

On Management of Very Large Scale Engineering Projects¹

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Abstract

Approaches to large scale engineering projects (LSEP) follows the paradigm established by the Manhattan project and the NASA's Space Exploration program. However, the following two assumptions are inherent to this paradigm. First, new technological innovations based upon a clear understanding of the basic principles that govern the entire system will be used. And secondly, thorough understanding of the goal of the project and its objectives and based upon these specifications, a design will be created and implemented. As a result the mission will be accomplished. In this paper, we concentrate on an important module of a LSEP and offer a quantitative approach for the successful management of the system.

Introduction

With the advances in science and engineering, projects with ever-increasing complexity and scale are becoming commonplace. Unfortunately, their very nature defies the use of traditional project management tools. The remarkable developments in science and engineering at the dawn of 21st Century make many undertakings, hitherto unthinkable, technically possible. However, their full realizations are only possible if such projects are to be successfully completed within the allotted budget – temporal and financial. In no other area of modern technology, this is more evident than in very large-scale engineering projects.

¹ An abbreviated version of this paper appeared in the **Proceedings of the Thirty-Sixth Annual Meeting of the Western Decision Sciences Institute**, Denver, April, 2007, ISSN 1098-2248, pp.122-124.

What we mean by a “very-large scale engineering project” (VLSE project) is undertakings like realization of [Eurochannel](#), or [Wal-Mart’s Supply Chain](#), and many other engineering accomplishments of the recent past. The apogee of all such projects is the America’s first great space vision, the Apollo program. President Kennedy launched the Apollo program in his 1961 message to Congress, establishing [a national goal](#): “before this decade is out, of landing a man on the moon and returning him safely to the earth.”

These projects are characterized, in addition to their overreaching technical requirements and their immense scales, by the complexity of the interaction among their elements. In other words, we cannot take the project apart and consider its parts independently of each other. If we do this, the project as a system loses its essential properties. Furthermore, as the eminent Operations Researcher, [Russell Ackoff](#) once stated “... *when the performance of each part taken separately is improved, the performance of the system as a whole may not be, and usually isn’t.*”

The significance of “modeling” for such systems is axiomatic. There are two types of mathematical models: descriptive and normative models. Among descriptive models, there are simulation models that describe how all or parts of the project will be realized over time as a function of parameters and policies. Normative models, or optimization models, on the other hand are developed to help managers make better decisions. “The construction of optimization models requires descriptive data and models as inputs.” [Shapiro, 2001] For example, one can simulate various policies in order to determine the best one among the ones that were tried. In modeling a very large-scale engineering project that has not been implemented before, one, in effect, is designing the project. This implies one has to attempt to choose the “best” design parameters and “best” operating policies among the feasible alternatives defined by the constraints. Thus descriptive models, by themselves, are not sufficient; but a number of them must be used in coherence within the context of an optimization model.

This multi-phased approach, implied by the above discussion will be illustrated in the context of a recent project that authors participated. The project was sponsored by Northrop-Grumman Corporation for functional modeling of Orion Spacecraft operations for the purpose of quantitative risk analysis for project management. In the following, after presenting brief background information on the Orion Project, the proposed approach

will be outlined. Then modeling and analyses are illustrated using hypothetical, but analogous, operations of the Orion Project.

Background

In January 2004, President George W. Bush announced the [Vision for Space Exploration](#) for NASA. This vision directs NASA “to develop and execute a program aimed at returning humans to the moon, sending explorers on to Mars, and facilitating future exploration activities to ‘*destinations beyond*’.”²

The end goal of NASA’s mission is to safely and affordably transport humans to and from *low earth orbit*, from earth to moon and back to earth, and ultimately to and from Mars and beyond. The *Crew Exploration Vehicle* (CEV³), which will also be used to transfer the crew and cargo to and from (and evacuate the crew from) the International Space Station, will achieve this.



Figure 1. Orion is the vehicle NASA's Constellation Program is developing to carry a new generation of explorers back to the moon and later to Mars.

“Orion will succeed the space shuttle as NASA's primary vehicle for human space exploration. Orion's first flight with astronauts onboard is planned for no later than 2014 to the International Space Station. Its first

² [“Report of the President’s Commission on Implementation of United States Space Exploration Policy,”](#) June 2004.

³ NASA announced on August 22, 2006 that its new Crew Exploration Vehicle (“CEV”) will be named “Orion”. Henceforth, the term *Orion* will be used when referring to Crew Exploration Vehicle.

flight to the moon is planned for no later than 2020. Orion is named for one of the brightest, most familiar and easily identifiable constellations. Orion will be capable of transporting cargo and up to six crewmembers to and from the International Space Station. It can carry four crewmembers for lunar missions. Later, it can support crew transfers for Mars missions. Orion borrows its shape from space capsules of the past, but takes advantage of the latest technology in computers, electronics, life support, propulsion, and heat protection systems. The capsule's conical shape is the safest and most reliable for re-entering the Earth's atmosphere, especially at the velocities required for a direct return from the moon. Orion will be 16.5 feet in diameter and have a mass of about 25 tons. Inside, it will have more than 2.5 times the volume of an Apollo capsule. The spacecraft will return humans to the moon to stay for long periods as a testing ground for the longer journey to Mars.”⁴



⁴ [“NASA Names New Crew Exploration Vehicle Orion.”](#)

Figure 2. Integrated CEV and Crew Launch Vehicle (CLV)

Orion (CEV) is a reusable, Apollo-derived cone-shaped capsule launched atop the CLV. The CEV consists of a Crew Module (CM), a Service Module (SM), and a Launch Abort System (LAS). The CEV is sized at 5.5-meter diameters for lunar polar missions carrying a crew of four, and is reconfigurable to accommodate up to six crewmembers for missions to ISS. The vehicle uses a Low Impact Docking System (LIDS) for ISS and lunar missions. *The vehicle is reusable for up to 10 missions* and will land on land with a water landing as a backup. The SM utilizes a pressure-fed liquid oxygen (LOX)/methane propulsion system.⁵

The **CLV** consists of a shuttle-derived four-segment Reusable Solid Rocket Booster (RSRB) first stage and a newly designed upper stage with one modified, and now expendable, SSME. It will launch 25 metric tons to low-Earth orbit and serve as the long-term crew launch capability for the United States.⁶

⁵ [GAO-06-817R Exploration Cost and Schedule.](#)

⁶ [Ibid.](#)

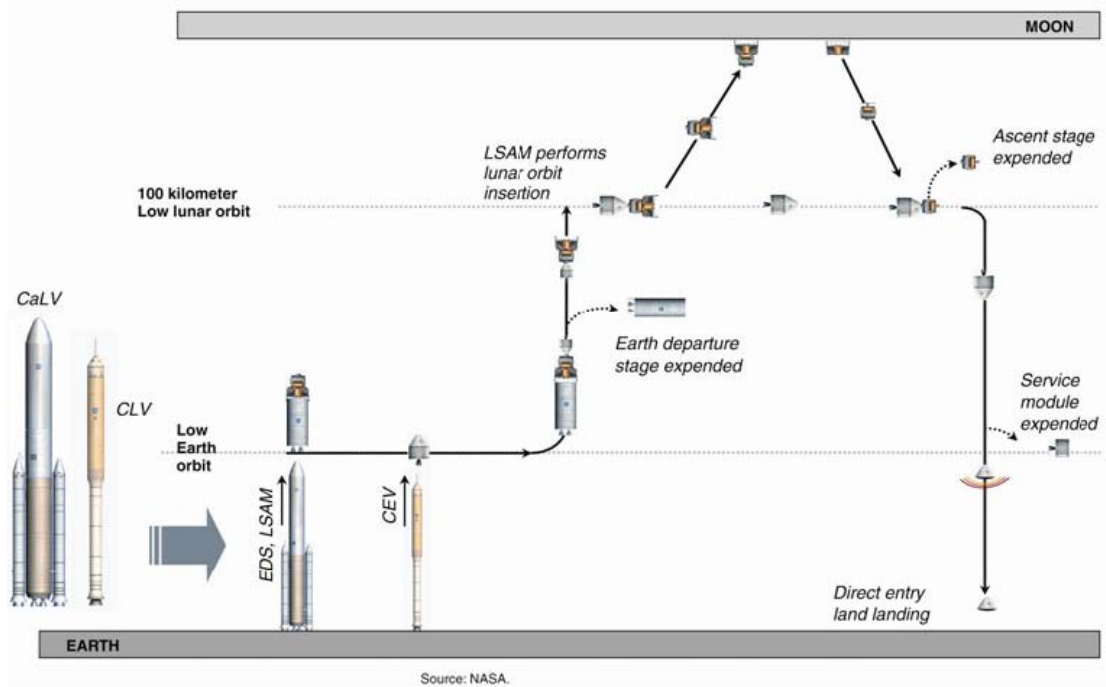


Figure 3. An outline of a launch mission for crew and cargo, utilizing rendezvous locations in low-Earth and low-lunar orbits.⁷

The other primary vehicles and elements of the **Exploration Systems Architecture Study (ESAS)**⁸ are

- ♦ **CaLV:** The CaLV will use a heritage shuttle external tank-derived LOX/liquid hydrogen core stage propelled by five redesigned SSMEs. Attached to this core stage are two newly developed five-segment RSRBs, allowing over 100 metric tons to be launched to low-Earth orbit. The upper stage, which also serves as the EDS, uses an external tank derived LOX/liquid hydrogen system and will employ two Saturn-derived J-2 engines.

⁷ [Ibid.](#)

⁸ [Ibid.](#)

- ♦ **LSAM:** The LSAM is an expendable two-stage module launched atop the CaLV. The descent stage will utilize a LOX/liquid hydrogen propulsion system while the ascent stage will use a pressure-fed LOX-methane propulsion system. A crew cabin will be located on the ascent stage and will have an airlock to allow docking with the CEV. The LSAM will be able to land at any location on the lunar surface and will house a four-member crew for up to 7 days.

In the design and development of complex systems, such as the Orion project, there are many decisions that require weighing and “trading” a number of conflicting criteria. For the Orion project, the priority order that should be considered in each design decision is the following:

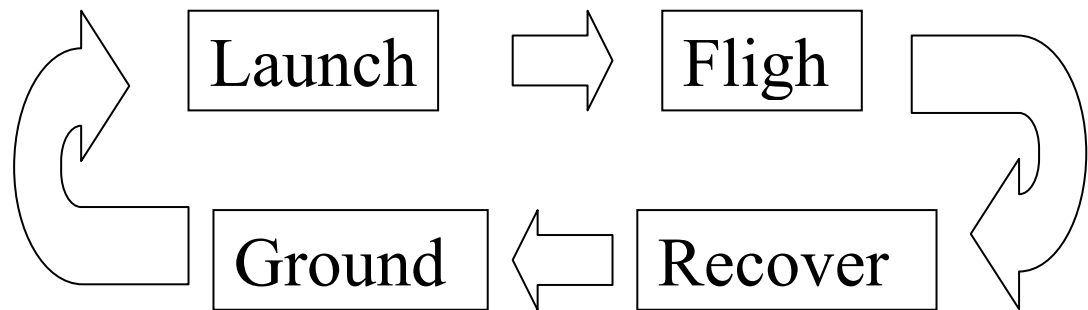
1. Safety and mission success.
2. Programmatic risk.
3. Extensibility and flexibility.

‘Test and evaluation’ for the Orion project is the essence.

Therefore, in addition to a thorough analysis and modeling of activities that make up all the essential operations, a meticulous quantitative risk analysis is imperative. The proposed approach in this study consists of four phases:

1. **Enumerate the activities**, with their complete duration estimates and resource requirements, which are necessary to accomplish each ‘operation’.
2. **Construct the network diagram** that depicts the inter-relationships among the activities, which highlights the ‘critical paths’ in the operation.
3. **Functional modeling** of the operation such that the full relationships among activities and their resource requirements are fully accounted for.
4. **Quantitatively analyze the risks** based on the Monte Carlo simulation of the operation.

In the Orion project, there are four operations as depicted below:



Specifically,

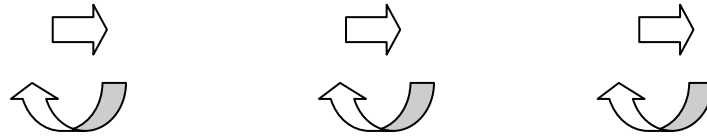
- ♦ **Launch** operation commences when Orion is ready to leave for launch,
- ♦ **Flight** operation commences when Orion is in space,
- ♦ **Recovery** operation commences with Orion ('Crew Module') touchdown at landing site, and
- ♦ **Ground** operation commences when the Crew Module is transported from the landing site to Kennedy Space Center.

Since the Crew Module will be "... reusable for up to 10 missions," the above operations are cyclic. After the **launch** and **flight** operations are successfully concluded and the Crew Module lands on earth, it is **recovered** and it is refurbished at the Spacecraft Production and Integration facility (the **ground** operation). NASA requires that this refurbishment turnaround time is required to be less than certain number of workdays.

Analysis and Modeling of Operations

This section presents the suggested approach for the analysis and modeling of each of the four operations in the Orion project. The approach consists of four phases:





The first phase lists the tasks, together with their processors, time durations, and resources requirements. The second phase constructs an activity-on-node network diagram on which the precedence relationships among the tasks/activities are clearly delineated. This provides a convenient means to verify the authenticity these relationships, and the resulting critical paths, by the domain experts. In the third phase, the functional flow of the operation is modeled using a model-based systems engineering tool, [CORE](#)⁹, which has capability of simulating the executable behavior of the modeled operation. In the final phase of the approach, the results obtained from the Monte Carlo simulation of the behavior of the model in the previous phase, are statistically analyzed with special emphasis on risks and uncertainties involved in the operation.

These phases will be illustrated using hypothetical, but analogous, operations of the Orion Project.

Activity List

This is a comprehensive list of all activities/tasks required in order to accomplish the required mission of the operation. As the applicable tasks are identified, the needed ground support equipment and skills required to manage each of these tasks are also identified. As the spacecraft design progresses, operations requirements became part of the architecture. This allows the estimation of task durations for applicable operations.

The preparation of the list involves following steps:

1. Itemizing tasks,
2. Estimating their durations,
3. Identifying the required expertise and equipment or other resources, and
4. Specifying any additional characteristics of the tasks.

⁹ <http://www.vitechcorp.com/>

Utilizing the expertise from past space missions, and after a number of iterations with the domain experts, the list is finalized in a spreadsheet file in which the rows are the tasks and the milestones; and the above information represented in the appropriate columns.

Itemizing tasks

The list contains all tasks. “Milestones” are zero-duration activities representing “events” in the operation. In addition, some tasks have “pre-operation” activity. These are activities without any predecessors and whose only successor is the task in question. Similarly, some tasks have “post-operation” activity whose predecessor is the activity in question, and its only successor is the appropriate milestone.

Estimating Task Durations

As far as their durations are concerned, there are three types of tasks:

- ♦ Activities with constant durations: for all practical purposes, there is no uncertainty concerning the durations of these activities. For example, a task may have a constant duration of 1 hour. Under all circumstances, this task can be completed in exactly one hour.
- ♦ Activities with three time estimates for their durations: these are the three parameters that can be estimated from experience for the activity’s duration; namely, *optimistic*, *expected* (“*most likely*”), and *pessimistic*. These can be used as the parameters of a triangular distribution, or of its ‘curved’ version – the PERT distribution¹⁰, in a Monte Carlo simulation setting. For example, there may exist a task that will most likely be completed in 0.5 hours; however, if everything goes right, we can complete it in 0.25 hours; but we are sure that it will not last longer than 0.75 hours.
- ♦ Activities with selection probabilities: under nominal conditions (that is, when everything goes as expected,) the task

¹⁰ This distribution is named after the PERT (Program Review and Evaluation Technique), which is a project scheduling technique when the activity durations are random variables, rather than constants as in CPM (Critical Path Method). The mean of the PERT distribution is a weighted average of its three parameters, with the “*most likely*” getting four times as much weight as the other two. (In MS Project, the user is allowed to adjust these weights.) The variance of the PERT distribution is estimated as one sixth of its squared range.

has a “nominal” duration; and under non-nominal conditions, for example, if there is an emergency, the task has a “non-nominal” duration. Any complementary probabilities for the occurrence of nominal and non-nominal conditions can be assigned, such as 95% and 5%, respectively. For example, a task, under nominal conditions (say, 95% of the time) will be instantaneous; however, if something goes wrong (5% of the time) it may take 0.2 hours to complete. Another task may take 0.1 hours under normal conditions, and will take 0.2 hours if there are some problems.

Identifying the Required Resources

The resource requirements for each task are estimated and are listed on the same spreadsheet as the other task related data.

Network Diagram

Prior to constructing the functional flow model of the operations using a model-based systems engineering tool, CORE, it was found extremely useful to construct a network diagram of the tasks in order to provide a top-level view of the precedence relationships among the activities. Data available in **Activity List** is used to construct a **MS Project model** of the operations in question. A partial view of the network diagram is presented below.

Functional Modeling

In order to design and specify a consistent system that satisfies the customer's needs and requirements, it is essential to 'solve' the problem in the 'logical domain' and then proceed with the physical design and implementation. This can be facilitated by a model-based systems engineering tool. CORE is such a tool. Specifically, CORE

- ♦ is based on a relational database with a defined schema that governs the relationships,
- ♦ has inherent system engineering capabilities generated from a database, such as functional flow block diagrams, N2 charts (which are essentially data flow diagrams, only differing in format,) IDEF0 diagrams (which are data flow diagrams with control and allocation information is added,) and hierarchy and interface diagrams,
- ♦ is a central repository for requirement information,
- ♦ generates specifications and other reports from the current database, insuring currency,
- ♦ provides an underlying scripting language for simulation extensibility and database management,
- ♦ is DoDAD (*Department of Defense Architecture Framework*) compliant and capable; consisting of three views: operational, systems, and technical, and
- ♦ forces a single 'language' of systems engineering (schema).

Finally, from the point of view of this analysis, CORE's most significant feature is the availability of the discrete event simulator that executes the *Extended Functional Flow Block Diagrams* and builds timeline views automatically. However, this feature, by itself, is not sufficient to perform a Monte Carlo simulation that can provide a basis for the quantitative analysis, which will be presented in the next section. Specifically it does not have the data capture capability that is necessary to perform the statistical analysis.

The model, whose *COREsim diagram* is presented in Figure 4 below, fully captures the characteristics of all tasks involved in the four

operations of the Orion project. The durations that were defined for functions in the model include all three possible durations; namely, the constant duration, random duration following various probability distributions, and ‘selection probability’ to account for the realization of non-nominal durations.

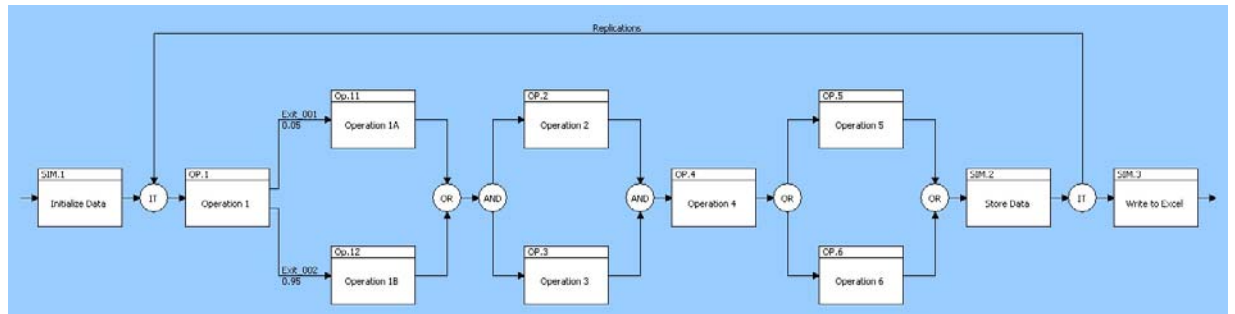


Figure 4. COREsim EFFBD of a sample representative functional model of operations.

This model consists of seven generic ‘functions’ representing all possible realizations of tasks that comprise the operations in the Orion project. In addition, there are three functions¹¹ defined for capturing simulation data. Specifically,

- ♦ SIM.1 Initialize Data: The script in this function initializes the values of global variables to zero.
- ♦ SIM.2 Store Data: The script in this function stores the captured time data into a collection of objects called TimeValues.
- ♦ SIM.3 Write to Excel: this function iterates through the allocated "array," and writes the time values to a spreadsheet file in **Comma Separated Value (.csv)** file format.

A screen shot of a sample run of the model with three iteration is shown in Figure 5.

¹¹ These scripts were written in SMALLTALK by Yuushi Kotow, the research assistant in the project.

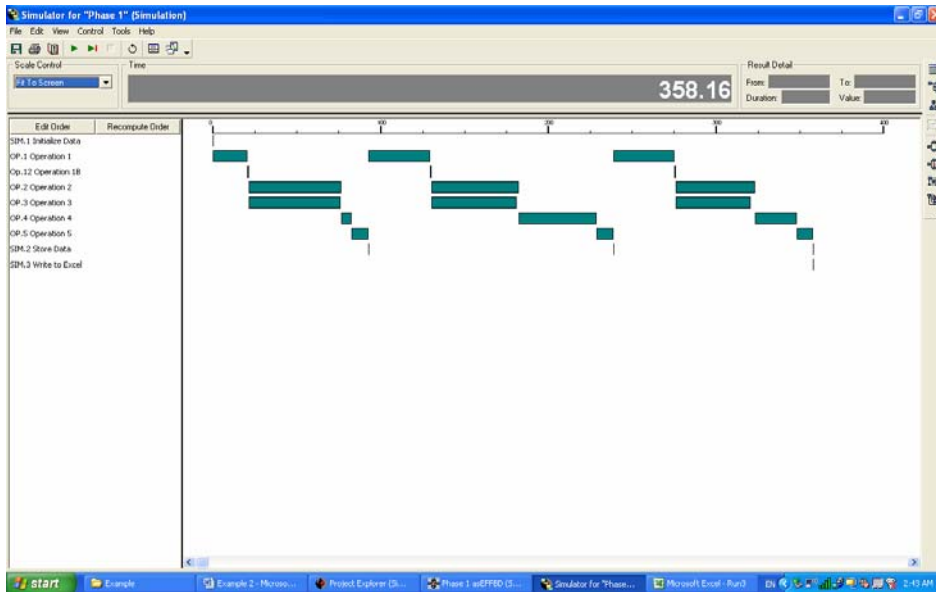


Figure 5. The timeline view of three iteration of the sample model.

The partial output of a simulation run of 1,000 replication of the sample model is given below in Figure 6.

The screenshot shows a Microsoft Excel spreadsheet titled "Microsoft Excel - Output.csv". The spreadsheet contains the following data:

	A	B	C	D	E	F	G	H	I
1	Durations								
2	113.87		n =	1000					
3	134.949		sample mean =	160.4033					
4	196.2475		stdev =	55.51204					
5	137.1354								
6	94.29131								
7	133.3483								
8	128.5853								
9	108.574								
10	103.3585								
11	172.6325								
12	136.4425								
13	176.5271								
14	102.8326								
15	146.8285								
16	138.2735								
17	226.8694								
18	215.9677								
19	143.2378								
20	158.1367								
21	106.7808								
22	127.8072								

Figure 6. Comma Separated Value (.csv) file output of the simulation run.

Output Analysis

This section briefly reviews the statistical analysis done on the results of the Monte Carlo simulation performed on the sample functional model presented in the previous section. The ultimate aim of this analysis is to quantify the risks associated with the planned operations in the Orion project.

Risk analysis is “the process of assessing risks, while risk management uses risk analysis to devise management strategies to reduce or ameliorate risk. In project management, these techniques are used to address the questions ‘how long will this project eventually take?’ (schedule risk), ‘how much will it finally cost?’ (cost risk), and ‘will its product perform according to specifications?’ (performance risk).” [Galway, 2004] The analysis below will help the project administrators find answers to questions such as:

- ♦ What are the chances of the operation being completed on schedule?
- ♦ What is the operations success rate?

If the project had continued, the analysis would have covered additional issues related with resources, such as:

- ♦ What are the chances of the operation being completed within budget?

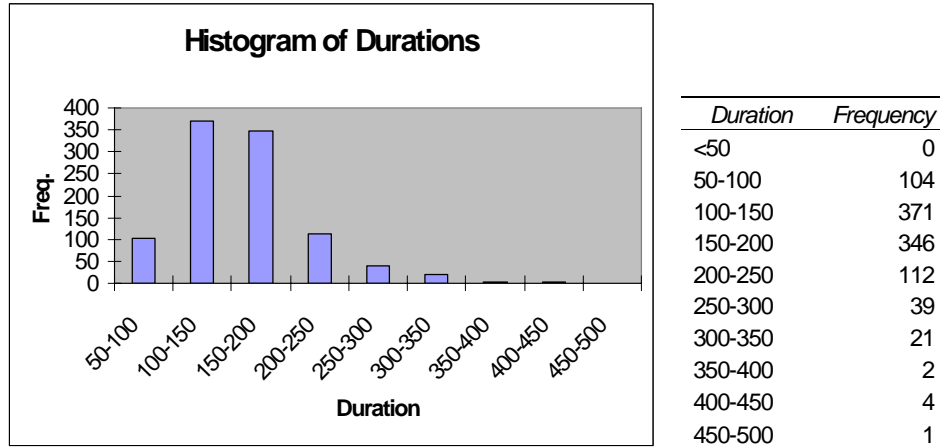
and other issues related with schedule risks, such as:

- ♦ What is the chance that a particular task will be on the critical path?
- ♦ Which tasks affect the project duration most?

Simulating the sample functional model described in the previous section for 1,000 replications, results in the raw data presented in Figure 6. These data can be considered as a sample of size 1,000 from an infinite population – all possible realizations of the operation in question. We will use this sample’s statistics to estimates the population parameters.

Histogram of Project Durations

Using MS Excel tools, the following frequency distribution and the histogram of the project durations can be obtained:



Point Estimates

n =	1000
sample mean =	160.40335
stdev =	55.512039

If one has to give a single number for the average time to complete the project it would be the sample mean, 160.4 time units, in this example.

Confidence Intervals

Clearly, the sample mean will not be exactly equal to the population mean. A better estimate would be an ‘interval estimate’; that is, a confidence interval for the population mean:

One can be 95% confident that the population mean is in the interval:

$$\left[\bar{x} \pm t_{v=n-1, \alpha/2} \frac{s}{\sqrt{n}} \right] = \left[160.403 \pm 1.9623 \frac{55.51}{\sqrt{1000}} \right] = [156.96, 163.85]$$

where the degrees of freedom, $v = n - 1 = 1,000 - 1$; the level of significance, $\alpha = 0.05$; sample mean,

$$\bar{x} = 160.403$$

and sample standard deviation, $s = 55.51$. That is, we can be 95% confident that the project duration will at most be 163.85 time units and at least be 156.96 time units.

Probability of Completion

If the assumptions of *Central Limit Theorem* are assumed to hold, we can state that

$$\text{Prob}\{\text{the project cannot be completed before 200 time units}\} = 23.78\%,$$

or

$$\text{Prob}\{\text{the project will be completed by 100 time units}\} = 13.83\%.$$

Probability of Success

If it is meaningful to define as ‘success’ when the project is completed by, say, 160 time units, then we can state that

$$\text{Prob}\{\text{success}\} = 55.20\%.$$

Conclusions

This paper presented a process that integrates project management tools and techniques to enable proactive management across all phases of a large scale engineering project. Monte Carlo Simulation was also used as an improved methodology to quantify schedule risk and consequently to provide more reliable estimates of probability of successful project completion time.

References

- ♦ Galway, L., “[Quantitative Risk Analysis for Project Management: A Critical Review](#),” WR-112-RC, Rand Corporation, February 2004.
- ♦ Shapiro, J. F., *Modeling the Supply Chain*, Duxbury, 2001.