mentioned above, the activities scheduled during this period vary between outdoor and indoor activities, resulting in expansion factors that vary with seasonal changes.

5. The final eight months of the contract term, or roughly the last 20%, taper the expansion factor down to zero. The reason for this is that the amount of scheduled activities decreases down to only punch list items, and it is assumed that the contractor does not want to push expansion to the last few months of the job – a dangerous situation of relying on the last few months to catch up, should the work be behind schedule. The table below is the expansion factors for the entire project.

Month Beginning on	EF
2/1/97	0
3/1/97	0
4/1/97	0
5/1/97	0
6/1/97	0
7/1/97	0
8/1/97	1
9/1/97	1
10/1/97	1
11/1/97	2
12/1/97	2
1/1/98	5
2/1/98	5
3/1/98	7
4/1/98	8
5/1/98	8
6/1/98	9
7/1/98	9
8/1/98	10
9/1/98	10
10/1/98	9
11/1/98	7
12/1/98	5
1/1/99	5
2/1/99	5
3/1/99	7
4/1/99	8
5/1/99	8
6/1/99	9
7/1/99	9
8/1/99	10
9/1/99	10
10/1/99	9
11/1/99	6
12/1/99	5
1/1/00	4
2/1/00	3
3/1/00	3
4/1/00	2
5/1/00	1
6/1/00	0

Table 5.2: Case Study: Expansion Factors

These expansion factors, along with the baseline early schedule and baseline late schedule earned values are as follows:

Month Beginning on	EF	Baseline Early Schedule Monthly	Cumulative	Baseline Late Schedule Monthly	Cumulative
2/1/97	0	$4,131,273	$4,131,273	$0	$0
3/1/97	0	$1,444,882	$5,576,155	$0	$0
4/1/97	0	$5,356,866	$10,933,020	$0	$0
5/1/97	0	$8,882,219	$19,815,239	$37,333	$37,333
6/1/97	0	$9,373,598	$29,188,837	$41,333	$78,667
7/1/97	0	$9,012,245	$38,201,082	$288,400	$367,067
8/1/97	1	$10,095,124	$48,296,206	$601,534	$968,600
9/1/97	1	$7,342,325	$55,638,531	$1,168,316	$2,136,916
10/1/97	1	$7,761,930	$63,400,461	$1,596,053	$3,732,969
11/1/97	2	$7,019,134	$70,419,595	$2,933,386	$6,666,355
12/1/97	2	$7,290,326	$77,709,921	$3,464,645	$10,130,999
1/1/98	5	$5,399,640	$83,109,561	$3,998,548	$14,129,547
2/1/98	5	$5,486,428	$88,595,989	$4,090,117	$18,219,664
3/1/98	7	$5,598,431	$94,194,419	$4,932,409	$23,152,073
4/1/98	8	$5,283,883	$99,478,302	$5,390,967	$28,543,040
5/1/98	8	$5,009,023	$104,487,325	$5,581,768	$34,124,808
6/1/98	9	$4,003,906	$108,491,230	$6,557,015	$40,681,822
7/1/98	9	$3,650,852	$112,142,083	$4,834,127	$45,515,949
8/1/98	10	$4,023,039	$116,165,121	$6,970,493	$52,486,442
9/1/98	10	$3,464,682	$119,629,803	$6,900,571	$59,387,013
10/1/98	9	$3,987,326	$123,617,129	$6,177,491	$65,564,504
11/1/98	7	$2,886,188	$126,503,317	$5,879,718	$71,444,222
12/1/98	5	$3,113,801	$129,617,118	$5,584,005	$77,028,227
1/1/99	5	$3,424,536	$133,041,655	$5,582,690	$82,610,917
2/1/99	5	$3,801,954	$136,843,609	$4,410,330	$87,021,247
3/1/99	7	$4,310,490	$141,154,099	$5,259,071	$92,280,318
4/1/99	8	$3,522,035	$144,676,134	$5,981,302	$98,261,620
5/1/99	8	$2,724,337	$147,400,471	$6,602,323	$104,863,943
6/1/99	9	$2,470,138	$149,870,609	$6,250,708	$111,114,651
7/1/99	9	$1,956,535	$151,827,144	$5,010,475	$116,125,126
8/1/99	10	$1,749,616	$153,576,760	$4,603,656	$120,728,782
9/1/99	10	$1,485,412	$155,062,172	$4,847,083	$125,575,865
10/1/99	9	$1,456,348	$156,518,520	$5,040,576	$130,616,440
11/1/99	6	$226,435	$156,744,955	$5,102,880	$135,719,321
12/1/99	5	$47,753	$156,792,708	$3,340,614	$139,059,935
1/1/00	4	$270,665	$157,063,373	$4,339,338	$143,399,273
2/1/00	3	$413,625	$157,476,998	$3,875,744	$147,275,017
3/1/00	3	$0	$157,476,998	$2,710,364	$149,985,380
4/1/00	2	$0	$157,476,998	$2,414,920	$152,400,300
5/1/00	1	$0	$157,476,998	$2,272,004	$154,672,305
6/1/00	0	$0	$157,476,998	$2,804,697	$157,477,002

Table 5.3: Case Study: Baseline Expansion Factors and Schedules

5.4 Monthly RPM Reports

The case study monthly updates manage to monitor monthly and cumulative earned value, providing snapshots of the commodity that mirrored overall project progress. Data from these monthly reports are analyzed using the Required Performance Method, producing required performance figures and charts. Graphical monthly RPM reports for this case study include the following charts:

1. Cumulative earned value curves for baseline early schedule, baseline late schedule, and actual earned value.

<u>Early Schedule RPM</u>

2. Monthly planned values chart, including baseline early schedule, actual earned value to date, and forecasted required performance.

3. Monthly expansion line chart, tracking the early schedule maximum and average monthly expansion for each monthly update.

4. Change in monthly expansion line chart, tracking the one-month and three-month change in early schedule maximum monthly expansion.

<u>Late Schedule RPM</u>

5. Monthly planned values chart, including baseline late schedule, actual earned value to date, and forecasted required performance.

6. Monthly expansion line chart, tracking the late schedule maximum and average monthly expansion for each monthly update.

7. Change in monthly expansion line chart, tracking the one-month and three-month change in late schedule maximum monthly expansion.

Accompanying each monthly graphical report are numerical data reports. The following section analyzes these reports for early warning indicators of impending schedule slippage. This chapter displays three monthly updates, providing snapshots during three phases of early warning: 1) when the project initially began showing early warning indicators for the late schedule, 2) when early warning indicators became more prominent, and 3) when the project has slipped behind schedule.

The first RPM report is from October 1, 1998, a time when the project is 13% ahead of the late schedule, 11 months before it official slips behind schedule, yet has begun to show initial early warning indicators of schedule slippage. These indicators are quantified in the following section, which analyzes the charts of each update for early warning indicators. Considering the smoke alarm analogy, this first update is right after the first smell of smoke comes from the kitchen. At this point, the schedule needs a root cause analysis to identify the source of the problem.

Four months later, the February 1, 1999 report confirms the pattern of impending schedule slippage, seven months before the project is behind schedule. The project is still 7% ahead of the late schedule, but underperformance is recognized in the RPM reports as a dangerous trend towards schedule slippage. In addition to the smell of smoke, it appears the kitchen may be on fire; corrective action must be taken.

The final report is for the September 1, 1999 update. At this time, the project has slipped behind schedule for the second consecutive month, and is deemed incapable of reaching the July 1, 2000, 41-month contract completion date; the kitchen is engulfed in flames. Time extensions are needed for project completion, with the project ultimately completing on October 31, 2001, an actual completion period of 57 months. By showing the RPM report at a date just beyond when the project fell behind the late schedule, the information shows that although only slightly behind schedule, the concept of expansion forecasts possibly unattainable required performance.

The following three updates provide snapshots of three separate phases of warning, yet all RPM graphical reports from the start date until September 1, 1999 (when the project is late and beyond recovery) are in Appendix A. Additionally, at the end of this chapter is a chronological summary table of early warning indicators for both the early and late schedules.

October 1, 1998

Month Beginning on	EF	Baseline Early Schedule Monthly	Baseline Early Schedule Cumulative	Baseline Late Schedule Monthly	Baseline Late Schedule Cumulative	Actual Earned Value Monthly	Actual Earned Value Cumulative	Δ Cum. Early	Δ Cum. Late	EARLY RPM Required Performance	EARLY RPM Percentage Expansion	LATE RPM Required Performance	LATE RPM Percentage Expansion
			$0		$0		$0						
2/1/97	0	$4,131,273	$4,131,273	$0	$0	$945,615	$945,615	$3,185,658	-$945,615				
3/1/97	0	$1,444,882	$5,576,155	$0	$0	$0	$945,615	$4,630,540	-$945,615				
4/1/97	0	$5,356,866	$10,933,020	$0	$0	$1,749,379	$2,694,994	$8,238,026	-$2,694,994				
5/1/97	0	$8,882,219	$19,815,239	$37,333	$37,333	$2,690,248	$5,385,242	$14,429,997	-$5,347,909				
6/1/97	0	$9,373,598	$29,188,837	$41,333	$78,667	$1,394,993	$6,780,235	$22,408,603	-$6,701,568				
7/1/97	0	$9,012,245	$38,201,082	$288,400	$367,067	$2,794,400	$9,574,635	$28,626,448	-$9,207,568				
8/1/97	1	$10,095,124	$48,296,206	$601,534	$968,600	$3,131,255	$12,705,890	$35,590,316	-$11,737,290				
9/1/97	1	$7,342,325	$55,638,531	$1,168,316	$2,136,916	$3,656,702	$16,362,592	$39,275,939	-$14,225,676				
10/1/97	1	$7,761,930	$63,400,461	$1,596,053	$3,732,969	$3,211,225	$19,573,817	$43,826,645	-$15,840,847				
11/1/97	2	$7,019,134	$70,419,595	$2,933,386	$6,666,355	$3,103,007	$22,676,824	$47,742,772	-$16,010,469				
12/1/97	2	$7,290,326	$77,709,921	$3,464,645	$10,130,999	$3,623,857	$26,300,681	$51,409,240	-$16,169,681				
1/1/98	5	$5,399,640	$83,109,561	$3,998,548	$14,129,547	$3,560,350	$29,861,031	$53,248,530	-$15,731,483				
2/1/98	5	$5,486,428	$88,595,989	$4,090,117	$18,219,664	$4,351,292	$34,212,323	$54,383,666	-$15,992,658				
3/1/98	7	$5,598,431	$94,194,419	$4,932,409	$23,152,073	$5,678,833	$39,891,155	$54,303,264	-$16,739,082				
4/1/98	8	$5,283,883	$99,478,302	$5,390,967	$28,543,040	$5,500,280	$45,391,435	$54,086,867	-$16,848,395				
5/1/98	8	$5,009,023	$104,487,325	$5,581,768	$34,124,808	$5,758,074	$51,149,509	$53,337,816	-$17,024,701				
6/1/98	9	$4,003,906	$108,491,230	$6,557,015	$40,681,822	$4,633,259	$55,782,768	$52,708,462	-$15,100,946				
7/1/98	9	$3,650,852	$112,142,083	$4,834,127	$45,515,949	$6,647,282	$62,430,050	$49,712,033	-$16,914,100				
8/1/98	10	$4,023,039	$116,165,121	$6,970,493	$52,486,442	$4,583,421	$67,013,471	$49,151,651	-$14,527,028				
9/1/98	10	$3,464,682	$119,629,803	$6,900,571	$59,387,013	$4,639,489	$71,652,960	$47,976,843	-$12,265,947				
10/1/98	9	$3,987,326	$123,617,129	$6,177,491	$65,564,504					$7,615,827	91.00%	$5,294,343	-14.30%
11/1/98	7	$2,886,188	$126,503,317	$5,879,718	$71,444,222					$5,708,355	97.78%	$5,192,825	-11.68%
12/1/98	5	$3,113,801	$129,617,118	$5,584,005	$77,028,227					$5,129,635	64.74%	$5,093,367	-8.79%
1/1/99	5	$3,424,536	$133,041,655	$5,582,690	$82,610,917					$5,440,370	58.86%	$5,092,052	-8.79%
2/1/99	5	$3,801,954	$136,843,609	$4,410,330	$87,021,247					$5,817,788	53.02%	$3,919,692	-11.12%
3/1/99	7	$4,310,490	$141,154,099	$5,259,071	$92,280,318					$7,132,657	65.47%	$4,572,178	-13.06%
4/1/99	8	$3,522,035	$144,676,134	$5,981,302	$98,261,620					$6,747,369	91.58%	$5,196,281	-13.12%
5/1/99	8	$2,724,337	$147,400,471	$6,602,323	$104,863,943					$5,949,671	118.39%	$5,817,302	-11.89%
6/1/99	9	$2,470,138	$149,870,609	$6,250,708	$111,114,651					$6,098,639	146.89%	$5,367,560	-14.13%
7/1/99	9	$1,956,535	$151,827,144	$5,010,475	$116,125,126					$5,585,036	185.46%	$4,127,326	-17.63%
8/1/99	10	$1,749,616	$153,576,760	$4,603,656	$120,728,782					$5,781,284	230.43%	$3,622,380	-21.32%
9/1/99	10	$1,485,412	$155,062,172	$4,847,083	$125,575,865					$5,517,079	271.42%	$3,865,807	-20.24%
10/1/99	9	$1,456,348	$156,518,520	$5,040,576	$130,616,440					$5,084,849	249.15%	$4,157,427	-17.52%
11/1/99	6	$226,435	$156,744,955	$5,102,880	$135,719,321					$2,645,436	1068.30%	$4,514,115	-11.54%
12/1/99	5	$47,753	$156,792,708	$3,340,614	$139,059,935					$2,063,586	4221.42%	$2,849,976	-14.69%
1/1/00	4	$270,665	$157,063,373	$4,339,338	$143,399,273					$1,883,332	595.82%	$3,946,828	-9.05%
2/1/00	3	$413,625	$157,476,998	$3,875,744	$147,275,017					$1,623,125	292.41%	$3,581,361	-7.60%
3/1/00	3	$0	$157,476,998	$2,710,364	$149,985,380							$2,415,981	-10.86%
4/1/00	2	$0	$157,476,998	$2,414,920	$152,400,300							$2,218,665	-8.13%
5/1/00	1	$0	$157,476,998	$2,272,004	$154,672,305							$2,173,877	-4.32%
6/1/00	0	$0	$157,476,998	$2,804,697	$157,477,002							$2,804,697	0.00%
										MAX Exp =	4221.42%	**MAX Exp =**	-21.32%
										AVG Exp =	126.76%	**AVG Exp =**	-12.50%

Table 5.4: Case Study: 10/1/1998 Numerical Report

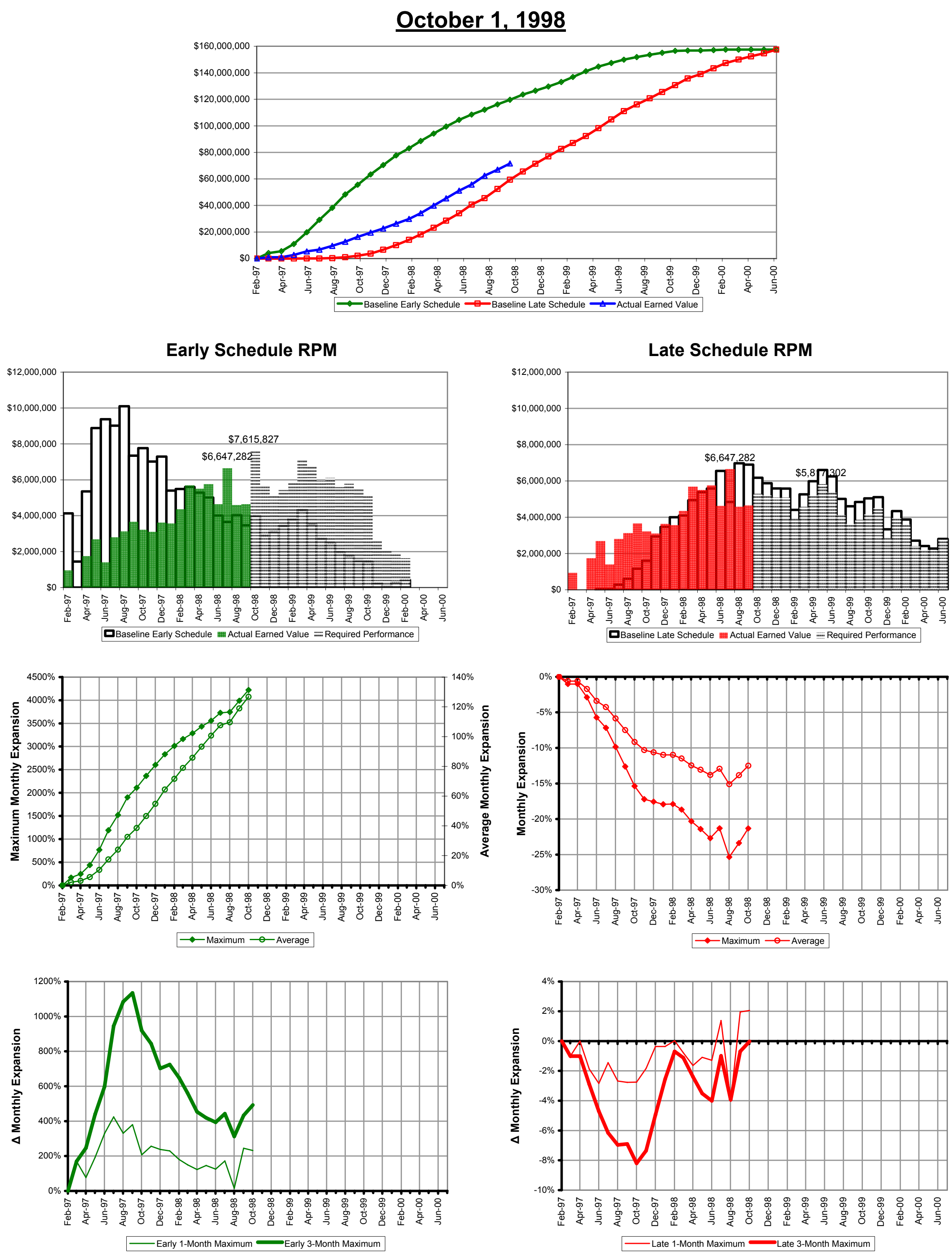


Figure 5.2: Case Study: 10/1/1998 Graphical Report

February 1, 1999

Month Beginning on	EF	Baseline Early Schedule Monthly	Baseline Early Schedule Cumulative	Baseline Late Schedule Monthly	Baseline Late Schedule Cumulative	Actual Earned Value Monthly	Actual Earned Value Cumulative	Δ Cum. Early	Δ Cum. Late	EARLY RPM Required Performance	EARLY RPM Percentage Expansion	LATE RPM Required Performance	LATE RPM Percentage Expansion
			$0		$0		$0						
2/1/97	0	$4,131,273	$4,131,273	$0	$0	$945,615	$945,615	$3,185,658	-$945,615				
3/1/97	0	$1,444,882	$5,576,155	$0	$0	$0	$945,615	$4,630,540	-$945,615				
4/1/97	0	$5,356,866	$10,933,020	$0	$0	$1,749,379	$2,694,994	$8,238,026	-$2,694,994				
5/1/97	0	$8,882,219	$19,815,239	$37,333	$37,333	$2,690,248	$5,385,242	$14,429,997	-$5,347,909				
6/1/97	0	$9,373,598	$29,188,837	$41,333	$78,667	$1,394,993	$6,780,235	$22,408,603	-$6,701,568				
7/1/97	0	$9,012,245	$38,201,082	$288,400	$367,067	$2,794,400	$9,574,635	$28,626,448	-$9,207,568				
8/1/97	1	$10,095,124	$48,296,206	$601,534	$968,600	$3,131,255	$12,705,890	$35,590,316	-$11,737,290				
9/1/97	1	$7,342,325	$55,638,531	$1,168,316	$2,136,916	$3,656,702	$16,362,592	$39,275,939	-$14,225,676				
10/1/97	1	$7,761,930	$63,400,461	$1,596,053	$3,732,969	$3,211,225	$19,573,817	$43,826,645	-$15,840,847				
11/1/97	2	$7,019,134	$70,419,595	$2,933,386	$6,666,355	$3,103,007	$22,676,824	$47,742,772	-$16,010,469				
12/1/97	2	$7,290,326	$77,709,921	$3,464,645	$10,130,999	$3,623,857	$26,300,681	$51,409,240	-$16,169,681				
1/1/98	5	$5,399,640	$83,109,561	$3,998,548	$14,129,547	$3,560,350	$29,861,031	$53,248,530	-$15,731,483				
2/1/98	5	$5,486,428	$88,595,989	$4,090,117	$18,219,664	$4,351,292	$34,212,323	$54,383,666	-$15,992,658				
3/1/98	7	$5,598,431	$94,194,419	$4,932,409	$23,152,073	$5,678,833	$39,891,155	$54,303,264	-$16,739,082				
4/1/98	8	$5,283,883	$99,478,302	$5,390,967	$28,543,040	$5,500,280	$45,391,435	$54,086,867	-$16,848,395				
5/1/98	8	$5,009,023	$104,487,325	$5,581,768	$34,124,808	$5,758,074	$51,149,509	$53,337,816	-$17,024,701				
6/1/98	9	$4,003,906	$108,491,230	$6,557,015	$40,681,822	$4,633,259	$55,782,768	$52,708,462	-$15,100,946				
7/1/98	9	$3,650,852	$112,142,083	$4,834,127	$45,515,949	$6,647,282	$62,430,050	$49,712,033	-$16,914,100				
8/1/98	10	$4,023,039	$116,165,121	$6,970,493	$52,486,442	$4,583,421	$67,013,471	$49,151,651	-$14,527,028				
9/1/98	10	$3,464,682	$119,629,803	$6,900,571	$59,387,013	$4,639,489	$71,652,960	$47,976,843	-$12,265,947				
10/1/98	9	$3,987,326	$123,617,129	$6,177,491	$65,564,504	$3,973,385	$75,626,345	$47,990,785	-$10,061,840				
11/1/98	7	$2,886,188	$126,503,317	$5,879,718	$71,444,222	$5,380,293	$81,006,638	$45,496,679	-$9,562,415				
12/1/98	5	$3,113,801	$129,617,118	$5,584,005	$77,028,227	$4,011,190	$85,017,828	$44,599,290	-$7,989,601				
1/1/99	5	$3,424,536	$133,041,655	$5,582,690	$82,610,917	$3,091,953	$88,109,781	$44,931,874	-$5,498,864				
2/1/99	5	$3,801,954	$136,843,609	$4,410,330	$87,021,247					$6,217,646	63.54%	$4,132,610	-6.30%
3/1/99	7	$4,310,490	$141,154,099	$5,259,071	$92,280,318					$7,692,459	78.46%	$4,870,262	-7.39%
4/1/99	8	$3,522,035	$144,676,134	$5,981,302	$98,261,620					$7,387,143	109.74%	$5,536,949	-7.43%
5/1/99	8	$2,724,337	$147,400,471	$6,602,323	$104,863,943					$6,589,444	141.87%	$6,157,970	-6.73%
6/1/99	9	$2,470,138	$149,870,609	$6,250,708	$111,114,651					$6,818,384	176.03%	$5,750,811	-8.00%
7/1/99	9	$1,956,535	$151,827,144	$5,010,475	$116,125,126					$6,304,781	222.24%	$4,510,578	-9.98%
8/1/99	10	$1,749,616	$153,576,760	$4,603,656	$120,728,782					$6,581,001	276.14%	$4,048,215	-12.07%
9/1/99	10	$1,485,412	$155,062,172	$4,847,083	$125,575,865					$6,316,796	325.26%	$4,291,642	-11.46%
10/1/99	9	$1,456,348	$156,518,520	$5,040,576	$130,616,440					$5,804,594	298.57%	$4,540,679	-9.92%
11/1/99	6	$226,435	$156,744,955	$5,102,880	$135,719,321					$3,125,266	1280.20%	$4,769,616	-6.53%
12/1/99	5	$47,753	$156,792,708	$3,340,614	$139,059,935					$2,463,445	5058.78%	$3,062,894	-8.31%
1/1/00	4	$270,665	$157,063,373	$4,339,338	$143,399,273					$2,203,218	714.00%	$4,117,162	-5.12%
2/1/00	3	$413,625	$157,476,998	$3,875,744	$147,275,017					$1,863,040	350.42%	$3,709,111	-4.30%
3/1/00	3	$0	$157,476,998	$2,710,364	$149,985,380							$2,543,732	-6.15%
4/1/00	2	$0	$157,476,998	$2,414,920	$152,400,300							$2,303,832	-4.60%
5/1/00	1	$0	$157,476,998	$2,272,004	$154,672,305							$2,216,460	-2.44%
6/1/00	0	$0	$157,476,998	$2,804,697	$157,477,002							$2,804,697	0.00%
										MAX Exp =	5058.78%	MAX Exp =	-12.07%
										AVG Exp =	183.88%	AVG Exp =	-7.34%

Table 5.5: Case Study: 2/1/1999 Numerical Report

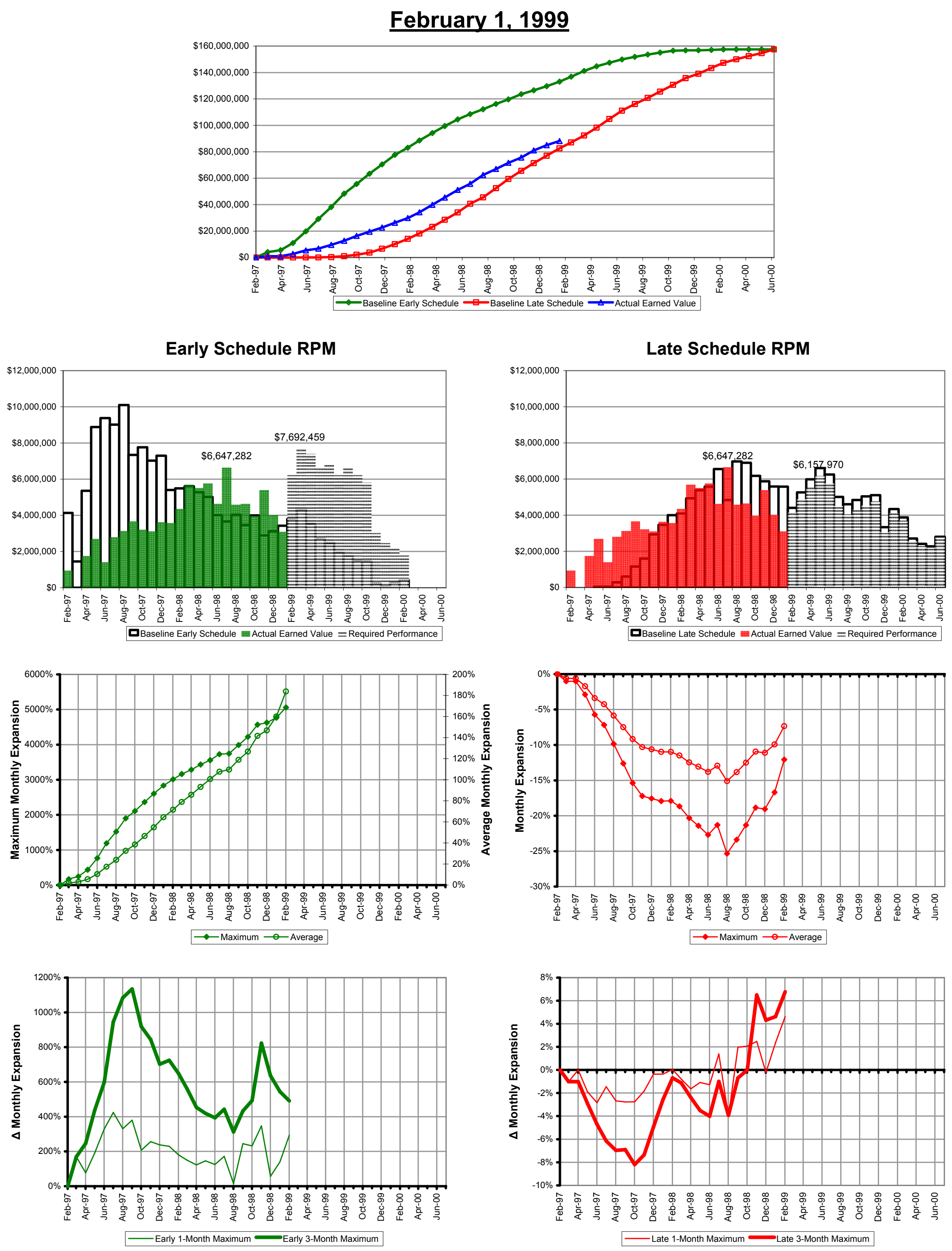


Figure 5.3: Case Study: 2/1/1999 Graphical Report

September 1, 1999

Month Beginning on	EF	Baseline Early Schedule Monthly	Baseline Early Schedule Cumulative	Baseline Late Schedule Monthly	Baseline Late Schedule Cumulative	Actual Earned Value Monthly	Actual Earned Value Cumulative	Δ Cum. Early	Δ Cum. Late	EARLY RPM Required Performance	EARLY RPM Percentage Expansion	LATE RPM Required Performance	LATE RPM Percentage Expansion
			$0		$0		$0						
2/1/97	0	$4,131,273	$4,131,273	$0	$0	$945,615	$945,615	$3,185,658	-$945,615				
3/1/97	0	$1,444,882	$5,576,155	$0	$0	$0	$945,615	$4,630,540	-$945,615				
4/1/97	0	$5,356,866	$10,933,020	$0	$0	$1,749,379	$2,694,994	$8,238,026	-$2,694,994				
5/1/97	0	$8,882,219	$19,815,239	$37,333	$37,333	$2,690,248	$5,385,242	$14,429,997	-$5,347,909				
6/1/97	0	$9,373,598	$29,188,837	$41,333	$78,667	$1,394,993	$6,780,235	$22,408,603	-$6,701,568				
7/1/97	0	$9,012,245	$38,201,082	$288,400	$367,067	$2,794,400	$9,574,635	$28,626,448	-$9,207,568				
8/1/97	1	$10,095,124	$48,296,206	$601,534	$968,600	$3,131,255	$12,705,890	$35,590,316	-$11,737,290				
9/1/97	1	$7,342,325	$55,638,531	$1,168,316	$2,136,916	$3,656,702	$16,362,592	$39,275,939	-$14,225,676				
10/1/97	1	$7,761,930	$63,400,461	$1,596,053	$3,732,969	$3,211,225	$19,573,817	$43,826,645	-$15,840,847				
11/1/97	2	$7,019,134	$70,419,595	$2,933,386	$6,666,355	$3,103,007	$22,676,824	$47,742,772	-$16,010,469				
12/1/97	2	$7,290,326	$77,709,921	$3,464,645	$10,130,999	$3,623,857	$26,300,681	$51,409,240	-$16,169,681				
1/1/98	5	$5,399,640	$83,109,561	$3,998,548	$14,129,547	$3,560,350	$29,861,031	$53,248,530	-$15,731,483				
2/1/98	5	$5,486,428	$88,595,989	$4,090,117	$18,219,664	$4,351,292	$34,212,323	$54,383,666	-$15,992,658				
3/1/98	7	$5,598,431	$94,194,419	$4,932,409	$23,152,073	$5,678,833	$39,891,155	$54,303,264	-$16,739,082				
4/1/98	8	$5,283,883	$99,478,302	$5,390,967	$28,543,040	$5,500,280	$45,391,435	$54,086,867	-$16,848,395				
5/1/98	8	$5,009,023	$104,487,325	$5,581,768	$34,124,808	$5,758,074	$51,149,509	$53,337,816	-$17,024,701				
6/1/98	9	$4,003,906	$108,491,230	$6,557,015	$40,681,822	$4,633,259	$55,782,768	$52,708,462	-$15,100,946				
7/1/98	9	$3,650,852	$112,142,083	$4,834,127	$45,515,949	$6,647,282	$62,430,050	$49,712,033	-$16,914,100				
8/1/98	10	$4,023,039	$116,165,121	$6,970,493	$52,486,442	$4,583,421	$67,013,471	$49,151,651	-$14,527,028				
9/1/98	10	$3,464,682	$119,629,803	$6,900,571	$59,387,013	$4,639,489	$71,652,960	$47,976,843	-$12,265,947				
10/1/98	9	$3,987,326	$123,617,129	$6,177,491	$65,564,504	$3,973,385	$75,626,345	$47,990,785	-$10,061,840				
11/1/98	7	$2,886,188	$126,503,317	$5,879,718	$71,444,222	$5,380,293	$81,006,638	$45,496,679	-$9,562,415				
12/1/98	5	$3,113,801	$129,617,118	$5,584,005	$77,028,227	$4,011,190	$85,017,828	$44,599,290	-$7,989,601				
1/1/99	5	$3,424,536	$133,041,655	$5,582,690	$82,610,917	$3,091,953	$88,109,781	$44,931,874	-$5,498,864				
2/1/99	5	$3,801,954	$136,843,609	$4,410,330	$87,021,247	$4,213,774	$92,323,555	$44,520,054	-$5,302,308				
3/1/99	7	$4,310,490	$141,154,099	$5,259,071	$92,280,318	$5,375,215	$97,698,770	$43,455,328	-$5,418,452				
4/1/99	8	$3,522,035	$144,676,134	$5,981,302	$98,261,620	$5,338,679	$103,037,449	$41,638,685	-$4,775,829				
5/1/99	8	$2,724,337	$147,400,471	$6,602,323	$104,863,943	$4,260,120	$107,297,569	$40,102,902	-$2,433,625				
6/1/99	9	$2,470,138	$149,870,609	$6,250,708	$111,114,651	$4,133,317	$111,430,886	$38,439,723	-$316,235				
7/1/99	9	$1,956,535	$151,827,144	$5,010,475	$116,125,126	$2,702,589	$114,133,475	$37,693,669	$1,991,651				
8/1/99	10	$1,749,616	$153,576,760	$4,603,656	$120,728,782	$3,065,535	$117,199,011	$36,377,750	$3,529,771				
9/1/99	10	$1,485,412	$155,062,172	$4,847,083	$125,575,865					$11,317,236	661.89%	$5,667,960	16.94%
10/1/99	9	$1,456,348	$156,518,520	$5,040,576	$130,616,440					$10,304,990	607.59%	$5,779,365	14.66%
11/1/99	6	$226,435	$156,744,955	$5,102,880	$135,719,321					$6,125,530	2605.20%	$5,595,407	9.65%
12/1/99	5	$47,753	$156,792,708	$3,340,614	$139,059,935					$4,963,665	10294.56%	$3,751,053	12.29%
1/1/00	4	$270,665	$157,063,373	$4,339,338	$143,399,273					$4,203,394	1452.99%	$4,667,689	7.57%
2/1/00	3	$413,625	$157,476,998	$3,875,744	$147,275,017					$3,363,172	713.10%	$4,122,007	6.35%
3/1/00	3	$0	$157,476,998	$2,710,364	$149,985,380							$2,956,627	9.09%
4/1/00	2	$0	$157,476,998	$2,414,920	$152,400,300							$2,579,095	6.80%
5/1/00	1	$0	$157,476,998	$2,272,004	$154,672,305							$2,354,092	3.61%
6/1/00	0	$0	$157,476,998	$2,804,697	$157,477,002							$2,804,697	0.00%
										MAX Exp =	10294.56%	**MAX Exp =**	16.94%
										AVG Exp =	932.71%	**AVG Exp =**	9.61%

Table 5.6: Case Study: 9/1/1999 Numerical Report

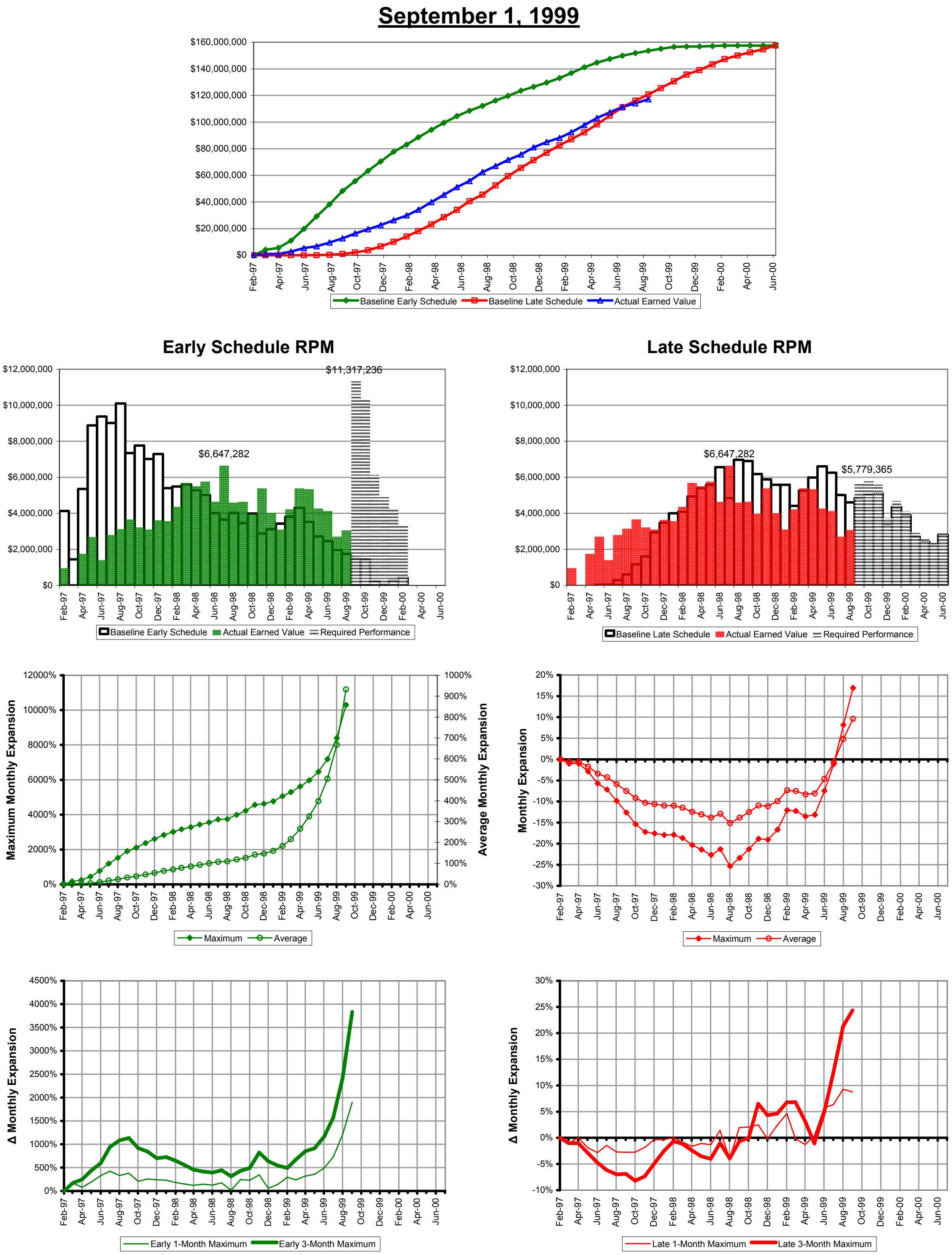


Figure 5.4: Case Study: 9/1/1999 Graphical Report

5.5 Analyzing the Information – Early Warning Indicators

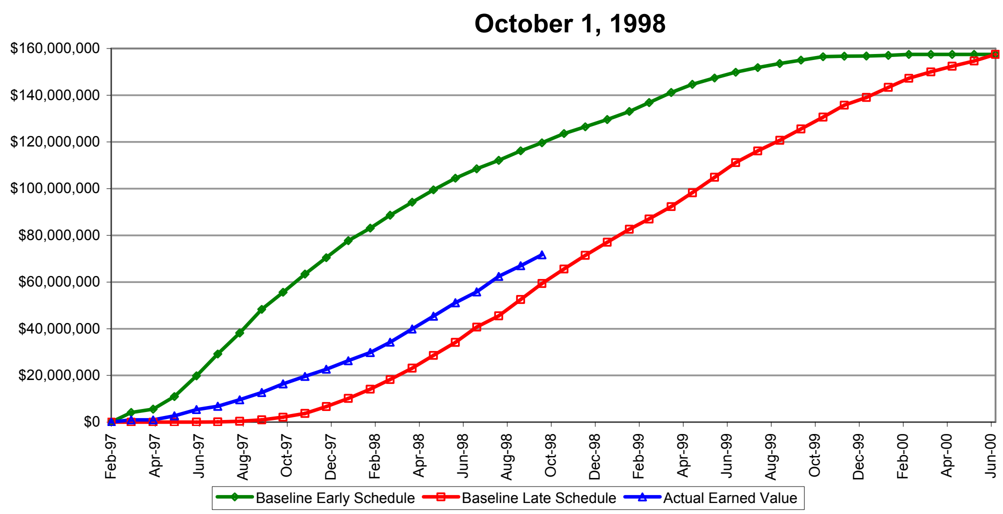
The final stage of the Required Performance Method takes the data and forecasts provided by the monthly RPM reports, analyzes them for early warning indicators of impending schedule slippage, and, if a "smoke alarm" goes off, calls a "time-out", performs a root cause analysis, and makes necessary changes. This section focuses on early warning indicators of impending schedule slippage for the case study.

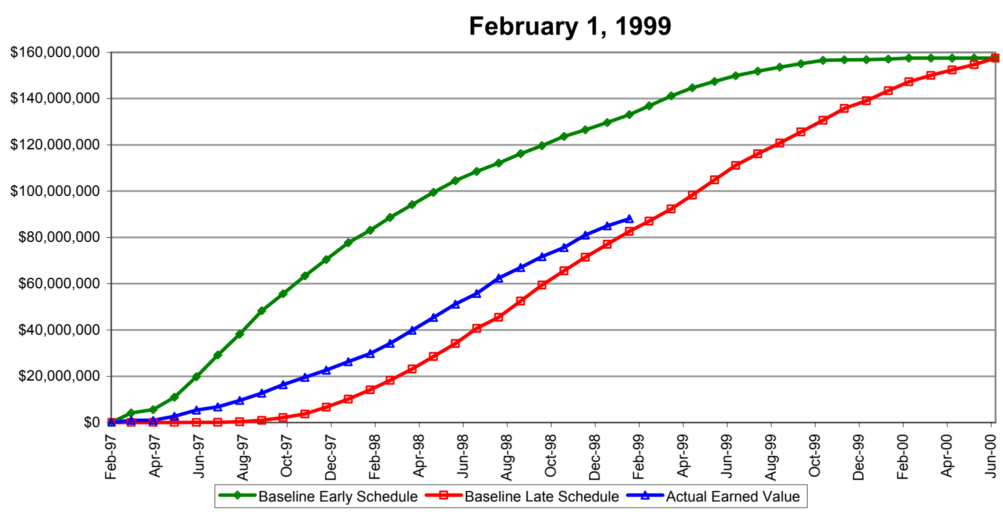
To recognize these indicators, the following sections go through each of the seven charts presented in the case study monthly graphical report. The first section speaks briefly on the cumulative earnings curve, followed by three sections on the Early Schedule RPM charts, and concluding with three sections on the Late Schedule RPM charts. The Early Schedule RPM charts serve their role as early warning indicators for making the 37-month early schedule completion date, while the Late Schedule RPM charts offer early warning indicators that the project is in danger of finishing beyond the 41-month contract completion date.

Following the discussion of each chart in the monthly RPM report, there is a chronological summary of monthly RPM reports that recognize early warning of schedule slippage. Additional monthly RPM reports referred to in this chapter are provided in Appendix A.

5.5.1 Cumulative Earned Value

The cumulative earned value curves track the actual earned value as it separates itself from the baseline early schedule, while running parallel with the baseline late schedule, before ultimately crossing the late schedule curve, indicating that the project is behind the late schedule.





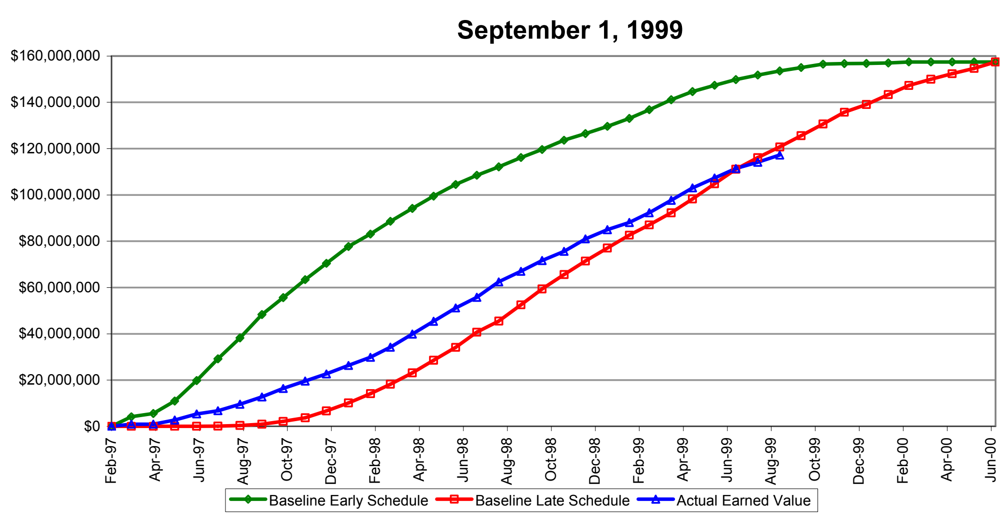


Figure 5.5: Case Study: Cumulative Earned Value

When looking at the earned value chart is that the original 38-month, consider that the calculated late schedule CPM was pushed back three months to represent the 41-month baseline late schedule. While the project very quickly falls behind the baseline early schedule, the actual earnings curve runs close to, but parallel with the baseline late schedule. The deviation between these late schedules is created in large part by the three months of project float in the 41-month baseline late schedule. However, the October 1, 1998 report shows the deviation has begun to shrink in the couple months from $16.9 million ahead of late schedule to $10.1 million ahead of late schedule, shrinking even more by the February 1, 1999 report ($5.3 million ahead of late schedule), and by July 1999, this gap shrinks to nothing, consuming all project float. The poor performance continues, crossing over the baseline late schedule, slipping further behind schedule.

5.5.2 Early Schedule Monthly Planned Values

The early schedule monthly planned value charts shows the project falling fast behind the baseline early schedule, as shown by the failure to earn the baseline early monthly value for the first 13 months of the project.

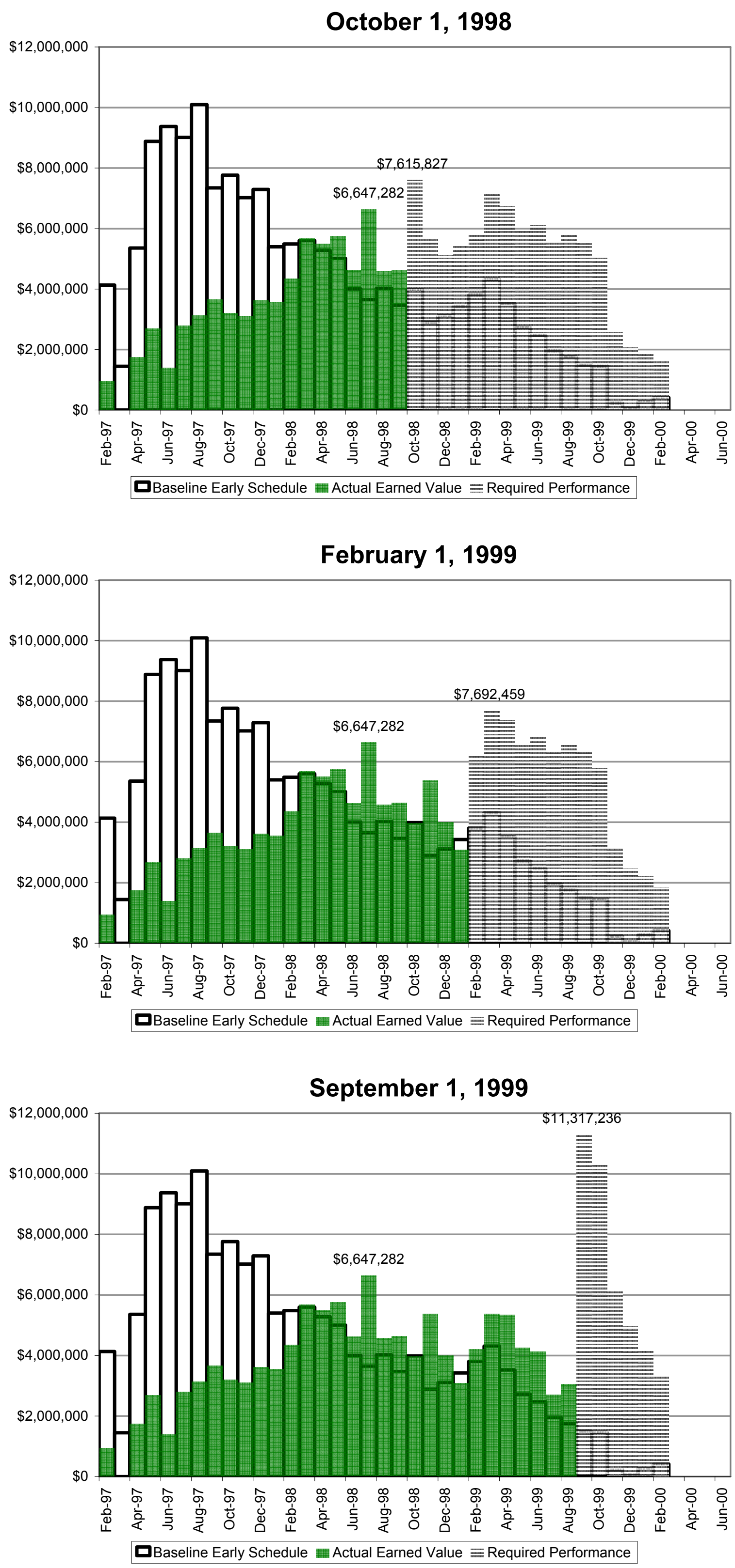


Figure 5.6: Case Study: Early Schedule Monthly Planned Values

While from March 1998 to August 1999, the contractor earned above the planned early values for 17 of 18 months, this expansion of work is miniscule compared to the required performance needed to complete the baseline early schedule in the 37-month period (by March 1, 2000). The early warning indicator from this chart is the failure to meet planned performance, which results in exceedingly large monthly values for required performance. The alarm would have been ringing after the first month, recognizing that the project is behind schedule.

Beyond this patent lack of production, when required performance values began exceeding the actual performance of any prior month, this was cause for concern that the early schedule completion would become unattainable. In fact, because of the slow start and failure to recover, actual performance was never higher than maximum required performance in an update. By October 1, 1998, forecasted required performance for two months has exceeded actual performance in any month. The other two updates show that the growth in required performance continues to insurmountable levels.

5.5.3 Early Schedule Monthly Expansion

The first impression from the early schedule monthly expansion chart is the extremely large values for maximum monthly expansion, a product of required monthly performance being far greater than planned monthly performance. For the last few months of the 37-month schedule, planned early schedule earnings were very low, accounting for the extreme maximum expansion values. In this situation, the trends in the monthly expansion line chart, coupled with the other early schedule RPM charts, serve as identifiers of schedule slippage. Furthermore, the average monthly expansion curve is the same sign (positive or negative) as the maximum curve, only of lesser magnitude.

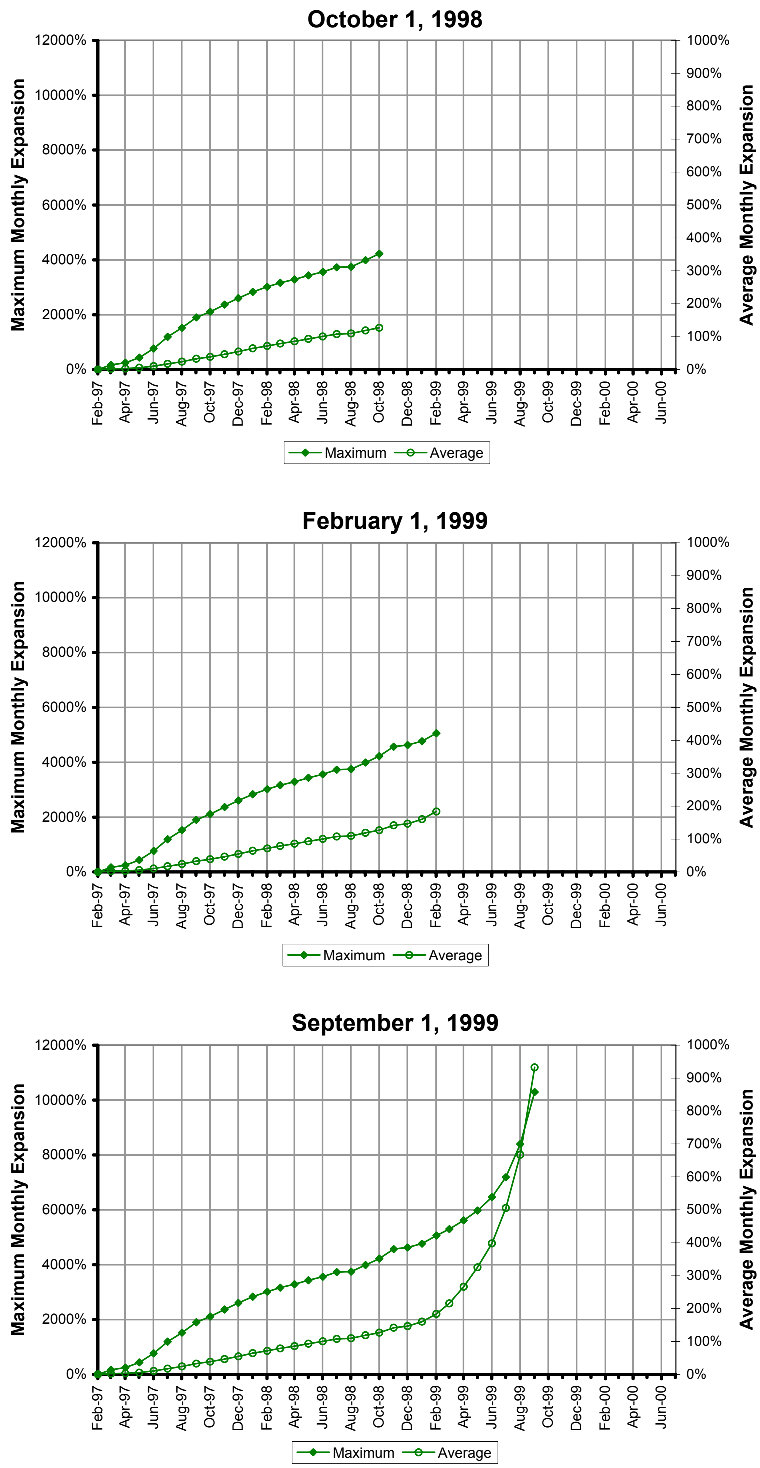


Figure 5.7: Case Study: Early Schedule Monthly Expansion

While the actual cumulative earnings curve runs parallel with the early schedule cumulative earnings curve – a false indication that the actual earnings are not falling any further behind the early schedule earnings – the monthly expansion values are gradually increasing, reflecting the reduction in time available to recover to the baseline schedule earnings curve.

Average expansion for the entire project surpasses 20% only six months into the 37-month duration. While in August 1998, both expansion values appear that they may level off, the failure to recover from nearly a year of underperformance proved fatal. Average expansion quickly surpasses the 30%, 40%, and 50% levels, dismissing any chance for early schedule recovery, reaching a level of 100% by June 1998 (required performance is *double* planned performance).

5.5.4 Early Schedule Change in Monthly Expansion

As was the case with the monthly expansion chart, the change in monthly expansion chart mirrors the extremely large values. Again, the focus on the chart is on the sign, peaks, valleys, and other trends. All values on this chart are positive, indicating that monthly expansion for every month to date was increasing. Even during the middle third of the project, when actual earned value was greater than planned for the those months, the slight amount of recovery that took place came up short of what was needed to overcome the large deficit in earnings distributed over the shrinking remaining duration of the project.

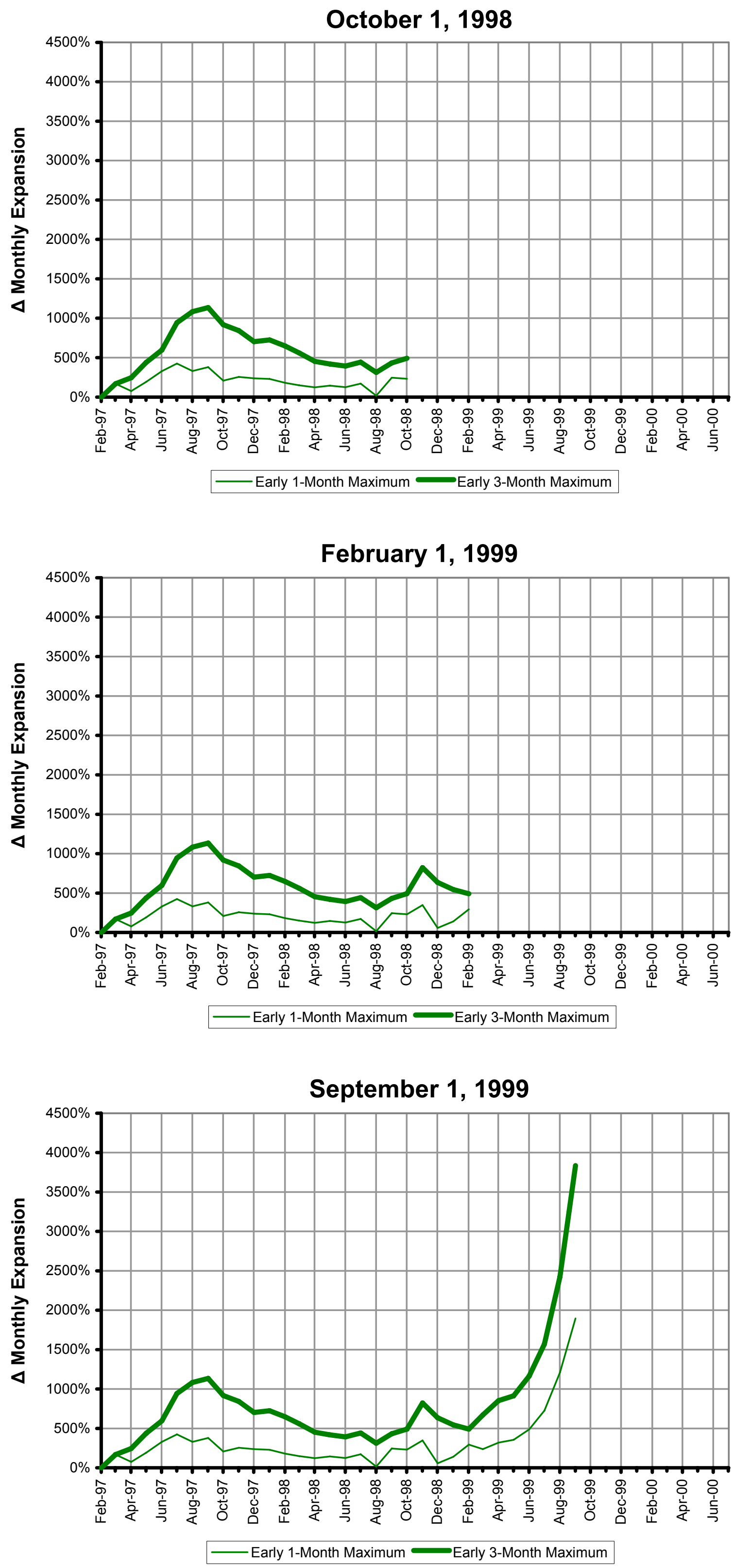
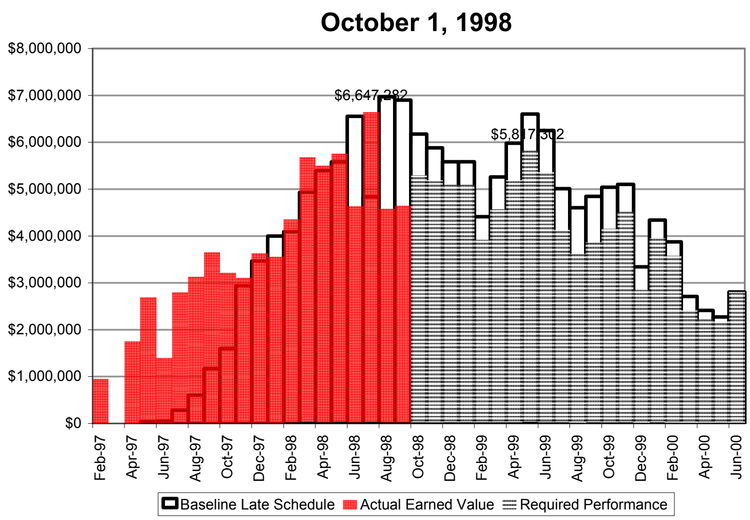


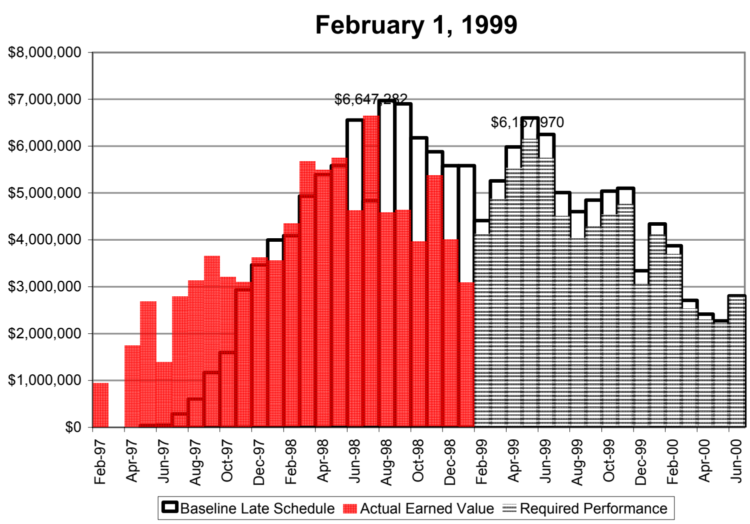
Figure 5.8: Case Study: Early Schedule Change in Monthly Expansion

Both curves on the above chart increase through August 1997, reflecting the exponential increase in maximum expansion in the first half year. Maximum expansion, while still on the rise, does not rise at such a dramatic rate from September 1997 to August 1998, but soon thereafter skyrockets as the recovery work increases and window for recovery decreases. The October 1, 1998 update shows two consecutive months of maximum monthly expansion exponentially increasing, followed by two more months of this pattern. On February 1, 1999, although still on the rise, the change in maximum expansion is slowing down. However, this pattern is brief, as the change in expansion dramatically increases, out of control each month until September 1, 1999.

5.5.5 Late Schedule Monthly Planned Values

Attaining the early completion schedule of 37 months is a worthwhile goal for the contractor. However, after the first several months of poor production, the more reasonable goal shifts to finishing the project with the 41-month contract period, on time. This is when the contractor's focus moves from the left side of the monthly RPM reports to the right side, monitoring Late Schedule RPM performance metrics.





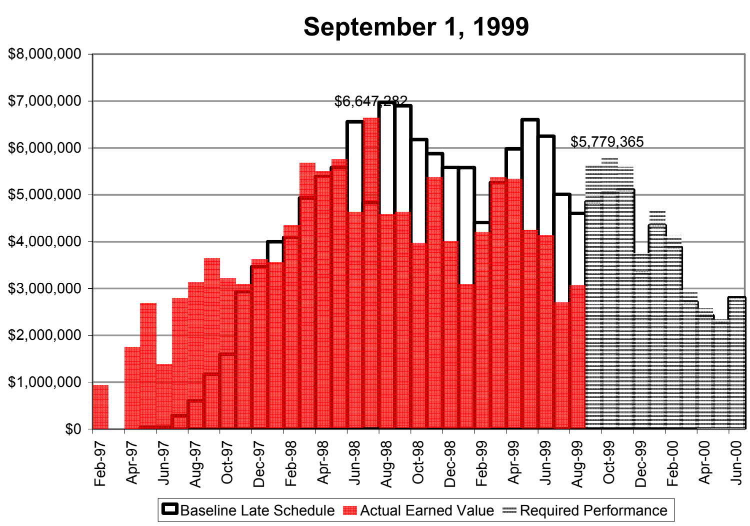


Figure 5.9: Case Study: Late Schedule Monthly Planned Values

Although actual monthly earned values have been falling short of the late monthly earnings, the cumulative earned value was still above planned – the project was still on schedule to complete within 41 months. However, by underperforming in three of the four months from June 1998 through September 1998, the cumulative earned value lost ground on the late schedule earned value. The pattern of underperformance continues, and in July 1999 cumulative earned value falls behind the late schedule earned value. By time of the August 1, 1999 update, the first month of officially recognizing the project is behind late schedule, maximum required performance needs to be at a level ($5.4 million) achieved only four times over the previous 31 months; a level double the previous month's actual earnings ($2.7 million). The large increase in required performance is due to falling behind schedule and lacking the ability to expand work in the final few months.

By September 1, 1999, the project has been behind the late schedule for two months, projecting seldom-achieved required performance ($5.8 million, achieved only once in 32 months), with only ten months remaining. The contractor must immediately develop a recovery plan to finish within the 41-month contract period. However, as evidence by the 57-month actual completion, the poor performance continues for the remainder of the late-completed project.

5.5.6 Late Schedule Monthly Expansion

The four months of project float created by the 41-month contract completion and the 37-month early completion allowed the contractor to work 10% ahead of the baseline late schedule cumulative earnings by November 1997. Over the following nine months, by earning very close to planned earnings, the contractor managed to reach nearly 15%

ahead of schedule. However, as recognized by the valley in the late schedule monthly expansion chart at August 1998, underperformance ensued. The October 1, 1998 reports shows two consecutive months of increasing expansion, including three of the last four months; this is a cause for alarm.

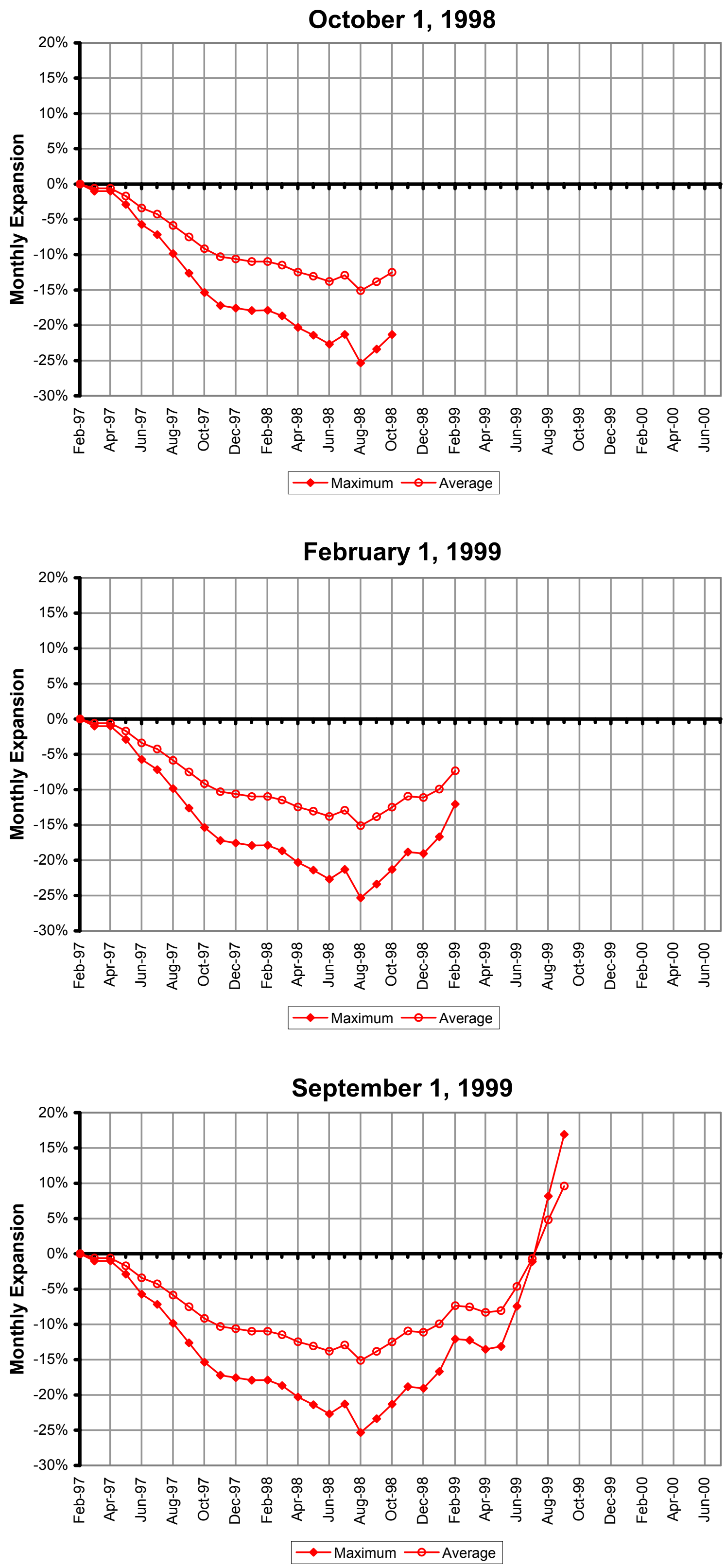


Figure 5.10: Case Study: Late Schedule Monthly Expansion

By February 1, 1999, the pattern noted above continues, as monthly expansion has increased in five of the last six months, from -15% to -7%. While from February 1999 – April 1999 the contractor is able to steady the increase in expansion, the prevention of slippage is short-lived; within the next four months, the schedule turns for the worse. In the September 1, 1999 report, while the contractor is only a total of 10% behind cumulative earnings, the maximum expansion for required performance is 17%. This 17% maximum monthly expansion is for the month immediately following the update (September 1999), with succeeding months also requiring expansions of 15%, 10%, and 12%, respectively. These required performances are greater alarm for concern than “10% behind schedule”.

5.5.7 Late Schedule Change in Monthly Expansion

As discussed with the two previous late schedule charts, the late schedule change in monthly expansion diagram reflects the contractor’s ability to get ahead of schedule in the first 20 percent of the job, perform close to planned until roughly the halfway point, and then begin to fall behind schedule in August 1998. On this chart, the transition from negative to positive expansion occurs around that time. While negative changes in monthly expansion are desirable, when the one-month and three-month changes in expansion both are zero or positive, as was the case on October 1, 1998, this was an indication that the project was headed in the wrong direction, a precursor to drastic increases in monthly expansion beginning in June 1999.

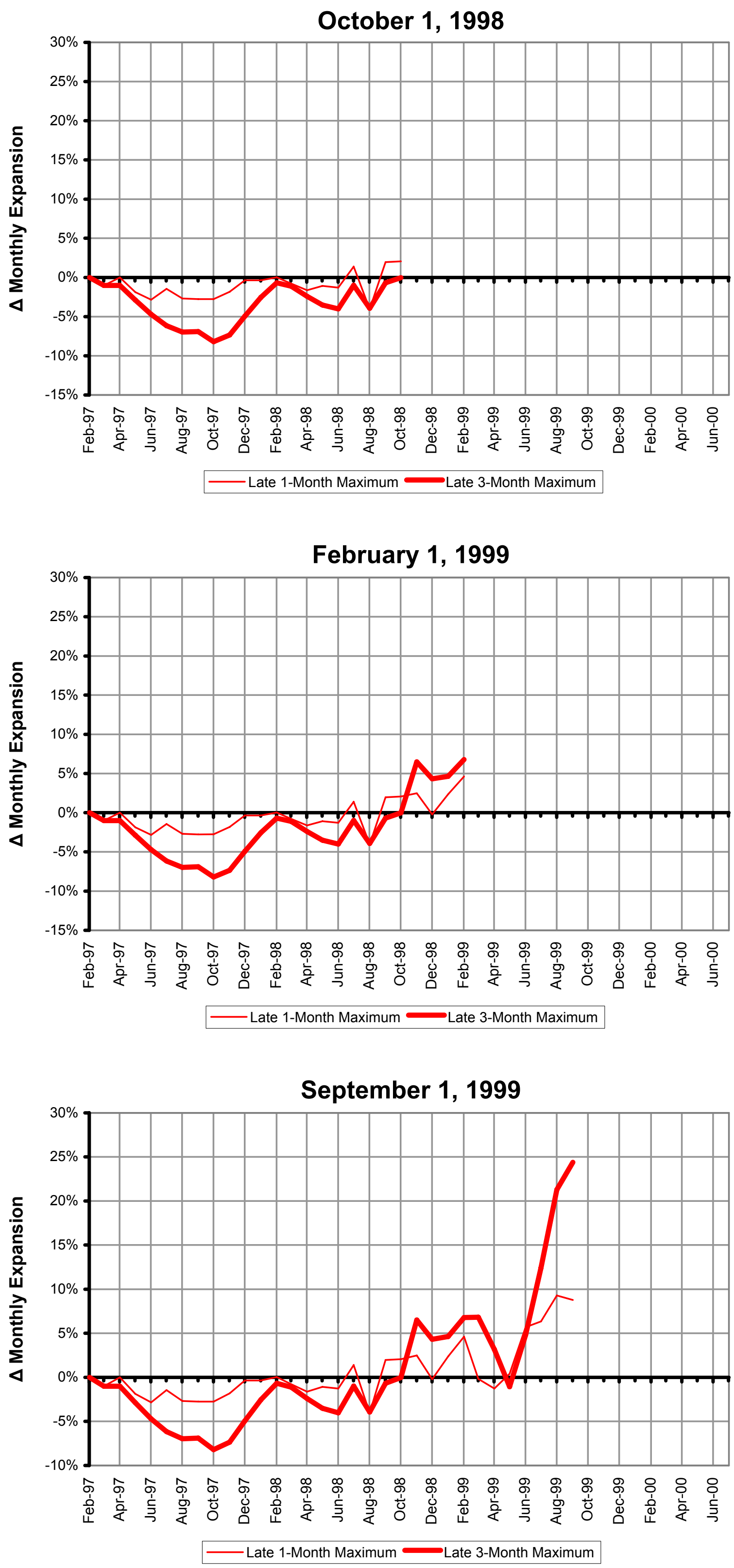


Figure 5.11: Case Study: Late Schedule Change in Monthly Expansion

5.5.8 A Summary of Early Warning Indicators

The previous section discusses the charts presented in the case study monthly RPM reports, along with their ability to show early warning indicators. The following table summarizes the early warning indicators and the date at which they occurred. Keep in mind that the project was not officially behind schedule until the August 1, 1999 update, when cumulative actual earned value through July 1999 dipped below the cumulative late schedule earned value. The chart is evidence that the RPM provides numerous early warning indicators before the project is officially behind schedule. Furthermore, if the contractor had their sights set on an early completion, the substantial early schedule early warning indicators quickly dismiss that goal. Appendix A contains all graphical schedule updates referenced in the table below.

Date / Monthly RPM Report	Early Schedule Early Warning Indicators	Late Schedule Early Warning Indicators
February 1, 1997	**Contract Start Date**	
February 1997 - February 1998	Contractor fails to earn early schedule monthly earnings for each of the first 13 months.	
March 1, 1997	Maximum early schedule monthly required performance exceeds values for planned early schedule performance for all months.	
June 1, 1997	Early schedule average monthly expansion exceeds 10%, four months into the project.	

August 1, 1997	Early schedule average monthly expansion exceeds 20%, six months into the project.	
September 1, 1997	Early schedule average monthly expansion exceeds 30%, seven months into the project.	
June 1, 1998	Early schedule average monthly expansion exceeds 100% (remaining work needs to be doubled).	
August 1998 - January 1999		Late schedule monthly expansion has increased for five of the past six months.
August 1998 - August 1999		Contractor fails to earn planned late schedule value for 12 of last 13 months. Window for expansion is shrinking: the last eight months of the project have reduced ability to expand work. In cumulative earnings chart, gap between actual earned value and baseline late schedule shrinks to nothing, consuming four months of project float.
September 1, 1998	Despite actual earnings above planned for August 1998, maximum monthly expansion continues to rise. Recovery work was not enough to overcome high deficit and shrinking time.	Actual earnings for two of last three months have been less than 75% of late schedule planned earned values.
October 1, 1998		Three-month change in late schedule maximum monthly expansion is at or above zero for the first time.
May 1999 - August 1999		Three-month change in maximum monthly expansion steadily increases from -1% to 21%.

August 1, 1999		Actual cumulative earned value drops below baseline late schedule earned value. Project is officially behind late schedule. Maximum late schedule required monthly performance is an earned value previously achieved only three times in 30 months of the project. Required performance for each of the next four months is more than twice the earned value in the previous month. Average monthly expansion is 5%, while maximum expansion is 8%.
September 1, 1999		Average monthly expansion is 10%, while maximum expansion is 17% Required performance for each of the next three months is a value achieved once in the previous 31 months of the project.
March 1, 2000	**37-Month Early Completion Date**	
July 1, 2000	**Contract Completion Date**	
October 31, 2001	**Actual Completion Date**	

Table 5.7: Case Study Early Warning Indicators

5.6 RPM and Traditional Performance Metrics

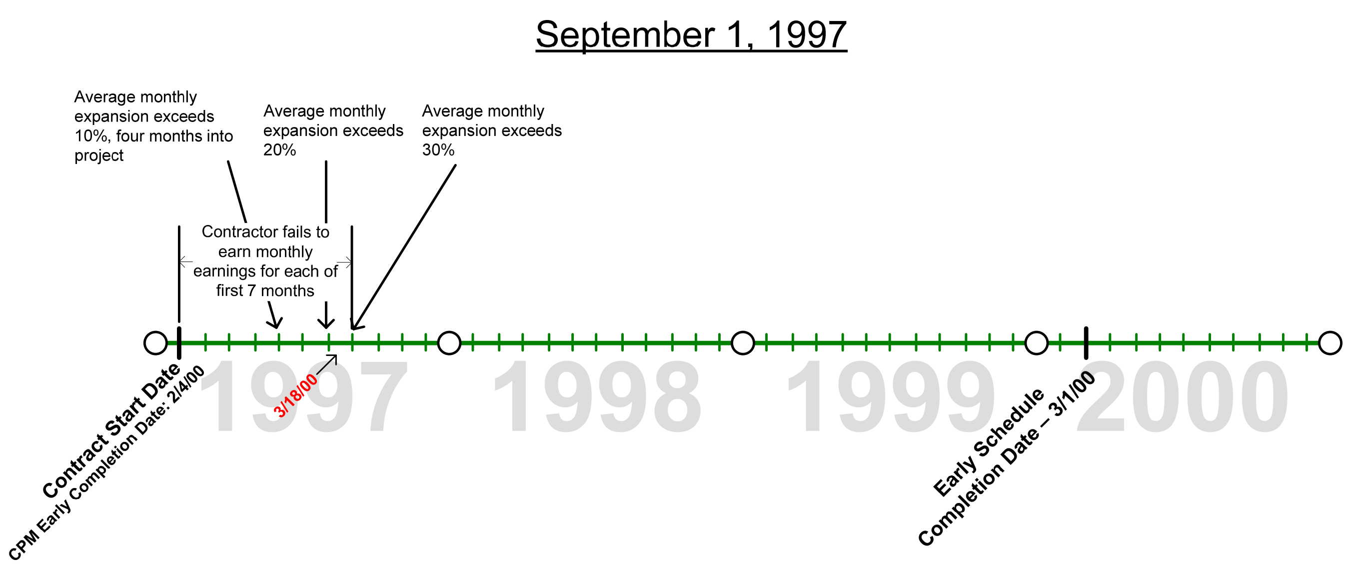
The case study demonstrates how the Required Performance Method is capable of providing early warning indicators that the project may be slipping behind schedule. In regards to the early schedule, the project was behind schedule after the first month, with the trend continuing thereafter. However, when considering the late schedule as the target schedule, because the project was not officially behind schedule until 30 months into the 41-month schedule, there was ample opportunity for an early recognition of trends that may indicate the project going sour. These indicators as recognized by the RPM are summarized in the table above. The following sections discuss two traditional performance metrics – the critical path method and the schedule performance index – and how their indicators compare with those of the Required Performance Method.

5.6.1 CPM Schedules

Schedules created by the critical path method (CPM) calculate a projected completion date based on activity durations and project logic, computing the shortest and longest paths for project completion. Computerized project scheduling tools, such as P3, utilize CPM in regular updates to track the computed completion date. Should a calculated completion date shift to a later date, this indicates a slip in schedule, whereas a shift to an earlier date indicates the project getting ahead on the schedule.

Case study historical updates calculated both the CPM early and late completion dates in regular intervals. However, because the project quickly fell behind the early schedule, ten months into the project the early schedule CPM calculated completion date was beyond the early completion date (March 1, 2000), and from then on, the CPM calculated completion date for the early and late schedules was the same date. The following charts track the CPM calculated completion date (below each axis) and how it correlates with RPM indicators of schedule slippage.

The first two charts parallel early schedule RPM indicators with the early schedule calculated completion date. The first update of the CPM calculated completion date comes on September 1, 1997. At this point, the RPM has shown numerous indicators that the project is in grave danger of finishing by the early schedule completion date of 3/1/00. The early schedule CPM calculated completion date is 17 days beyond the early schedule completion date. While making up 17 days in the next 30 months may seem like a minor task, to do so, total work must be expanded by 30%. The February 1, 1999 update recognizes the grave danger in reaching the early schedule completion date. The CPM calculated completion date is four months beyond the early schedule completion date, and planned work must nearly be tripled (average expansion approaching 200% of planned work).



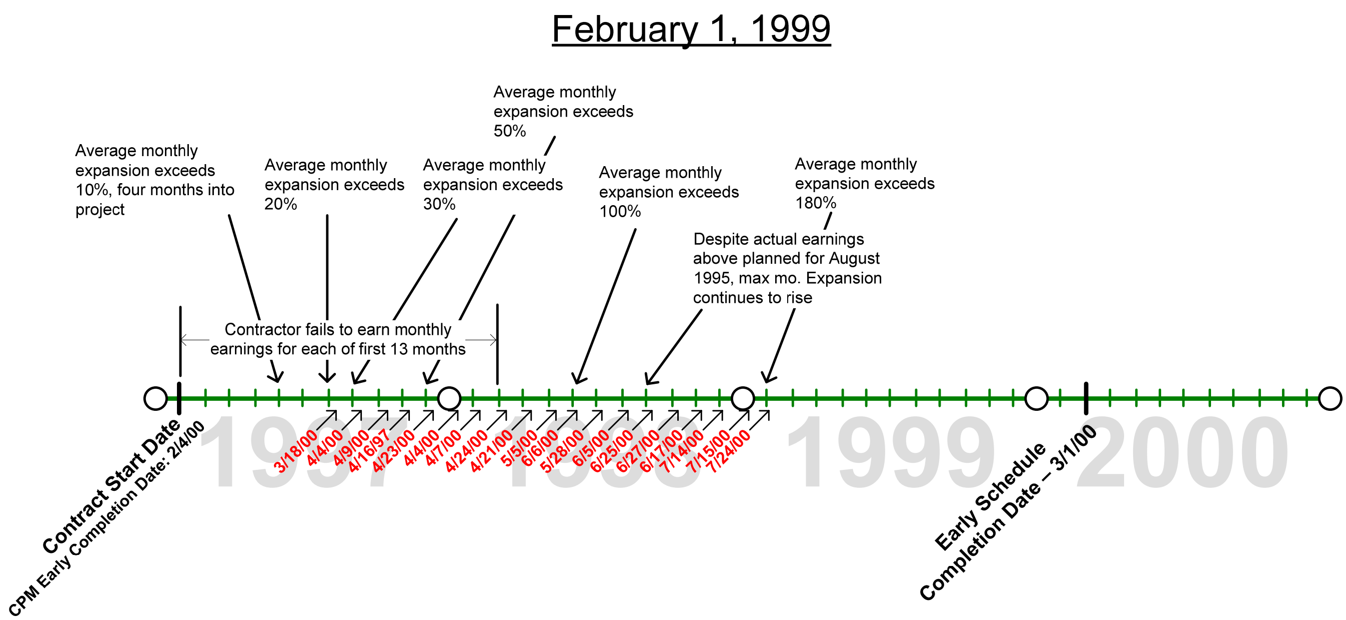
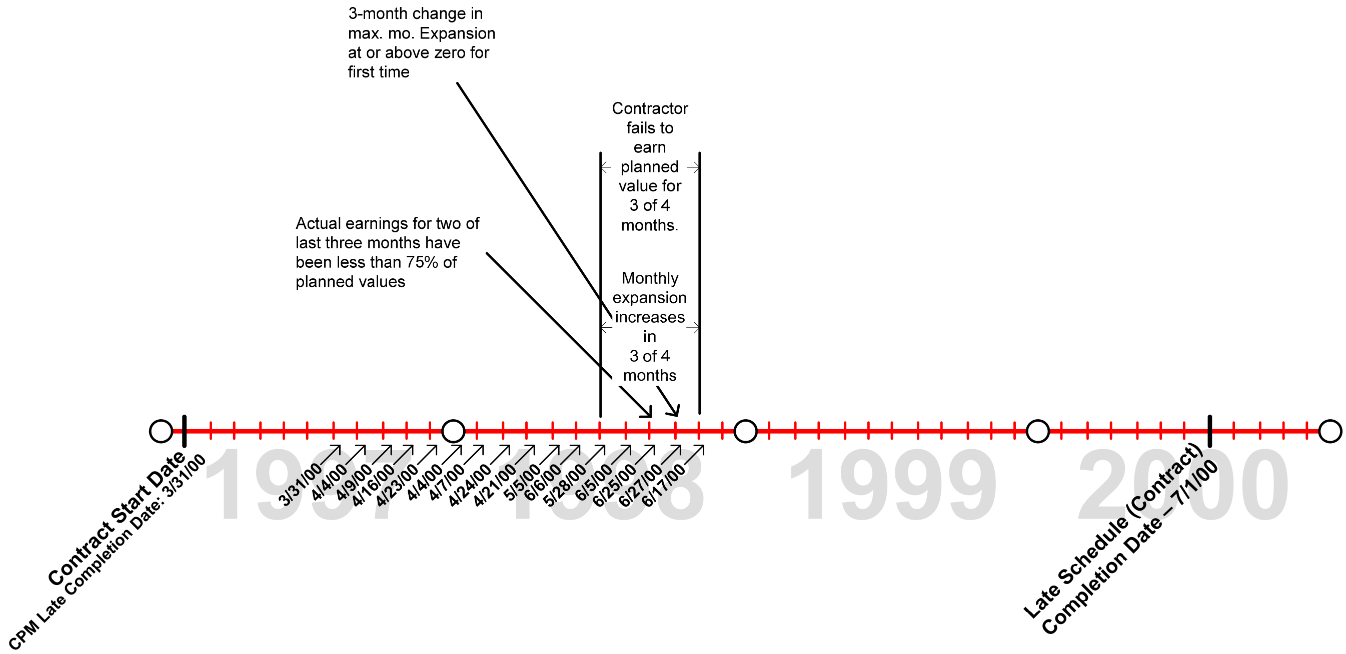


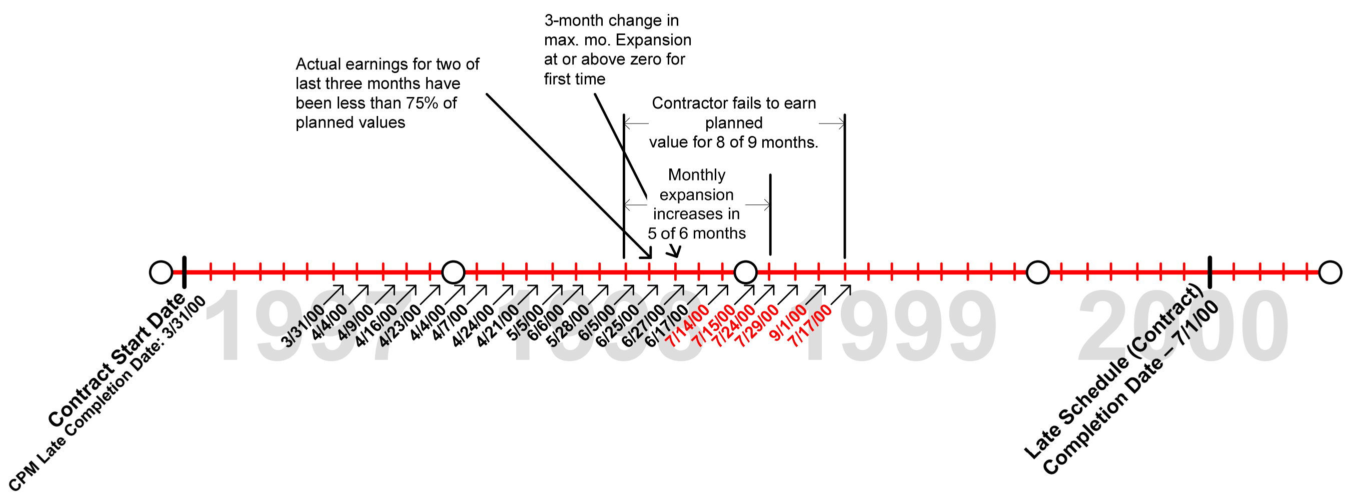
Figure 5.12: Early Schedule RPM with CPM Dates

The following three charts track late schedule RPM indicators of slippage with the late schedule CPM calculated completion date. At the time of the first chart, October 1, 1998, the calculated completion date is still before the contract completion date, yet there have been numerous warnings of schedule slippage recognized by the RPM. Failure to perform to plan over the last four months has called for attention that the project may potentially slip behind schedule. By May 1, 1999, the late schedule calculated completion date is over two weeks beyond the contract completion date, and there have been RPM indicators of impending slippage for the previous nine months. By September 1, 1999, when the project is officially two months behind schedule, the RPM has shown many indicators of impending slippage, and the CPM calculated completion date is now three months past contract completion date.

October 1, 1998



May 1, 1999



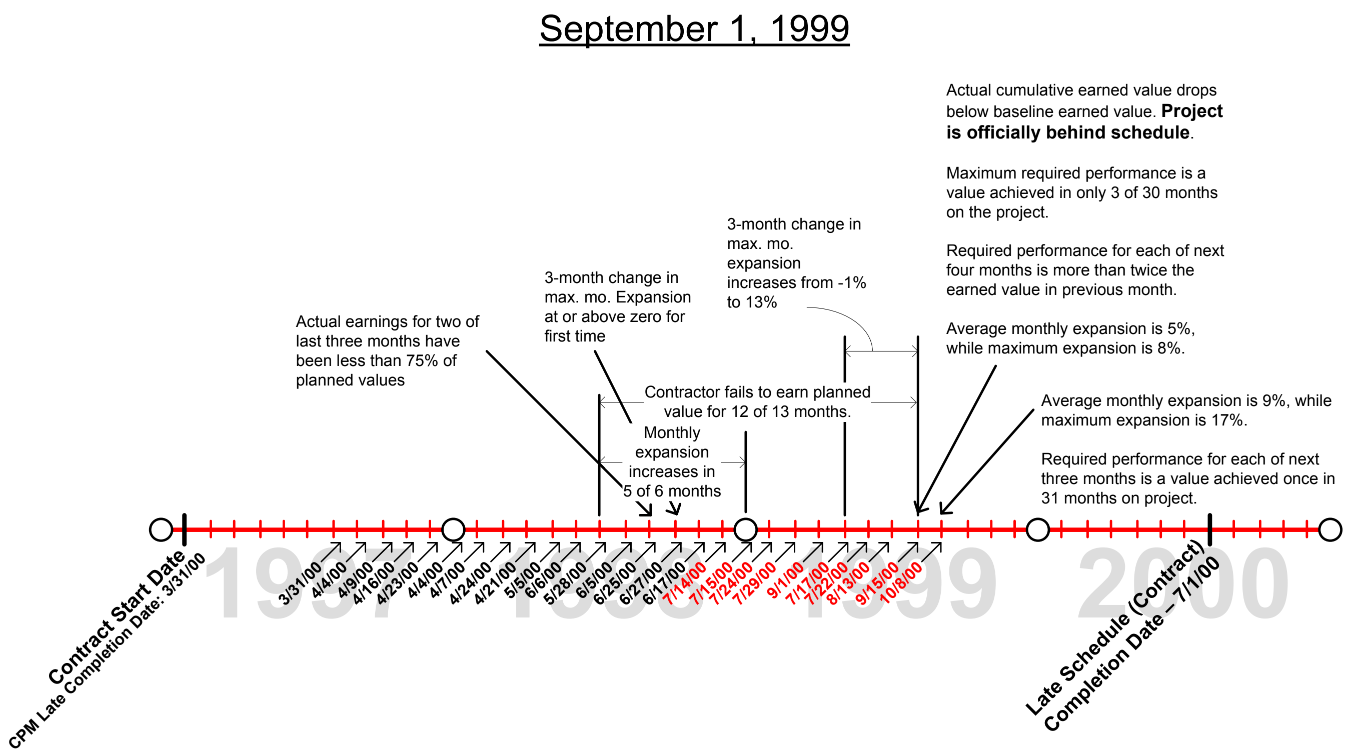


Figure 5.13: Late Schedule RPM with CPM Dates

5.6.2 Schedule Performance Index

The second traditional performance metric to compare to the RPM is the schedule performance index (SPI). The SPI is calculated by the formula SPI = BCWP/BCWS, where BCWP is the budgeted cost of work performed and BCWS is the budgeted cost of work scheduled. It is a ratio of how much work has been completed to date, to how much work was planned to be completed to date. A value over 1.0 is favorable, indicating more has been accomplished than planned, and the project is ahead of schedule. The SPI, as applied to the case study is shown below.

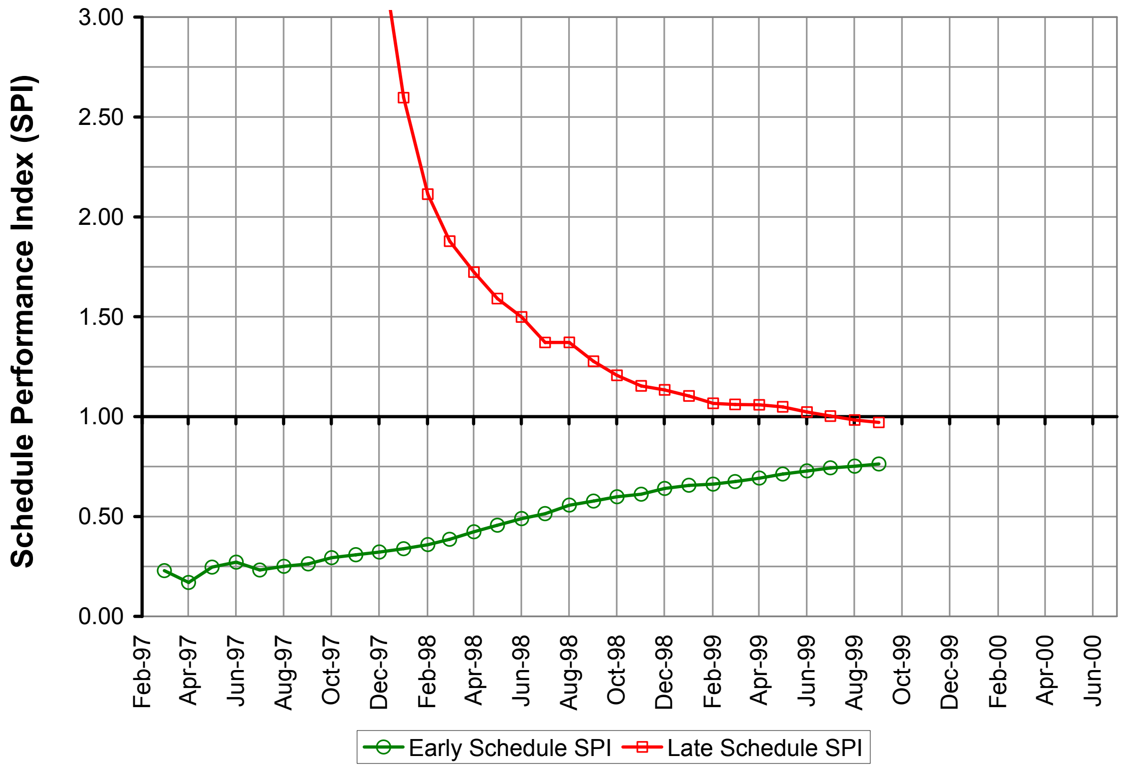


Figure 5.14: Case Study SPI

Considering the early schedule SPI, for the first half year of the project, the contractor earned roughly 25% of the planned value to date. By September 1999, the early schedule SPI steadily increases to 0.76, indicating that the contractor has earned just over three-quarters of the planned value to date. The increase in this performance metric typically represents making up ground on the schedule. However, it focuses on what has been accomplished rather than what needs to be accomplished. When considering what performance is required for timely completion, as shown in Figure 5.7, the RPM recognizes the ominous prospect of completing the project by the early schedule completion date.

The late schedule SPI starts by indicating earnings well above the planned values, but steadily approaches the value of 1.0, crossing it in August 1999 when the project falls behind late schedule. In September 1999, the late schedule SPI is 0.97, acknowledging the project has earned 97% of the late schedule earned value to date. This value may not be as concerning an alarm as the performance needed for late schedule timely completion (shown in Figure 5.10). At this time, the late schedule RPM indicates average monthly expansion of 10% and maximum monthly expansion of 17%. The SPI says the project is 3% behind schedule *to date*, but the RPM says that the project is 17% behind schedule in what *needs to be done*. Both performance metrics show trends in their late schedule assessment that indicate the project is in danger of timely completion, but by focusing on the future and what needs to be done, the RPM forecast expresses a much greater concern.

Chapter 6 – Contributions, Conclusions, and Recommendations

The purpose of this research is to develop schedule performance metrics for forecasting schedule slippage. To do so, the research set out and accomplishes its three objectives of developing the intellectual framework for schedule control, developing and describing a control system that can be used, and demonstrating the control system. This chapter summarizes the contributions, conclusions, and recommendations of the research.

6.1 Expressing Concern in Terms that are More Tangible

The key intellectual ingredient of the research is a paradigm shift from control based on scheduled completion date to control based on required performance. This shift enables forecasts to express concern in terms that are more tangible. When performing schedule control based on forecasted completion date, early warnings of slippage may come if the forecasted completion date is slipping to a later date, or possibly even beyond the contract completion date. Concern could be expressed by noting that "the projected completion date has slipped two weeks over the last three months", or "the project is projected to complete 20 days beyond the contract completion date." In response to these statements, side-stepping the threatening forecast can be done by saying "I can make it up", and "don't worry, we have plenty of time to catch up", and "we can make up two weeks in three months – no problem." In contrast, the Required Performance Method translates ominous forecasts into terms that are more tangible.

Using the RPM, the contractor may be in trouble because they are predicting an over stress on a resource situation, a type of numerical, material difference. The RPM takes the statement "You're going to be late" to a tangible "You're going to be late *because*…" For example, "the project is in danger of timely completion because the number of crews needs to be increased from four to six", or "to finish on time, you need to move 1 million cubic yards of earth in each of the next two months, when you have yet to do that on this project." This change in philosophy forces the contractor to realize potential slippage in real terms.

6.2 The Development of Schedule Control Framework

The schedule control framework developed in Chapter 3 bridges the gap between progress monitoring systems and early warning systems, within the domain of construction scheduling. The framework stresses the importance of each stage of schedule control. Each progressive stage is as reliable as the previous stage, i.e. you can only measure to the detail with which you define, compare to the detail with which measure, and so on. Therefore, forecasts and early warning systems are only as reliable as the progress monitoring systems on which they are based. Forecasting is determining where you plan to be, based on where you are, and where you have been.

The schedule control framework adds to the body of knowledge of the construction industry, serving as a guide for the development of schedule control systems and early warning systems.

6.3 RPM as an Objective, Forward-Looking Early Warning System

The Required Performance Method is designed to meet the criteria outlined by the intellectual framework for schedule control systems. Furthermore, the RPM is built based on existing progress monitoring tools able to be produced in a normal scheduling environment, ensuring that the method is ready for immediate implementation.

The RPM is a forward-looking control system that takes data from progress monitoring, applies the contractor's ability to expand work through expansion factors, and produces forecasts of the required performance needed for timely completion of the project. This procedure is designed to take the subjectivity out of forecasting, enabling those people without years of experience to recognize indicators of potential slippage – so that schedulers have a tool beyond their gut instinct. Early warning tools facilitate prevention of, rather than reaction to schedule slippage.

Preventing schedule slippage in the RPM is a product of dependable forecasts based on reliable, up-to-date data. The cornerstones of the RPM are analyzing the most current data, forcing "look-ahead" required performance schedules, evaluating the ability to expand future work, and redefining the schedule.

The RPM takes a more forward-looking approach, moving attention to what needs to be done rather than focusing on what has been accomplished. For instance, the schedule performance index (SPI) is a classic performance metric that focuses on what *has been accomplished* to date, whereas the Required Performance Method focuses on what *needs to be accomplished*. SPI tells you where you are with respect to where you are supposed to be, while the RPM tells you where you need to be.

6.4 Flexibility of the RPM

The case study example illustrates how the Required Performance Method allows the contractor to forecast performance needed to accomplish an early or late schedule. However, the contractor is not bound to these two (or however many) schedules. While this case study focuses solely on attaining either the early or late schedule completion, there are opportunities for adjustments. Should a contractor adjust the completion date, whether earlier or later, the original schedule can be redefined, and the required performance indicators are adjusted accordingly.

Upon concluding that a project may not finish on time, the contractor can apply the RPM to that adjusted completion date. Alternatively, if the projected completion date is unknown, applying the history of expansion on that project may prove helpful in determining an adjusted completion date.

The flexibility of the RPM is attributed to its foundation as a cyclic control system. The ability to take action and redefine allows for a control technique that evolves as the project evolves.

6.5 Limitations of RPM as a Tool

While the RPM is an asset to schedule controllers, it is not intended to be relied on as the sole source for forecasting schedule slippage. The technique is a *tool* used in schedule forecasting and providing early warnings. Its purpose is to recognize indicators of schedule slippage and bring attention to these indicators. There are components in construction projects, beyond the progress of driving commodities, which may cause schedule slippage.

Another limitation of the RPM, as presented in the case study early schedule RPM analysis, are the extreme values for maximum monthly expansion that arise when distributing required performance to months with low or zero planned value. However, regardless of the situation, the average monthly expansion values, as well as the monthly values for required performance (as shown on the monthly planned values charts) are consistent throughout. Additionally, while the maximum expansion percentages may be high, the shape and trends in these charts are accurate, just greater in magnitude.

6.6 Implementing the RPM on Future Projects

Demonstrating the Required Performance Method using the case study highlights its ease of application to real project data. The case study tracks earned value, a common, universal commodity that mirrors project progress. However, the demonstration project could have been the control of earthwork on a new roadway construction, or steel on a major building construction project. Whichever commodity used, a contemporaneous application of the required performance method is no more difficult that the retrospective case study.

Although the RPM is regarded as a tool for the *contractor* to determine the required performance to complete *their* work, there is potential for use by the owner, also. From the owner's perspective, they are entitled to knowing how their project will be completed. Should the contractor fall behind schedule, the owner has the right to know that the project may not complete on time. The owner may suggest certain thresholds for expansion; for example, should the contractor forecast a monthly maximum expansion beyond 15%, the contractor may be obligated to inform the owner of how they plan to complete the work on time – a valid recovery plan.

Thresholds for expansion have potential for even greater use: associating maximum expansion values during certain stages of projects with various levels of risk. While a maximum expansion of 5% may not be that risky at the beginning of the project, should there be a required expansion of 5% at the end of the project, after months of underperformance, the risk level is higher. The chart below is an idea for a monthly expansion chart that attributes stages of risk to the expansion values, recognizing that there is greater risk for untimely completion (less room for error) at the end of the project. The boundaries between designated risk levels are arbitrarily selected, and may be defined in the future, once a history of expansion data and project outcomes is built.

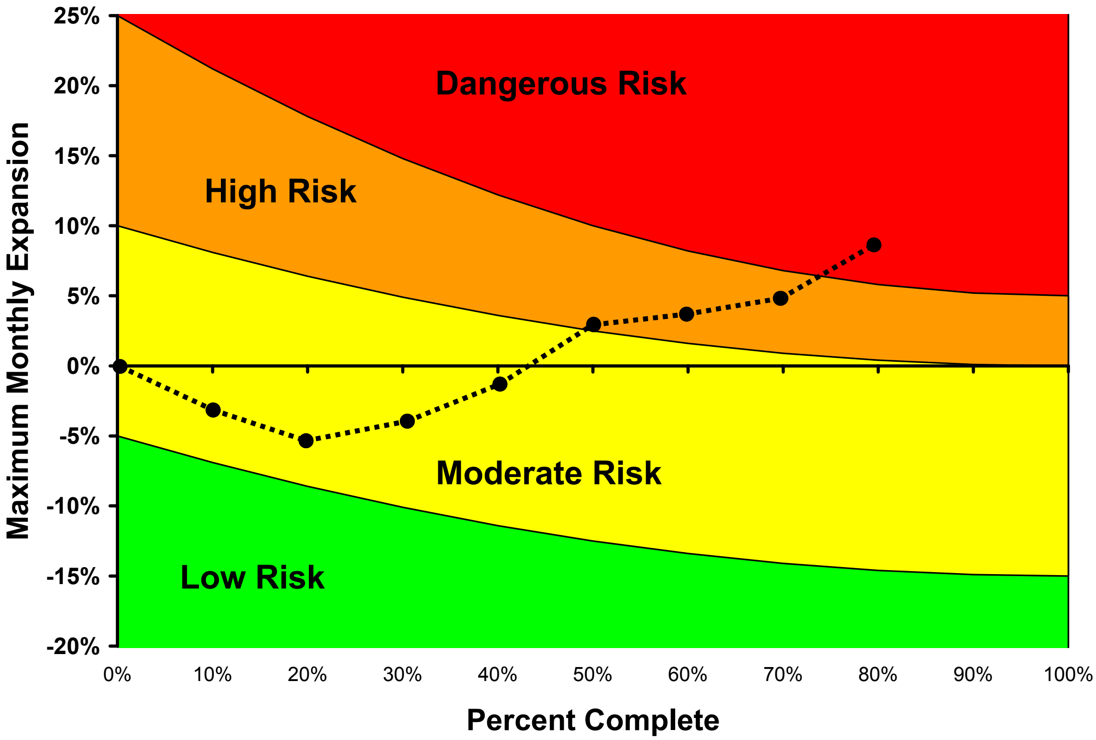


Figure 6.1: Maximum Expansion with Stages of Risk

The owner may even attribute additional contractual requirements for each risk level. The *Act* stage of the control system may be a spectrum of actions, rather than just "time-out, root cause analysis, and redefine." This spectrum of actions would relate to the various risk levels by increasing the severity of the action with increased risk level. An example hierarchy of actions may be:

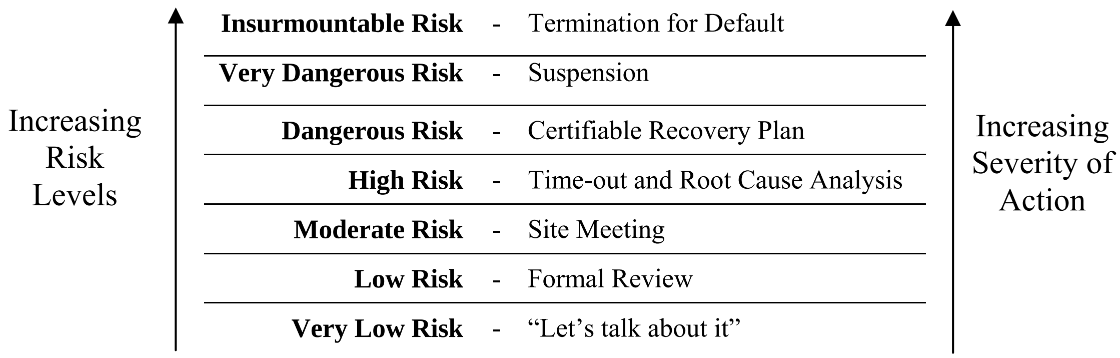


Figure 6.2: Spectrum of Actions

The risk level may increase as shown in Figure 6.1, or it could possibly increase by other means, e.g. the number of consecutive months with required performance within 10% of your maximum actual performance; or possibly the number of months with required performance above your planned maximum performance. Furthermore, the risk level for late schedule RPM may be a couple steps higher than that for the early schedule RPM, the reason being that failing to perform to the late schedule has a higher risk of the project not performing to the worst-case scenario schedule, resulting in untimely project completion.

The real-world application of the Required Performance Method may require multiple sets of expansion factors for each schedule being monitored, i.e. defining separate sets of expansion factors for each the early and late schedules. For projects with a large amount of float, or discrepancies between multiple schedules, the work performed in each month, from schedule to schedule, is different. The expansion factor is the ability to *expand the work* in each month, therefore if the work is different, the expansion may be different.

A possible addition to the system is to define expansion factors for each activities that comprise the work in each month. Assigning expansion factors to each activity adds detail to the system. The expansion factor for each month could be a weighted average of the expansion factors for activities within that month. Certain driving activities have a greater influence on schedule performance, and therefore would be assigned a greater weighted value.

6.7 Recommendations for Implementation and Research

This research achieves its objectives of developing the intellectual framework for schedule control, and developing and demonstrating the Required Performance Method. The next step for the RPM is to implement the control system in real-time on construction projects. The ideal projects for application are those with driving commodities tied to the project schedule. These projects provide data that accurately represent the project progress, as well as fill the function of the define stage of the RPM.

The RPM shall be treated as any other pioneer technique, proceeding with caution and watching it closely. With all innovative techniques, there is a learning period. The innovative aspect and backbone of the RPM are the expansion factors, and these expansion factors will take time to be fine-tuned. The expansion factors force the contractor to plan ahead and anticipate their ability to expand work. Improving their anticipation will form a more detailed list of considerations when setting expansion factors.

Forming a history of maximum monthly expansions and the projects that that finished behind schedule, as well as those that were able to recover, will help define the thresholds previously discussed, and potentially place and shape the curves of the *Maximum Expansion with Stages of Risk* diagram.

As the Required Performance Method is tested and implemented on construction projects, expansion factors will be fine-tuned, thresholds will be established, and the construction industry will benefit from an innovative, objective, reliable schedule performance metric for forecasting schedule slippage.

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Appendix A – Case Study

	Data Date	EARLY SCHEDULE Max Exp	EARLY Δ1-Mo Max	EARLY Δ3-Mo Max	EARLY Avg Exp	EARLY Δ1-Mo Max	EARLY Δ3-Mo Max	LATE SCHEUDLE Max Exp	LATE Δ1-Mo Max	LATE Δ3-Mo Max	LATE Avg Exp	LATE Δ1-Mo Max	LATE Δ3-Mo Max
Start	**2/1/97**	0.0%	0.0%	0.0%	0%	0.0%	0.0%	0%	0.0%	0.0%	0%	0.0%	0.0%
	3/1/97	169.3%	169.3%	169.3%	2.08%	2.1%	2.1%	-1.01%	-1.0%	-1.0%	-0.60%	-0.6%	-0.6%
	4/1/97	246.1%	76.8%	246.1%	3.05%	1.0%	3.0%	-1.01%	0.0%	-1.0%	-0.60%	0.0%	-0.6%
	5/1/97	437.9%	191.7%	437.9%	5.62%	2.6%	5.6%	-2.88%	-1.9%	-2.9%	-1.71%	-1.1%	-1.7%
	6/1/97	767.0%	329.1%	597.6%	10.48%	4.9%	8.4%	-5.72%	-2.8%	-4.7%	-3.40%	-1.7%	-2.8%
	7/1/97	1191.0%	424.1%	944.9%	17.47%	7.0%	14.4%	-7.17%	-1.4%	-6.2%	-4.26%	-0.9%	-3.7%
	8/1/97	1521.5%	330.5%	1083.7%	24.00%	6.5%	18.4%	-9.85%	-2.7%	-7.0%	-5.86%	-1.6%	-4.1%
	9/1/97	1901.3%	379.8%	1134.3%	32.60%	8.6%	22.1%	-12.62%	-2.8%	-6.9%	-7.50%	-1.6%	-4.1%
	10/1/97	2108.9%	207.7%	917.9%	38.57%	6.0%	21.1%	-15.37%	-2.8%	-8.2%	-9.16%	-1.7%	-4.9%
	11/1/97	2365.4%	256.5%	843.9%	46.59%	8.0%	22.6%	-17.20%	-1.8%	-7.4%	-10.30%	-1.1%	-4.4%
	12/1/97	2603.6%	238.2%	702.3%	54.84%	8.3%	22.2%	-17.56%	-0.4%	-4.9%	-10.62%	-0.3%	-3.1%
	1/1/98	2833.1%	229.5%	724.1%	64.45%	9.6%	25.9%	-17.92%	-0.4%	-2.5%	-10.97%	-0.4%	-1.8%
	2/1/98	3013.8%	180.7%	648.3%	71.60%	7.2%	25.0%	-17.89%	0.0%	-0.7%	-10.97%	0.0%	-0.7%
	3/1/98	3163.5%	149.7%	559.9%	78.95%	7.4%	24.1%	-18.68%	-0.8%	-1.1%	-11.48%	-0.5%	-0.9%
	4/1/98	3286.7%	123.1%	453.6%	85.81%	6.9%	21.4%	-20.31%	-1.6%	-2.4%	-12.46%	-1.0%	-1.5%
	5/1/98	3432.3%	145.6%	418.5%	93.26%	7.4%	21.7%	-21.40%	-1.1%	-3.5%	-13.07%	-0.6%	-2.1%
	6/1/98	3557.2%	124.9%	393.7%	100.66%	7.4%	21.7%	-22.69%	-1.3%	-4.0%	-13.80%	-0.7%	-2.3%
	7/1/98	3729.0%	171.8%	442.3%	107.60%	6.9%	21.8%	-21.30%	1.4%	-1.0%	-12.93%	0.9%	-0.5%
	8/1/98	3744.7%	15.7%	312.5%	109.66%	2.1%	16.4%	-25.34%	-4.0%	-3.9%	-15.11%	-2.2%	-2.0%
	9/1/98	3989.5%	244.8%	432.3%	118.98%	9.3%	18.3%	-23.37%	2.0%	-0.7%	-13.84%	1.3%	0.0%
	10/1/98	4221.4%	231.9%	492.4%	126.76%	7.8%	19.2%	-21.32%	2.1%	0.0%	-12.50%	1.3%	0.4%
	11/1/98	4568.1%	346.7%	823.4%	141.73%	15.0%	32.1%	-18.84%	2.5%	6.5%	-10.95%	1.6%	4.2%
	12/1/98	4625.0%	56.9%	635.5%	146.89%	5.2%	27.9%	-19.06%	-0.2%	4.3%	-11.11%	-0.2%	2.7%
	1/1/99	4765.1%	140.1%	543.7%	160.08%	13.2%	33.3%	-16.69%	2.4%	4.6%	-9.93%	1.2%	2.6%
	2/1/99	5058.8%	293.6%	490.6%	183.88%	23.8%	42.1%	-12.07%	4.6%	6.8%	-7.34%	2.6%	3.6%
	3/1/99	5297.2%	238.4%	672.2%	215.77%	31.9%	68.9%	-12.25%	-0.2%	6.8%	-7.53%	-0.2%	3.6%
	4/1/99	5617.4%	320.1%	852.2%	266.22%	50.5%	106.1%	-13.53%	-1.3%	3.2%	-8.31%	-0.8%	1.6%
	5/1/99	5972.4%	355.0%	913.6%	325.28%	59.1%	141.4%	-13.13%	0.4%	-1.1%	-8.07%	0.2%	-0.7%
	6/1/99	6460.1%	487.7%	1162.9%	397.98%	72.7%	182.2%	-7.45%	5.7%	4.8%	-4.63%	3.4%	2.9%
	7/1/99	7187.3%	727.2%	1570.0%	505.36%	107.4%	239.1%	-1.11%	6.3%	12.4%	-0.68%	3.9%	7.6%
	8/1/99	8397.4%	1210.1%	2425.0%	667.16%	161.8%	341.9%	8.16%	9.3%	21.3%	4.82%	5.5%	12.9%
	9/1/99	10294.6%	1897.2%	3834.5%	932.71%	265.5%	534.7%	16.94%	8.8%	24.4%	9.61%	4.8%	14.2%
	10/1/99												
	11/1/99												
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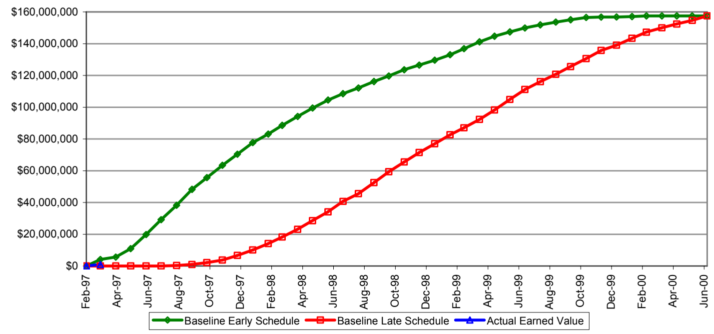
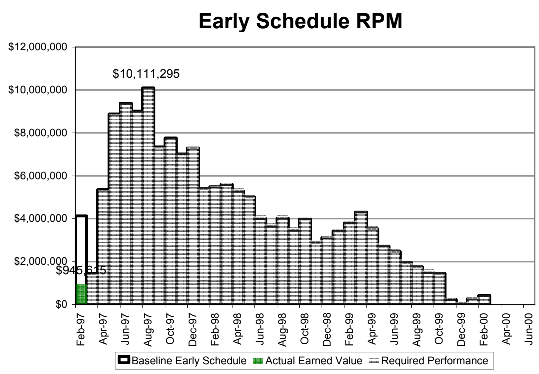
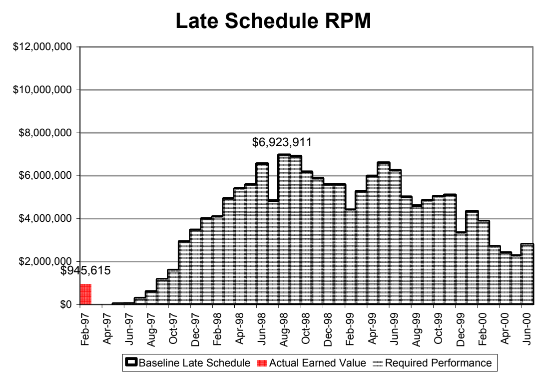
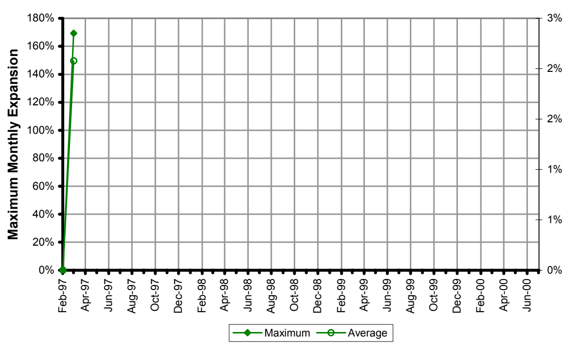
Completion	**7/1/00**												

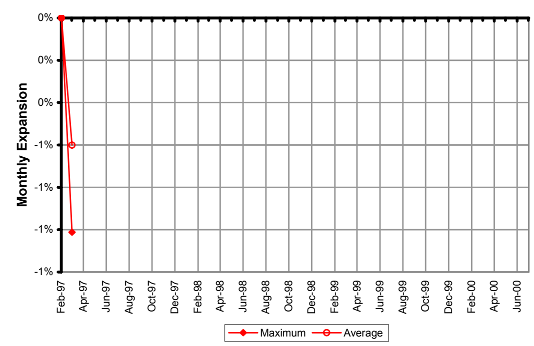
March 1, 1997

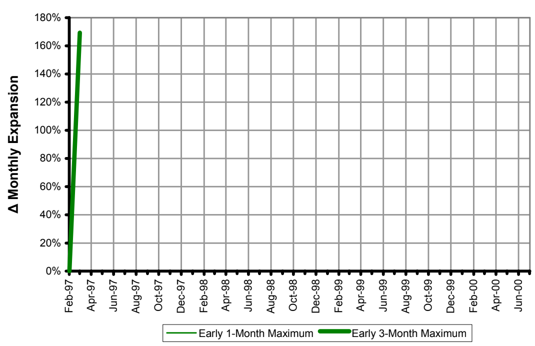


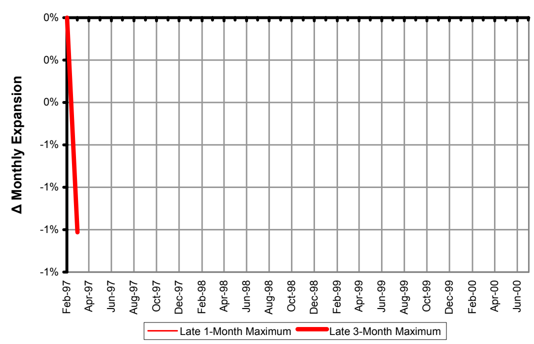












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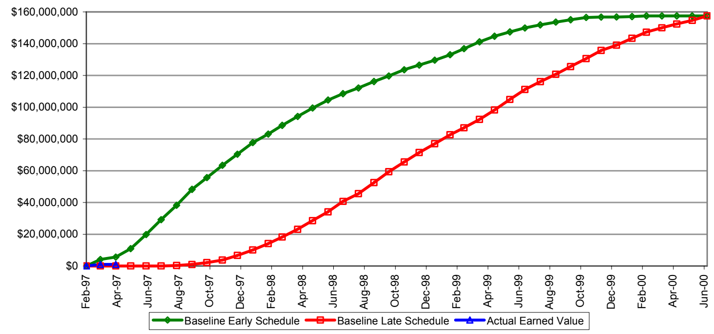

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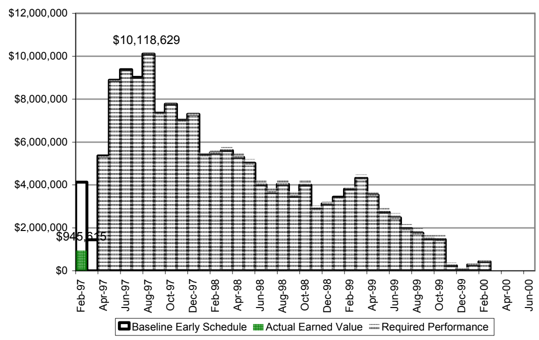

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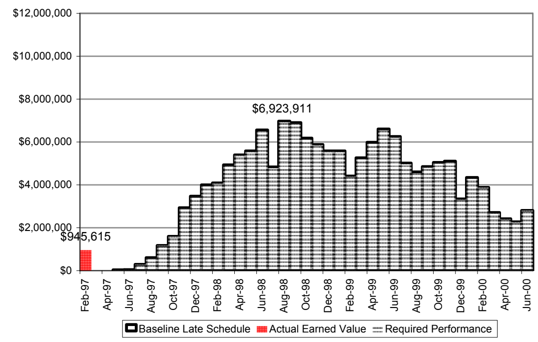

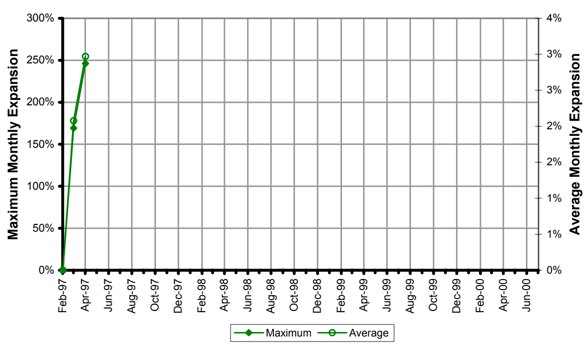

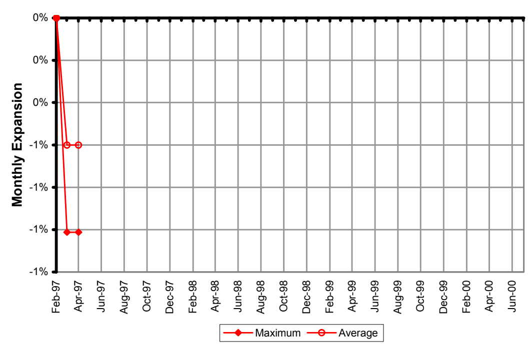

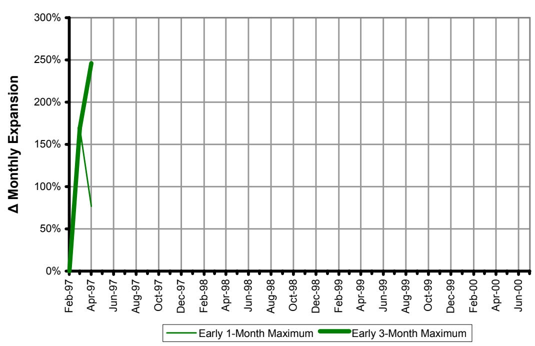

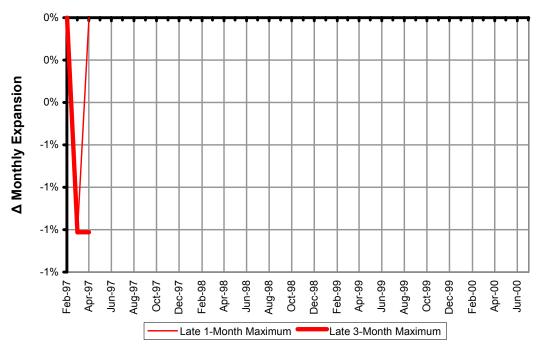

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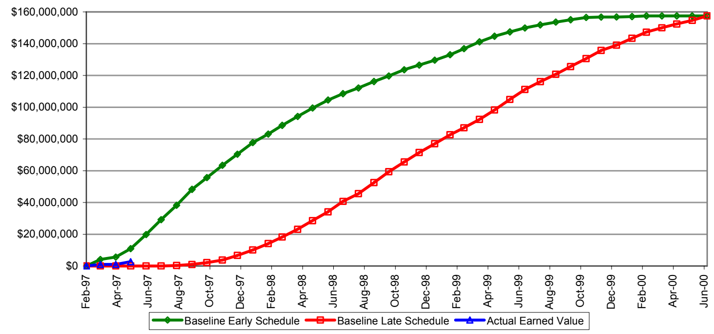

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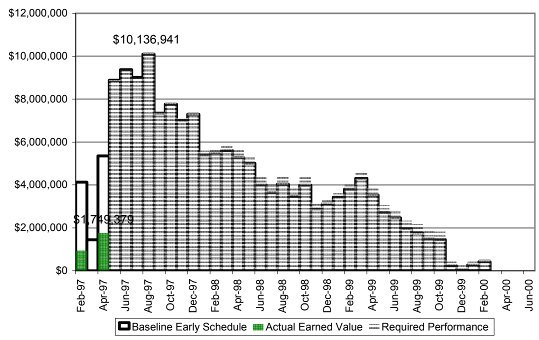

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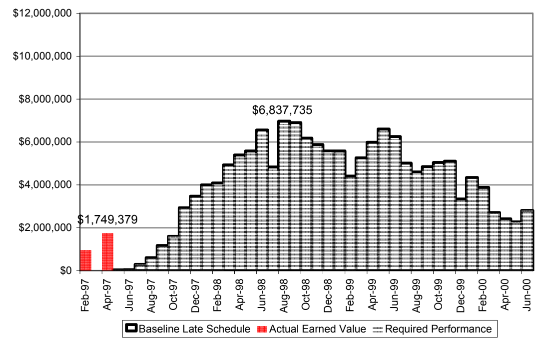

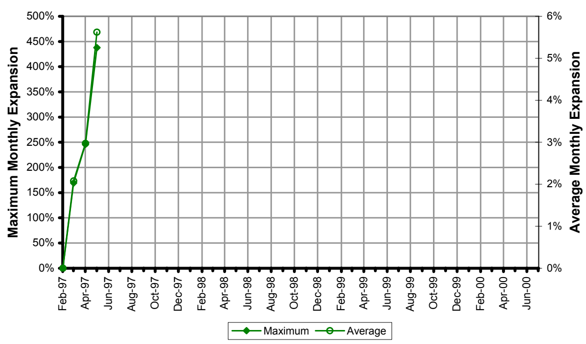

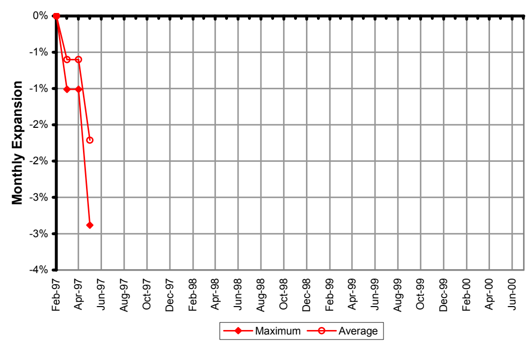

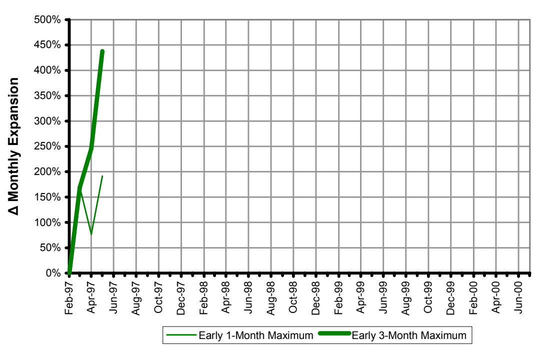

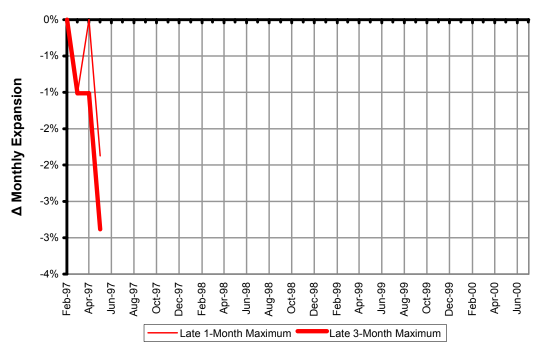

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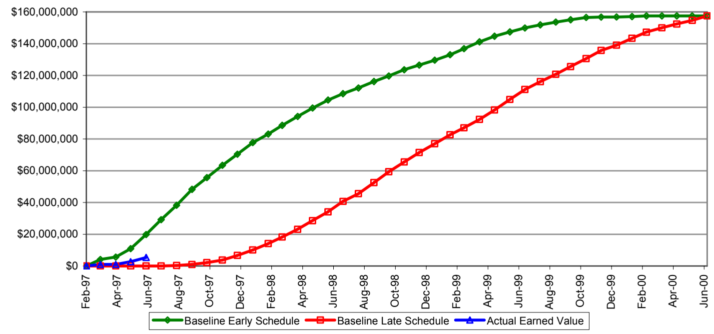

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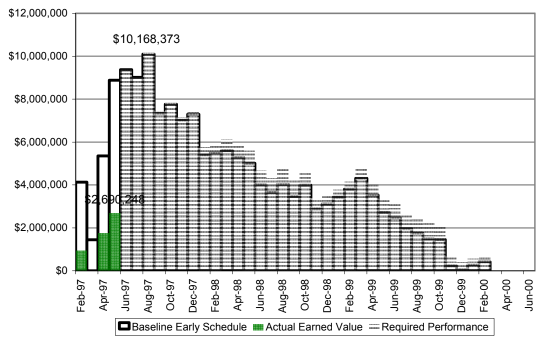

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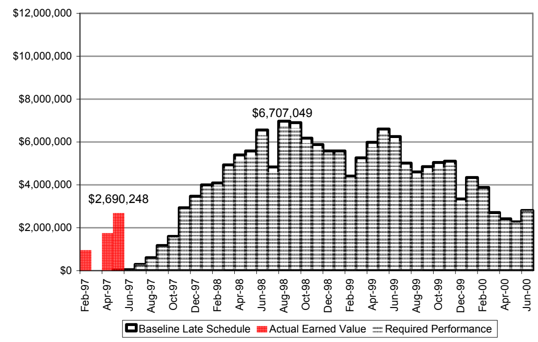

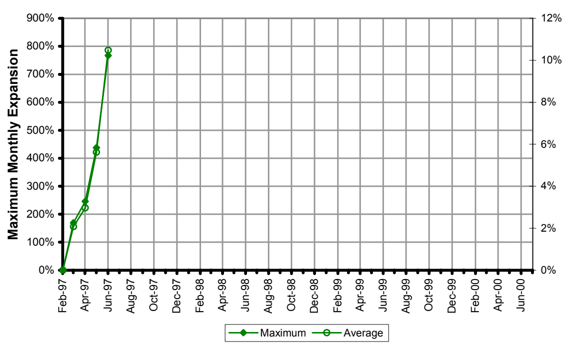

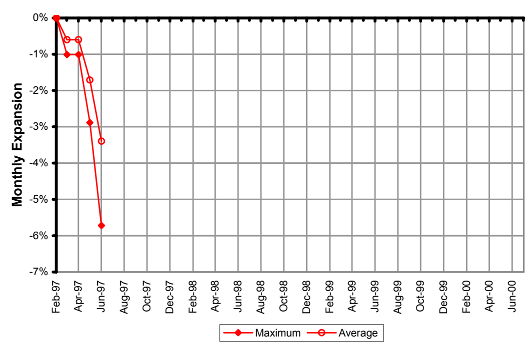

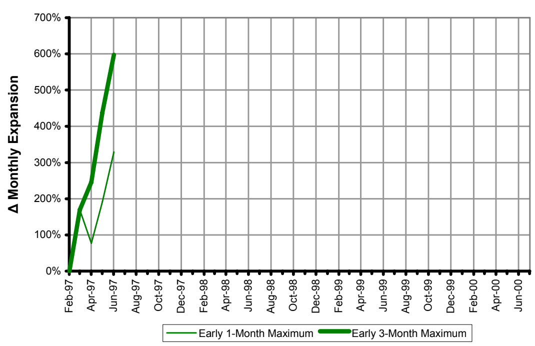

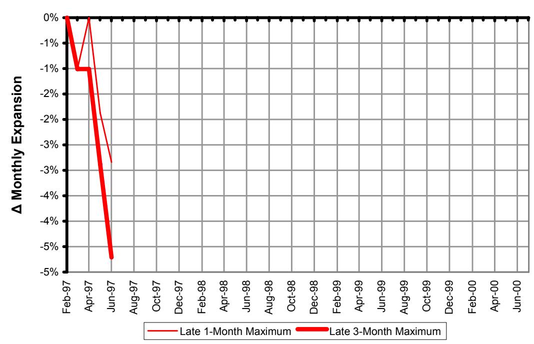

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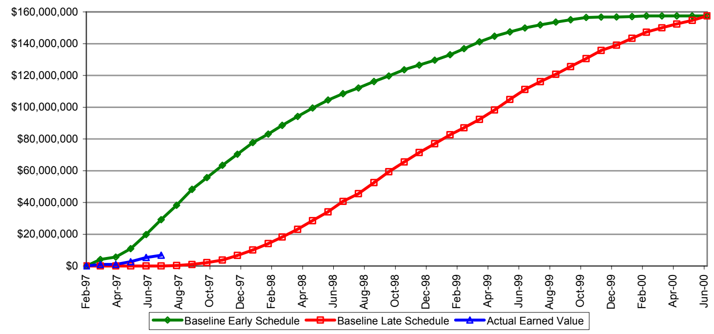

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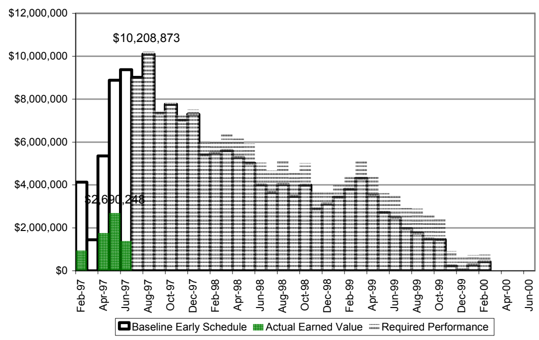

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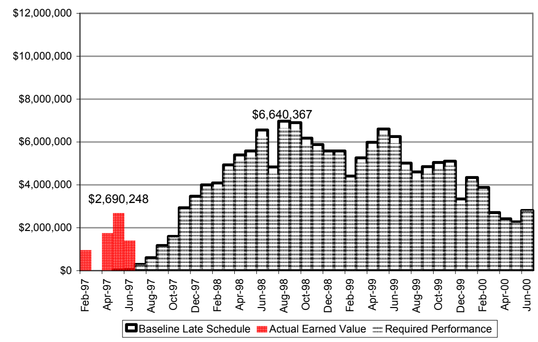

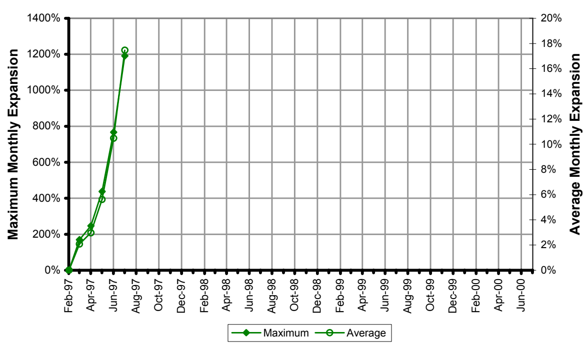

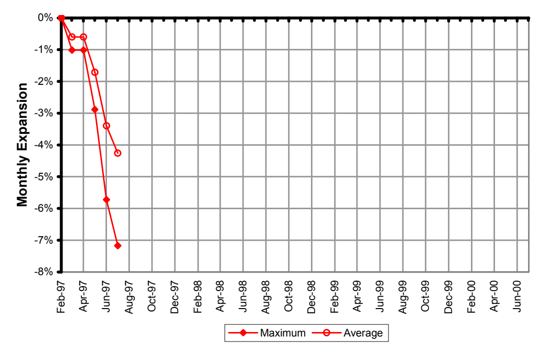

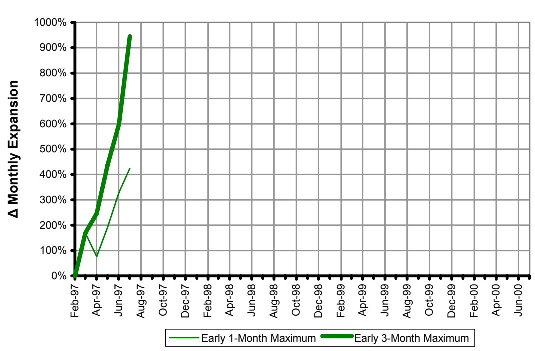

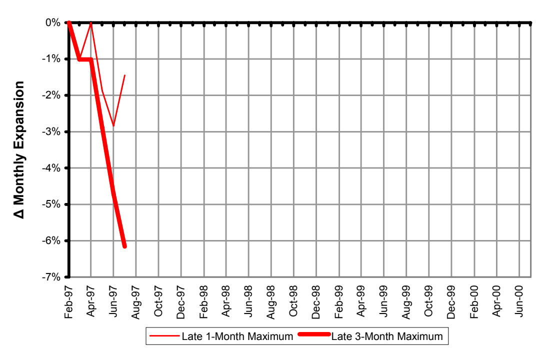

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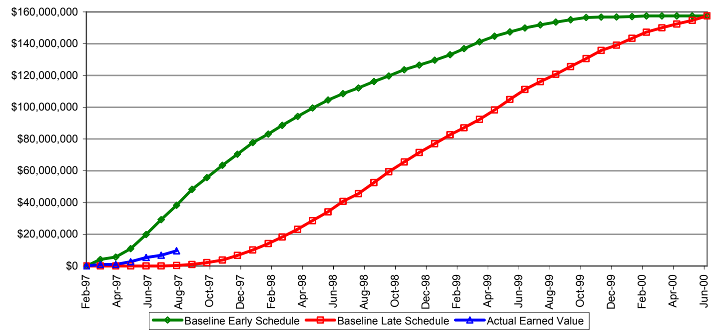
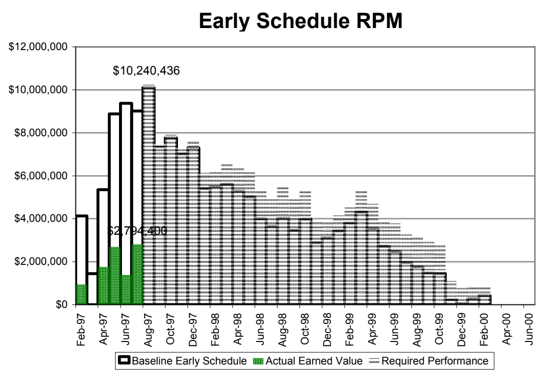
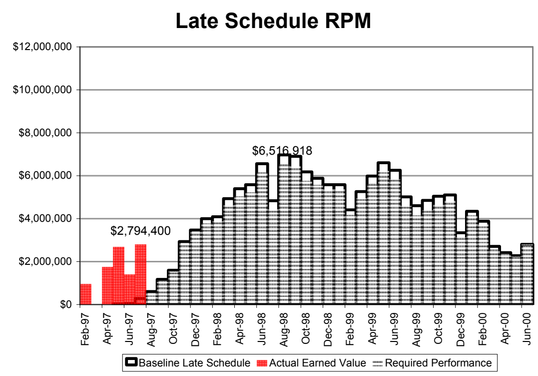
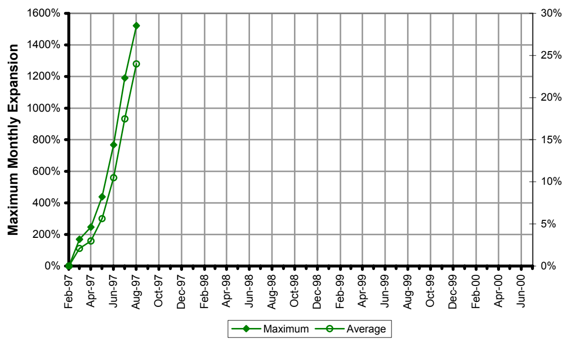
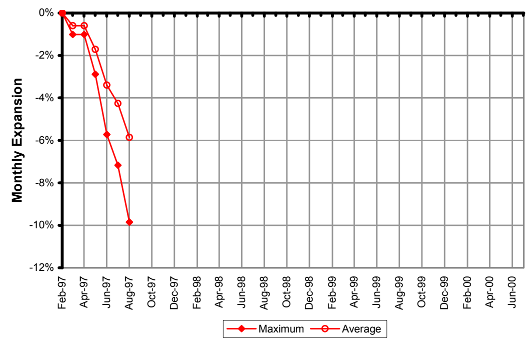
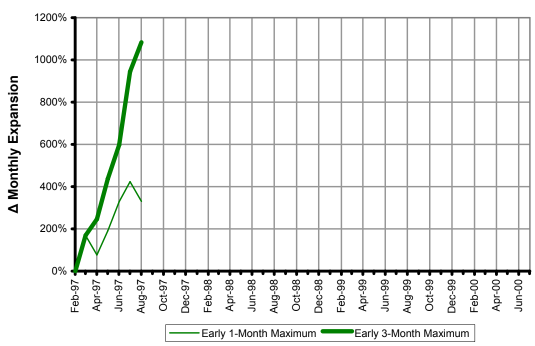


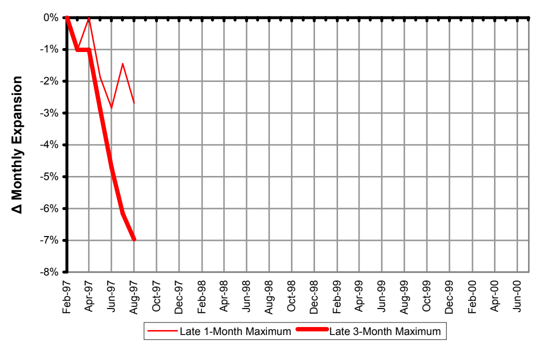




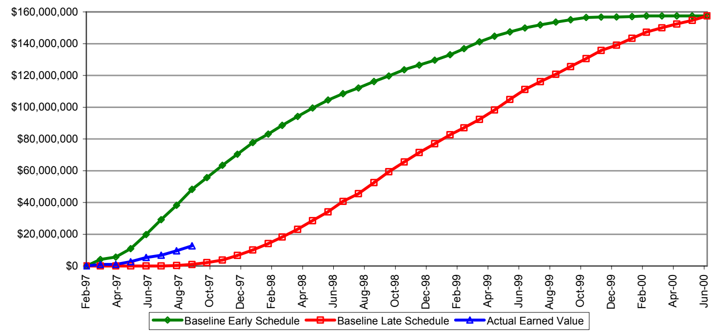




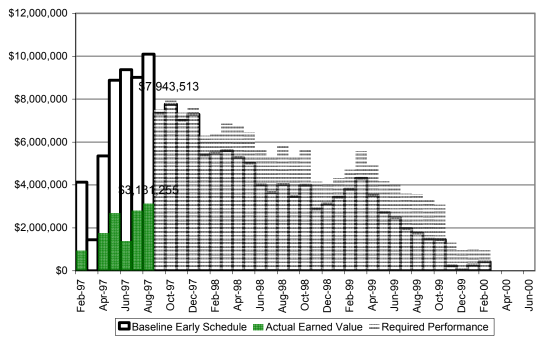




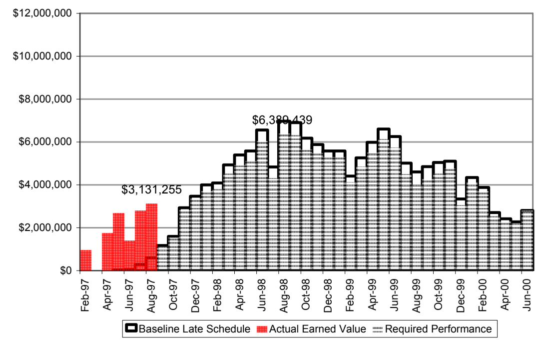
September 1, 1997

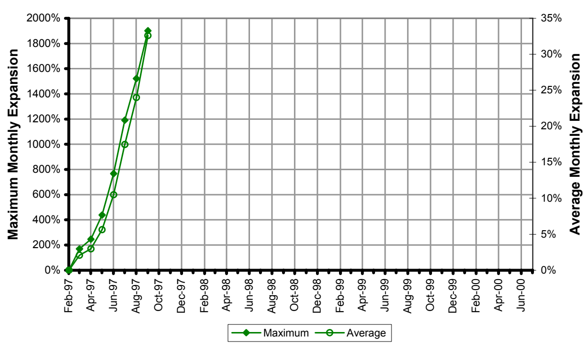


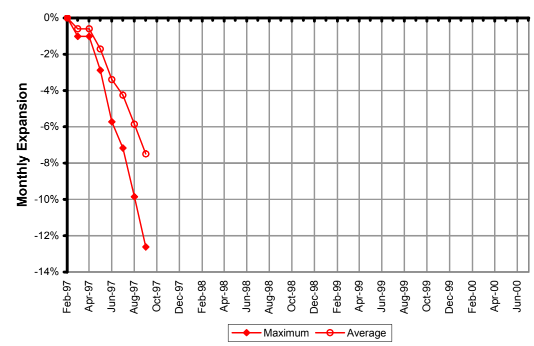
Early Schedule RPM

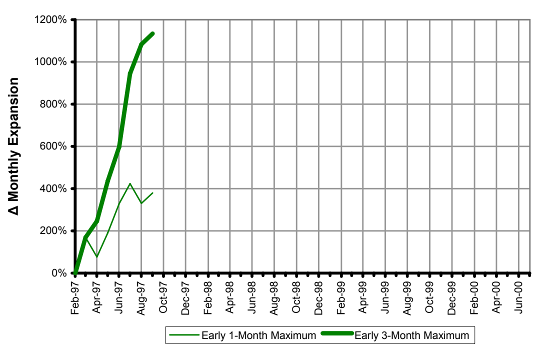


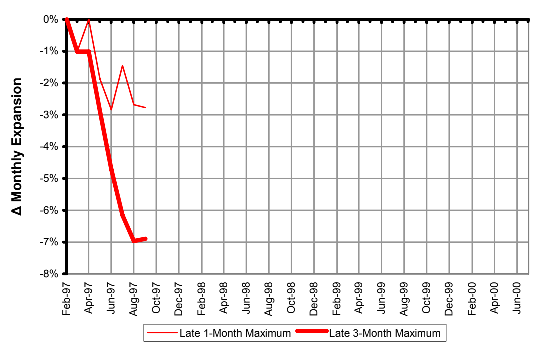
Late Schedule RPM



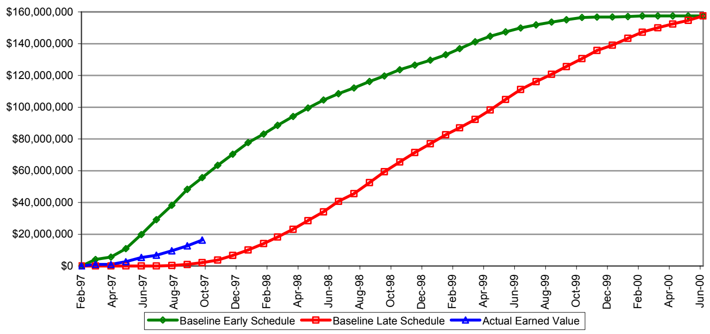




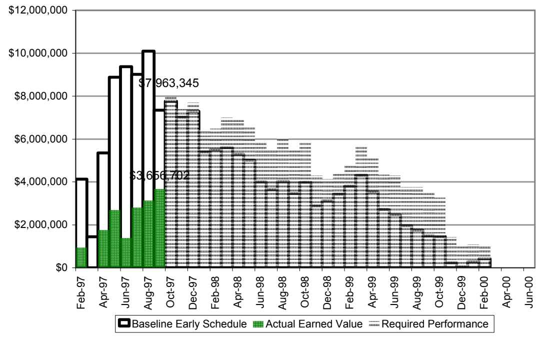




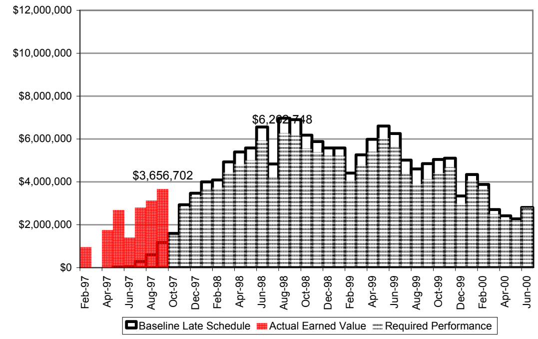
October 1, 1997

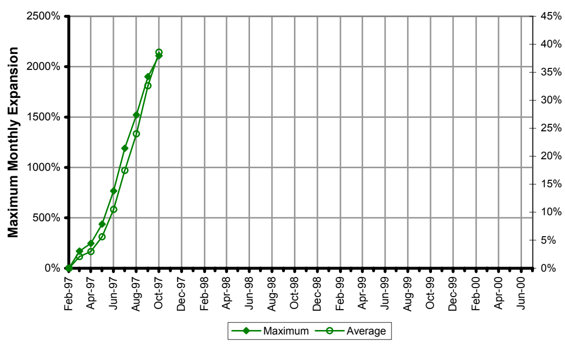


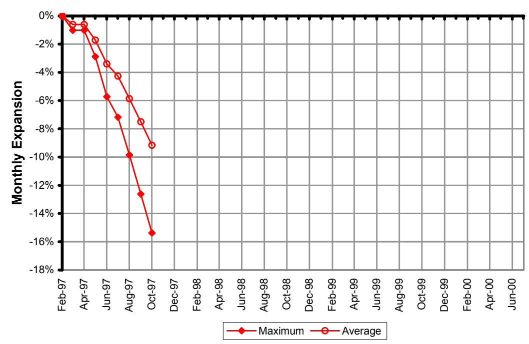
Early Schedule RPM

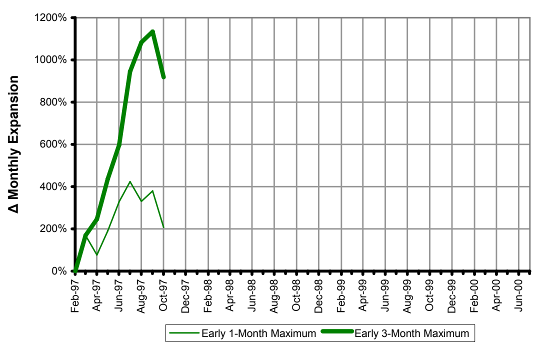


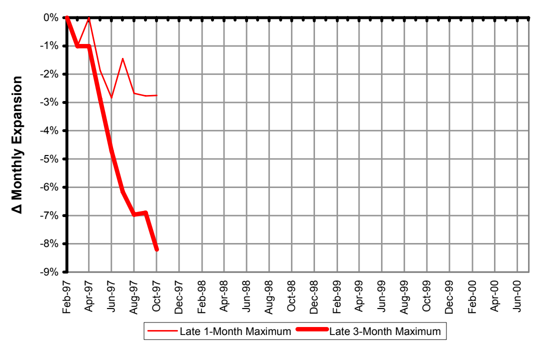
Late Schedule RPM



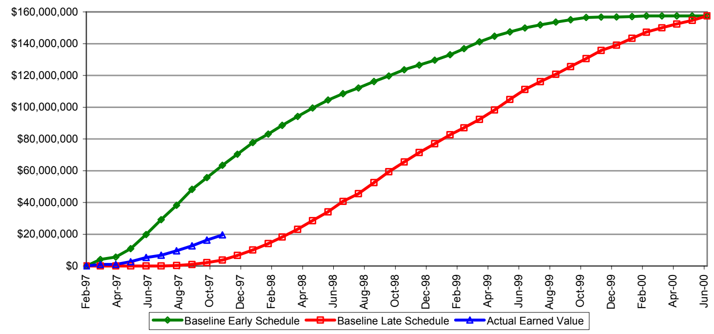




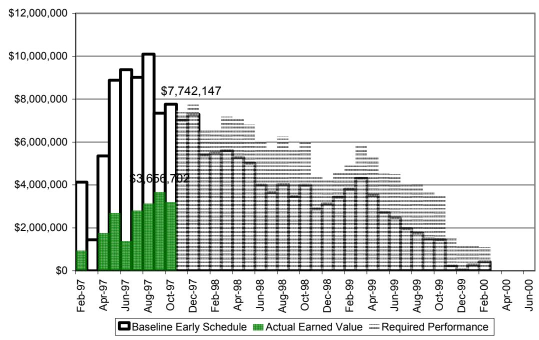




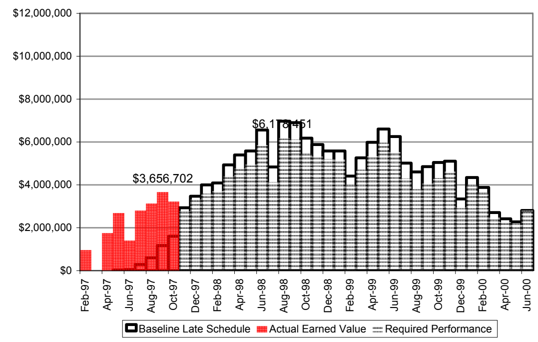
November 1, 1997

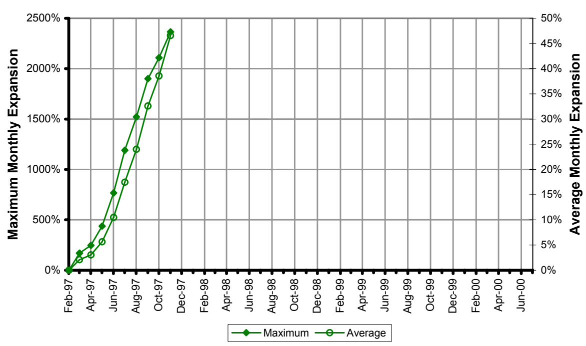


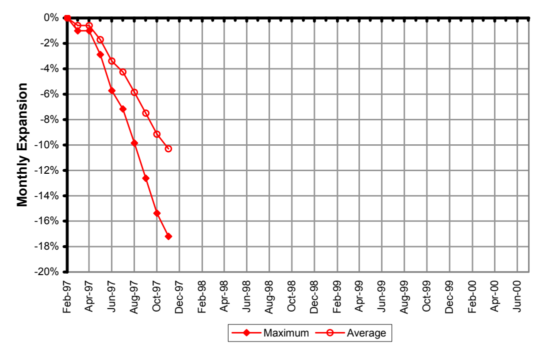
Early Schedule RPM

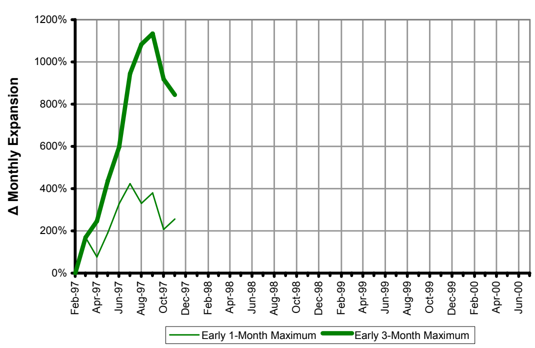


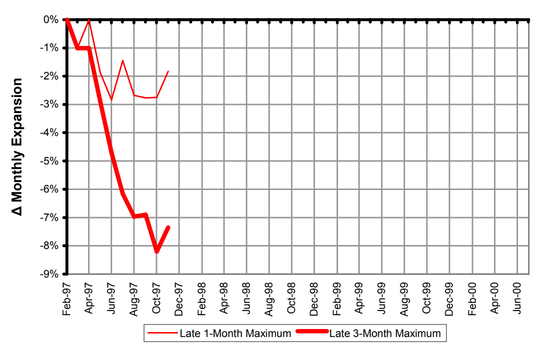
Late Schedule RPM



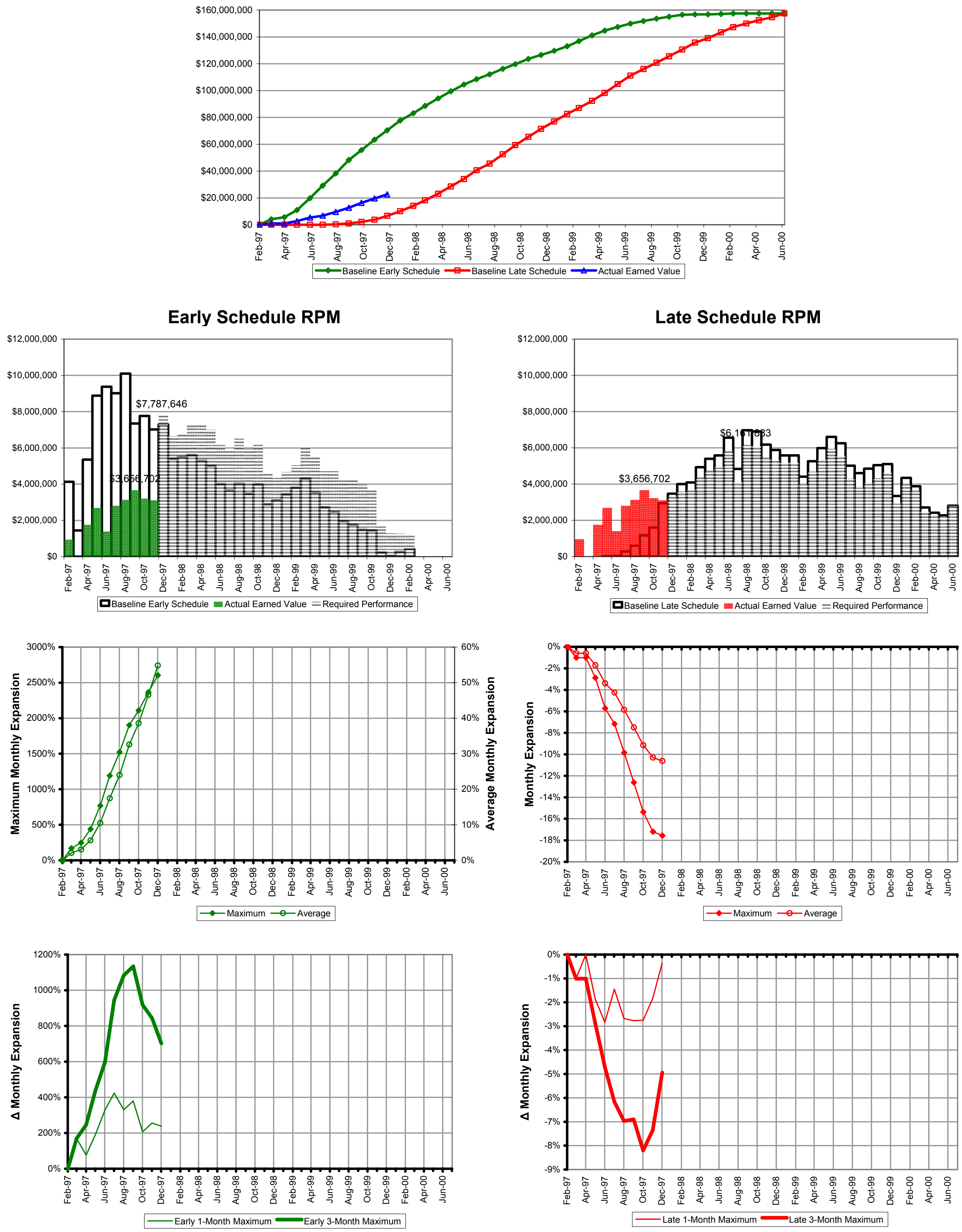




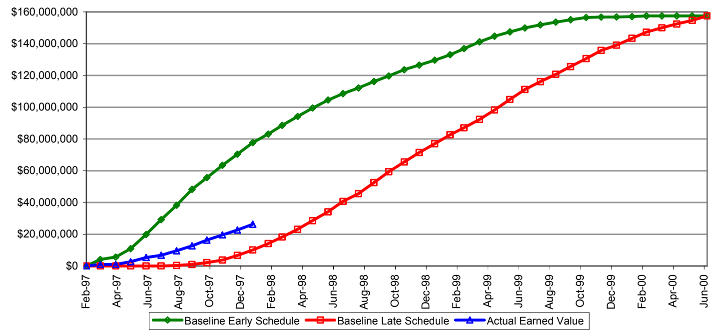




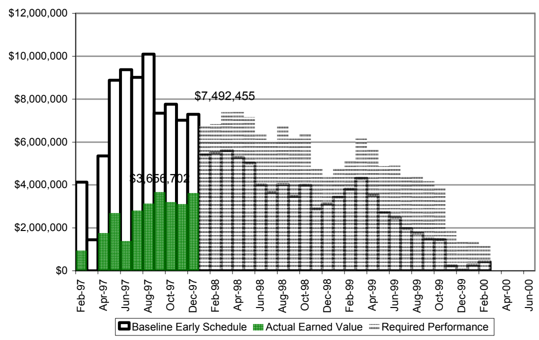
December 1, 1997



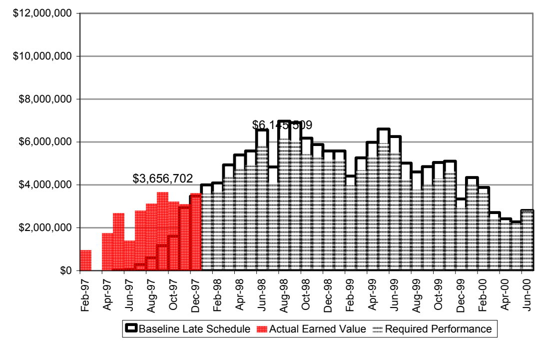
January 1, 1998

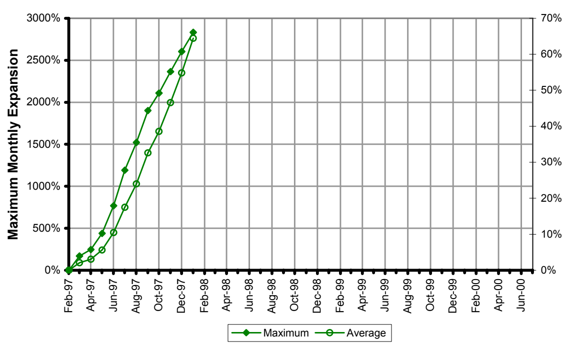


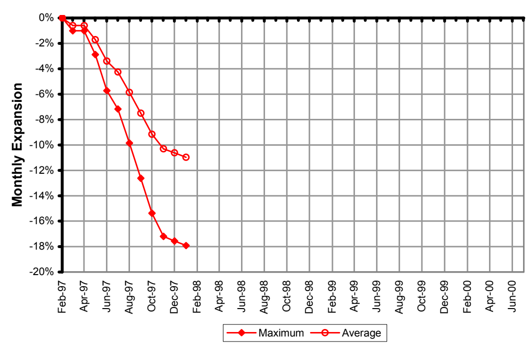
Early Schedule RPM

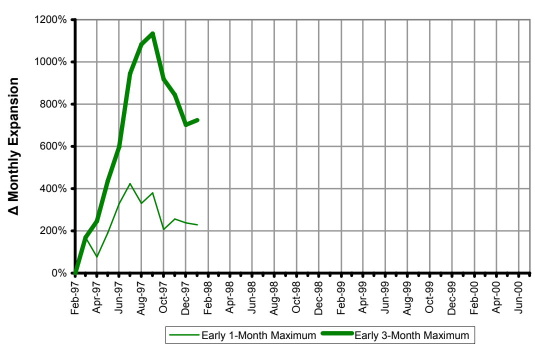


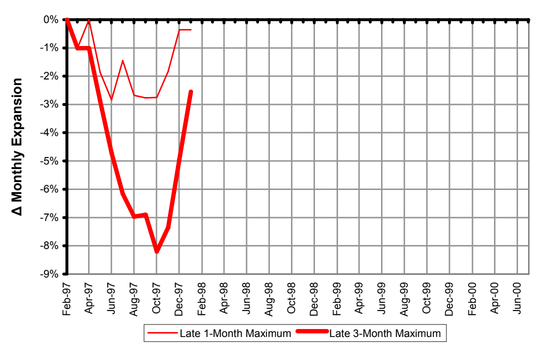
Late Schedule RPM



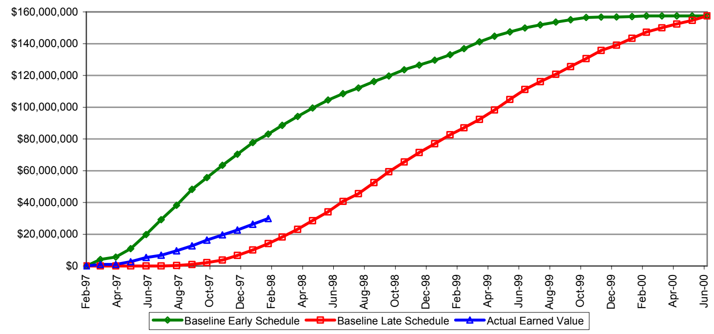




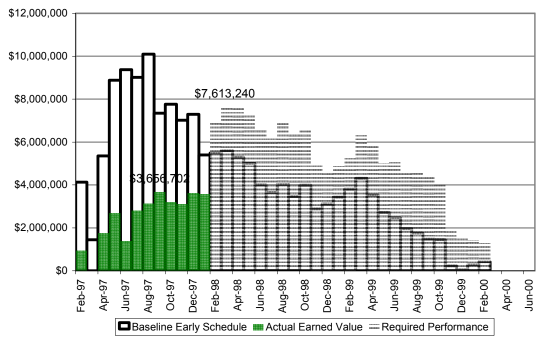




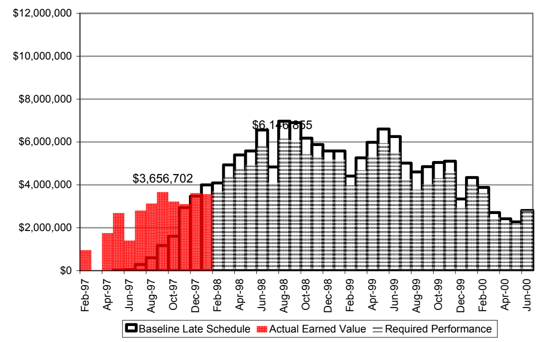
February 1, 1998

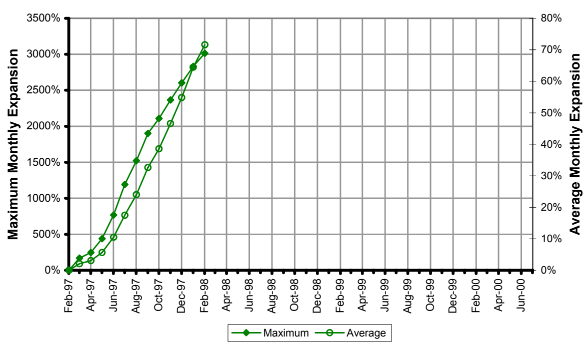


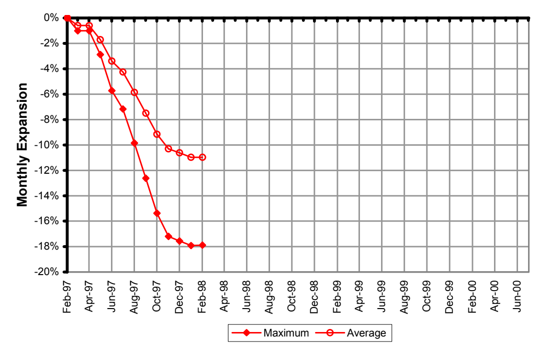
Early Schedule RPM

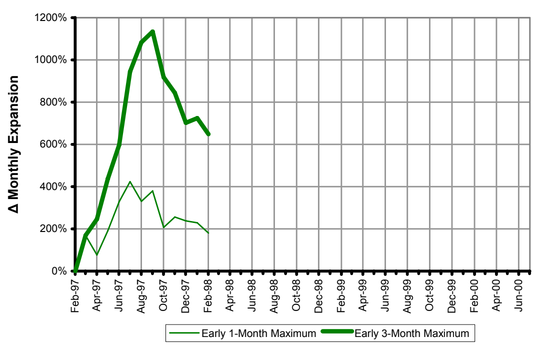


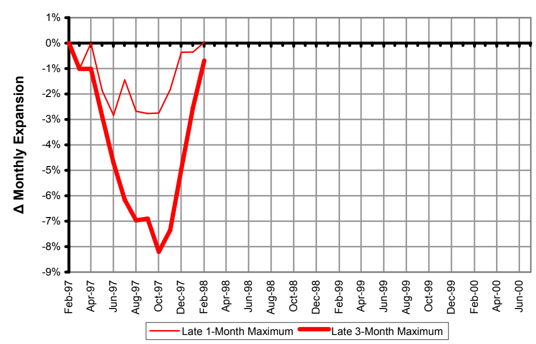
Late Schedule RPM



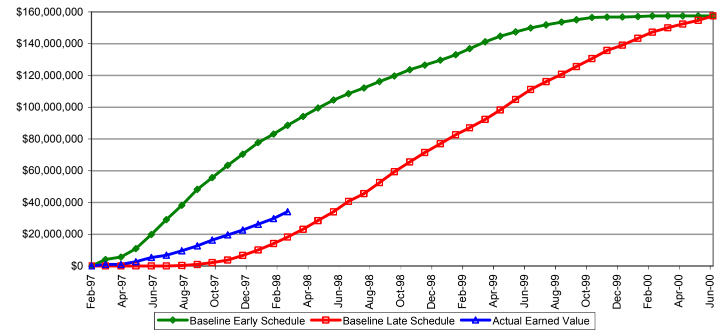




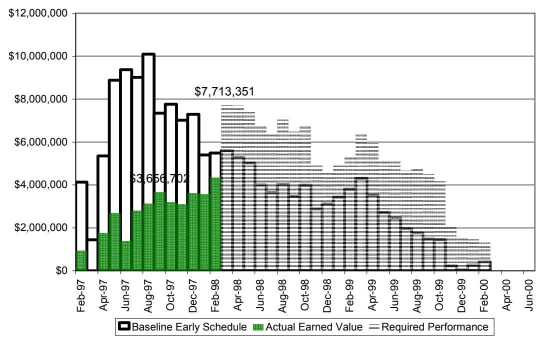




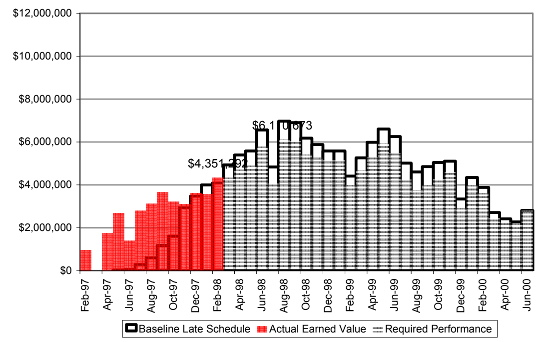
March 1, 1998

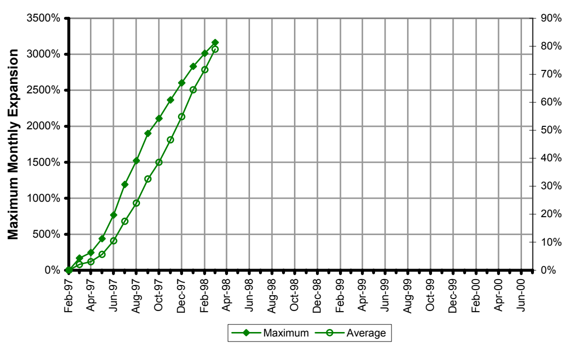


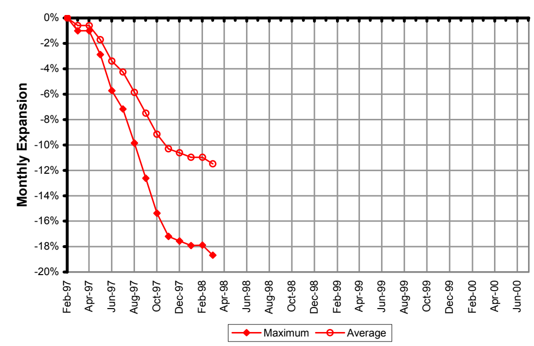
Early Schedule RPM

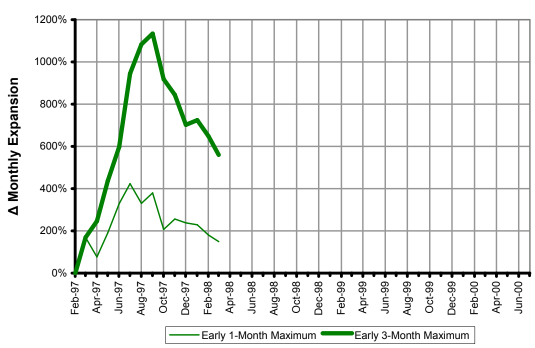


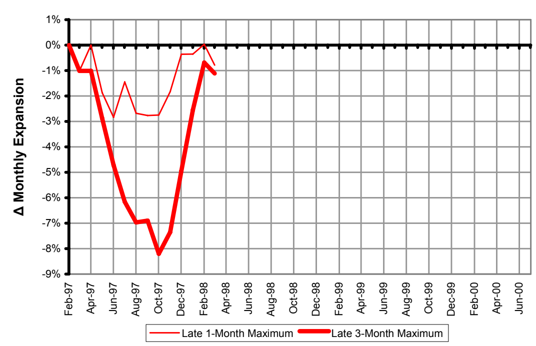
Late Schedule RPM



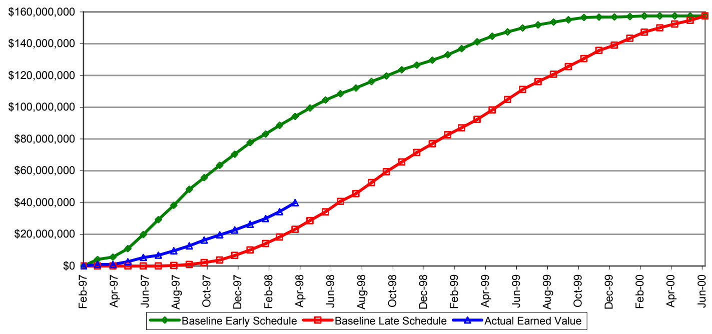




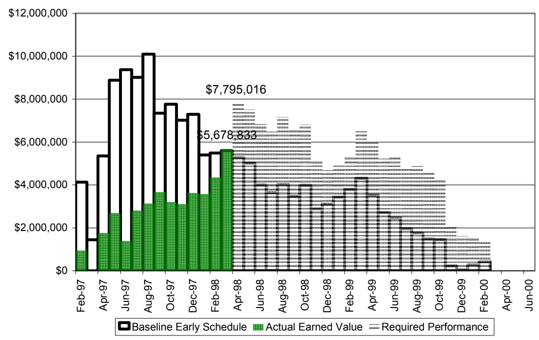




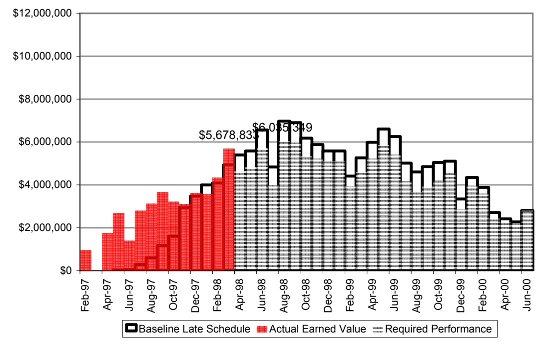
April 1, 1998

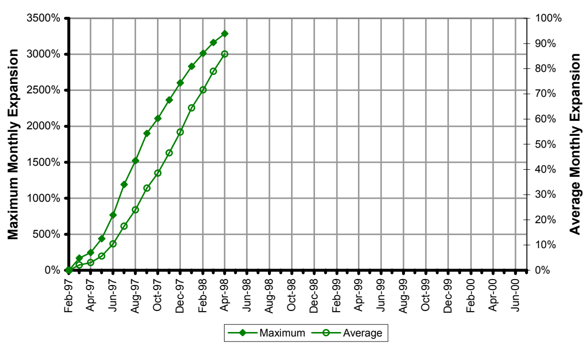


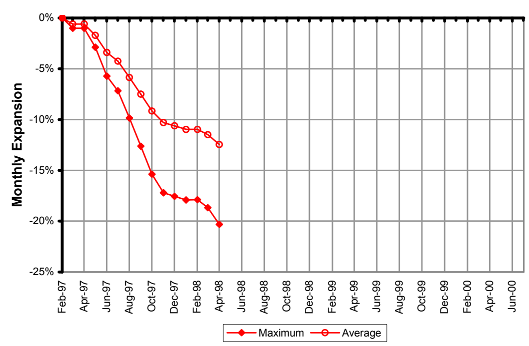
Early Schedule RPM

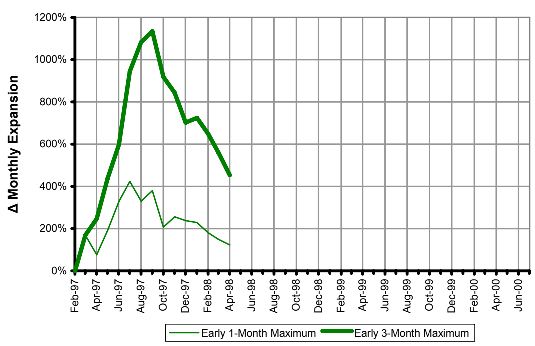


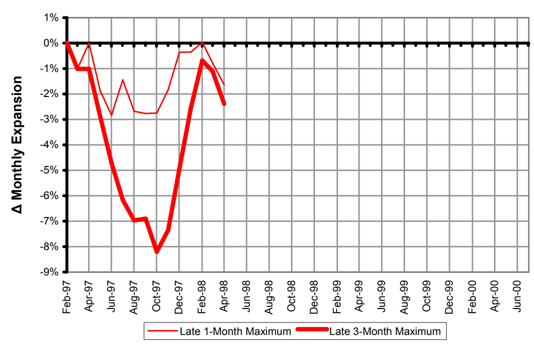
Late Schedule RPM



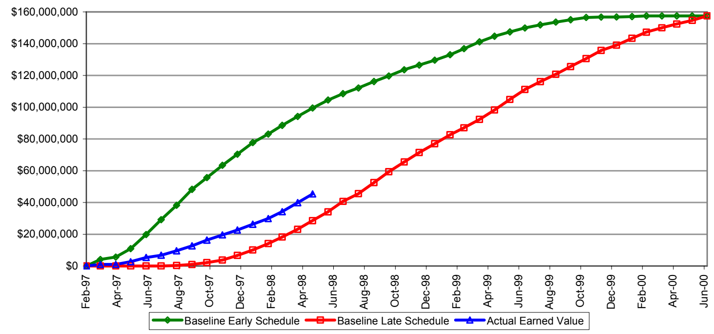




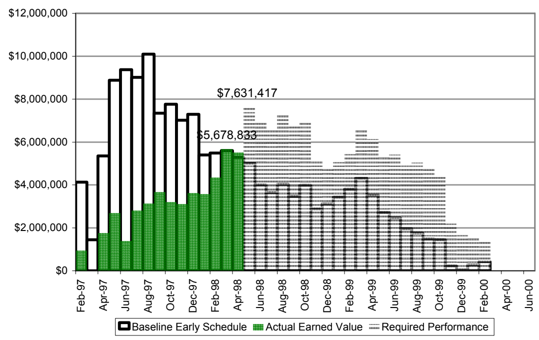




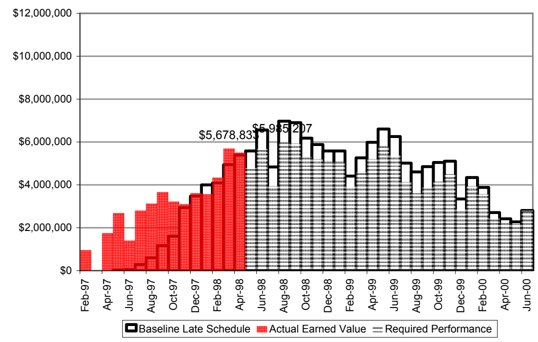
May 1, 1998

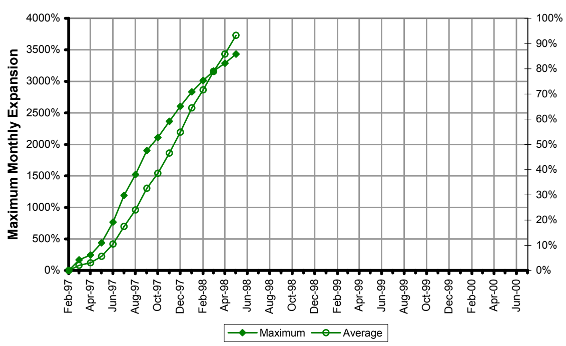


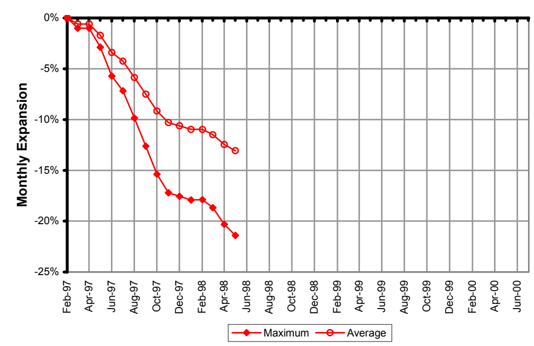
Early Schedule RPM

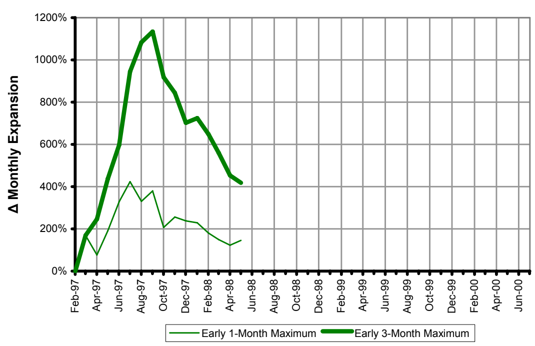


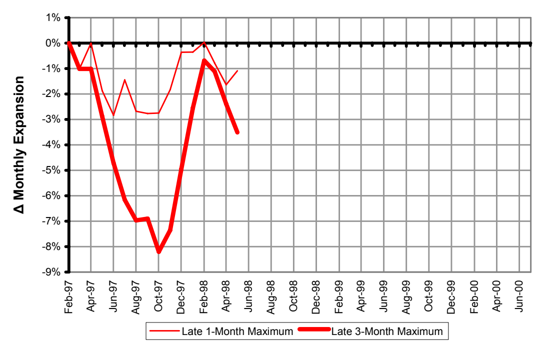
Late Schedule RPM



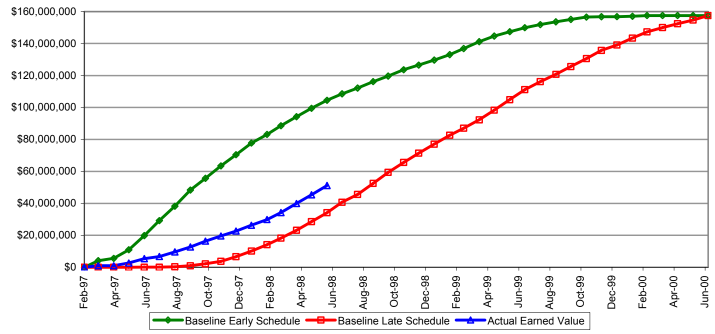




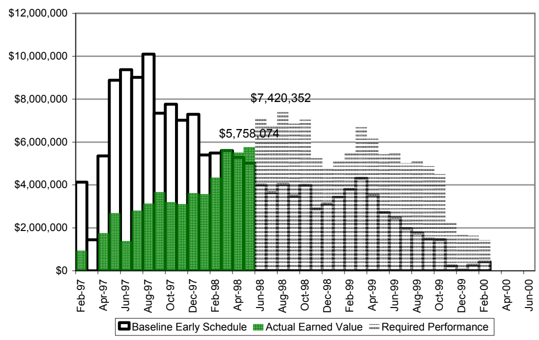




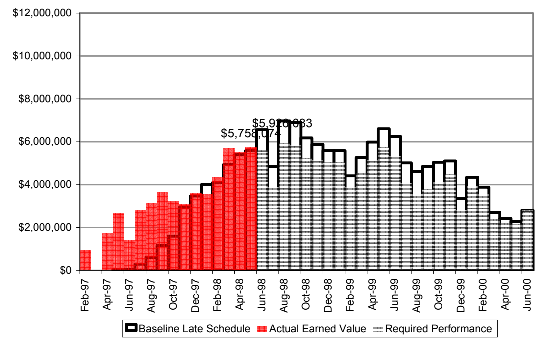
June 1, 1998

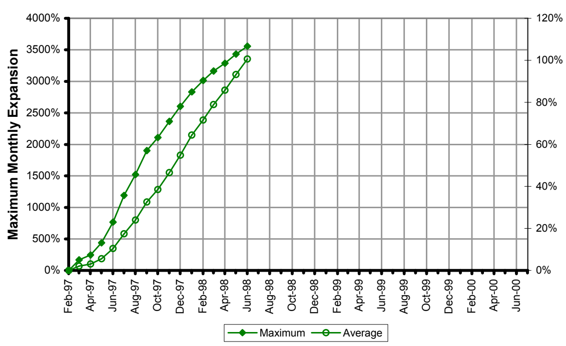


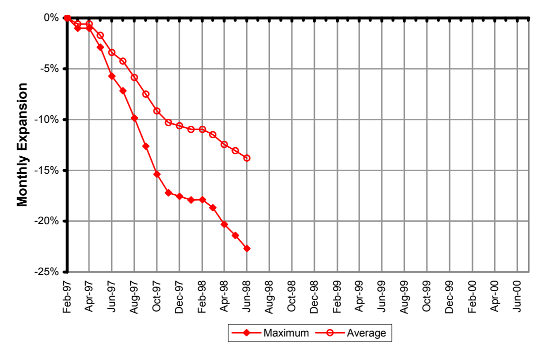
Early Schedule RPM

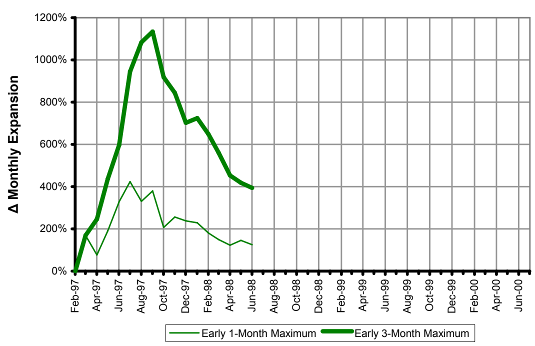


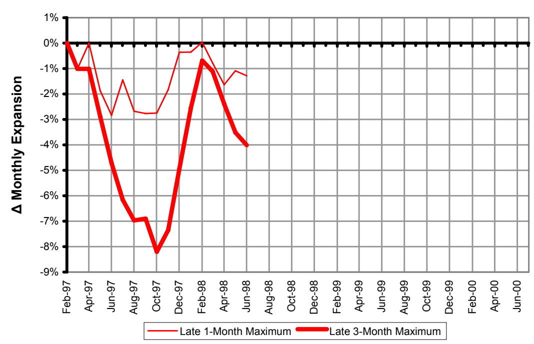
Late Schedule RPM



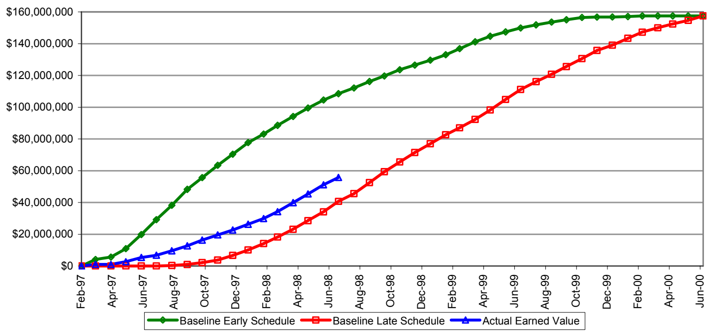




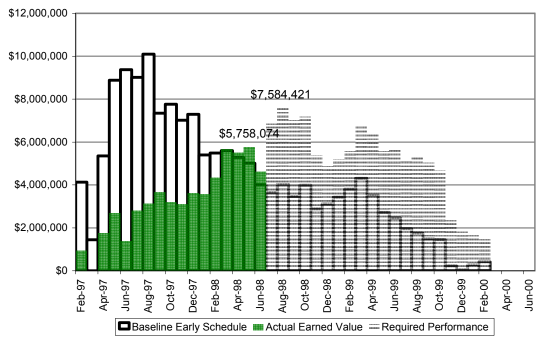




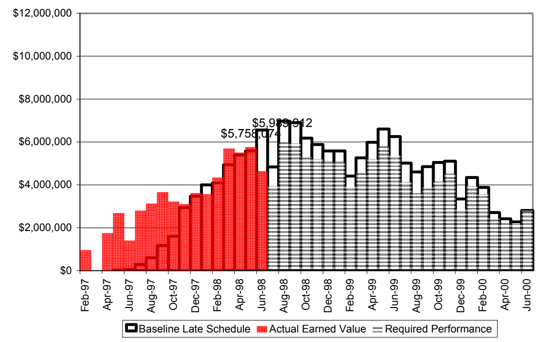
July 1, 1998

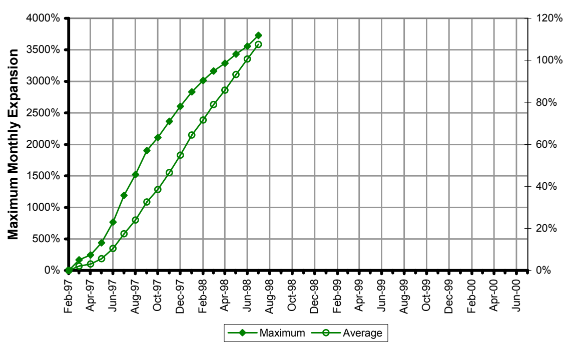


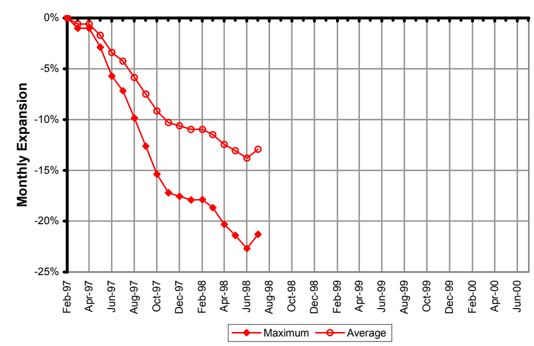
Early Schedule RPM

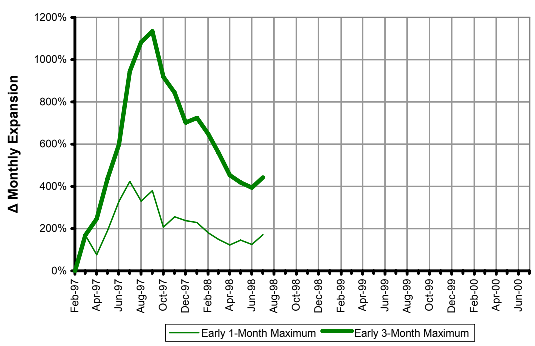


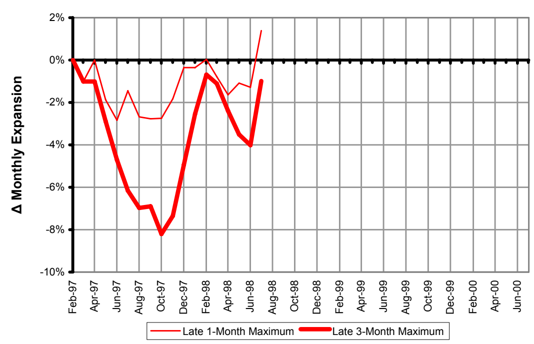
Late Schedule RPM



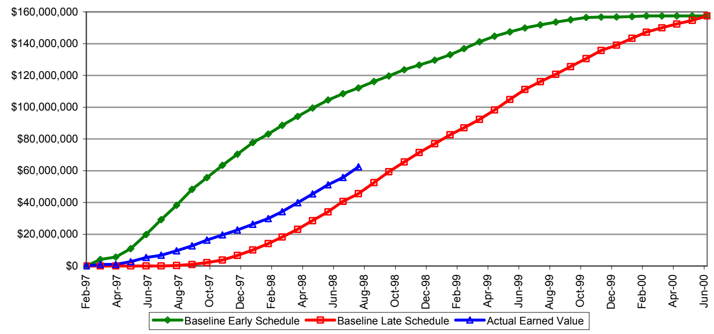




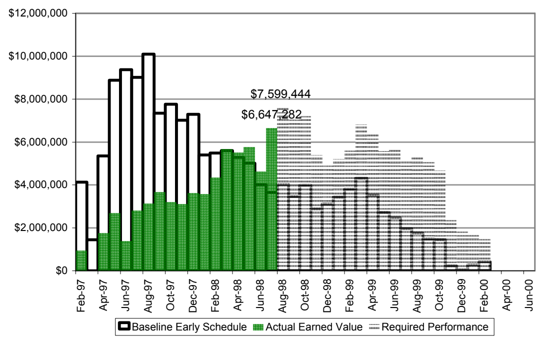




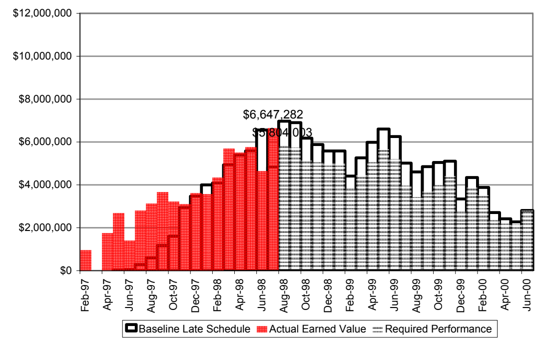
August 1, 1998

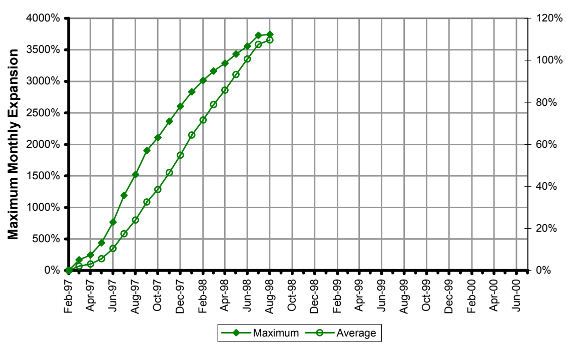


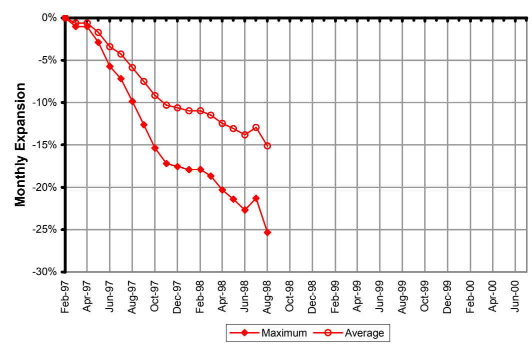
Early Schedule RPM

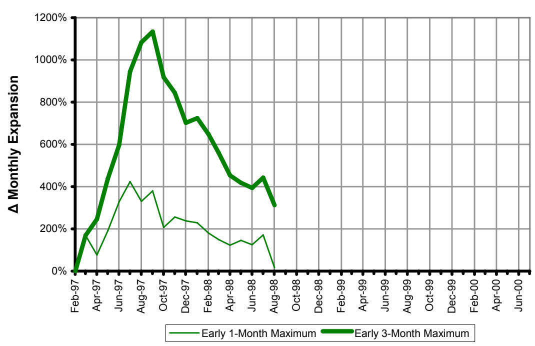


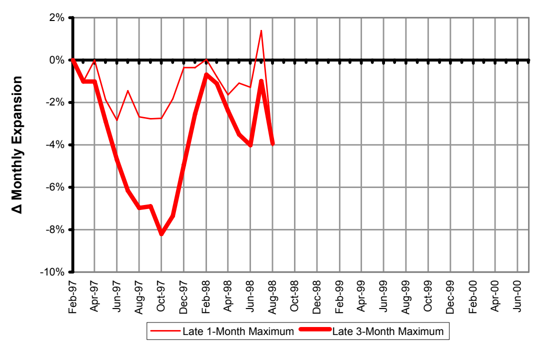
Late Schedule RPM



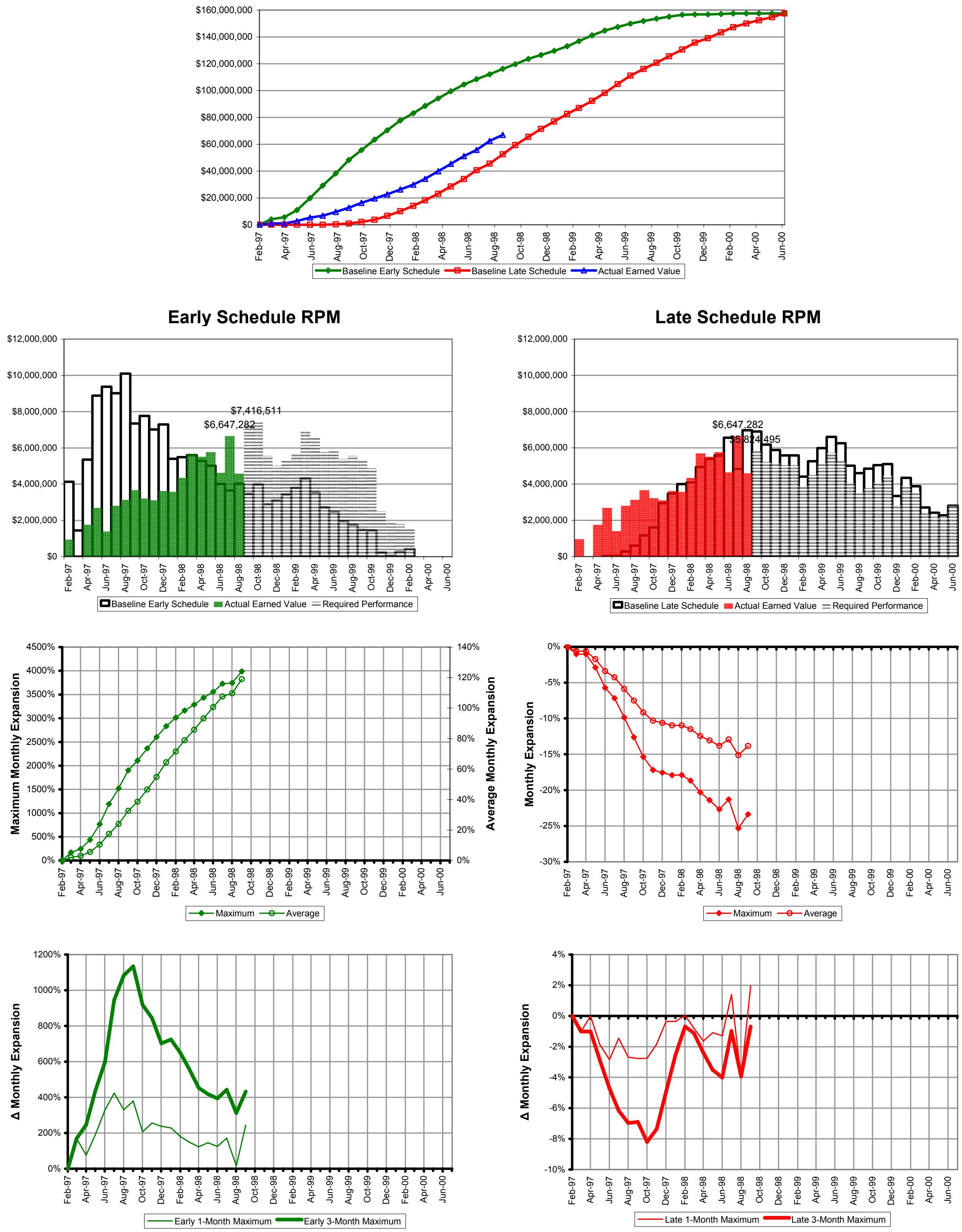




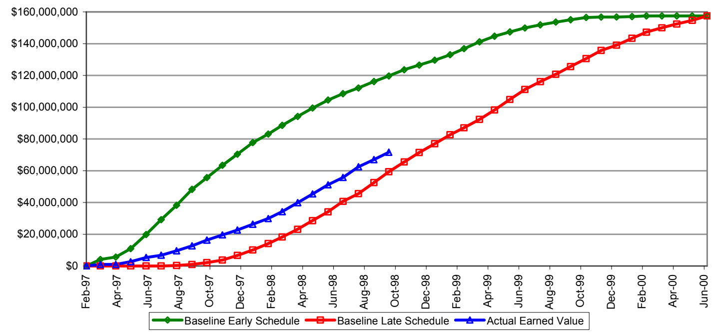




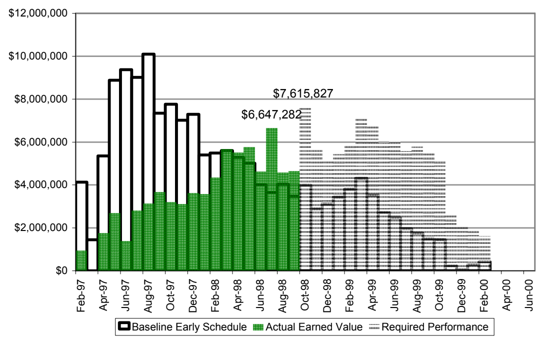
September 1, 1998



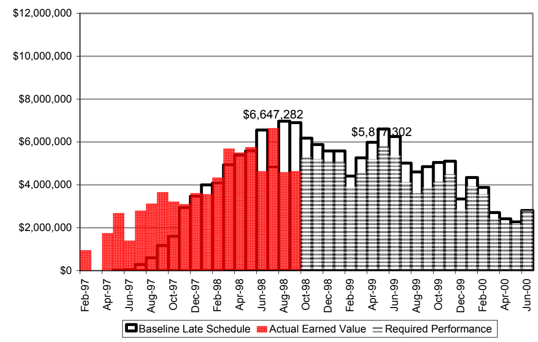
October 1, 1998

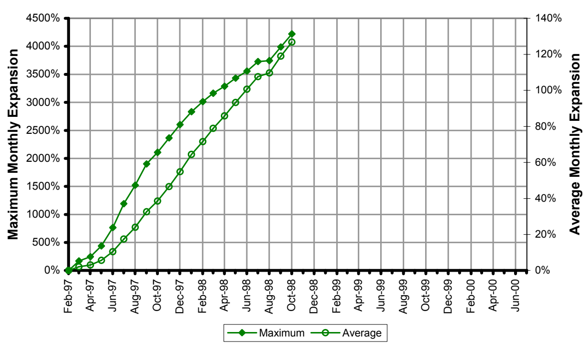


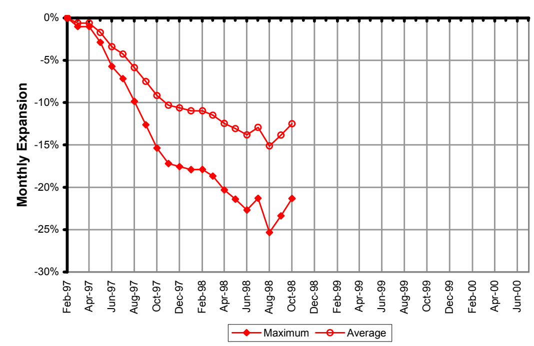
Early Schedule RPM

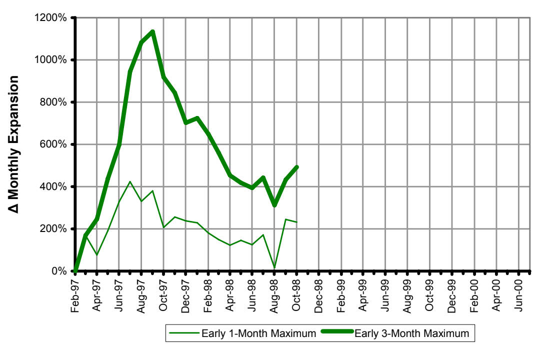


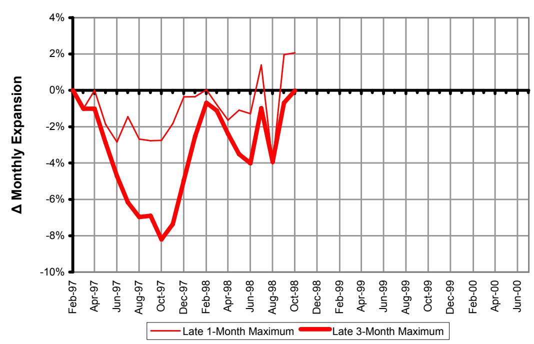
Late Schedule RPM



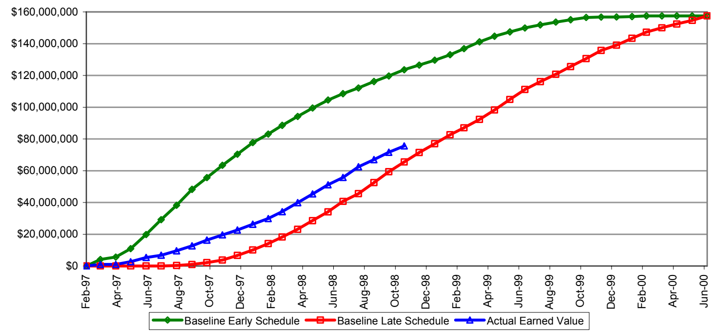




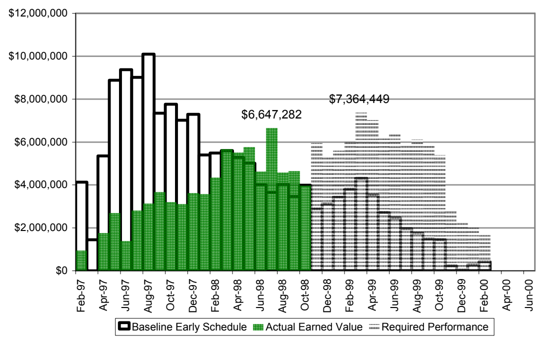




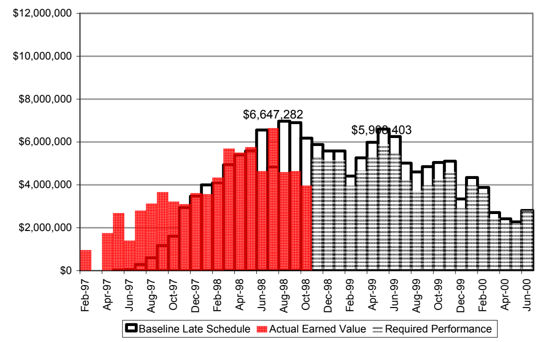
November 1, 1998

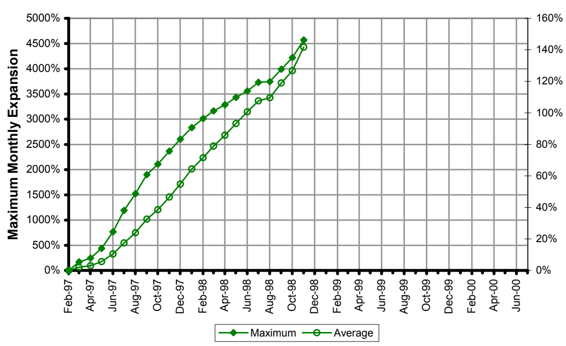


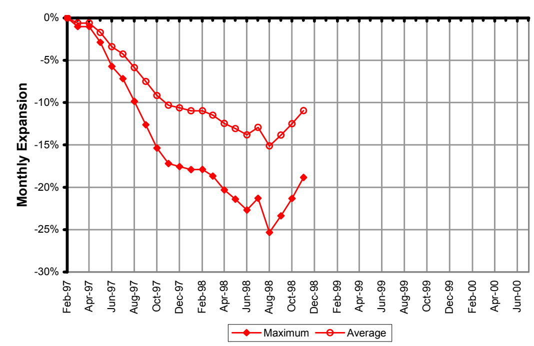
Early Schedule RPM

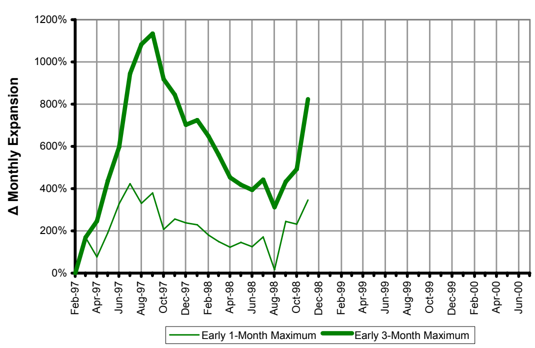


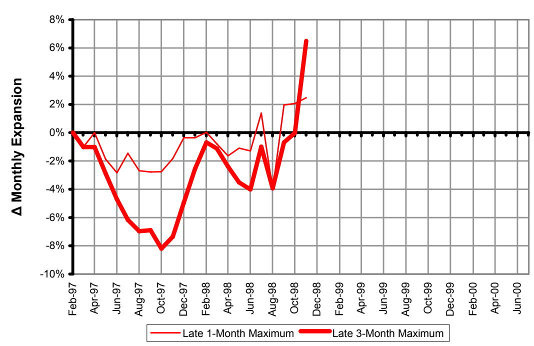
Late Schedule RPM



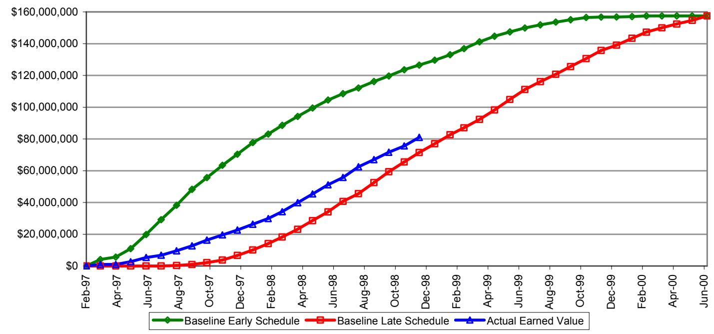




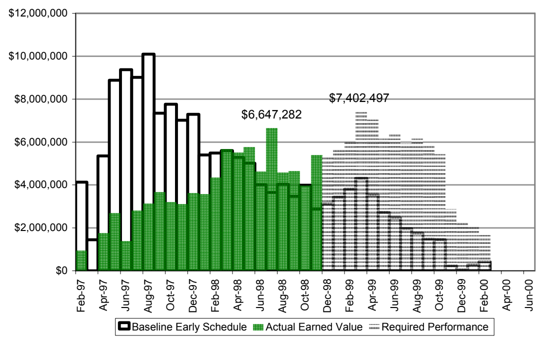




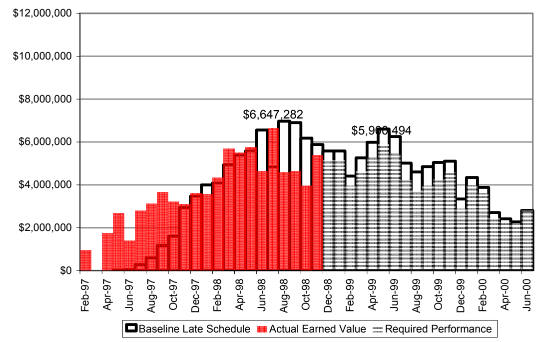
December 1, 1998

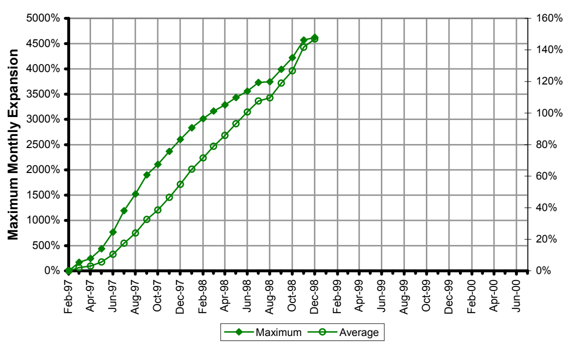


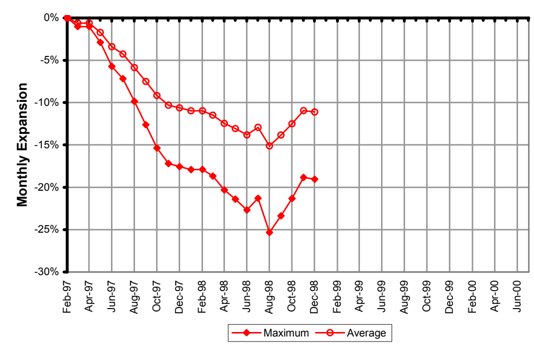
Early Schedule RPM

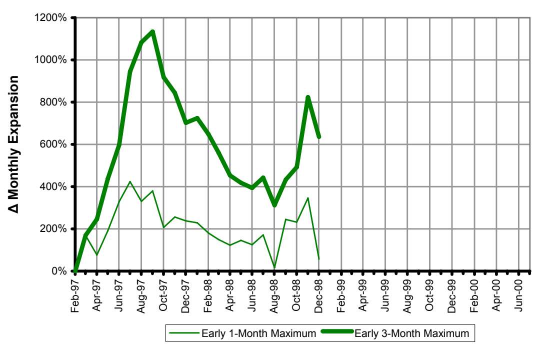


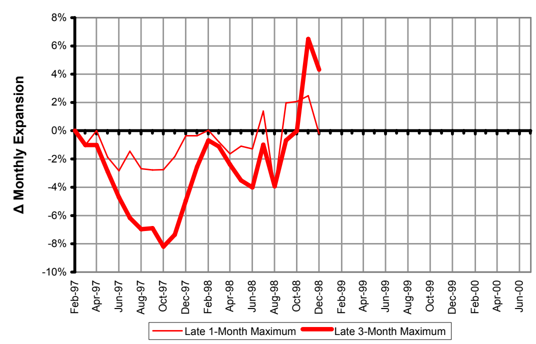
Late Schedule RPM



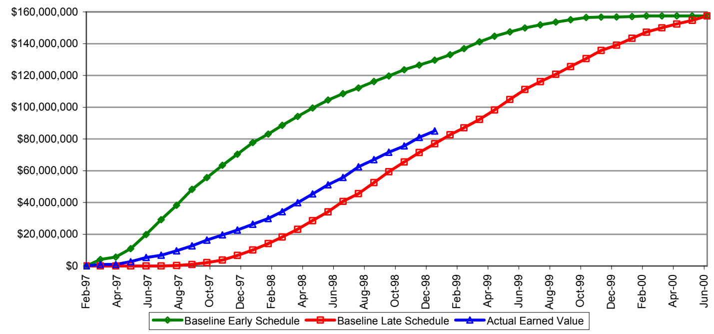




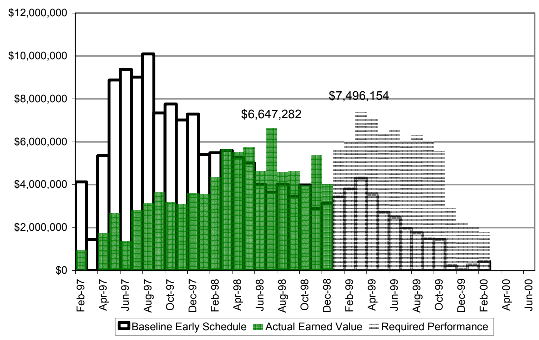




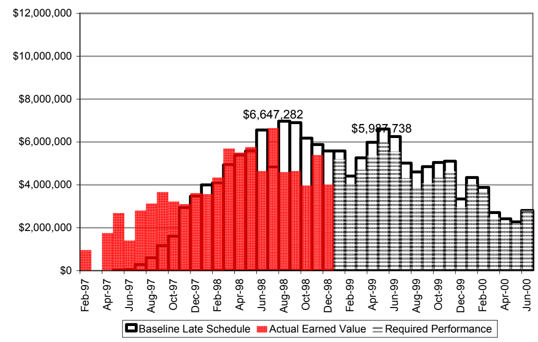
January 1, 1999

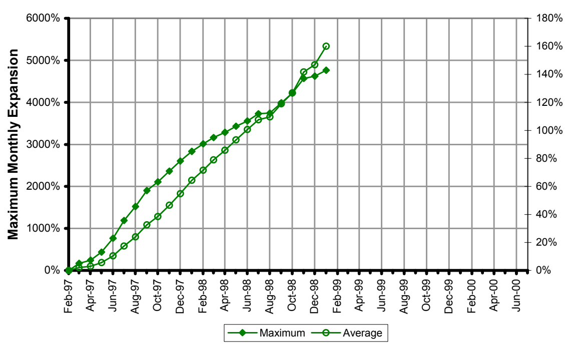


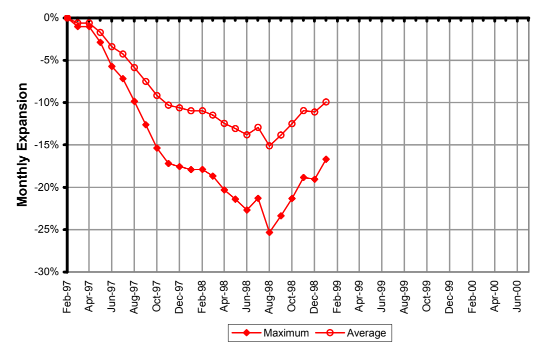
Early Schedule RPM

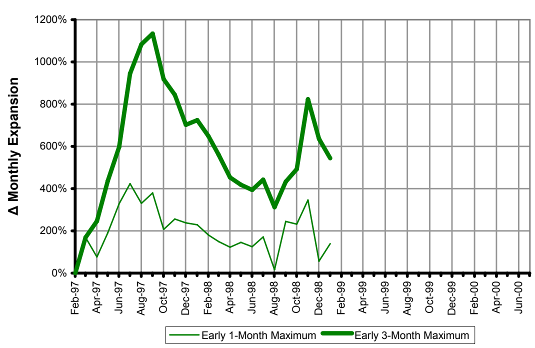


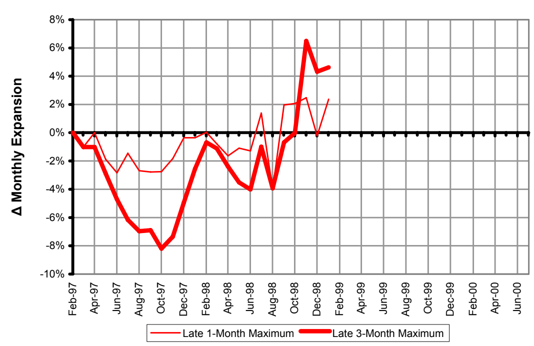
Late Schedule RPM



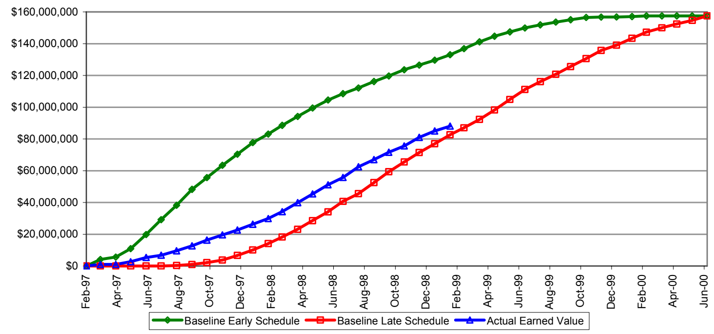




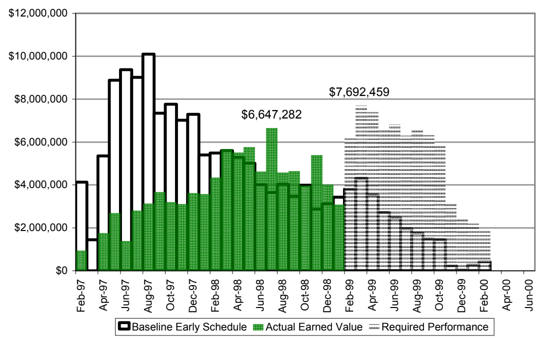




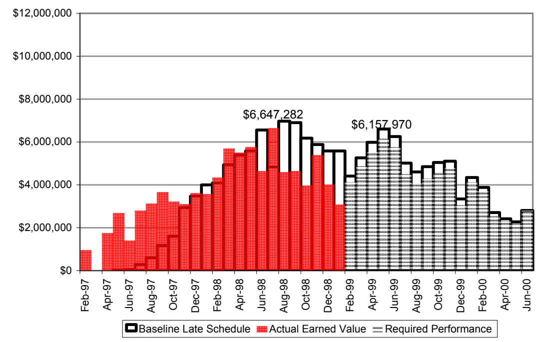
February 1, 1999

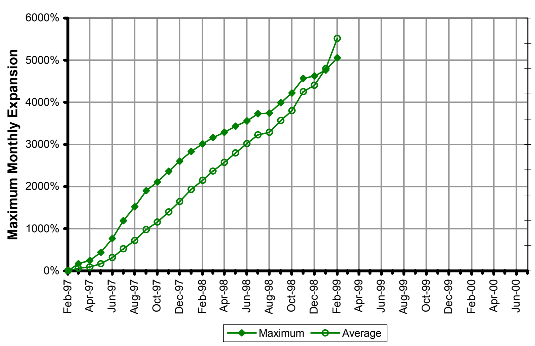


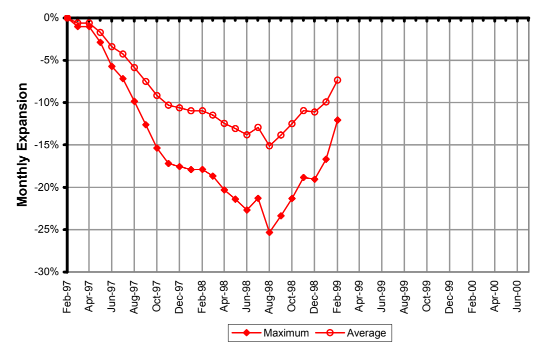
Early Schedule RPM

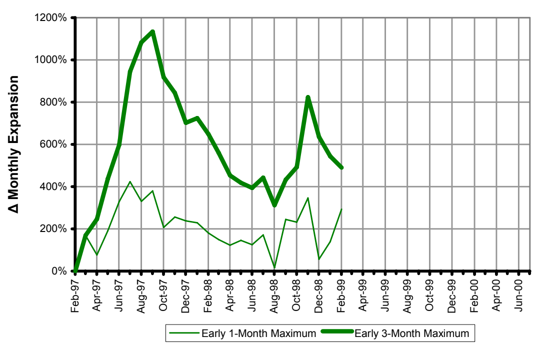


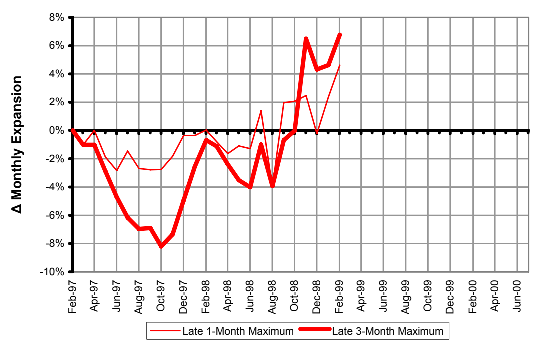
Late Schedule RPM



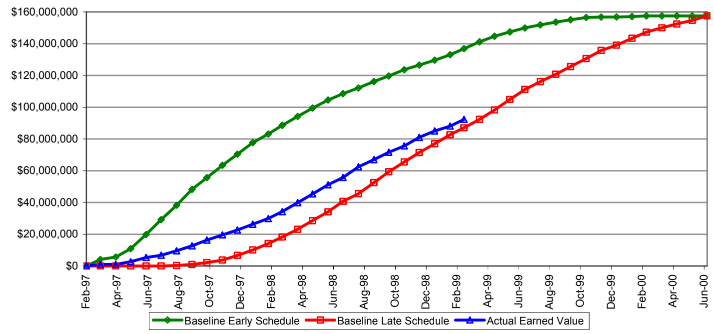




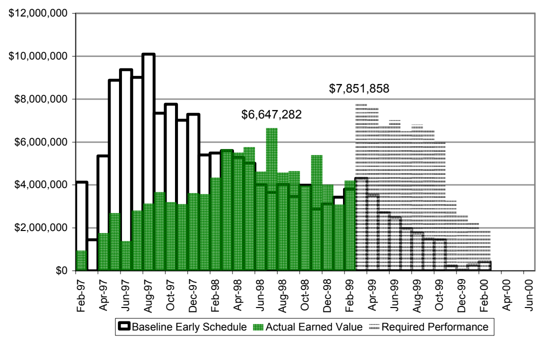




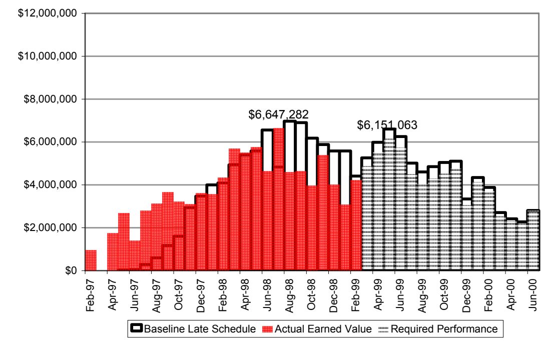
March 1, 1999

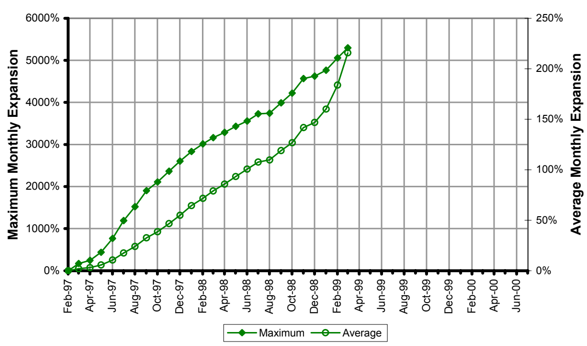


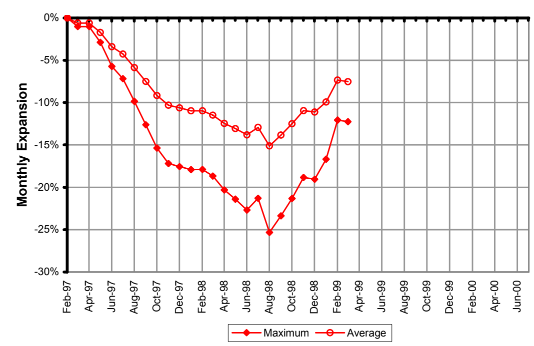
Early Schedule RPM

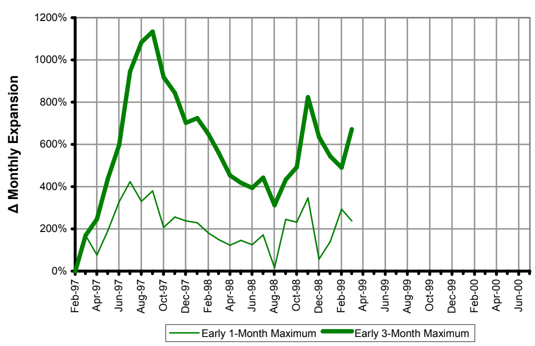


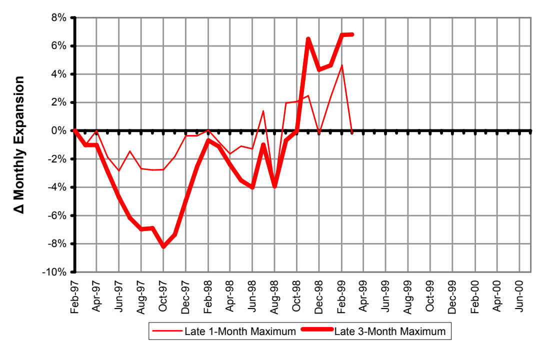
Late Schedule RPM



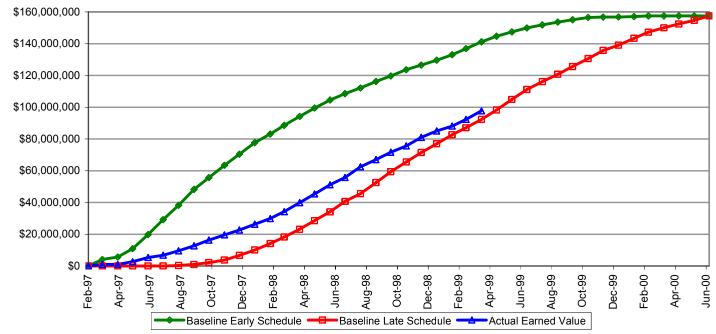




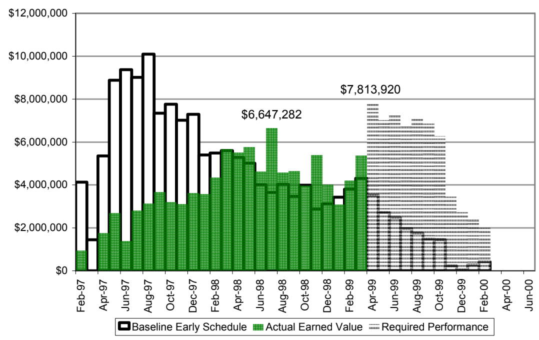




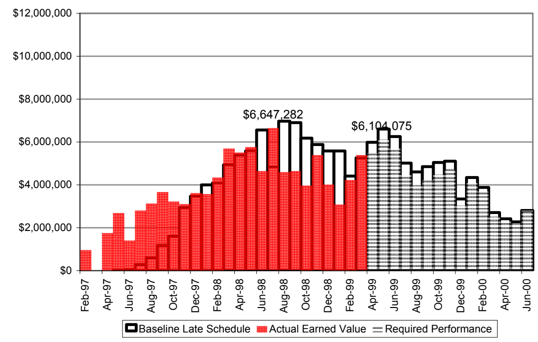
April 1, 1999

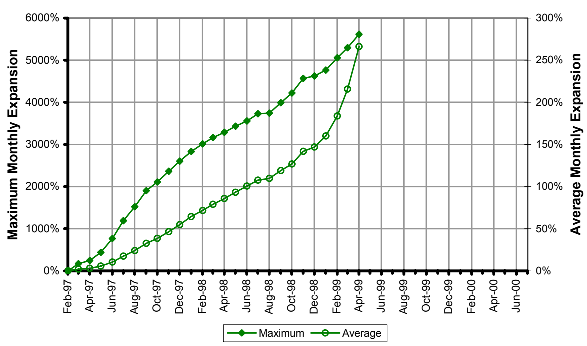


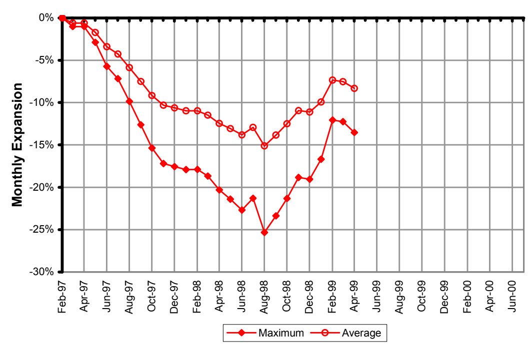
Early Schedule RPM

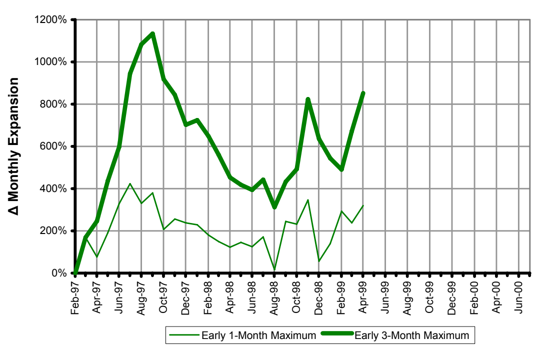


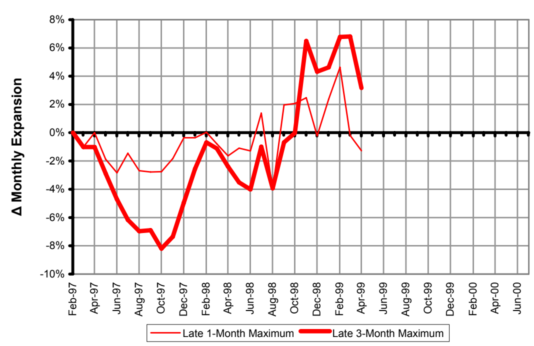
Late Schedule RPM



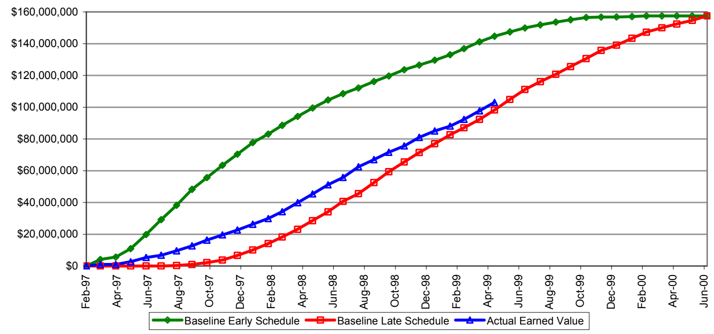




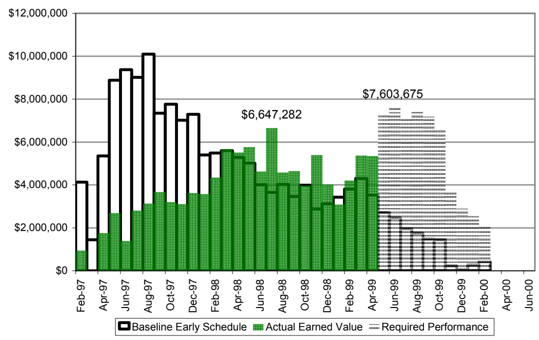




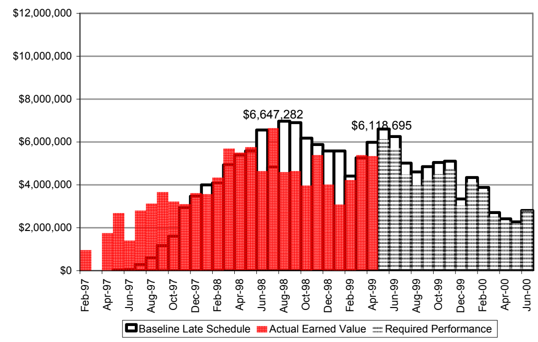
May 1, 1999

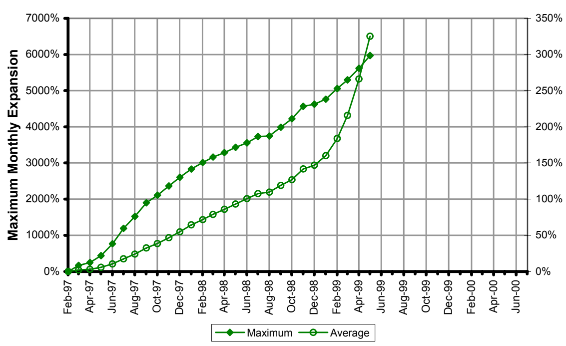


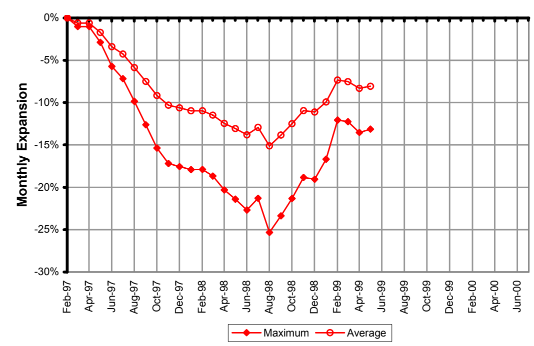
Early Schedule RPM

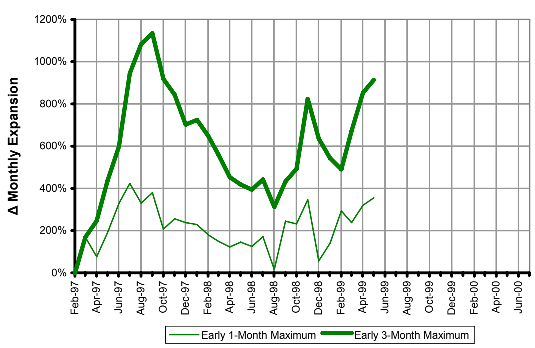


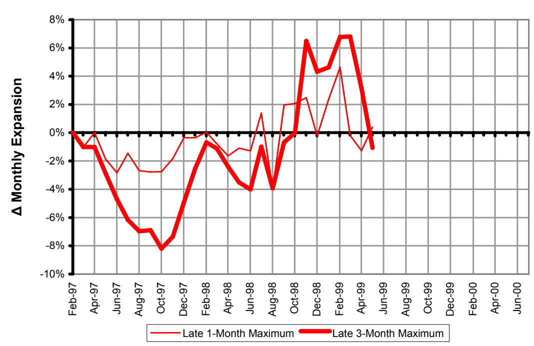
Late Schedule RPM



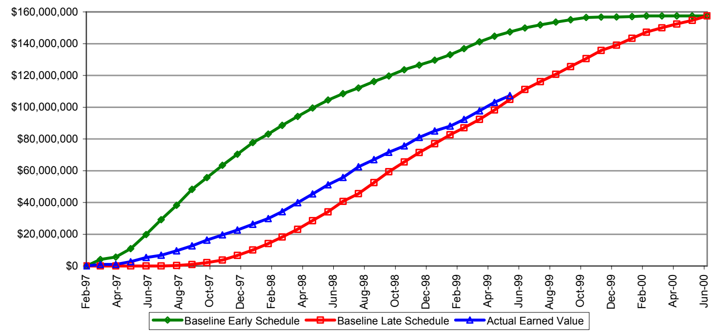








June 1, 1999



$160,000,000
$140,000,000
$120,000,000
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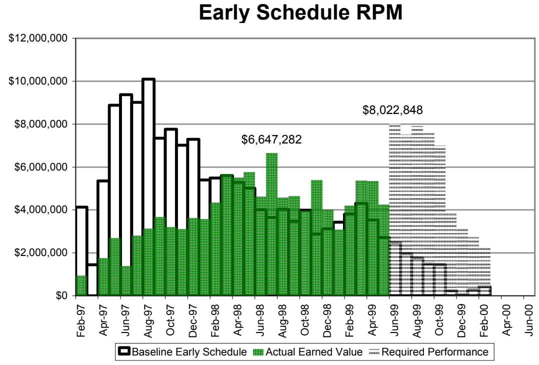
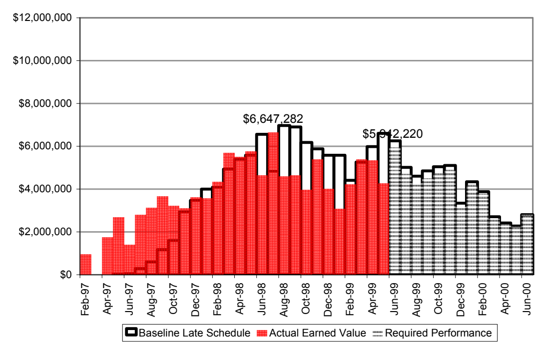
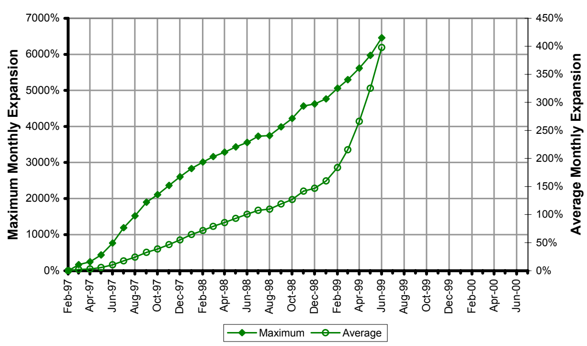
$20,000,000
$0
Baseline Early Schedule
Baseline Late Schedule
Actual Earned Value



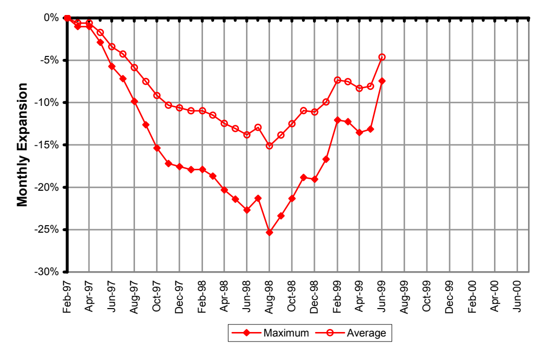
Early Schedule RPM
$8,022,848
$6,647,282
Baseline Early Schedule
Actual Earned Value
Required Performance



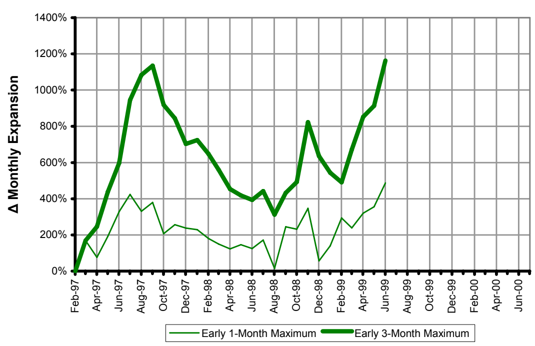
Late Schedule RPM
$6,647,282
Baseline Late Schedule
Actual Earned Value
Required Performance



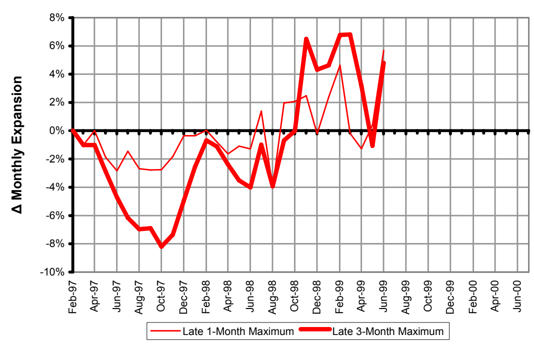
Maximum Monthly Expansion
Average Monthly Expansion
Maximum
Average



Monthly Expansion
Maximum
Average

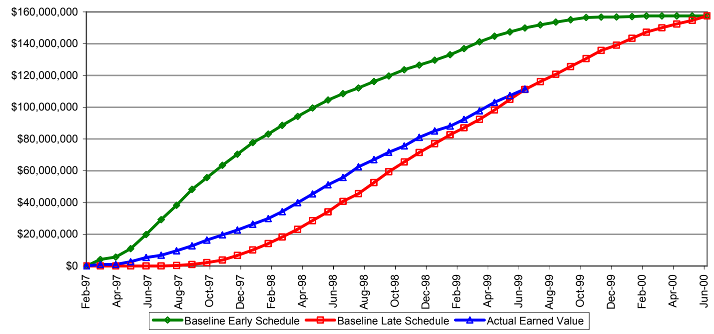


Δ Monthly Expansion
Early 1-Month Maximum
Early 3-Month Maximum

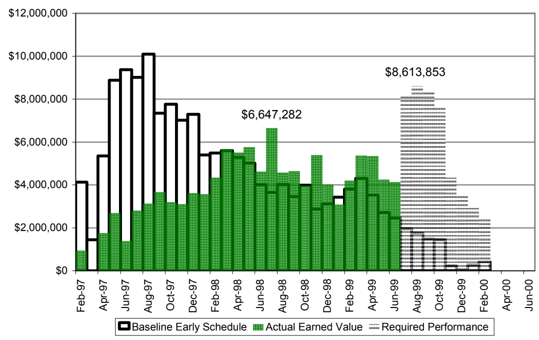


Δ Monthly Expansion
Late 1-Month Maximum
Late 3-Month Maximum

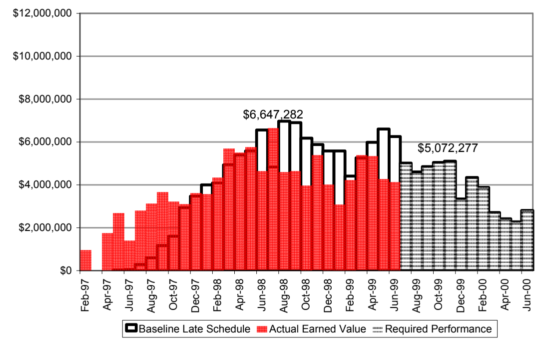
July 1, 1999

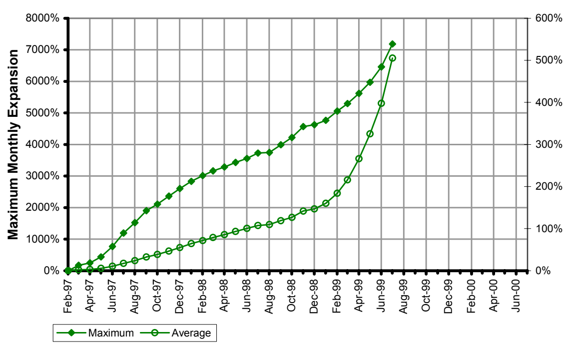


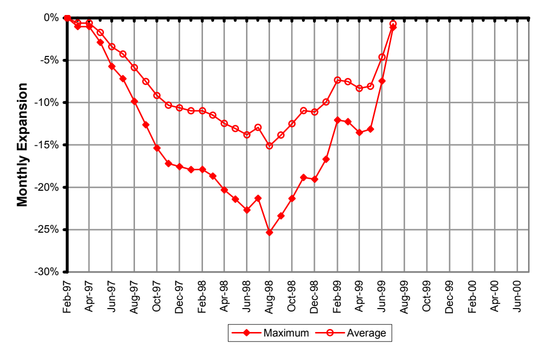
Early Schedule RPM

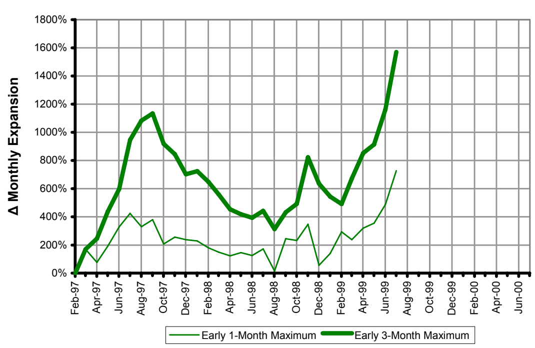


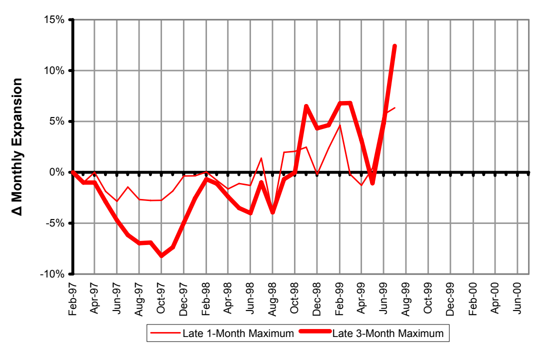
Late Schedule RPM



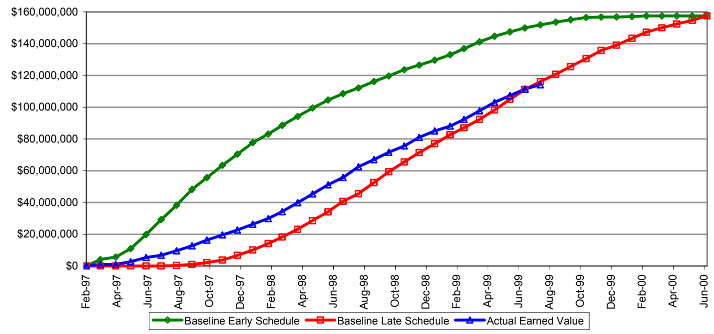




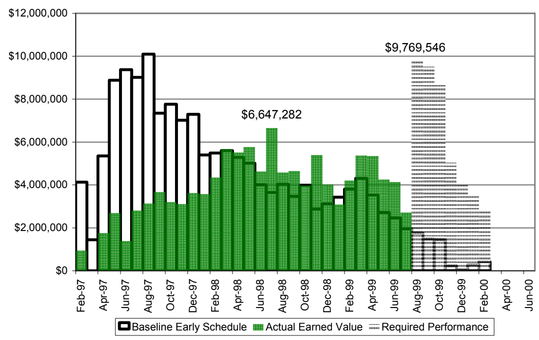




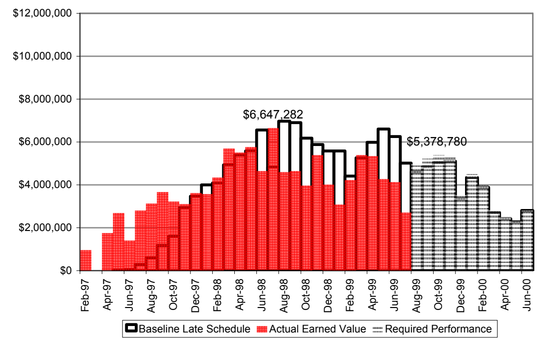
August 1, 1999

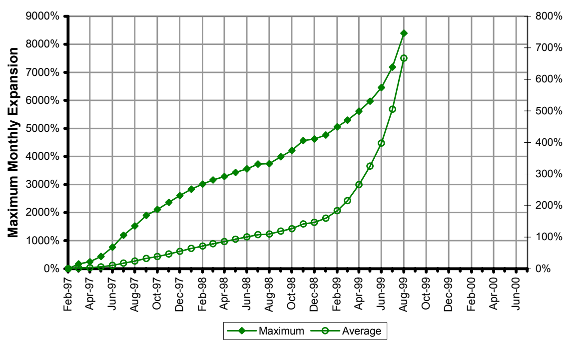


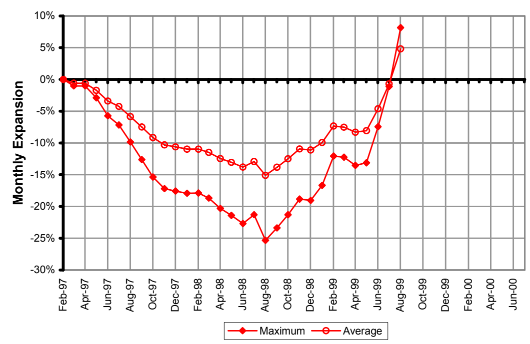
Early Schedule RPM

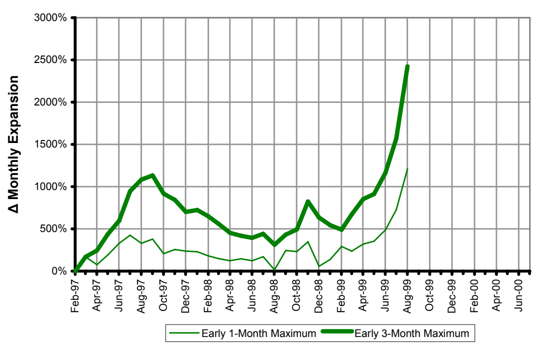


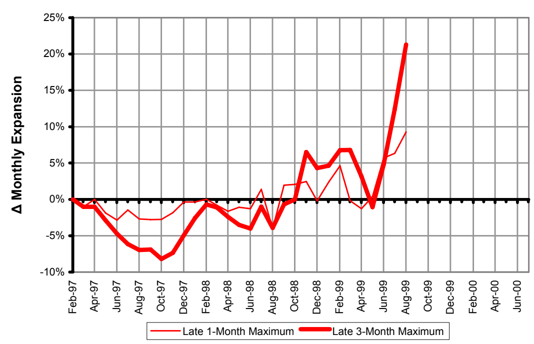
Late Schedule RPM



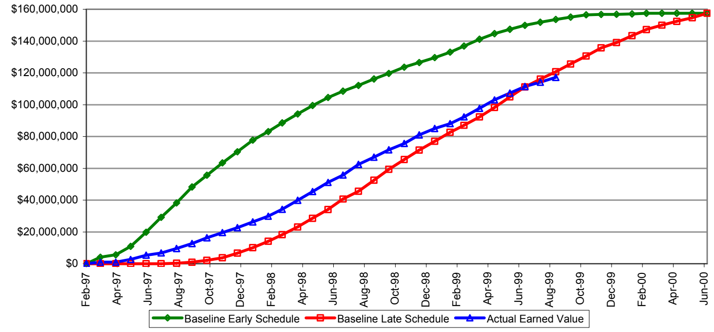




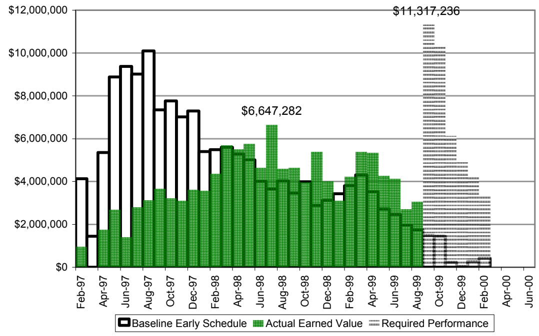




September 1, 1999



Early Schedule RPM



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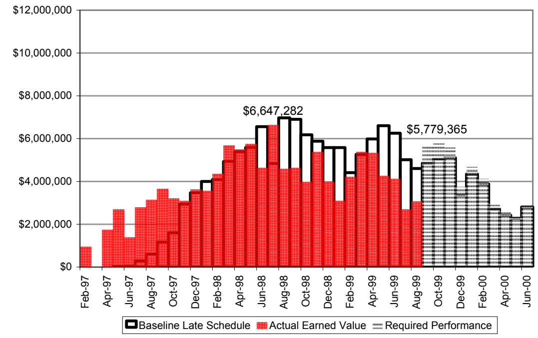
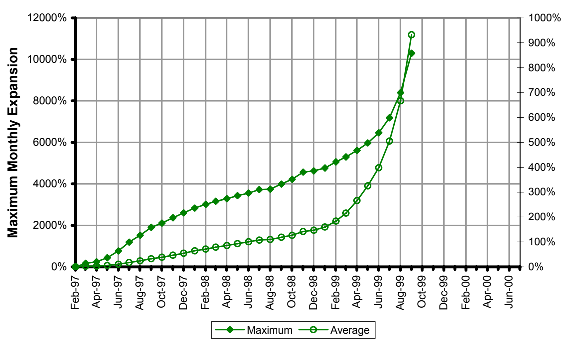
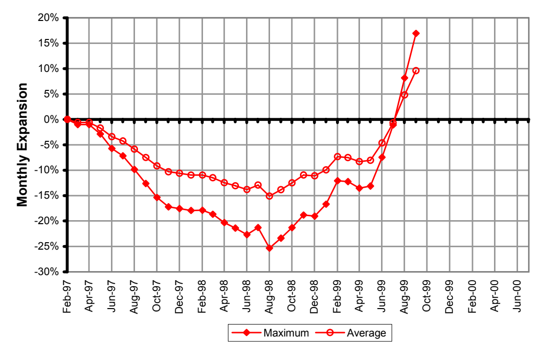
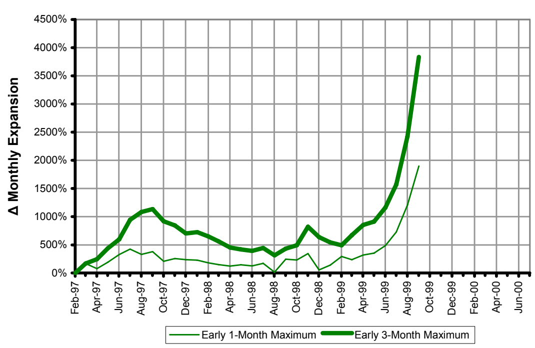
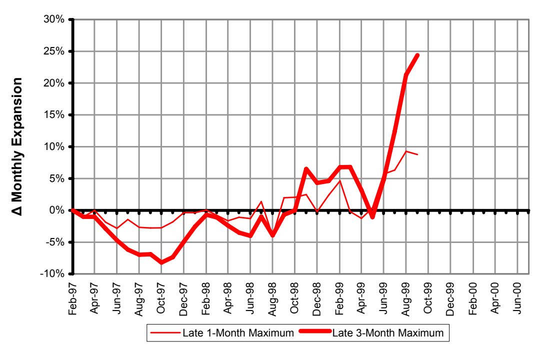


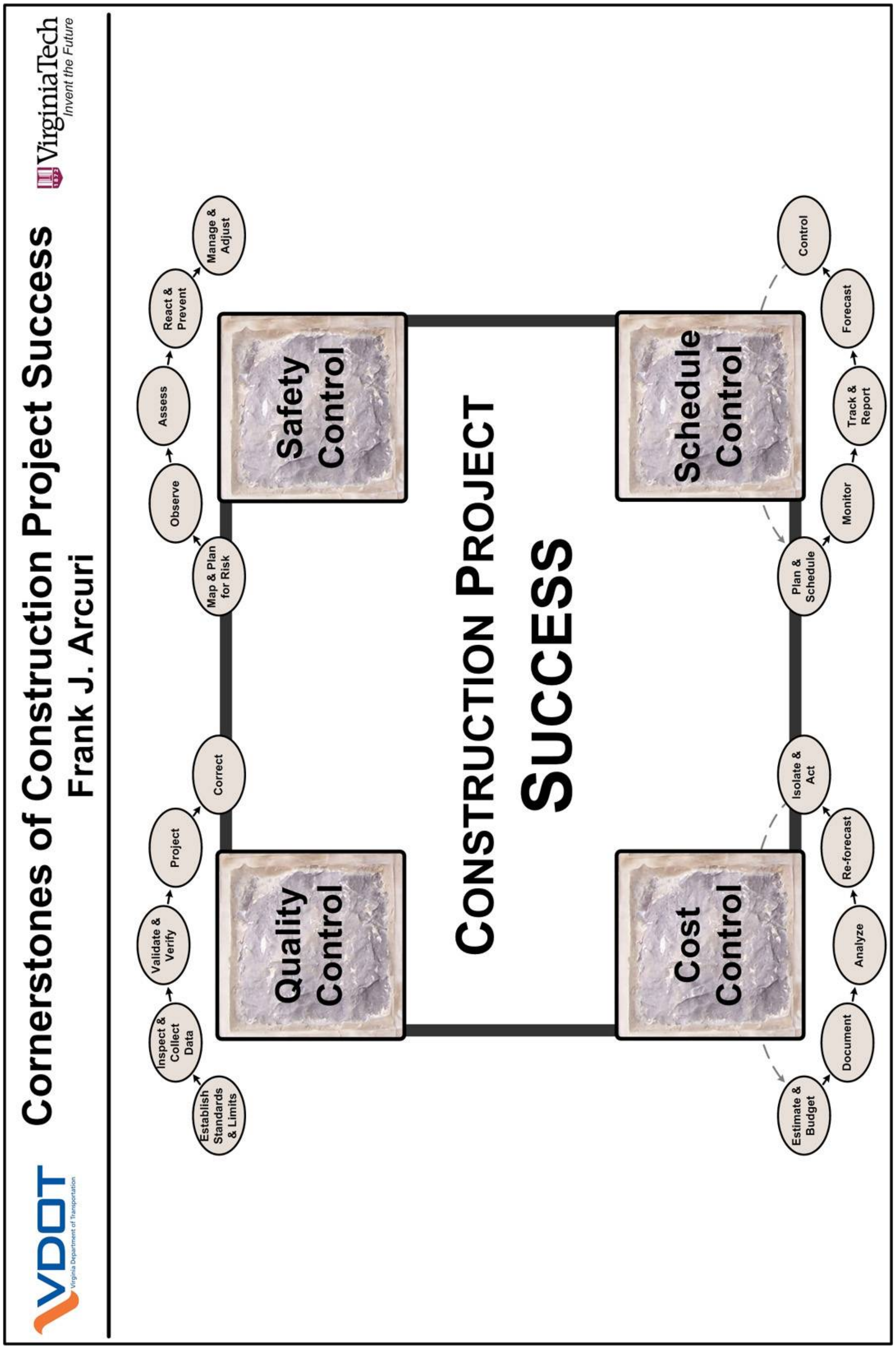


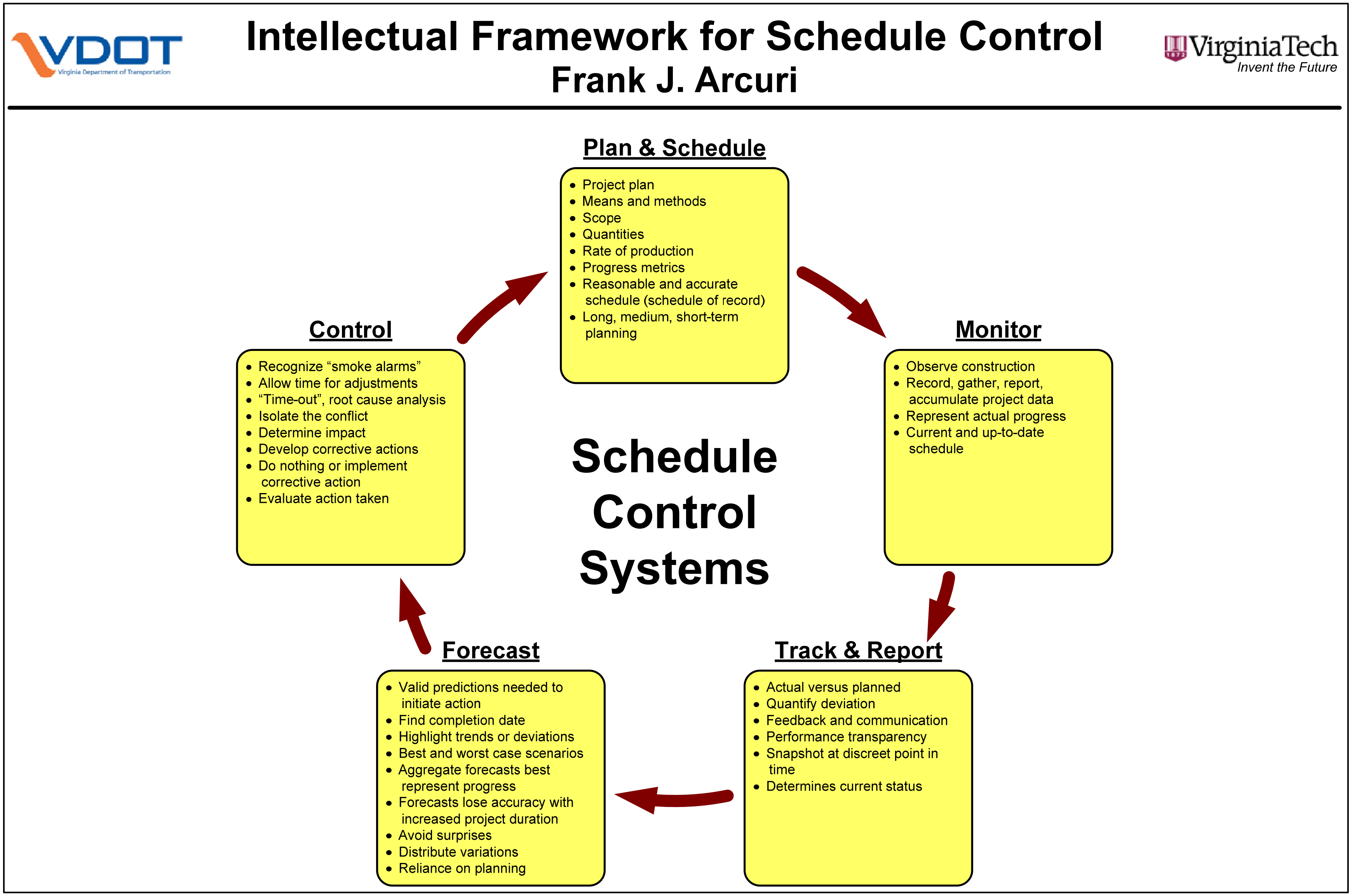






Appendix B – Supplemental Graphics




VDOT
Virginia Department of Transportation
Intellectual Framework for Schedule Control
Frank J. Arcuri
VirginiaTech
Invent the Future
Plan & Schedule
• Project plan
• Means and methods
• Scope
• Quantities
• Rate of production
• Progress metrics
• Reasonable and accurate schedule (schedule of record)
• Long, medium, short-term planning
Monitor
• Observe construction
• Record, gather, report, accumulate project data
• Represent actual progress
• Current and up-to-date schedule
Track & Report
• Actual versus planned
• Quantify deviation
• Feedback and communication
• Performance transparency
• Snapshot at discreet point in time
• Determines current status
Forecast
• Valid predictions needed to initiate action
• Find completion date
• Highlight trends or deviations
• Best and worst case scenarios
• Aggregate forecasts best represent progress
• Forecasts lose accuracy with increased project duration
• Avoid surprises
• Distribute variations
• Reliance on planning
Control
• Recognize "smoke alarms"
• Allow time for adjustments
• "Time-out", root cause analysis
• Isolate the conflict
• Determine impact
• Develop corrective actions
• Do nothing or implement corrective action
• Evaluate action taken
Schedule Control Systems

VITA

Frank J. Arcuri was born on January 28, 1983 in Utica, New York. He was raised in the Central New York city of Utica, where his parents, Frank and Wanda Arcuri, reside. He has an older sister, Michelle Arcuri, who resides in Albany, New York with her fiancé Francis Blanchard. His longtime girlfriend, Alicia Gifford, resides in Stamford, Connecticut.

Frank graduated Salutatorian from Thomas R. Proctor High School in 2001. He studied civil engineering at Union College in Schenectady, New York, graduating Magna Cum Laude with a Bachelor of Science in Civil Engineering in 2005. That fall, he continued his studies at Virginia Polytechnic Institute and State University in the Vecellio Construction Engineering and Management Program, where he was named a Charles E. Via Masters Fellow, and later a Vecellio Masters Fellow. There, under the direction of Dr. Michael C. Vorster and Dr. John C. Hildreth, he graduated in 2007 with a Master of Science in Civil Engineering. Frank resides in New York, New York and works for the Fluor Corporation as a project engineer at Ground Zero, building the World Trade Center Transportation Hub.