

APPLYING A STOCHASTIC LINEAR SCHEDULING METHOD TO PIPELINE CONSTRUCTION

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ABSTRACT: Pipeline construction is a highly repetitive and resource-intensive process that is exposed to various constraints and uncertainties in the working environment. Effective look-ahead scheduling based on the most recent project performance data can greatly improve project execution and control. This study enhances the traditional linear scheduling method with stochastic simulation to incorporate activity performance uncertainty in look-ahead scheduling. To facilitate the use of this stochastic method, a computer program, Stochastic Linear Scheduling Method (SLSM), was designed and implemented. Accurate look-ahead scheduling can help schedulers to better anticipate problem areas and formulate new plans to improve overall project performance.

Keywords: Pipeline construction; Linear scheduling; Simulation.

1. INTRODUCTION

Construction planning is a fundamental and challenging aspect of the management and execution of construction projects. In order to achieve reliable progress, efficient crew performance and a good coordination of various construction activities through careful planning and scheduling is indispensable. Poor scheduling can result in considerable waste as laborers and equipment become idle due to delayed completion of preceding tasks, limited availability of needed resources, or other space and time constraints.

Two types of schedules are frequently used in a construction project: master schedules and look-ahead schedules [1]. A master schedule provides management with the big picture of project time and procedure. A look-ahead schedule, or short-interval schedule, a schedule maintained during the actual construction operation, is an extraction from the master schedule that specifies the details of current performance and work scopes, along with coordination for the upcoming several weeks or months. A look-ahead schedule should be developed based on the most recent project performance data, and it must be updated periodically so that it can accurately reflect the current project status and provide a reliable forecast for future project performance. Compared with a master schedule, a look-ahead schedule provides the operation-level managers a more detailed and realistic view of future performance and potential problems so that waste and delays can be identified and eliminated.

Pipeline construction is a highly repetitive and resource-intensive process that is exposed to various

constraints and uncertainties in the working environment. Effective look-ahead scheduling based on the most recent performance data can help to ensure a smooth and continuous work flow. Traditionally, look-ahead scheduling has been presented in a bar chart or Critical Path Method (CPM) formats. The Linear Scheduling Method (LSM) provides an alternative. LSM is a graphical tool designed specifically for scheduling repetitive linear construction projects, such as pipeline projects [1]. In this research, LSM is used as the underlying algorithm for look-ahead scheduling. The pipeline construction process and the use of LSM are further described in the next section.

Regardless of the schedule format, the current industry practice of look-ahead scheduling is based on a deterministic analysis of actual project data—i.e., forecasting future performance using average past performance. This deterministic method is unable to consider the variability of productivity in forecasting future performance, which may result in a considerable amount of work interruption and crew idle time. This study enhances the traditional LSM with stochastic simulation to incorporate uncertainty in look-ahead scheduling. Further, this approach is demonstrated in an actual pipeline construction project case study. An introduction to pipeline construction, LSM, and past relevant studies is presented in the next section. This is followed by a description of the proposed stochastic linear scheduling method and the case study.

2. BACKGROUND

2.1 Pipeline Construction

A pipeline construction project operates like a moving assembly line, involving a variety of sequenced tasks and specialized crews, as shown in Figure 1. The specific location of the pipeline route is first identified and marked with stakes. The pipeline right-of-way is cleared of vegetation and graded to ensure a leveled base. Backhoes or trenching machines are then used to excavate a pipeline trench. This is followed by stringing the individual pipe sections along the trench line. Individual joints of pipe may also be bent to a desired angle, if required. After stringing and bending are completed, the pipe sections are welded together, coated, inspected, and placed on temporary supports along the edge of the trench. The pipe assembly is then lowered into the trench and tied into the preceding pipe section. The trench is then backfilled. After backfilling and cleaning up, the pipeline is hydrostatically tested for strength and leaks.

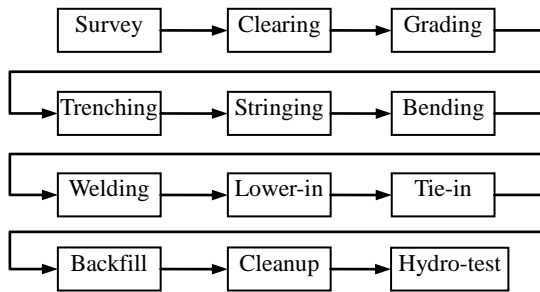


Figure 1. Pipeline construction process.

2.2 Linear Scheduling Method (LSM)

LSM is designed for scheduling linear construction projects that contain a family of repetitive and nearly identical tasks [1]. It represents a repetitive activity as a production line in a two-dimensional time and space graph, as illustrated in Figure 2. The horizontal axis represents time, and the vertical axis is the location of an activity or a crew. The slope of a production line represents its productivity rate. A production line may be a straight line if the productivity rate is constant. However, in real-world operations, a production line typically features varying slopes due to the variability in productivity rates, which can be attributed to many factors, such as quantity and complexity of work and weather conditions. The horizontal distance between two lines is a graphic representation of the time float, or time buffer, between the activities. Similarly, the vertical distance represents the physical distance, or space buffer, between the activities. Much previous research has shown that LSM allows better representation of scheduling information than the conventional CPM or bar charts in terms of time and space constraints, activity location, and productivity rates [2]. It is important that work continuity be maintained in order to achieve efficiency in a linear construction project. In this regard, LSM is particularly

useful in visualizing work flow and time and space constraints so that a scheduler can easily adjust activity start time or balance productivity rates to achieve work continuity. Therefore, LSM is used in this research for look-ahead scheduling of pipeline construction projects.

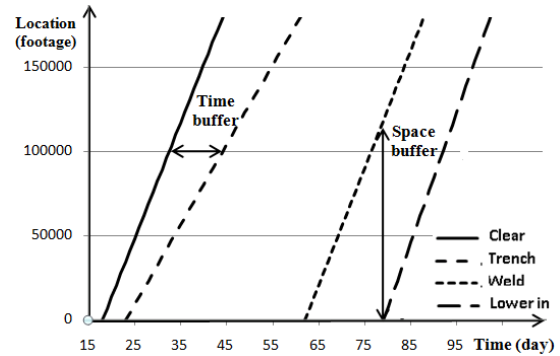


Figure 2. A sample LSM chart.

2.3 Related Research

Though look-ahead scheduling has been used for many years in construction, few publications provide information on it. In fact, the few sources that addressed the topic did little more than provide definitions [1]. Schedulers typically rely on readily available project progress data and their own subjective judgments in forecasting future performance, and the resulting look-ahead schedule is deterministic in nature.

Past research in LSM has been focused on applying LSM in early project planning, but uncertainty in project performance has not been fully addressed. Srisuwanrat and Ioannou [3] studied the optimization of repetitive schedules when activity durations are probabilistic. Two algorithms were developed to optimize work continuity and project cost by adjusting the start time of repetitive activities. In this study, only precedence logic relationships between activities were modeled, and productivity rates per day were assumed to follow the normal distribution. To make LSM suitable for practical look-ahead scheduling of horizontal linear construction projects (e.g., pipeline construction), our research here enhances the previous research in two areas: (1) formalizing the procedure of productivity data collection and analysis for measuring productivity variability in repetitive activities, and (2) modeling both time and space buffer constraints between activities while considering productivity variability. The following two sections describe the proposed stochastic linear scheduling procedure along with a case study applying the method to pipeline construction.

3. STOCHASTIC LINEAR SCHEDULING METHOD

3.1 System Procedure

The proposed Stochastic Linear Scheduling Method (SLSM) enhances the traditional LSM with the

capability of modeling the variability in activity performance based on actual productivity data. Simulation input modeling provides a way for a scheduler to measure and evaluate the variability in activity performance and later to incorporate it into look-ahead scheduling. To achieve this, actual project performance data must be properly collected and analyzed in order to measure the variability. Once productivity data are collected, they will be analyzed through a standard simulation input modeling procedure, which involves fitting the productivity data to standard statistical distributions and then determining the best-fitted distribution based on goodness-of-fit tests. The information received from input modeling allows schedulers to represent the variability of activity performance in the form of probability distributions. The data collection and input modeling procedures are further described and demonstrated through the case study.

For look-ahead scheduling purposes, the impact of the variability of activity productivity rates on future project performance is further evaluated through discrete-event simulation in SLSM. Discrete-event simulation is a mathematical-logical model representing a real-world system that evolves over time, allowing users to experiment with the model to analyze and predict system performance. To facilitate the use of SLSM, a computer program, Stochastic Linear Scheduling Method (SLSM), was designed and implemented. The program allows a scheduler to model and analyze repetitive linear construction projects using graphic modeling tools while considering variability in activity performance. This computerized tool and its development and application is described in the following sections.

Once the model is established, the scheduler can conduct “what-if” analysis or risk analysis by experimenting with the computerized simulation and observing its behavior. For example, experiments can be conducted to evaluate baseline schedule, total project duration, individual activity performance, and activity idle time. Accurate look-ahead scheduling can help schedulers to better anticipate problem areas and formulate new plans to improve overall project performance.

3.2 Simulation Program

The SLSM program was implemented within a simulation tool development environment, Symphony, which allows a developer to design highly flexible simulation tools supporting graphical and hierarchical modeling [4]. The developed SLSM program can accurately model repetitive activities, precedence relationships, and time and space buffers, and it allows users to experiment with the model and observe outputs through a variety of output reports. SLSM contains two fundamental modeling elements: *Project* and *Activity*,

as described in Table 1. Using these two elements, a scheduler can assemble a model to graphically represent repetitive activities involved in a linear construction project. For the current version of the program, the model output data are exported to a Microsoft Access database where graphic results such as an LSM chart can be produced.

Table 1. SLSM Modeling Elements

Element	Description
<i>Project</i>	The <i>Project</i> element represents the linear construction project and is the parent element of any <i>Activity</i> element. Users can specify the total quantity of work for the project in the <i>Project</i> element. The element also handles collecting simulation results and exporting these results to an external database.
<i>Activity</i>	This is a generic element that can represent either a predecessor or successor. Each instance of the <i>Activity</i> element has an input port and an output port. When the output of an <i>Activity</i> element is connected to the input of another activity element, the former <i>Activity</i> element becomes the predecessor, while the latter element becomes the successor. If the input of an element does not connect to any <i>Activity</i> element, this activity becomes the first activity of the project and its daily start and finish events are controlled only by the total work quantity. The activation of other <i>Activity</i> elements with predecessors is determined by the performance of their predecessors and user-defined time and/or space buffers.

4. A CASE STUDY OF PIPELINE CONSTRUCTION

A pipeline construction project was selected to demonstrate and evaluate the applicability of the proposed SLSM for look-ahead scheduling. The sample project involves the construction of approximately 130 miles of 30-inch pipeline. The case study was focused on understanding the current practice of look-ahead scheduling, collecting actual performance data, and demonstrating the usage of SLSM.

In this project, the contractor was responsible for main pipe installation activities such as trenching, stringing, bending, pipe laying, backfilling, tie-in, cleaning, and hydro-testing. Several subcontractors were also involved in this project for activities such as horizontal directional drilling, concrete work, and coating.

The original look-ahead schedule was prepared by the contractor in a table format on a weekly basis. The

look-ahead schedule contains information on upcoming activities, mile-post targets, and comments. Three sources of information are collected in preparing the look-ahead schedule. The first source of information is the most recent activity progress data, monitored daily by the contractor and expressed in terms of footage per day. The second source of information is a list of potential operation problems identified through discussion among field managers, superintendents, and subcontractors at the weekly meeting. The third source of data is the forecast of upcoming work performance based on a scheduler's evaluation of each activity's recent productivity and its predecessor's progress. The productivity forecast is calculated deterministically as a moving average of the previous 3 to 5 weeks' productivity rates.

In a linear construction project, maintaining a crew's continuous performance is essential to achieving the activity milestones because successor activities can only be performed after their predecessors are completed. Therefore, achieving reliable milestones for each activity is extremely desirable for maintaining a smooth operation and minimizing the overall project duration. As mentioned previously, LSM is an effective scheduling method for linear construction work and, therefore, it was proposed to the contractor as an alternative look-ahead scheduling method. Furthermore, the proposed SLSM allows schedulers to evaluate the impact of the variability of project performance and take proactive measures to prevent work interruptions and thus reduce crew idle time. The application of SLSM in the sample project is described in the following sections.

4.1 Data Collection

In the sample project, the contractor already had a well-structured progress-monitoring and reporting system that continuously captured performance data that could be used to model the variability of productivity rates. Physical construction progress data were collected through the Construction Daily Progress Report prepared by superintendents. In addition to progress data, this report also contained information about working conditions, quality, safety, and regulatory compliance. Daily construction progress is measured by "From" and "To" stations, which represent the start location and the end location of a crew in a working day, respectively. Table 2 shows a sample of daily progress data, from which the productivity rate measured by footage per day can be easily derived. Productivity rates were reported in the same way for other activities, such as clearing, grading, trenching, bending, welding, lower-in, tie-in, backfill, and cleanup. As of fall 2008, 2 to 5 months of data were collected for the above-mentioned activities as they progressed to different locations.

Table 2. Daily Progress and Productivity

Date	Task	Station		Footage	Productivity (ft/d)
		From	To		
9/15	Stringing	5484+00	5636+00	15,000	15,000
9/16	Stringing	5636+00	5705+83	6,983	6,983
9/17	Stringing	5705+83	5806+00	10,017	10,017
9/18	Stringing	5806+00	5972+00	16,600	16,600
9/19	Stringing	5972+00	6140+00	16,800	16,800

Traditionally, the contractor analyzes productivities on a weekly basis for look-head scheduling. As mentioned above, the productivity of the future work is estimated as the average of the 3 to 5 preceding weeks' productivity rates. In the proposed SLSM method, it is suggested that daily productivity rates be used in lieu of weekly rates in order to better reflect the variability of project performance. The following section discusses how to model this variability based on the collected daily productivity data.

4.2 Input Modeling

In order to accurately represent the variability of an activity's performance, the productivity rate of an activity can be modeled as a probabilistic distribution [5]. The process of determining the underlying statistical distribution of an activity's productivity rate is an example of simulation input modeling, which provides a way for a scheduler to evaluate the variability in activity performance. To establish a statistical distribution to represent an activity's productivity, the above-mentioned daily productivity data was used. The input modeling procedure involves two steps: distribution fitting and a goodness-of-fit test. The burden of the input modeling procedure can be greatly reduced by using commercially available input-modeling software. For this project, BestFit® [6], recently incorporated into a risk-analysis program called @RISK, was used. For the purposes of this research, the program will be referred to hereinafter as BestFit.

Distribution fitting

The first step in modeling an activity's productivity rate is to generate a histogram to provide understanding of the characteristics related to type and shape of possible underlying distributions. Theoretical standard distributions, such as normal, beta, and triangular distributions, can be used to "test-fit" the data set and the histogram. Parameters of these distributions can be determined through this fitting process. Because of the use of computerized input-modeling software, a large number of standard distributions can be automatically fitted to the data set in a short period of time. For example, BestFit provides 28 different probability distributions for fitting a data set. These candidate

distributions are ranked by the quality of fit, as described below.

Goodness-of-fit test

While any of the standard distributions can be used to represent the raw data, they can be very different in terms of how closely they represent the true underlying distribution of the productivity data. To test the quality of fit, there are heuristic procedures based primarily on visual inspection as well as goodness-of-fit methods based on statistical hypothesis tests [5]. To make input modeling easier to learn and use by industry practitioners, the goodness-of-fit test approach was adopted, because these tests are typically automated in input-modeling software. A goodness-of-fit test is a statistical hypothesis test that is used to determine if the raw data points are an independent sample from a particular statistical distribution. It describes statistically how well a standard distribution fits a set of raw data. Frequently used tests include the Chi-square test and the Kolmogorov-Smirnov test [6].

While determining distribution parameters and selecting the best-fitted distribution is difficult to perform manually, input-modeling software such as BestFit automates this process and makes input modeling much more accessible to practitioners who lack knowledge in statistics. The input to BestFit is the daily productivity rate of an activity, as discussed previously. The output from BestFit is a list of ranked and parameterized distributions. A user can then pick the best-fitted distribution to represent the activity's performance. Table 3 shows the selected distributions along with their parameters for a group of repetitive activities. It should be noted that the data were scaled uniformly for confidentiality reasons.

Table 3. Selected Input Models

Task Name	Statistical Distributions
Surveying	Exponential with mean = 16629
Clearing	Exponential with mean = 9527
Grading	Normal with mean = 2874 and standard deviation = 1363
Trenching	Triangular with low limit = 670, most likely = 1809, and high limit = 10720
Stringing	Normal with mean = 4837 and standard deviation = 3011
Bending	Beta with a = 2.3, b = 3.4, low = 670, and high = 13812
Welding	Beta with a = 1.2, b = 1, low = 700, and high = 9800
Lower-in	Normal with mean = 5882 and standard deviation = 3033
Tie-in	Exponential with mean = 2007
Backfill	Beta with a = 1.2, b = 2.9, low = 804, and high = 15758
Clean up	Normal with mean = 3688 and standard deviation = 1221

4.3 Simulation Modeling

The pipeline construction operation can be modeled using the developed SLSM program. A *Project* element must first be defined. A user determines the default total work quantity in footage and the location of the external database for exporting simulation output. Within this *Project* element, a user can add multiple *Activity* elements to represent individual activities. These *Activity* elements can be linked together to show the precedence relationships between them.

For each *Activity* element, four user input parameters must be defined: planned start time, time buffer, space buffer, and productivity rate (ft/d). An activity's planned start time is measured as the number of days between the first day of the project and the first day of the activity. Time buffer and space buffer are measured by days and footage, respectively, and are optional. The productivity rate can be specified as either a constant value or a statistical distribution, as discussed in the previous section.

To demonstrate the use of the SLSM program, two models were implemented: one model for the deterministic baseline schedule and the other for a simulated look-ahead schedule. For the baseline model, activities' planned start times and productivity rates were quoted from the contractor's baseline schedule. For the look-ahead model, actual data and the distributions defined in Table 3 were used to represent the productivity rates. A screenshot of a sample SLSM model and a data-entry form for an *Activity* element are shown in Figure 3.

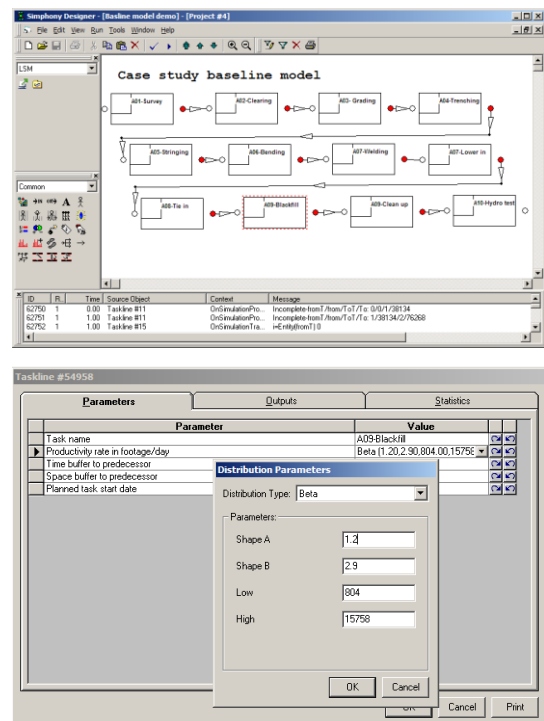


Figure 3. An SLSM model and model inputs.

4.4 Output Analysis

After a model and its parameters are set, users can experiment with the simulation model and collect outputs. A simulation experiment usually contains a large number of runs, often as many as more than 30. Each simulation run represents one observation of the possible future project performance and it predicts the project performance based on a set of random productivity rate values generated according to the distributions defined in Table 3. The results from these simulation runs can then be gathered and used to forecast project as well as individual activity performance. This section demonstrates some sample outputs from simulation experiments.

Figure 4 shows a comparison of the deterministic baseline schedule (solid lines) and a simulated look-ahead schedule (dotted lines). It can be seen that the actual productivity rates deviate from the deterministic estimates in the baseline schedule. Outputs from the simulated look-ahead schedule model can be used to analyze the uncertainty of the total project duration. Each of the many simulation runs predicts a possible total project duration scenario. The duration data can be used to determine either the probability of completing a project within a certain number of days or the project duration corresponding to a certain risk level. Figure 5 shows the probability distribution of the total project duration. For example, according to this distribution, the probability of completing the project within 300 days is only 26%, but the project has a 90% chance to complete within 334 days.

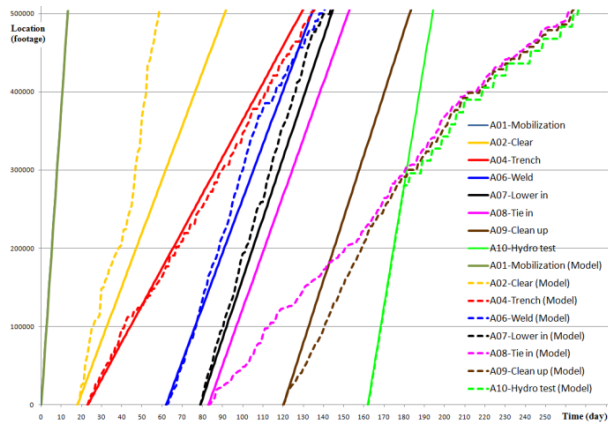


Figure 4. A comparison of baseline schedule and simulated look-ahead schedule.

Many observations related to an individual activity’s productivity rate and idle time can also be obtained. As an example, the performance range chart can forecast the performance of an activity on a certain confidential interval. Figure 6 shows the performance range of the clean-up activity.

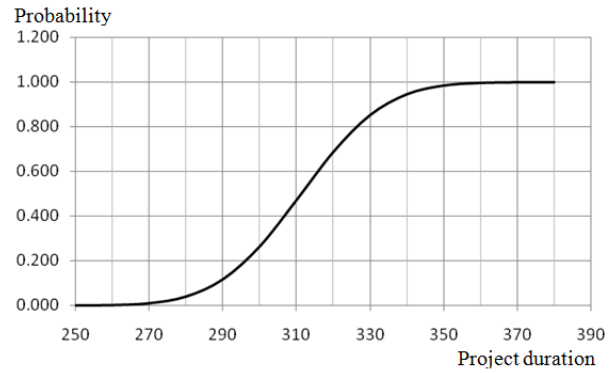


Figure 5. Probability distribution of total project duration.

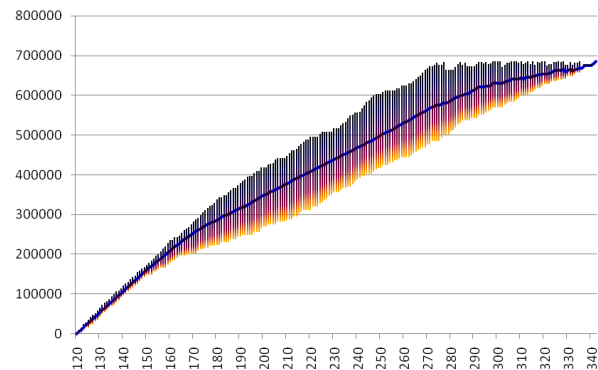


Figure 6. Activity performance range chart.

A careful analysis of the activity idle-time pattern can also allow a scheduler to better anticipate problem areas and formulate new plans to reduce idle time and interruptions while considering the total project duration. The new plans may involve resource reallocation, modification of the planned start time of an activity, or revision of the time and space buffer requirements. For example, the actual performance of the tie-in activity is substantially slower than the planned rate and causes major delays in the subsequent activities. It indicates that more tie-in crews should be added in order to reduce the overall project duration and avoid the idle time of succeeding activities such as cleanup and hydro-testing. After these adjustments, the simulation model can be modified accordingly and additional simulation experiments can be conducted to examine the performance of the new plan.

CONCLUSIONS

This research introduces computer simulation as an alternative tool for look-ahead scheduling in linear construction projects. In the proposed method, actual performance data is first collected from ongoing construction operations and used to model the variability of activity performance. This variability is then incorporated into a process simulation model that can be used to generate look-ahead schedules. A

computer program, SLSM, was designed and implemented. SLSM allows schedulers to model and analyze repetitive linear construction projects while considering variability in activity performance. Various data analyses can be performed based on the simulation output data—e.g., evaluating baseline schedule, the total project duration, individual activity performance, and idle time. Better capability in forecasting future project performance based on actual productivity data can help a scheduler anticipate problem areas and formulate new plans to improve project performance.

The current research allows a scheduler to freely design model parameters and experiment with them to measure the resulting project performance. This design-and-experiment approach may prove to be too time consuming in searching for the optimal or near-optimal solutions. Schedule optimization with the consideration of uncertainty in activity performance needs to be studied in future research. Such a reliable optimization algorithm can help a scheduler quickly design alternative plans that can lead to better overall project performance.

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