# Risk Analysis for Large Engineering Projects: Modeling Cost Uncertainty for Ship Production Activities

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*ABSTRACT* – **Monte Carlo simulation of activity networks has generated interest as a method for cost/schedule risk analysis during the design and contracting stages of large engineering projects. Commercial software for project risk analysis is now widely available as extensions to many popular project management/scheduling software packages. However, many cost and uncertainty modeling issues remain to be addressed, in terms of both practical implementation and underlying methodology. Several of these issues were examined in the course of developing a risk analysis methodology for the domain of commercial ship production. These include: statistical dependence of risk-related activities; expert elicitation of activity duration uncertainty; net present value representation for production costs, contract penalty costs, etc.; and determination of contract payments at project milestones.**

*Key words:* Project risk analysis, shipbuilding, production cost uncertainty, simulation

## INTRODUCTION

Many engineering enterprises have begun to seriously explore, and in some cases routinely use, Monte Carlo simulation to analyze financial risk for large production/construction projects. While earlier simulation-based methods/softwares have had limited use for many years [1], the advent of faster/cheaper hardware and integration with commercial project management software has renewed interest among potential commercial users. The types of production projects for which intensive financial risk modeling appears particularly justified are "one-off" or small series production efforts which require innovative design activity; tight coordination of multiple subcontractors; and strict cost/schedule constraints. Projects with these characteristics are found in diverse engineering domains including shipbuilding (the domain of interest here), civil construction (such as large dike projects), or science-mission satellites.

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There are strong incentives to consider (or, for some skeptical managers, reconsider) simulation-based risk analysis methods. First, large engineering projects are increasingly high risk, low margin ventures due to competitive pressures to lower costs and adopt rapid innovations in fabrication technologies, work organization, and networks of suppliers/subcontractors. Second, traditional methods of cost and schedule estimation -- which rely strongly on extrapolation from past design/manufacturing data and the intuition of experienced personnel -- are proving inadequate for rapidly changing competitive/technical environments. Especially when contract penalty clauses and other time-sensitive costs are present, severe losses may be suffered even though at first the project seemed a profitable one.

Successful adoption of Monte Carlo-based risk analysis appears to require intensive internal development and incremental refinement by companies. Cooper and Chapman, for example, recommend that methodology design be a distinct early-phase task for each project [2]. The resulting techniques are typically considered highly proprietary, since they are tightly coupled with competitive practices and data. Several recent overviews of risk analysis methods have included discussion of activity network simulation [3, 4], and related theoretical work has been in the research literature for some time [5, 6]. For this project, a risk analysis methodology and prototype software were developed to be applicable to the pre-contract design stage of U.S. commercial shipbuilding [7]. After examining current "best practice" for risk analysis in a related industry (a large civil engineering firm [8]) and surveying existing commercial risk analysis packages, we concluded that development of an original methodology was warranted. This methodology, extensible to other large engineering project domains, uses as inputs the PERT/CPM network of production activities and cost data typically available at the pre-contract design stage in a U.S. shipyard.

**Risk Factors for U.S. Commercial Shipbuilding**

Defense downsizing has forced U.S. yards, which have long been sustained by government ship procurements, to compete for commercial customers with well established international shipbuilders in Japan, Korea, Europe and elsewhere. To develop their own competitive edge, some U.S. shipbuilding concerns are creating innovative designs for ocean-going vessels. To drive down costs, new production processes must also be designed which take advantage of innovations in fabrication technologies, work organization, and networks of suppliers/subcontractors.

However, innovative design and build strategies require particular attention to risk factors that may impact cost and delivery time.  For example, a build strategy under consideration by some ship owners and shipbuilders is the use of multiple off-site subcontractors for fabrication of mid-body hull structure modules for double-hulled tankers [9].  This could reduce the time required at the ship erection site as well as total delivery time, and facilitate rapid series construction.  (This concept is somewhat similar to the subcontractor and final assembly approach pioneered by Boeing).  However, total cost and delivery time is difficult to estimate due to several design/production factors.  Smaller-sized hull modules than previously fabricated might be necessary for barge transport to the site (200 tons about maximum possible). Delivery times and quality control for prospective subcontractors are uncertain.  On the one hand, the smaller module size might improve subcontractor learning curves and get them up to speed faster, but there are also possible "downstream" problems such as structural alignment at the erection site.  Administration mechanisms for hull subcontractors must be developed.  Process innovations for outfitting (assembly of piping, electrical, and other system components into the hull structures) also have great potential benefit, but also uncertainty.  Pre-outfitting of the hull modules prior to erection is a relatively recent innovation.  At one shipyard visited, the only previous large commercial ship produced had been about 15-20% pre-outfitted, but managers were hoping to increase that to 40-50% for future builds. They believed that Japanese yards are able to do about 80-90% pre-outfitting.

Other related risk issues are engineering change orders (ECO's) and rework.  Engineering changes can come from a variety of sources -- owner-requested changes, inadequate design specifications, interface problems for vendor-furnished equipment, etc.  As a rough rule of thumb, rework at one yard visited was considered to be about 2.5 times more expensive than the original build.  However, shipyard management often push to get work started early in order to ensure that construction crews are working.  Additionally, there may be contract clauses or other accepted practices that encourage early purchase of materials or early construction.

Many foreign yards can provide prospective owners with fast, highly detailed quotes and contract packages for requested design variations from their "catalog" of standard ship designs developed and refined over a period of years.  By contrast, most U.S. shipbuilders still use pre-contract cost estimating methods based on burdened man-hours per ton of hull steel. Such methods have apparently been adequate for traditional government contracting and more standardized, small ship construction.  For large commercial vessels, however, this combination of lack of competitive experience, new product designs and production innovations clearly entails high risk.  It also calls into question the ability of existing methods of ship cost estimation to help analyze risk during design stages for applications such as: determining firm fixed-price bids; contract design for liquidated damage clauses, payment milestones, etc.; complex make-or-buy subcontracting decisions; and evaluation of different production process design alternatives.

## REPRESENTING COST UNCERTAINTY IN AN ACTIVITY NETWORK

As is generally true for most large engineering projects, financial risk in shipbuilding can be highly time-dependent. Long completion times often exceed one year with total costs exceeding forty million dollars. Aside from increased direct labor costs, delays in delivery time can tie up facility resources and often require payments for liquidated damage clauses in production contracts. There are large cash disbursements for equipment and material deliveries, complicated financing arrangements, and payments based on percent completion milestones. As well as discounted cash flow effects, there may be complex scheduling interdependencies which greatly affect time-dependent cost uncertainty. A risk analysis method that can integrate schedule and cost information using activity networks would seem desirable.

In this model, therefore, it was assumed that the predominant sources of cost uncertainty correspond to uncertainty in the durations of production activities and total completion time. A method to calculate the cost for a project with given fixed activity durations in each iteration of the Monte Carlo method is then sufficient to quantify the uncertainty in the project cost. Production activities are represented in a directed network $\mathcal{P}$ (i.e., a PERT network of the type typically used for scheduling estimation at the pre-contract stage). This may be described as a tuple ($\mathcal{N}$, $\mathcal{A}$), where

$$\begin{cases} \mathcal{N} = \{1,2,3,...,n\}\text{: a set of events (milestones)} \\ \mathcal{A} = \{(i,j) \mid (i,j) \in \mathcal{P}\}\text{: a set of activities} \end{cases} \quad . \tag{1}$$

For cost representation in an activity network, direct labor rates, material costs, and subcontractor payments are relatively simple to assign as variable cost attributes for production activities. Representation of many indirect costs can be more problematic, as overhead allocation and related cost accounting conventions are particular to each production enterprise. Indirect costs that can potentially be assigned as overhead burden to direct production activities can include:

> Production-related "indirect" labor: Quality control, material handling, work supervision, production engineering, etc.
> Activity-specific equipment: depreciation, leasing, O&M, etc.
> Activity-specific supplies, energy, commodity materials

Fixed costs for facilities, support staff, etc. are by definition not activity dependent, but could include capital improvements such as a refurbished dry dock or large capacity cranes.

**Important Modeling Issues**

An overview of critical modeling issues addressed in the course of developing the methodology/software is given below. This is followed by a more detailed discussion of cost elements represented in the activity network.

**Size and complexity of the network.** With hardware advances, computer processing time for simulating large networks is becoming less of an obstacle. Instead, the constraint on network size/complexity is the granularity of cost/schedule data available during contract tendering and design stages. At contract tendering, risk analysts observed at one civil engineering firm [8] use at most a 100-activity network for their in-house methodology/software. Schedule estimators interviewed at several shipyards, however, typically develop pre-contract PERT/CPM scheduling networks of 200-250 activities (using only fixed duration times and no cost data) [7]. With the idea of integrating cost and schedule uncertainty modeling tasks, this size (~250) was chosen for the largest test case during software development, and cost data matched accordingly. In the post-contract phase, after detailed production planning data becomes available, networks of ~1500-10,000 activities are typically constructed for use in day-to-day project management.

**Elicitation of distribution parameters.** For innovative product designs and/or fabrication methods, historical data for estimates of duration time of production activities are often unavailable or even misleading; subjective judgment of experts is necessary to define uncertainty distributions. The commercial risk analysis packages examined by the authors equate lower bound, most likely, and upper bound estimates supplied by the expert with the bounding and mean parameters for a triangular distribution. To improve upon this, a new input method for subjective estimation of parameters for triangular distributions was developed. It uses results of recent research in eliciting expert judgment [10] which found that "upper bound" and "lower bound" estimates of experts usually correspond to p-th quantile points in a triangular distribution rather than the actual upper and lower bounds of the distribution itself. In the software implementation, project personnel can graphically define the shape of the distribution while correcting for an assumed discrepancy between user input values and distribution parameters.

In the method indicated in Figure 1, the expert may use each of the sliding buttons to modify either the lower bound, most likely estimate or the upper bound. Eliciting these three numbers almost simultaneously reduces the anchoring bias that could occur when these numbers are elicited in a prescribed order. In addition, feedback is generated at the same time in terms of the mean, median and standard deviation. Finally, when an expert decides that he is satisfied with his current estimates he may generate a histogram for additional feedback. The histogram associated with Figure 1 is given in Figure 2. Using Figure 2 an expert can easily calculate the percentage of activities which would finish in a particular time frame. After observing the histogram the expert may redraw the distribution or accept his current estimates. The method described above resembles the histogram technique developed in [11].

It should also be noted that -- when fitted to the same parameters for lower bound, upper bound, mean, and standard deviation -- the choice of any theoretical distribution with finite support (beta, triangular, etc.) to model these activity duration distributions appeared to have a relatively small effect on simulation results for total project cost (or duration). Therefore, the triangular distribution was chosen for its computational simplicity.

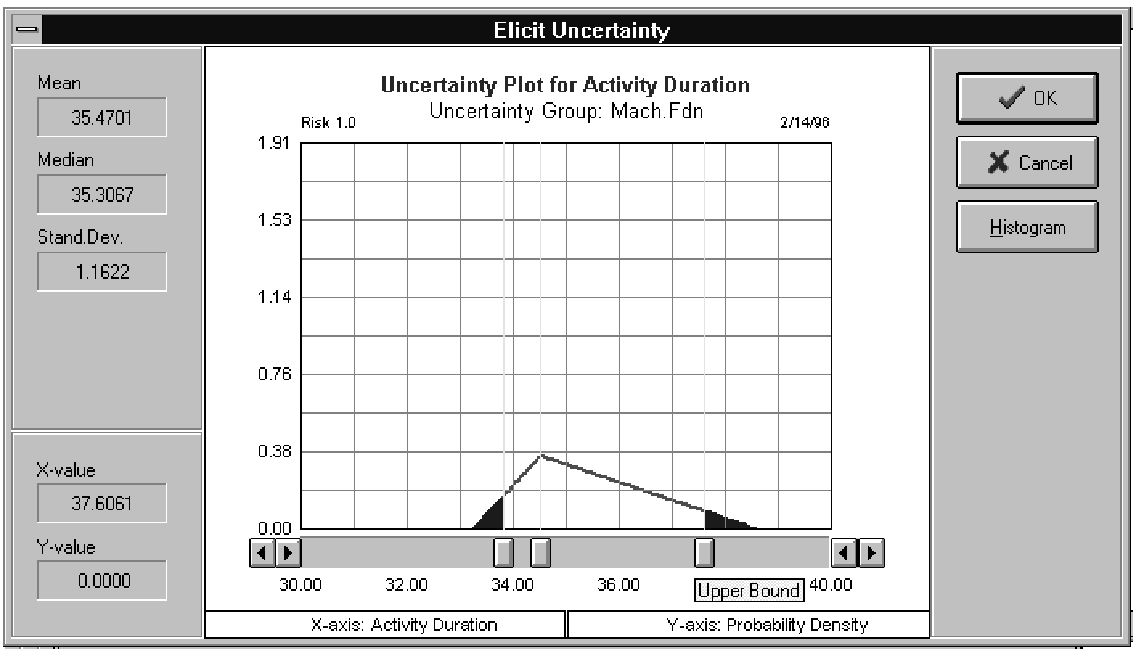


Figure 1. Graphical method for input of activity duration parameters

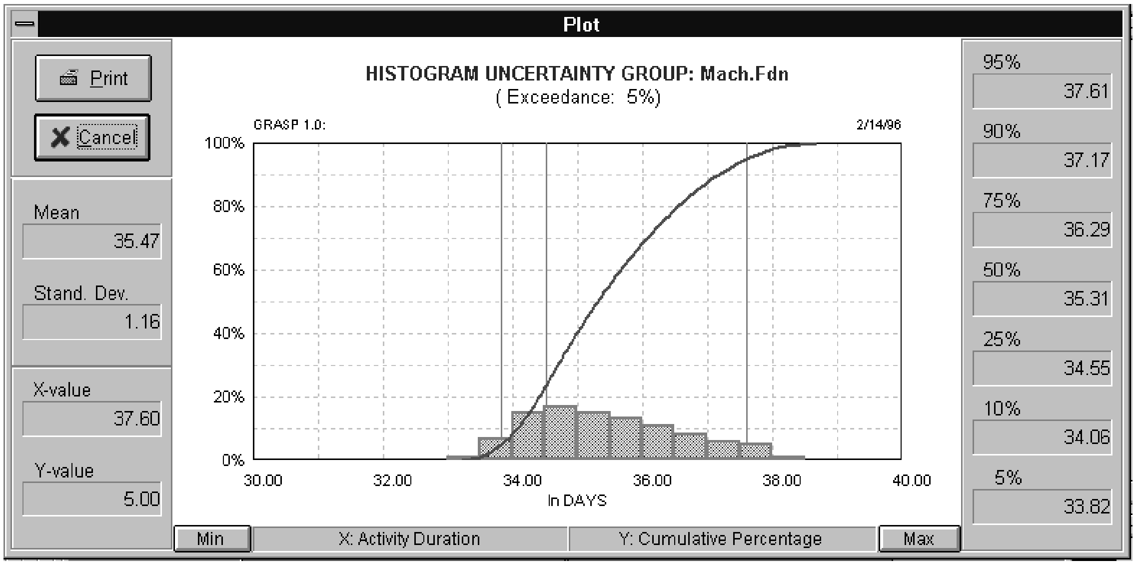


Figure 2. Histogram associated with Figure 1.

**Statistical dependence for risk-related activities.** In Monte Carlo simulation of project networks, a distribution of the uncertainty of total project cost/time is approximated by repeated random sampling of individual activity durations in the network and repeated quantifications of project cost/time. However, independent marginal distributions for the uncertainty of the activity durations are typically assumed. This is often a reasonable assumption for many discrete processes, such as a sequence of physical production activities in manufacturing simulations. However, for risk-impacted engineering projects it can lead to serious underestimation of total project cost/time uncertainty.

Consider a hypothetical example in the shipbuilding domain. A new design for a tanker hull structure is proposed which would utilize identical hull sub-blocks for the full length of a constant-cross-section hull mid-body, in theory greatly simplifying production. As well as the new hull block design, a promising but not-yet-implemented type of robotic fabrication is proposed. If twenty-four such hull sub-blocks are required, the time to fabricate and erect each hull-block is uncertain, but each activity duration has in common factors which contribute to this uncertainty. These factors might include impact of engineering change orders, production efficiencies for robotic fabrication, etc. Alternately, there may be risk dependencies for dissimilar activities which are collectively influenced by some external risk factor -- an example would be risk of bad weather for painting, outfitting of piping and electrical systems and other activities scheduled under the "open sky" in the same time period.

Groups of activities such as described above are candidates for statistical dependence modeling. To develop a model exhibiting dependence between the uncertainties, a multivariate distribution must be constructed which exhibits dependence between marginal distributions for each risk-related element. A choice of dependence related to modeling risk factors or common causes is *positive dependence.* Intuitively, two random variables are positive dependent when large values of one variable tend to be associated with large values of the other random variable.

There is a large body of literature on the general concept of statistical positive dependence [12], and some risk analysis packages have limited capabilities for defining risk dependencies in project networks [3]. For this project, positive statistical dependence was modeled using a method originally developed for modeling uncertainty in system reliability in [13], which had been implemented in the software package [14] and used to estimate damage to the Dutch Dike System due to the recent flooding in Spring 1995. Prior to the project described here, however, this method had not been applied to project networks. In this method, positive dependencies between the marginal distributions for risk-related activities are modeled in directed graphs (dependency diagrams). Using an efficient sampling strategy to sample bivariate distributions for each arc in dependency diagram, "risk groups" of related activities can be defined in the methodology/software to model dependence between activity durations. The approach is described in detail in [13].

**Representing learning curve effects.** In the proposed shipbuilding project described, as in many large engineering projects, there were sequences of similar activities which were expected to exhibit learning curve behavior. In the example cited above, the nearly identical structural sub-blocks were to be successively fabricated, erected, and outfitted with piping and electrical gear. It was desired that learning curve representation should model not only a decrease in mean completion time of an activity, but also a decrease in uncertainty of activity duration (the more experiences a particular activity, the more certain one would be in how long it would actually take to complete this activity). Also, the representation of learning behavior should be compatible with the statistical dependence concept and related risk groups described above.

Assume uncertainty in the activity duration modeled using a triangular distribution with parameters A, M and B. Let $l$ be the amount of times that one completed an activity, $l = 0,1,2,\ldots.$ . Let $\mathcal{S}$ be the percent of learning each time an activity is completed, $0 \leq \mathcal{S} \leq 100\%$. It will then be assumed that the uncertainty in the activity duration after $l$ completions, with learning speed $\mathcal{S}$ is modeled by a triangular distribution with parameters $A(l,\mathcal{S})$, $M(l,\mathcal{S})$ and $B(l,\mathcal{S})$, where

$$\begin{cases} A(l,\mathcal{S}) = A \\ M(l,\mathcal{S}) = A + \left(\frac{100-\mathcal{S}}{100}\right)^{l} * (M\text{-}A) \quad 0 \le \mathcal{S} \le 100\%,\ l = 0,1,2,\ldots \\ B\ (l,\mathcal{S}) = A + \left(\frac{100-\mathcal{S}}{100}\right)^{l} * (B\text{-}A) \end{cases} \tag{2}$$

Note that when $l = 0$ or $\mathcal{S}$=0 (2) reduces to A, M and B. When S $>$ 0 and $l \to \infty$ (2) reduces to A, A and A (i.e. with certainty the activity duration will take no longer than A time units). Figure 3 depicts the change in a triangular distribution of an activity duration with 50% learning.

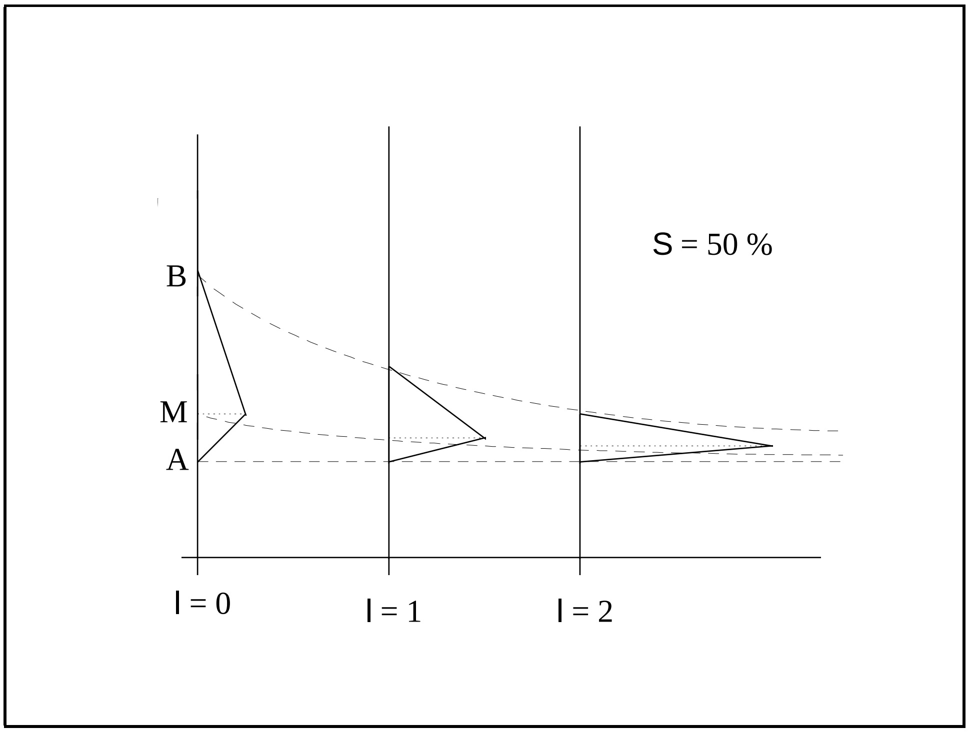


Figure 3. Graphical representation of the learning curve model

**Cost Representation in the Activity Network**

As mentioned, cost uncertainty in the model is a function of the duration uncertainty of activities. Therefore cost elements can be represented in a deterministic network model to which the Monte Carlo method is applied. When calculating the net present value (NPV) of a project $\mathcal{P}$, the following assumptions were made: 1) The time unit for NPV calculations is a week; 2) the project starts at t=0, the beginning of a week; 3) an activity will start at its earliest event time; 4) the total weekly costs are paid at the end of a week; 5) a week consists of m working days (m varies between 5 and 7 days). As currently implemented, only deterministic values are assumed for $\delta_{ij}$ and $\gamma_{ij}$ (cash disbursements and receipts at beginning or end of an activity, such as material, equipment and subcontractor costs), $\omega$ (periodic fixed costs), and r (opportunity cost of capital). Clearly, there is some degree of uncertainty for these as well as other factors (inflation, financing costs, etc.), and trade-offs between model complexity and validity are particular to each project. However, modeling time-related cost uncertainty of production activities was considered predominant for the reasons stated earlier.

The cost representation is defined with three contributions to the net present value: activity-specific, fixed, and penalty clause costs, which are further detailed in the following sections:

$$NPV(\mathcal{P}) = NPV_{activities} + NPV_{fixed} + NPV_{clause} \qquad (3)$$

Some activities may only span one or several contiguous working days, while others span weeks or months. Also, activity duration uncertainty was to be solicited from experts in terms of *working* days. Hence, reconciling *working* time and *absolute* time was necessary to calculate net present value in an activity network cost model. Let $\lceil x \rceil$ be the smallest integer bigger than a real number x. Likewise, let $\lfloor x \rfloor$ be the largest integer smaller than a real number x. Define

$$a_{ij} = \lceil \frac{t_{ij}}{m} \rceil, \quad b_{ij} = \lceil \frac{t_{ij}+d_{ij}}{m} \rceil, \quad n = \lfloor \frac{T}{m} \rfloor \qquad (4)$$

where $n \geq 1$ is assumed.

**Activity-specific and periodic fixed costs.** Activity-specific costs are comprised of two parts which correspond to a) direct labor and "variable" overhead costs dependent on activity duration and b) incoming or outgoing cash flows that occur at the beginning or end of the activity:

$$NPV_{activities} = NPV_{time} + NPV_{cash} \qquad (5)$$

Suppose $b_{ij} \geq a_{ij}+1$, where $a_{ij}$ is the number of the week in which activity (i,j) starts and $b_{ij}$ is the week in which activity (i,j) will be completed. The NPV for labor and overhead associated with an activity starting at $t_{ij}$, lasting a duration $d_{ij}$ and daily rate $\alpha_{ij}$ at a weekly interest of r then equals

$$NPV_{time}(t_{ij}, d_{ij}, \alpha_{ij}) =$$

$$\frac{(m*a_{ij} - t_{ij})*\alpha_{ij}}{(1+r)^{a_{ij}}} + \sum_{i=a_{ij}+1}^{b_{ij}-1} \frac{m*\alpha_{ij}}{(1+r)^{i}} + \frac{(m*b_{ij} - t_{ij} - d_{ij})*\alpha_{ij}}{(1+r)^{b_{ij}}} \qquad (6)$$

where $a_{ij}$ and $b_{ij}$ are given by (2) and (3) and the convention that $\sum_{i=a_{ij}+1}^{a_{ij}} \equiv 0$. The subscript *time* is used to indicate that this NPV calculation relates to dependence between cost and duration of an activity. Note that in the calculation above it is assumed that an activity always starts at its earliest event time. Of course this is a simplifying assumption and formula (6) may easily be adapted to the case where an activity starts somewhere between its earliest event time and its latest event time.

Since planned activities can span multiple weeks or even months, it becomes important to know whether cash disbursements (e.g., set-up or purchasing costs) occur at the beginning or end of an activity to account for discounted cash flow effects. An amount $\delta_{ij}$ will be associated with cash flow at the beginning of an activity. An amount $\gamma_{ij}$ will be associated with cash flow at end of an activity. Note that both $\delta_{ij}$ and $\gamma_{ij}$ may be positive or negative. Let $a_{ij}$ and $b_{ij}$ be defined as in (4). Then the net present value associated with incoming and outgoing cash flows follows as

$$NPV_{cash}(t_{ij}, d_{ij}, \delta_{ij}, \gamma_{ij}) = \frac{\delta_{ij}}{(1+r)^{a_{ij}-1}} + \frac{\gamma_{ij}}{(1+r)^{b_{ij}}}. \qquad (7)$$

Note that in (7) it is assumed that cash flow at the beginning of an activity occurs in the week just before an activity starts and cash flow at the end of an activity occurs in the week in which the activity ends.

As discussed, it is not realistic to ascribe all indirect project costs to specific activities defined in the network. Some are better modeled as periodic fixed costs, time-dependent only on completion time for a critical path realized for each iteration of the Monte Carlo simulation. $NPV_{fixed}$ (T) was therefore defined by a simple variation of the uniform series present worth expression found in any engineering economics text.

**Penalty clause-related costs.** Let C be the completion time agreed upon in a contract in days. Often, such as in the shipbuilding industry, engineering contracts contain daily penalty (liquidated damage) clauses of a fixed amount per period, say $\pi$. (Other performance-related penalty clauses which are not time-dependent were not included in this model). Define

$$n' = \begin{cases} 0 & \frac{7}{m}T < C \\ \lfloor \frac{7}{m}T - C \rfloor & \frac{7}{m}T \geq C \end{cases} \quad (8)$$

That is, n' is the total number of days the project is delayed according to the contract. Assume $n' \geq 1$ and let the daily interest rate be $r_d$. The NPV associated with the penalty clause then equals

$$\pi * \frac{(1+r_d)^{n'}-1}{r_d(1+r_d)^{n'+C}},\ n' \geq 1 \quad (9)$$

Summarizing, the total NPV of a project with total duration T and activity durations $d_{ij}$ equals

$$NPV(\mathcal{P}) = \sum_{(i,j)\in\mathcal{A}} \Big( NPV_{time}(t_{ij}, d_{ij}, \alpha_{ij}) + NPV_{cash}(t_{ij}, d_{ij}, \delta_{ij}, \gamma_{ij}) \Big) +$$

$$NPV_{fixed}(T,\omega) + \quad (10)$$

$$NPV_{clause}(T,C,\pi)$$

**Costs at project milestones under uncertainty.** One advantage of a network-based cost simulation is the ability to examine changes in uncertainty of cash flow as the project proceeds. This can be particularly useful for determining appropriate payment milestones (associated with the completion of any activity in the network) during the contract negotiation phase of a project. The following formula gives an estimate of total net present value at the end of the completion of an activity (i,j), denoted with $\mathcal{P}_{(i,j)}$, coinciding with the definition of a milestone as a node in an activity-on-arc network. Note that $t_{ij}$ is the earliest event time of an activity, and $\tau_{ij}$ is the latest event time of an activity. Let $F_{ij}$ be the set of activities that have been completed before $\tau_{ij}+d_{ij}$, i.e.

$$F_{ij} = \{ (k,l) \mid t_{kl}+d_{kl} \leq \tau_{ij}+d_{ij} \} \quad (11)$$

and $O_{ij}$ is the set of ongoing activities at time $\tau_{ij}+d_{ij}$, i.e.

$$O_{ij} = \{ (k,l) \mid t_{kl} \leq \tau_{ij}+d_{ij} \leq t_{kl}+d_{kl} \}. \quad (12)$$

Note that,

$$\frac{\tau_{ij}+d_{ij} - t_{kl}}{d_{kl}} * 100 \quad (13)$$

for an activity (k,l) in $O_{ij}$ is the percent completion of an ongoing activity at time $\tau_{ij}+d_{ij}$. An estimate for the total Net Present Value at the end of an activity (i,j) then follows as

$$\mathrm{NPV}(\mathcal{P}_{(i,j)}) = \tag{14}$$

$$\sum_{(k,l)\in F_{i,j}} \left( \mathrm{NPV}_{time}(t_{kl}, d_{kl}, \alpha_{kl}) + \mathrm{NPV}_{cash}(t_{kl}, d_{kl}, \delta_{kl}, \gamma_{kl}) \right) +$$

$$\sum_{(k,l)\in O_{i,j}} \left( \frac{\tau_{ij}+d_{ij}-t_{kl}}{d_{kl}} \right) \mathrm{NPV}_{time}(t_{kl}, d_{kl}, \alpha_{kl}) +$$

$$\sum_{(k,l)\in O_{i,j}} \left( \frac{\delta_{kl}}{(1+r)^{a_{kl}-1}} + \frac{\gamma_{kl}}{(1+r)^{b_{kl}}} * 1_{[0,\tau_{ij}+d_{ij}]}(b_{kl}) \right) +$$

$$\mathrm{NPV}_{fixed}(\tau_{ij}+d_{ij}) +$$

$$\mathrm{NPV}_{clause}(\tau_{ij}+d_{ij}, C, \pi).$$

## IMPLEMENTATION AND EXAMPLE

The software testbed for the risk analysis methodology/simulation was developed in Delphi (this is a Pascal-based software development environment which facilitates Windows applications). The first step in model creation is input of activity network data from a commercial project management software package. As currently created for schedule estimation in shipyards, this typically contains only precedence information and fixed activity durations. For the risk model, cost data, risk dependency groups, and uncertainty distributions for activity durations are assigned as a second pre-processing step before the Monte Carlo simulation. Also, shipyard activities are coded using an activity breakdown structure developed to simplify assignment of cost rates and other input data.

The implementation is illustrated here with a small, 18-activity network from a well-known ship construction reference [15] shown in Figure 4. Triangular distributions for activity durations are assigned using the published deterministic duration times as mean values. Some arbitrary cost assumptions for this example include: 46 $/hr. labor, overhead rate of 53%, a fixed periodical cost of 1000 $/wk., and no penalty clause for liquidated damages. Crew sizes of between 4 and 20 twenty were assigned for each task. A single-shift 8 hour workday, 5 day work week, and an opportunity cost of capital of 10% were assumed.

For illustration purposes, a single risk dependency group for "engineering change orders" was created which included all 18 activities (Figure 5). Numerical values on each arc indicate the degree of positive dependence, i.e. the percentage of explanation in total uncertainty of an activity's duration that can be associated with a given risk factor.

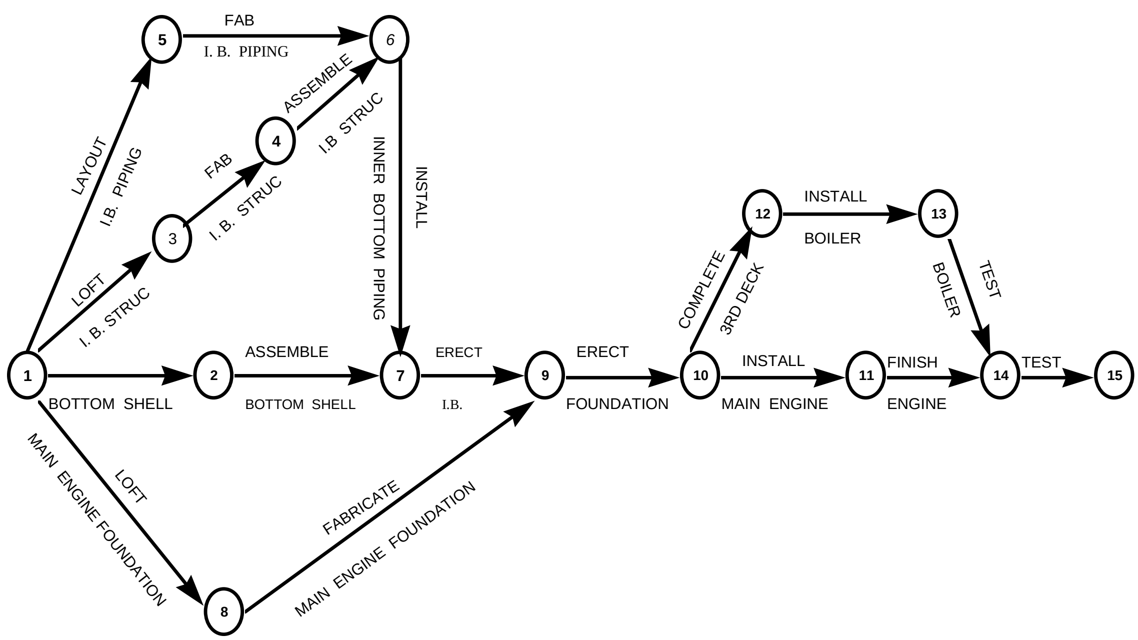


Figure 4. Example network of ship production activities (Taggert [15])

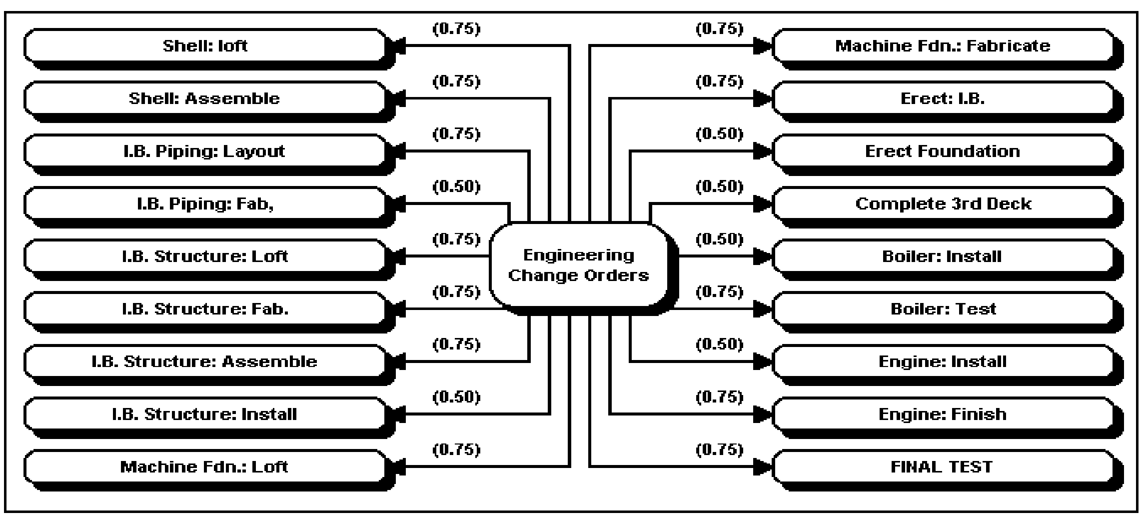


Figure 5: Dependence diagram

After Monte Carlo simulation for this example, an exceedance plot and histogram are generated as shown in Figure 6. Results in Figure 6 incorporate statistical dependence modeling and, for comparison, independence between the uncertainties in the activity durations (i.e., traditional Monte Carlo) is shown in Figure 7.

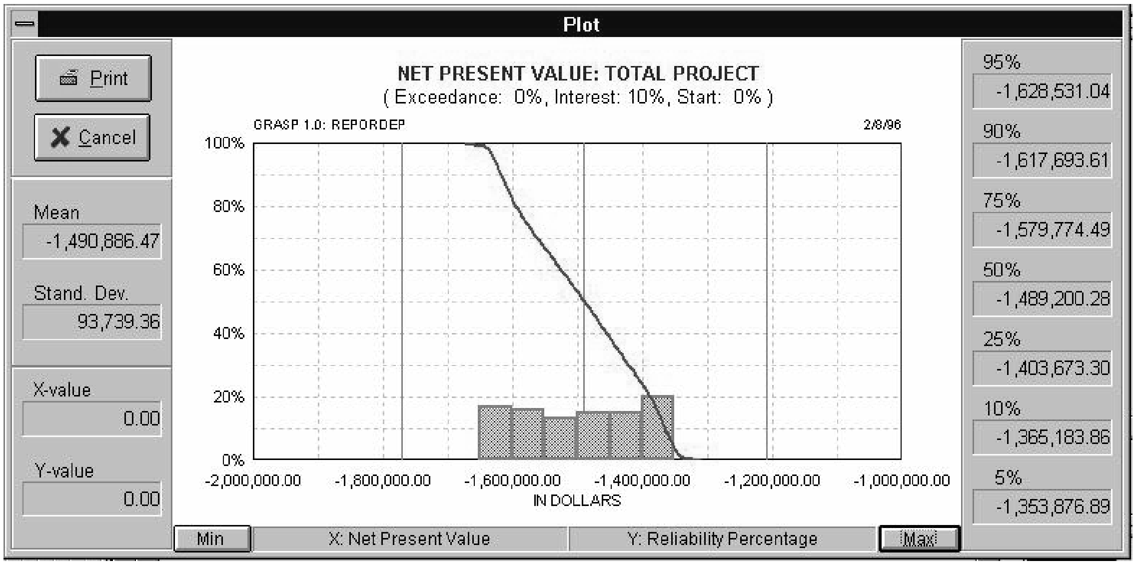


Figure 6: Monte Carlo assuming statistical positive dependence

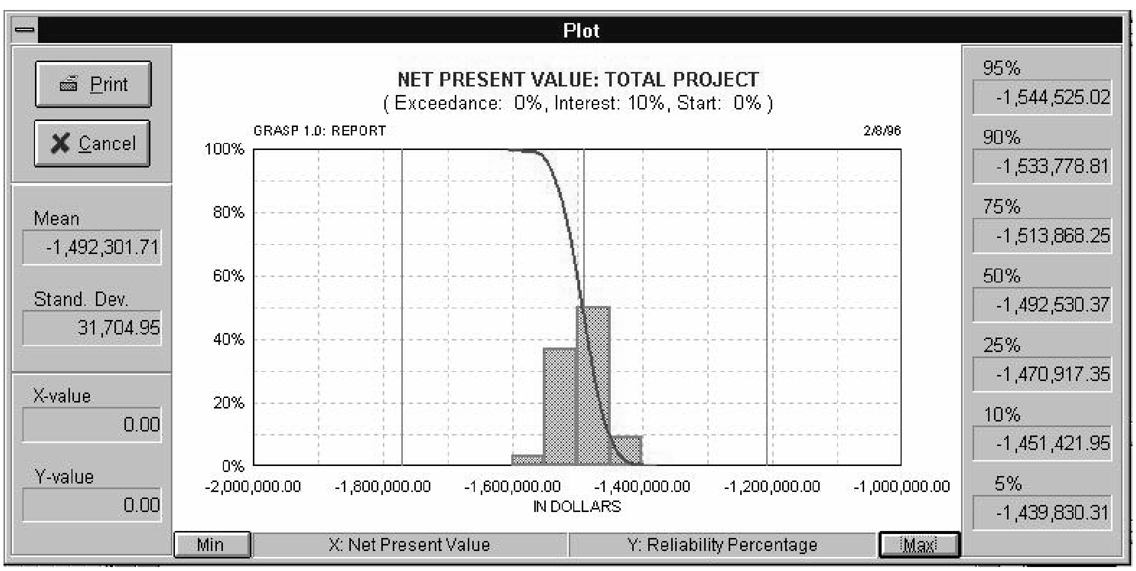


Figure 7: Traditional Monte Carlo assuming statistical independence.

In practice, of course, interpretation of analysis results depends on confidence in data and modeling assumptions. One general observation is that uncertainty assuming dependence is *greater* than assuming independence, but *less than* a deterministic PERT analysis using pessimistic/most likely/optimistic values (indicated by the vertical bars in the plots). Assuming dependence (Figure 6) the NPV for cost will be *less than* $1.63 million with 95% certainty. Assuming independence (Figure 7) the equivalent NPV would be $1.54 million. Whether this difference is meaningful depends on resolution of the model and the particular decision-making application (e.g., absolute cost for bidding vs. relative cost for ranking of designs).

**Uncertainty at Project Milestones and Contract Payments.** Perhaps more insightful than exceedance plots is the progression of uncertainty at chosen project milestones during the project life cycle. Figure 8 contains the 5%, 50% and 95% quantiles of the NPV distributions which occur after completion of 10 activities with high-criticality indices. The band generated in Figure 8 may thus be interpreted as a 90% probability interval of the NPV at the different chosen milestones. Clearly, as there is no incoming cash flow (no contract payments are modeled), the NPV decreases monotonically going from one milestone to the next.

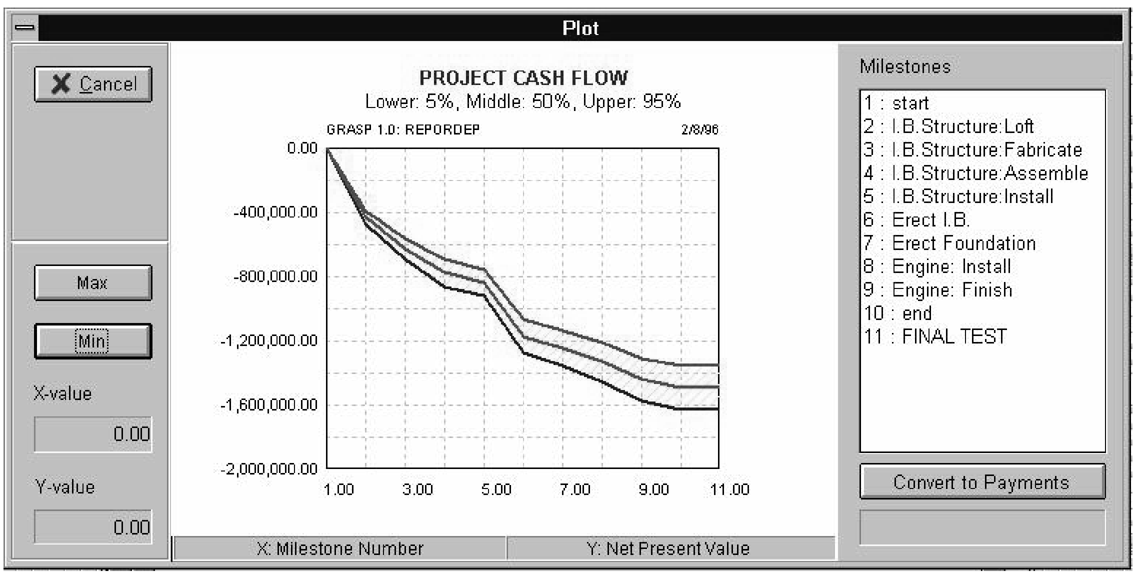


Figure 8. 5%, 50% and 95% of Net Present Value at different milestones
(No Contract Payments, with statistical positive dependence)

Consider an application of this method for the contract design stage. The 50% Net Present Values at each milestone could be converted into a contract payment to ensure a discounted cash flow over the project which does not become too negative (the 5% or 95% Net Present Values could have been used as well, depending on risk averseness). The resulting payments at the end of each activity on path 1 are given in Table 1.

| Activities | Path 1 | Contract Payments |
|---|---|---|
| **1** | I.B. Structure:Loft | $ 424,546.63 |
| **2** | I.B. Structure:Fabricate | $ 197,976.60 |
| **3** | I.B. Structure:Assemble | $ 150,855.28 |
| **4** | I.B. Structure:Install | $ 62,587.57 |
| **5** | Erect: I.B. | $ 338,637.12 |
| **6** | Erect: Foundation | $ 76,733.20 |
| **7** | Engine: Install | $ 86,192.60 |
| **8** | Engine: Finish | $ 110,197.10 |
| **9** | FINAL TEST | $ 50,477.90 |

Table 1. Contract Payments at the end of the activities of Path 1
calculated using 50% Net Present Values

Next, the discounted cash flow over the project can be generated again with the contract payments (Figure 9). As would be expected to 50% value of the NPV at each milestone equals zero.

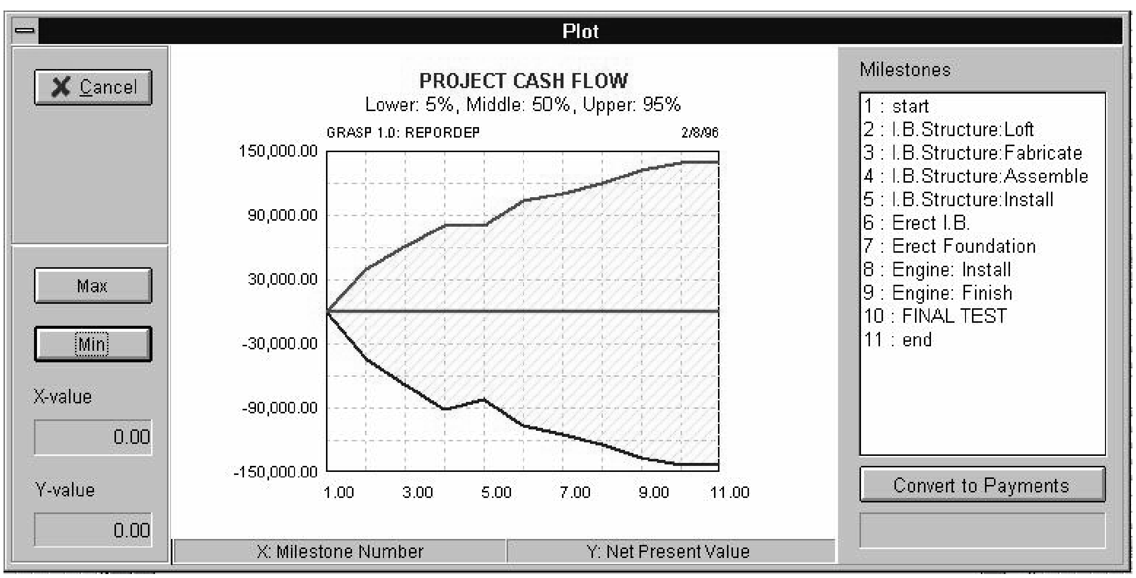


Figure 9. 5%, 50% and 95% of Net Present Value at different milestones
(With Contract Payments, with statistical positive dependence)

**Contract Penalty Clauses.** Finally, to completely the analysis, assume that liquidated damages of $10,000 have to be paid each day the vessel delivery is delayed after 189 days (135 workings days when assuming a week contains 5 working days), as agreed upon in the building contract. The effect on the cash flow and uncertainty in the Net Present Value is given in Figure 10.

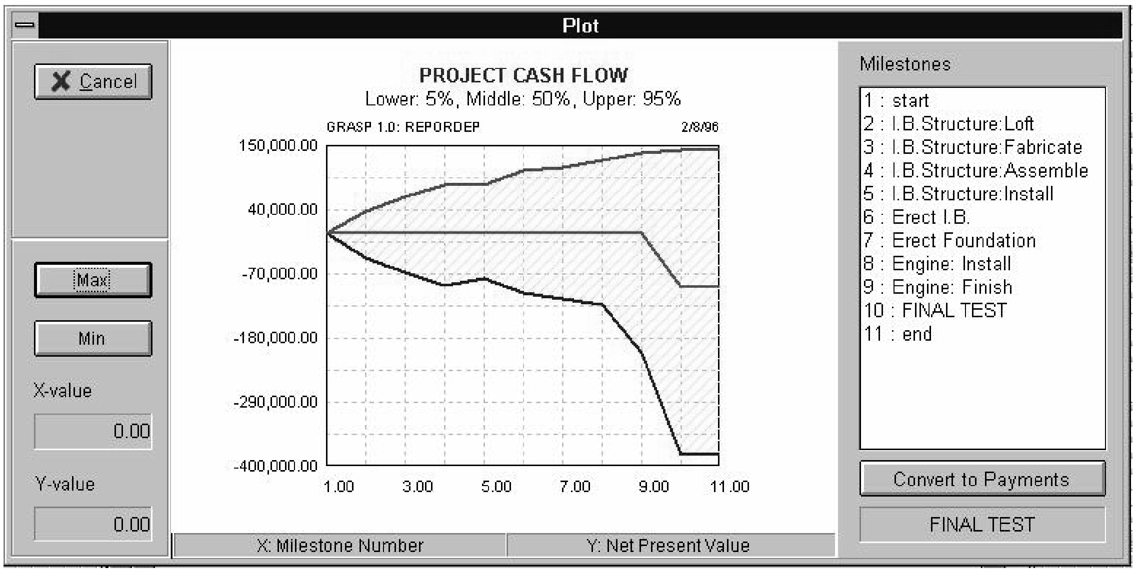


Figure 10. 5%, 50% and 95% of NPV at different milestones
(With Contract Payments, with stastical dependence, with penalty clause.)

A full-scale case study incorporating proprietary data was developed prior to delivery of the methodology/software to a commercial shipbuilding consortium. The data set is more complex (250 activities), and includes multiple risk groups, costs, and schedule typical of the scale and scope of shipyard data available at the pre-contract stage [16, 17]. It assumes significant product and process design innovations for a 40,000 dwt. double hull product carrier, including a "virtual shipyard" concept for subcontracting the fabrication of structural submodules for the hull mid-body. Several dependency diagrams were used to model risk due to subcontracted fabrication of the mid-body sub-blocks. Some of the methodology and implementation issues encountered during this project are discussed in the summary and conclusions.

## SUMMARY AND CONCLUSIONS

Although simulation modeling of physical systems is fast becoming an every day tool for many engineering applications, risk analysis of engineering projects using network simulation is still in its infancy. While some front-running companies have already integrated simulation-based risk analysis into their project decision-making processes, many others are still understandably skeptical. But despite the caveats cited above, simulation-based project risk analysis will likely become a valuable tool for engineering managers. Existing deterministic methods to predict schedule and cost (e.g., PERT/CPM and traditional cost estimating) provide only point estimates which are often unrealistic and do not utilize the valuable and at least partially quantifiable information about activity uncertainty that can be gathered from experienced production personnel. Issues relevant to practical implementation and methodology improvement are being addressed in on-going testing, and are summarized below.

**Practical Implementation Issues**

• Buy-in by project participants is essential. Data collection for activity duration uncertainty and risk modeling requires input from many engineers and managers, driven by a commitment to the approach from upper-level management. At one large Dutch civil engineering firm visited, risk analysis using network simulation method was incrementally refined and integrated with existing practices for two years before wide acceptance [8]. But for four years since then it had been used routinely on all large projects over $10 million.

• The cost uncertainty analysis should be normalized with results of existing cost estimating practices in the firm. It is already common in many companies to use two or more independent cost estimating procedures during design phases, then resolve the outcomes (for example, using parametric costing models). Ideally, the central tendency (an absolute cost measure) can be calibrated with other nominal point estimates, while other uncertainty characteristics (relative cost measures) are refined by consensus modeling of risk factors and input data. In existing practice, however, nominal and contingency costs are often implicitly combined in the estimates of subtasks/subsystems provided by lower level project participants. These can be highly subjective according to each manager's experience and risk averseness.

• Understanding the trade-offs between network size/complexity and validity of analysis is a trial-and-error process for each firm. There is obviously some point of diminishing returns for increased model complexity.

• Determination of valid risk groups for modeling statistical dependence requires careful consideration by experts for factors such as engineering change orders, subcontractor efficiencies, etc. However, the statistical dependence modeling concept is a potentially significant innovation for project network simulation. It has been successfully applied in other risk analysis domains (e.g., reliability in the Dutch dike system) and merits further investigation for project networks.

**Methodology Issues**

• The activity network assumed in this methodology has a deterministic, acyclic graph structure. That is, it assumes that all activities in the network will be realized one time and only one time during the project. This assumption was necessary since only PERT/CPM network data is currently available from shipyard sources, and it may be reasonable for well understood construction methods. However, it is more questionable for highly concurrent processes which include both product and process design innovations. Also, network modeling thus far does not include other dynamic effects such as schedule recovery/compression (e.g., adding a third shift for work crews). Possible enhancements to the stochastic PERT network might include conditional branching to model alternative possible paths which have non-deterministic realization probabilities, or incorporation of Precedence Diagramming Method (PDM) start-to-finish and finish-to-finish activity relationships. More generally, there are many unresolved questions about modeling the product realization process (PRP) [18], and the benefits of increased modeling sophistication will remain unclear until large scale field testing by practitioners occurs.

• An activity breakdown structure that hierarchically groups related ship production activities was used to greatly simplify data entry/modification for cost and time elements. This is necessarily different from a traditional systems-oriented work breakdown structure. The U.S. Navy's Ship Work Breakdown Structure (SWBS), for example, provides an hierarchical breakdown based on functional system decomposition (hull structure, electric plant, propulsion system, etc.) -- not activity classification [19]. The activity hierarchy used here could be better integrated with existing classification schemes for work packages (such as suggested for a product-oriented work breakdown structures (PWBS) [20]). Beyond this, an object-oriented representation of activities could probably improve many facets of data entry, manipulation, and validation -- a tedious process for large ~250 activity networks even using the breakdown structure described above. Multiple class inheritance and other object properties for activity representations were incorporated in an earlier project [21]. These can, for example, help define templates of activity subprocesses with class-inherited precedence relationships; adjust for discrepancies between subjective input values and distribution parameters for particular classes of production activities; aid assignment of activity risk groups using multiple inheritance schemes.

## NOMENCLATURE

| | |
|---|---|
| T | : The completion time of the project in total *working* days. |
| C | : The completion time of the project agreed upon in a contract in total days. |
| n | : The completion time of the project in total days. |
| n' | : The total number of days the project is delayed after a contract-specified time C. |

$r$ : Effective weekly interest rate (opportunity cost of capital)

$r_d$ : Effective daily interest rate (opportunity cost of capital)

$m$ : The number of working days contained within a week.

$t_{ij}$ : Earliest event time of activity (i,j) in working days.

$\tau_{ij}$ : Latest event time of activity (i,j) in working days.

$d_{ij}$ : The duration of activity (i,j) in working days.

$a_{ij}$ : Week number in which activity (i,j) starts.

$b_{ij}$ : Week number in which activity (i,j) ends.

$\alpha_{ij}$ : Cost rate for each working day of activity (i,j), which includes total direct labor and "variable" overhead.

$\delta_{ij}$ : Disbursements (positive) or receipts (negative) at the beginning of an activity.

$\gamma_{ij}$ : Disbursements (positive) or receipts (negative) at the end of an activity.

$\omega$ : Aggregate weekly periodical cost associated with the project.

$\pi$ : Cost per day due to liquidated damages due to a penalty clause within the contract, when project surpasses contract time C

$F_{ij}$ : The set of activities that have been completed before $\tau_{ij} + d_{ij}$

$O_{ij}$ : The set of activities that are ongoing at time $\tau_{ij} + d_{ij}$

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