Schedule Risk Analysis: Why It is Important and How to Do It

Stephen A. Book
Chief Technical Director
MCR, Inc.
390 No. Sepulveda Blvd.
El Segundo, CA 90245
(310) 640-0005 x244
sbook@mcri.com

Presented to Session on

Business Cases and Acquisition Strategies

Ground System Architectures Workshop (GSAW 2002)

The Aerospace Corporation, El Segundo, CA

13-15 March 2002

Abstract

Ability to accurately define the duration of a sequence of tasks is challenged by uncertainties similar to those encountered in building an estimate of a program's future cost, namely the impact of technical adversity, resource constraints, and programmatic obstacles. Schedule-risk analysis is the process of associating a degree of confidence with each schedule-duration estimate. The combination of defining probability distributions for various scheduled task durations and establishing network relationships among the tasks allows one to forecast the probability of meeting the targeted dates of key milestone events. Schedule-risk analysis takes account of the fact that in the uncertain art of schedule estimating the best we can hope to do is to estimate the degree of uncertainty associated with each possible project duration. This tutorial explains the context and basic principles of conducting and documenting a schedule-risk analysis. Duration estimates derived from schedule-risk analyses strengthen management control by providing insight into the sources, likelihoods, and probable magnitudes of possible schedule slips in government procurements. The commonly used "most probable duration", which does none of this, cannot serve as a management and budgeting tool after the project commences, since no particular confidence level, error bound, or risk issues are associated with it.

Contents

Contents

- The Difference Between Cost Estimating and Schedule Estimating
- The Project Schedule Network and Its Critical Path
- The Schedule-Risk Imperative and How to Deal with It
- Summary

Cost Estimating

- **The Process**
  - List Cost Elements in Linear List
  - Estimate the Cost of Each Element
  - Sum All Those Estimates
  - Result is an Estimate of Total-System Cost
- **The Units**
  - Money (e.g., Dollars)
- **The Mathematics**
  - Adding

Schedule Estimating

- **The Process**
  - Do Not List Schedule Elements in a List
  - O.K., You Can Estimate the Duration of Each Element
  - But Do Not Sum All Estimates
  - Result Would not be Estimate of Total-Project Duration
- **The Units**
  - Time (e.g., Months)
- **The Mathematics**
  - Not Adding
- **Why Does This Matter?**
  - It Illustrates the Fundamental Difference between Dollars and Time
  - Dollars Can Be Moved From One Task to Another, So Underruns and Overruns Cancel Each Other Out
  - Time Cannot Be Moved From One Activity to Another, So “Ahead-of-schedule” and “Behind-schedule” Conditions Cannot Cancel Each Other Out (the “Behind-schedule” Condition Remains)

Time is More Complex Than Money

- **A Task, Project, or Program Consists of a Set of a Large Number of Specific Individual Activities, Interrelated among Themselves in Complicated Ways**
- **The Arrangement of Those Complicated Interrelationships is Called a "Network"**
- **A Network is, More Precisely, a Linking of the Individual Activities that Indicates for Each Particular Activity …**
  - Which Activities ("Predecessors") Must be Completed Prior to the Start of that Particular Activity, and
  - Which Activities ("Successors") Cannot Start Until that Particular Activity is Completed
- **A "Schedule" is a Listing of Activities, together with Time Durations Allocated to the Completion of Each One**
- **A "Schedule Network" is a Network in which Each Activity is Allocated a Time Duration**

Contents

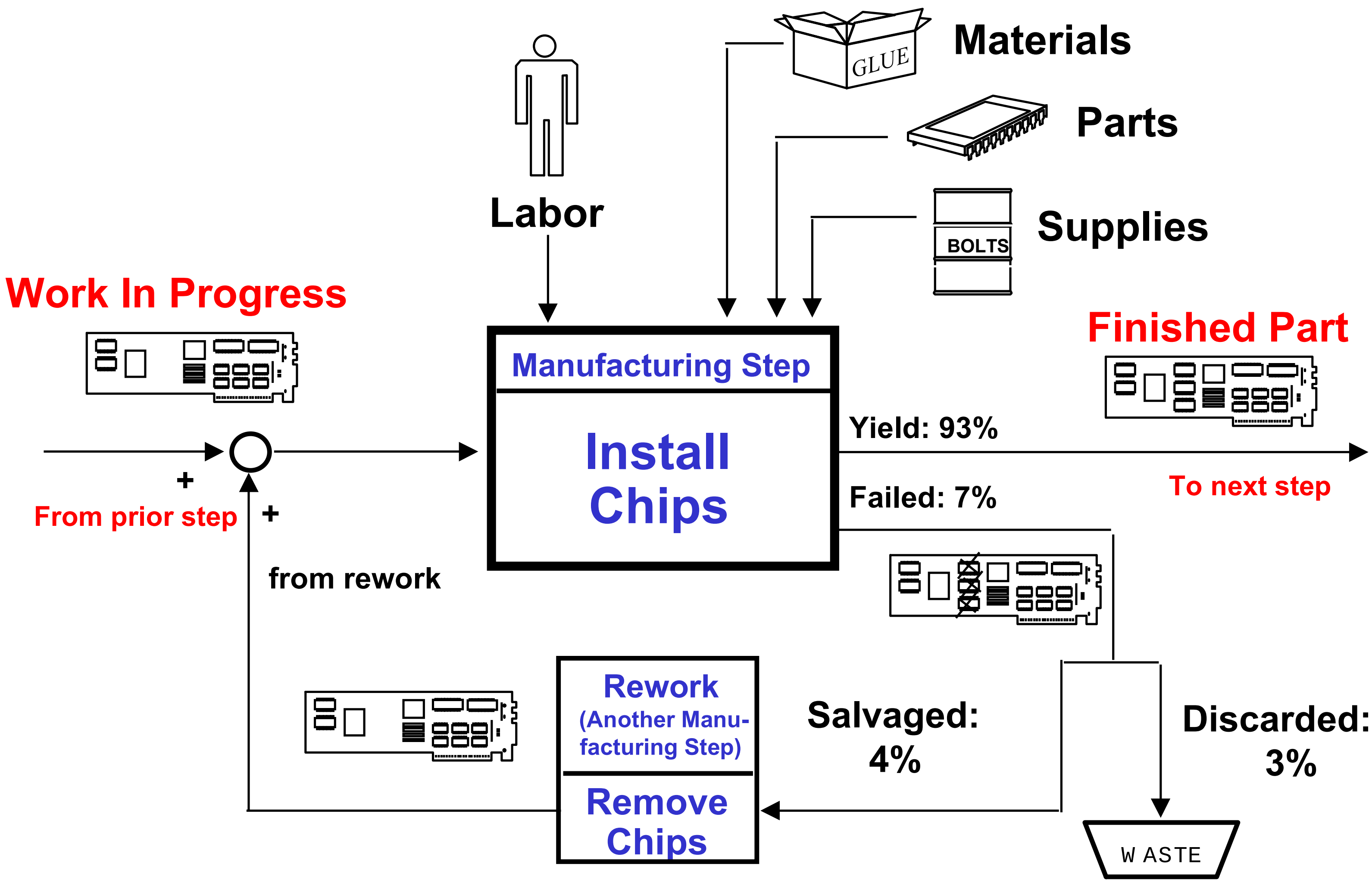
- The Difference Between Cost Estimating and Schedule Estimating
- The Project Schedule Network and Its Critical Path
- The Schedule-Risk Imperative and How to Deal with It
- Summary

How to Build and Analyze a Schedule Network

- **Break Process Flow Into Small Steps of Clearly Defined Activities, Modeling Predecessor and Successor Relationships among Steps**
- **Estimate ...**
  - … Time Duration of Each Step Based on Probable Work Time for Each Type of Labor Involved
  - … Yield Statistics at Each Step: What Fraction of Products Output are Expected to be Good?
- **Define Rework Loops if it's Possible to Rework Bad Parts**
- **Combine* Step Durations to Obtain an Estimate of Total Time Required to Meet Specific Milestones**
- **Identify the "Critical Path" through the Network, namely the List of Individual Activities that, if Delayed, Will Delay the Entire Project**

*** Not Necessarily "Add"**

Example: A Manufacturing Step



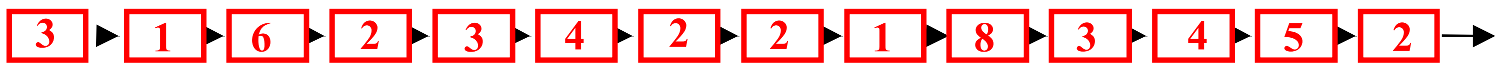
Schedule Networks in Context

- **Analogy: "Schedule Network" is to Schedule Analysis as "Work Breakdown Structure" is to Cost Analysis**
  - Work Breakdown Structure: a List of All Features of a Project that Require Expenditure of Some Amount of Dollars to Complete
  - Schedule Network: an Arrangement of All Features of a Project that Require Expenditure of Some Amount of Time to Complete
- **Here's a Different Cost-Analysis Analogy: "Schedule Network" is the Schedule-Analysis Version of Activity-Based Costing (ABC) Model**
  - Activity-Based Costing Model
    - Also Called "Bean-Counting" or "Bottom-up" Model
    - Generic Shell for Modeling Costs of Project Development and Production Processes
    - Analyst Assigns Appropriate Cost Estimates to Each Activity Involved in Development and Production
  - Schedule Network
    - Generic Shell for Modeling Durations of Project Development and Production Processes
    - Analyst Assigns Appropriate Duration Estimates to Each Activity Involved in Development and Production (Activity Durations Typically Serve as Basis for Contractor Cost Estimates)

Ways of Arranging Predecessor and Successor Activities in a Network

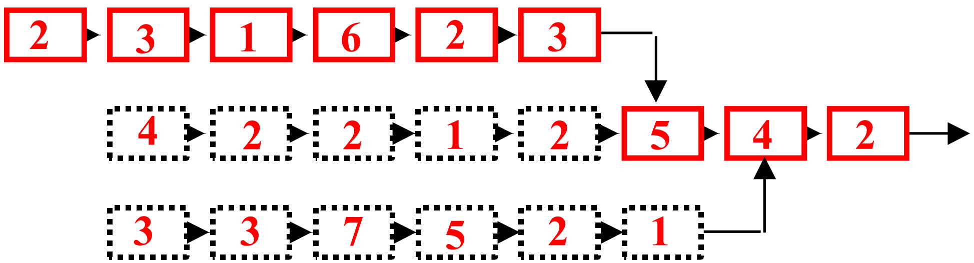
- "Serial" Arrangement: Two Activities are "in Serial" if Each is a Predecessor or a Successor of the Other
- "Parallel" Arrangement: Two Activities are "in Parallel" if Neither is a Predecessor or a Successor of the Other
- "Tree Structure": A Mixture of Serial and Parallel Activities
- "Feedback Loop": A Sequence of Activities that Contains at Least Two Activities that are both Predecessors and Successors of Each Other

Serial Network in Detail



- Number in Each Box Indicates Number of Days Allocated to Task Represented by Box
- Serial Network's Critical Path Passes Through All Boxes, and its Duration is the Sum of the Durations of the Individual Activities in the Serial Network
- Critical Path, Consisting of Boxes Outlined in Solid (Red) Lines, has Total Duration = 46 days

Parallel Network in Detail



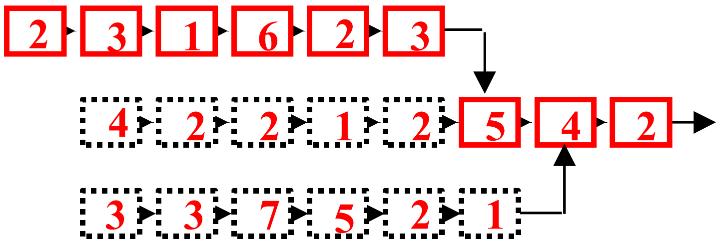
- Numbers in Boxes Indicate Number of Days Allocated to Task Represented by Box
- Parallel Network's Critical Path Passes Through Those Boxes whose Combined Duration is the Longest Possible through the Network
- Critical Path, Consisting of Boxes Outlined in Solid (Red) Lines, has Total Duration = 28 Days
- Sequences of Boxes Outlined in Dotted Black Lines Have "Slack Time", 6 Days and 1 Day, Respectively

Why Cost-Analysis Software Cannot be Used for Schedule Analysis

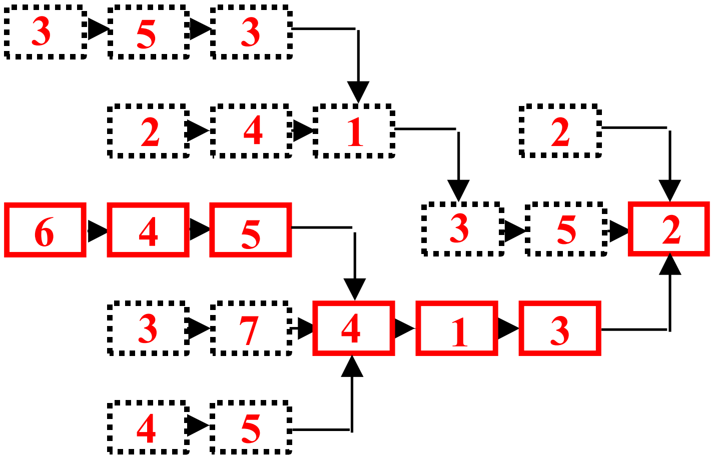
- A Work- Breakdown Structure for Cost Analysis is a "Linear" List, so Total Project Cost is Calculated by Adding Together the Costs of All Items on That List

0.0	TOTAL BRILLIANT EYES PROGRAM
1.0	SPACE BRILLIANT EYES SYSTEM
1.1	System-Level Costs
1.2	Space Vehicle (SV) Segment
1.2.1	SV Program Level
1.2.2	Space Vehicle Prime Mission Equipment
1.2.2.1	Space Software
1.2.2.2	Space Vehicle
1.2.2.2.1	Space Vehicle IA&T
1.2.2.2.2	Sensor Payload
1.2.2.2.3	Insertion Vehicle
1.2.2.2.4	Survivability
1.2.3	Prototype Lot
1.2.4	Spare Parts
1.2.5	Technology and Producibility
1.2.6	Aerospace Ground Equipment
1.2.7	Launch Support
1.3	Engineering Change Orders (ECOs)
1.4	Other Government Costs
1.5	Risk

- A Schedule Network (Unless it is Entirely Serial) is Not Linear, and Therefore Total Project Duration Cannot be Calculated by Adding Together the Durations of All Activities in the Network

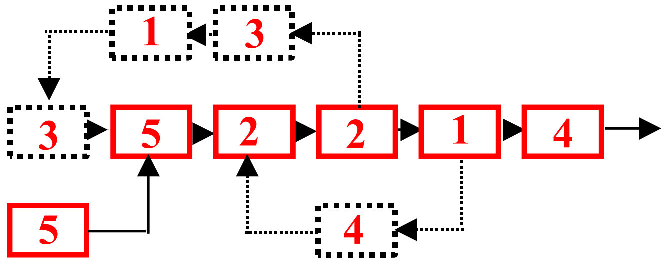


Tree-Structured Network in Detail



- Numbers in Boxes Indicate Number of Days Allocated to Task Represented by Box
- Critical Path Passes Through Those Boxes whose Combined Duration is the Longest Possible through the Network
- Critical Path, Consisting of Boxes Outlined in Solid (Red) Lines, has Total Duration = 25 Days
- Sequences of Boxes Outlined in Dotted Black Lines Have "Slack Time", 3 Days, 5 Days, 21 Days, 5 Days and 6 Days, Respectively

Feedback Loop in Detail



- Numbers in Boxes Indicate Number of Days Allocated to Task Represented by Box
- Critical Path Passes Through Those Boxes whose Combined Duration is the Longest Possible through the Network
- If "Feedback" is not Exercised, Critical Path, Consisting of Boxes Outlined in Solid Red Lines, Has Total Duration = 19 Days
- If "Feedback" is Exercised Once, All Boxes Lie on the Critical Path, which then Has Total Duration = 44 Days

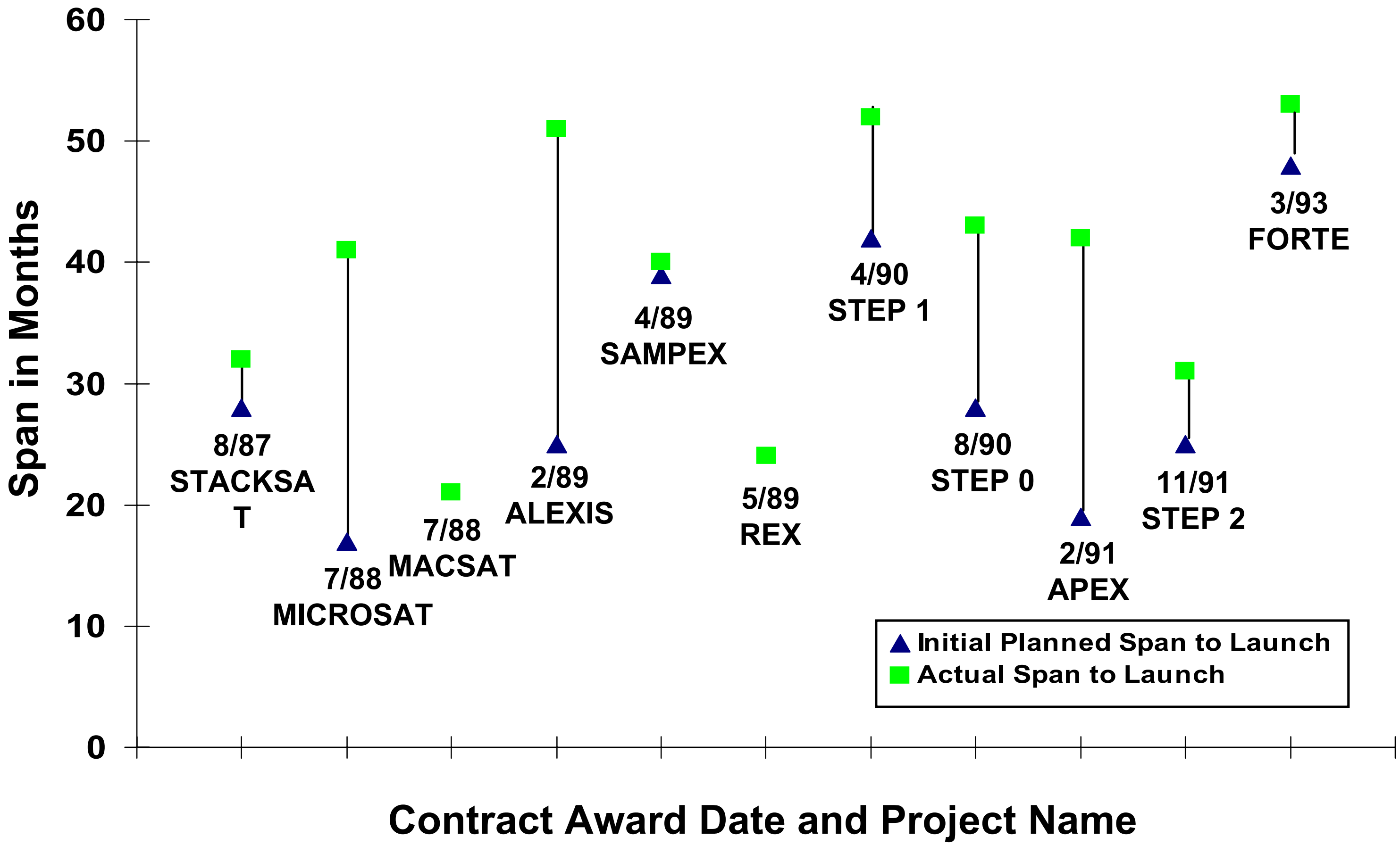
Network Schedule Analysis Process

- **Establish Logical Flow of How Activities Lead to Completion of Project**
  - Define How Activities are Linked
  - Determine Order in which Activities Must be Done
  - Identify Milestone Activities and "Choke Points"
- **Estimate Activity Duration Times**
- **Evaluate Project Completion Time**
  - Construct Critical Path
  - Sum Estimated Duration Times of Activities that are on the Critical Path to Estimate Total Project Duration
  - Compare the Total-Duration Estimate with Project's Required Completion Time

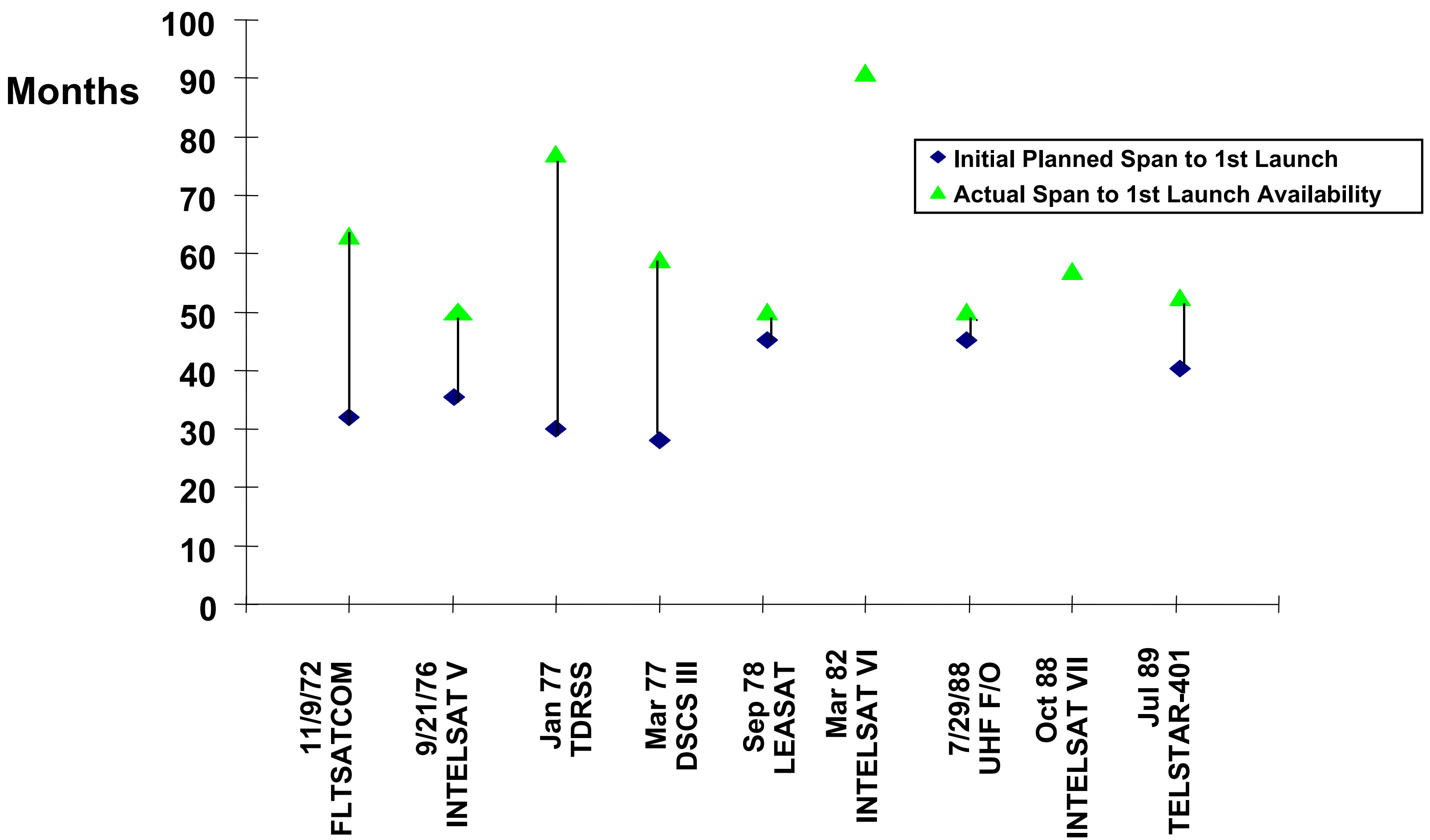
Schedule “Drivers” Impact Schedule

- Weight of Components and Subsystems
- Power, Cooling, Attitude-Control Needs
- Integration and Testing
- Thrust Requirements
- Data Memory Requirements
- Number of Source Lines of Code to be Written
- Software Testing Complexity
- Special Mission Equipment
- Subcontractor Interrelationships
- Etc., etc., etc.

Smallsat Schedule History: Months from Development Contract Award to Launch



Satellite Development Contract Award to First Launch Availability



Contents

- The Difference Between Cost Estimating and Schedule Estimating
- The Project Schedule Network and Its Critical Path
- The Schedule-Risk Imperative and How to Deal with It
- Summary

The Trouble with Schedule Estimating

- **Project Management and User Organizations Need to Estimate Project Schedule for Use in**
  - Analysis-of-Alternative Studies at "Idea" Stage
  - "Handoff" Analyses at "Go/NoGo" Stage
  - Project Planning after "Go-Ahead" Authority Given
- **But Historical Record Consistently Shows that High-Tech Development and Production Projects Tend to Take Longer to Complete than Estimated, Sometimes by Wide Margins**
- **End of Cold War Led to Questions Being Asked**
  - **"Why Do Projects Always Take Longer than Anticipated"**
  - **"Why are We Always Surprised When They Do?"**
- **Objective of this Section: Answer those Questions and Suggest Method of Avoiding Unanticipated Schedule Slips**

1st Problem: No "Point" Estimate of Schedule Duration Can be Correct

- **Schedule Duration, Particularly of a Project that Pushes State of the Art in One or More Areas, is Necessarily Nebulous at Project Start due to Several Factors**
  - Existing Technical Capability Often Falls Short of Project Needs
  - Software Requirements Cannot be Described in any Finite List
  - "Normal" Schedule Slips of Varying Lengths Result from Integration Problems, Test Failures
  - Various Other Anticipatable and/or Unforeseen Events
- **"Point" Estimate of Project Schedule Duration Cannot be "Correct" Because**
  - Point Estimates of Activity Durations are not Correct
  - Project Point Estimate is Sum of "Incorrect" Activity Estimates
- **"Actual" Project Duration Will Fall Within Some Range Surrounding "Point" Estimate (with some degree of confidence)**
  - The Best We Can Hope to Do Is to Understand the Uncertainty
  - Understanding the Uncertainty Will Help Us Make Provision for It

Traditional Schedule-Estimating “Roll-Up” Process

- Construct Network of Project’s Activities
- Determine Best Estimate of Time Duration for Each Activity in Network
- Compare Activities’ Best Estimates to Find Network’s Critical Path
- Sum All Best-Estimate Durations of Activities on the Critical Path
- Define Sum to be Best Estimate of Project’s Schedule Duration

2nd Problem: Term “Best” Estimate Has No Standard Definition

- **For Each Activity, Is “Best” Estimate …**
  - ... That Activity’s “Most Likely” Duration (“Mode”)?
  - … Its 50th-Percentile Duration (“Median”)?
  - … Its “Expected” Duration (“Mean”)?
- **These Three Definitions Lead to Numbers that are Almost Always Different from Each Other**
- **Roll-Up “Best” Estimate of Complete Project Duration (as described on previous chart) is Almost Never One of These**

Schedule Durations Have Probability Distributions

- **How Do We Know That?**
  - "Best" Estimate is not the Only Possible Estimate, so Other Estimates Must be Considered "Worse"
  - Common Use of Phrase "Most Likely Duration" Implicitly Assumes that Other Possible Durations are "Less Likely"
  - "Mean," "Median," "Mode" are Statistical Terms Characteristic of Probability Distributions
- **This Discussion Implies that Activity Durations Have Probability Distributions, i.e., They are "Random Variables"**
- **"Actual" Project Duration is an Uncertain Quantity that Can be Modeled as Sum of Random Variables**

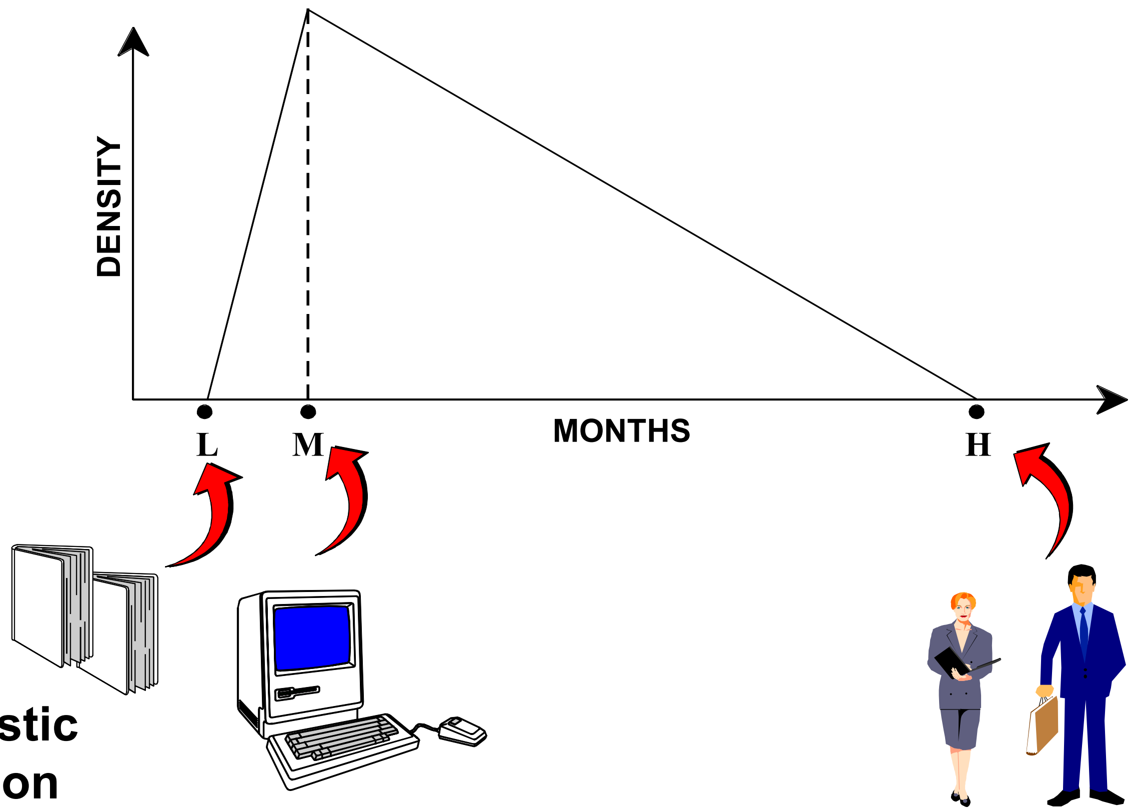
“Risk Drivers” Impact Activity-Duration Uncertainty

- Beyond-State-of-the-Art Technology, e.g., in Power, Thrust, Attitude Control, Data Processing, Communications
- Unusual Production Requirements, e.g., Use of Toxic Materials, Geographically Dispersed Facilities
- Cost Constraints, e.g., Project Funding Stretch-Out
- Software Development Issues
- Interfaces Among Multiple Contractors
- Subcontractor, Supplier Viability
- System Integration and Testing
- Unforeseen Events
- Etc., etc., etc.

Modeling an Activity Duration's Probability Distribution

- **One Way to Start: Compile Duration Estimates from Different Sources and Rank Estimates in Magnitude, e.g.,**
  - Contractor's Estimate
  - Project Manager's Estimate
  - "Independent" Estimate
  - Risk-impacted Estimate
- **Associate Confidence Levels with Ranges between Estimates, Using Information Available in Different Situations and at Different Stages of Project Development**
  - Cannot Be Looked up in the Back of the Book
  - Is Not Directly Derivable From Historical Data Due to Availability of Only Incomplete Information on Canceled Programs
  - Must Be Subjective, Knowledge-based Consensus of Technical Experts in a Particular WBS Element, Usually the Same People Who Are Developing the Project's Risk-Mitigation Plan and Maintaining the "Risk Watch List"
  - Should Be Standard Part of Risk-Mitigation Plan

A Limited-Information Model: Triangular Distribution of Activity Duration

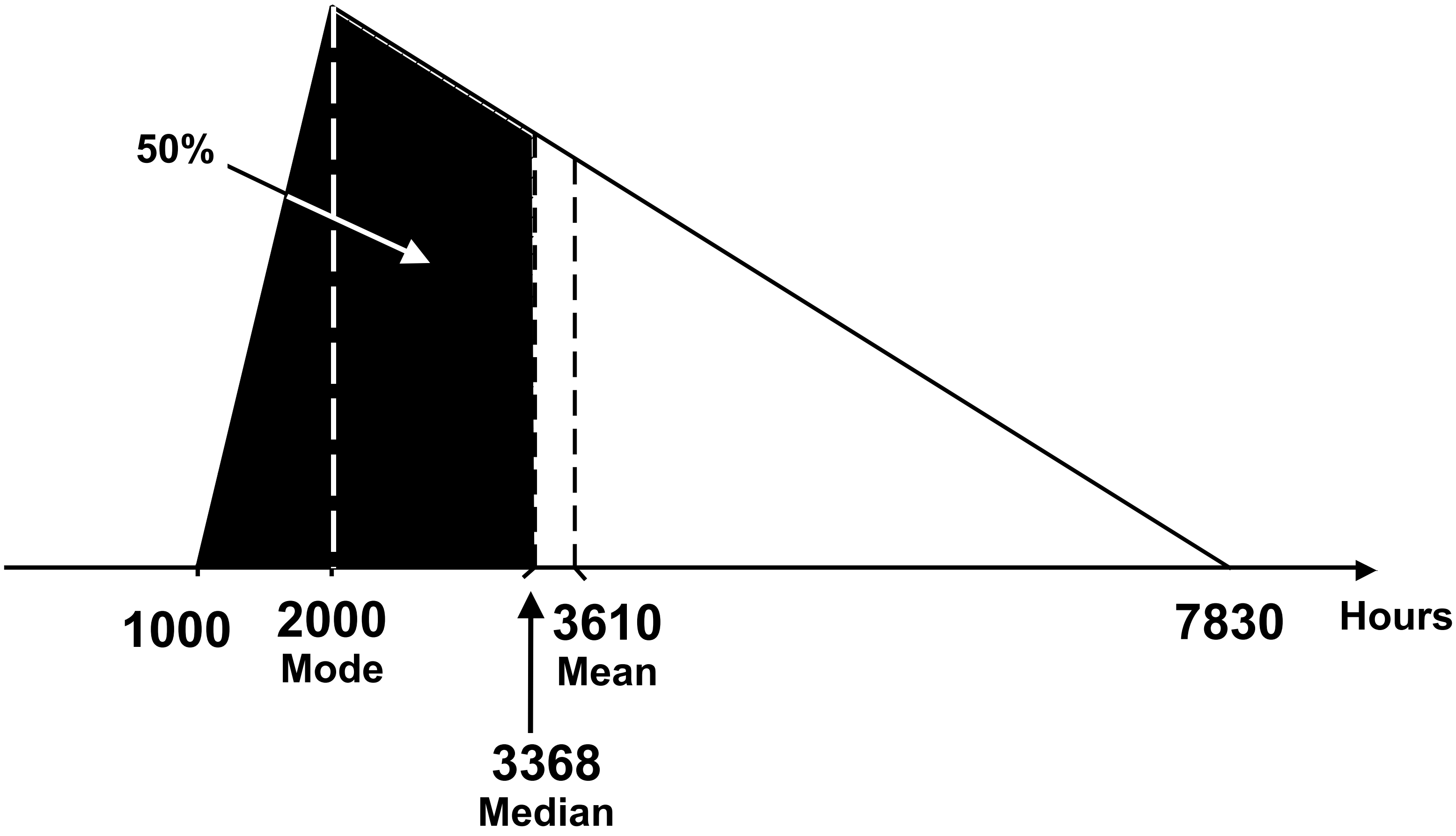


Optimistic Duration

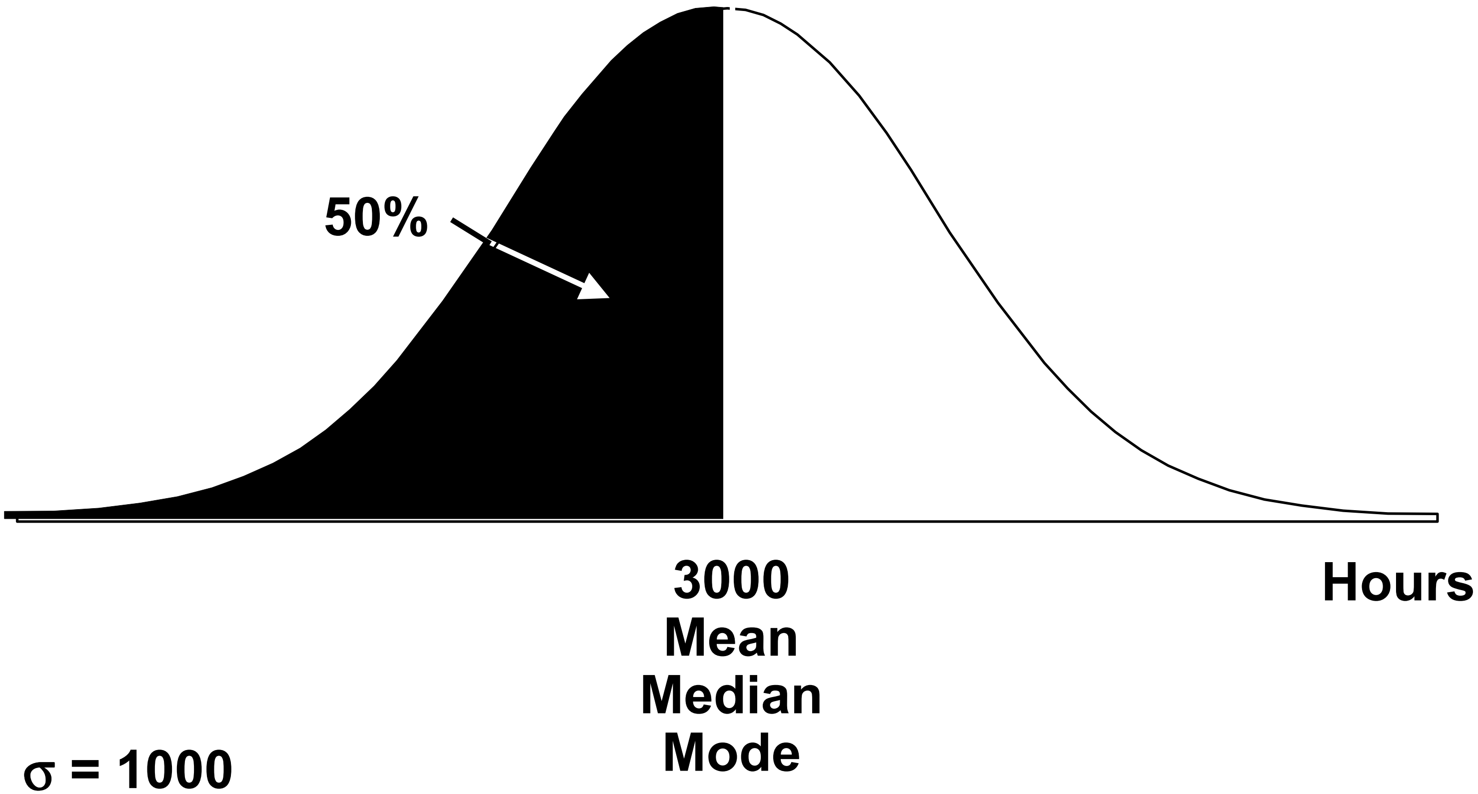
Best-Estimate Duration (Mode)

Schedule Implication of Technical Assessment

Statistical Characteristics of Triangular Duration Distributions



Statistical Characteristics of of Normal (Gaussian) Distributions



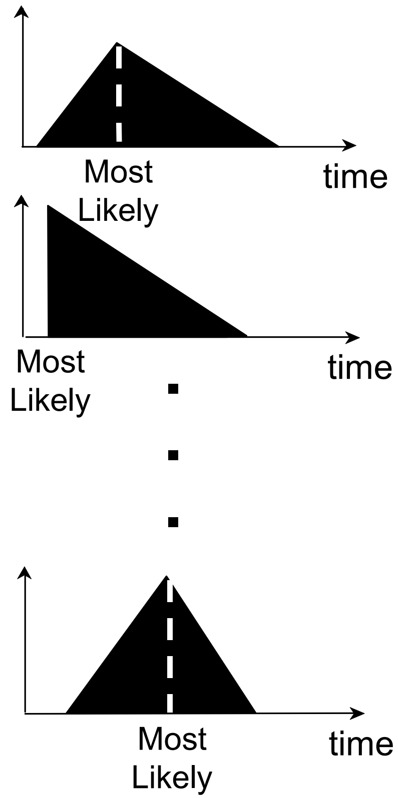
σ = 1000

Applying The Central Limit Theorem

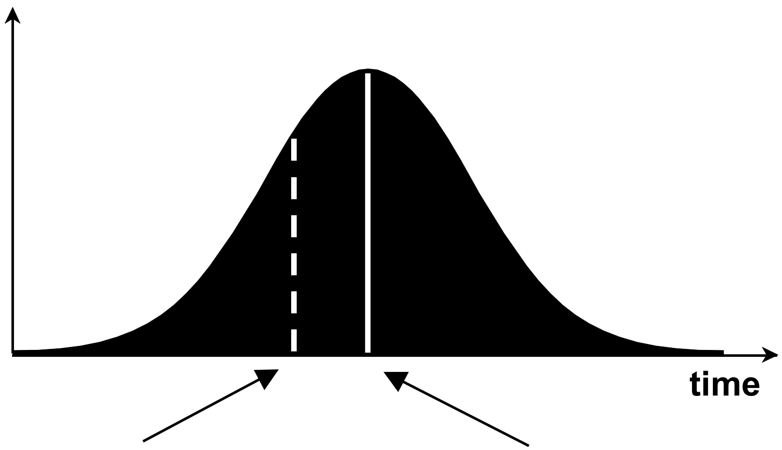
- **Probability Distribution of Project's Total Duration is Obtained by Statistically Summing Distributions of all Activities Along the Schedule Network Critical Path**
- ***Central Limit Theorem of Statistics*: If Number of Critical Path Activities is "Large," Probability Distribution of Total Duration is "Approximately" Gaussian**
- ***Another Statistical Theorem (not related to Gaussian distribution) States*: Sum of Activity-Duration Means = Total-Duration Mean**
- **But, because Gaussian Distribution is Symmetric, for the Total- Duration Distribution, Mean = Median = Mode**
  - Sum of Activity-Duration Means = Total-Duration Mean
  - Sum of Activity-Duration Means = Total-Duration Median
  - Sum of Activity-Duration Means = Total-Duration Mode
- **Therefore**
  - **Sum of Activity-Duration Medians < Total Duration Median**
  - **Sum of Activity-Duration Modes < Total Duration Mode**

3rd Problem: Roll-Up of Most Likelies Not Same as Most Likely Total Duration

TRIANGULAR DURATION DISTRIBUTIONS OF CRITICAL-PATH ACTIVITIES



CRITICAL-PATH ACTIVITY DURATION DISTRIBUTIONS MERGED INTO PROJECT'S TOTAL-DURATION DISTRIBUTION



The Fundamental Equation of Schedule Estimating

$$1 + 1 = 3$$

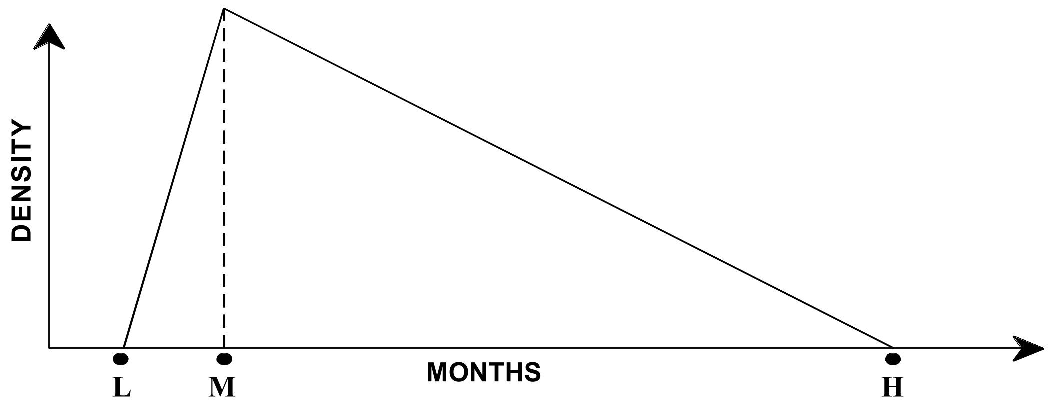
Schedule-Risk Analysis

- **"Schedule Risk": A Working Definition**
  - Inadequacy of Planned Project Schedule to Allow Sufficient Time for All Required Tasks To Be Completed so that Project Can Meet Its Stated Objectives
- **"Schedule-Risk Analysis": A Procedure**
  - Model Activity Durations as Uncertain Quantities (i.e., Random Variables) That Have Probability Distributions
  - Combine Activity-Duration Distributions Statistically (e.g., by Monte Carlo Sampling) to Generate Cumulative Distribution of Project's Total Duration
  - Read off 70^{th} Percentile Duration, 90^{th} Percentile Duration, etc., from Cumulative Distribution to Estimate Probable Additional Amounts of Time Needed to Complete Project at Various Confidence Levels
  - Quantify Confidence in "Best" Estimate (or Any Estimate, Such as the Congressionally-Mandated Schedule) of Project Duration

A Schedule-Risk Analysis is Really a Computer Simulation of Project Duration

- *Computer Simulation of System Performance* **Using Monte Carlo Analysis is a Standard Analysis Technique in Engineering Work, where Key Technical Characteristics are Modeled as Random Variables, e.g.,**
  - Weight, Power, Thrust, Other Physical Characteristics
  - Pointing Accuracy
  - Location Accuracy
  - Aiming Precision
- **Schedule-Risk Analysis, where Activity Durations Are Modeled As Random Variables, Enables the Analyst to Develop a** ***Computer Simulation of Project Duration*** **to Model Project Schedule Progress**

Triangular Probability Distribution of Random Duration D

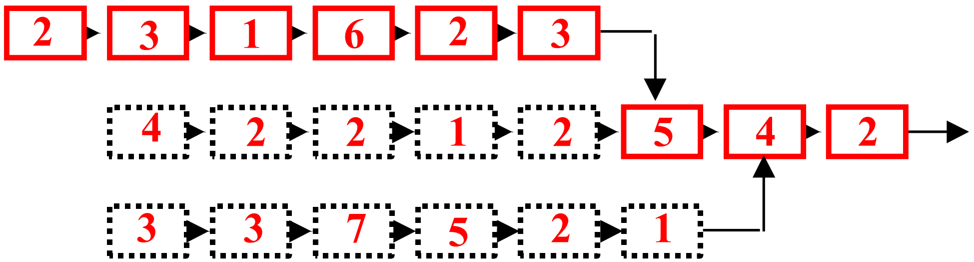


- An Activity's "Random Duration" is Random Variable that Represents Range of Possible Numerical Values of Activity's Actual Duration
- If Triangular Probability Distribution in Diagram Models a Random Duration D, the Possible Values of D are All Located between L and H, but More Likely Concentrated near M
- Random Durations Can be Generated by Monte Carlo Process, which Selects Random Numbers According to a Specific Probability Distribution

Combining Activity Durations to Obtain Complete Project Duration

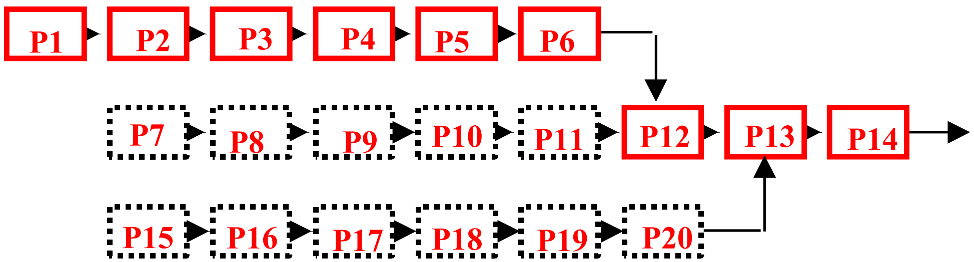
- **The Monte Carlo Sampling Process**
  - Random Sampling Models Activity Durations on Basis of Their Probability Distributions
  - **There is No Unique "The Critical Path"**, because Each Monte Carlo Pass through Network Typically Produces a Different Critical Path
  - Project Duration for Each Monte Carlo Pass Equals Sum of Durations of Activities that are on that Pass' Critical Path
  - Probability Distribution of Project Duration is Established by Compiling Project Durations of All Monte Carlo Passes
- **@Risk™, Risk+™ Software Can be Applied to Implement the Process**
  - Commercially Available Third-Party Add-on to Microsoft® Project Schedule-Analysis Software
  - Software Outputs Percentiles of Project's Total Duration, Project Total-Duration Probability Density, Cumulative-Distribution Graphics, Each Activity's Probability of Being on Critical Path

Parallel Network with Constant Durations



- Numbers in Boxes Indicate Number of Days Allocated to Task Represented by Box
- Critical Path Passes Through Those Boxes whose Combined Duration is the Longest Possible through the Network
- Critical Path, Consisting of Boxes Outlined in Solid (Red) Lines, has Total Duration = 28 Days
- Sequences of Boxes Outlined in Dotted (Black) Lines Have "Slack Time", 6 Days and 1 Day, Respectively

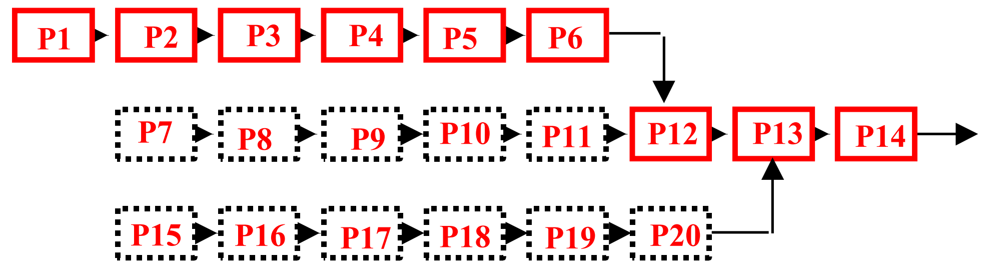
Parallel Network With Random Durations

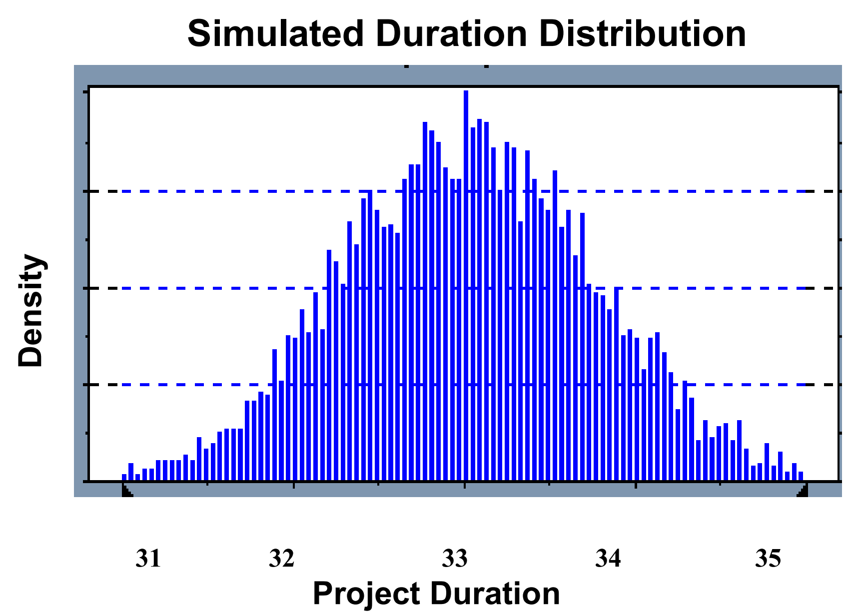


- **Random Variable (P1, P2, …, P20) in Box Represents Number of Days to Complete Task Represented by Box**
- **Which Boxes Constitute the Critical Path Depends on which Possible Values of Each Random Duration Actually Occur**
  - Each Path through Network Has Some Probability of Being the Critical Path
  - If Monte Carlo Random Numbers are Used to Model the Network, Each Path's Probability of Being the Critical Path and a Probability Associated with Each Possible Value of the Schedule Duration Can be Estimated

Schedule-Risk Duration Statistics by Monte Carlo Sampling

Project Duration Statistical Summary	
Mean	33.2
Mode (Most Likely)	33.0
Median Duration	32.9
Standard Deviation	1.5
20th Percentile	32.2
40th Percentile	32.7
60th Percentile	33.2
80th Percentile	34.0
95th Percentile	34.4





Risk-Impacted Duration Estimates vs. Roll-up "Best" Estimate

- **Risk-Impacted Duration Estimates Range from 20th Percentile of 32.2 Days to a 95th Percentile of High of 34.4 Days, with Most Likely Value of 33.0 Days**
- **Recall (from earlier chart) "Best" Estimate of Project Duration Based on Roll-up of Critical-Path-Activity Best Estimates**
  - "Critical Path, Consisting of Boxes Outlined in Solid Red Lines, has Total Duration = 28 Days"
  - Risk Analysis Illustrates that So-Called "Best" Estimate is NOT the Most Likely Project Duration, but Instead is an Underestimate (sometimes substantial) of Same

Contents

Summary

- **Project Schedule Status Must be Assessed in Terms of a Critical Path through the Schedule Network**
  - A Schedule Network is an Arrangement of Activities Involved in Completing a Project, along with …
    - … the Order in which Activities Must be Done, and
    - … an Estimate of the Time Required to Do Each of Them
  - The Critical Path through a Network Comprises the Subset of Activities that, if not Completed on Time, Will Delay the Entire Project
- **Because Actual Activity Durations are Uncertain (and More Likely than not to Exceed their Most Likely Values), Project Schedule Duration Must be Modeled Statistically**
  - Schedule-Risk Analysis, the Process of Modeling Activity Durations Statistically and the Critical Path by Monte Carlo Sampling, Enables the Analyst to Conduct a ***Computer Simulation of Project Duration***
  - Do Not Sum Most Likely Activity Durations, because if you do You Will Almost Certainly Underestimate Most Likely Project Duration

Speaker's Bio

Dr. Stephen A. Book is Chief Technical Director of MCR, Inc. In that capacity, he is responsible for ensuring technical excellence of MCR products, services, and processes by encouraging process improvement, maintaining quality control, and training employees and customers in cost and schedule analysis and associated program-control disciplines. Dr. Book joined MCR in January 2001 after 21 years with The Aerospace Corporation, holding the title "Distinguished Engineer" during 1996-2000 and having served as Director, Resource and Requirements Analysis Department, during 1989-1995. While at The Aerospace Corporation, he worked on a wide variety of Air Force programs and directed a vigorous program of cost research into methods of conducting cost and schedule risk analyses and deriving cost-estimating relationships. Dr. Book has given numerous technical and tutorial presentations on cost-risk analysis and other statistical aspects of cost and economics to DoD, NASA, and ESA Cost Symposia, the AF/NASA/ESA Space Systems Cost Analysis Group (SSCAG), and professional societies such as the International Society of Parametric Analysts (ISPA), Society for Cost Estimating and Analysis (SCEA), Military Operations Research Society (MORS), and the American Institute of Aeronautics and Astronautics (AIAA). He has served on national panels as an independent reviewer of NASA programs such as the 1998 Cost Assessment and Validation Task Force on the International Space Station ("Chabrow Committee") and the 1998-99 National Research Council Committee on Space Shuttle Upgrades. He currently serves as chair of the Risk Subgroup of SSCAG and is a member of the Economics Technical Committee of AIAA. Dr. Book earned his Ph.D. in mathematics, with concentration in probability and statistics, at the University of Oregon.