Excessive Project Cost – Where It Comes From: A Quantum Perspective

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Introduction: Project Statistics and Central Limit Theorem

Accurate prediction of project cost and duration remains an important but not fully resolved problem. It is well-known that actual project costs and durations usually exceed their planned values. The following table shows statistical results for work breakdown structures (WBS) in defense and space industries, with project costs systematically

	Cost/Budget Growth		
Study	**Average**	**Median**	**% overruns**
NASA in the 90s	36%	26%	78%
NASA in the 70s	43%	26%	75%
NASA in the 80s			
Gruhl study	61%	50%	95%
GAO study	83%	60%	89%
DoD	45%	27%	76%

exceeding their planned values (Schaffer, 2004 NASA Cost Study). More detailed studies also demonstrate strong asymmetry of cost distribution functions. Typical project statistics for a sample of 258 public projects (from Flyvbjerg, Holm, Buhl, APA Journal, 2002, No. 3) compares

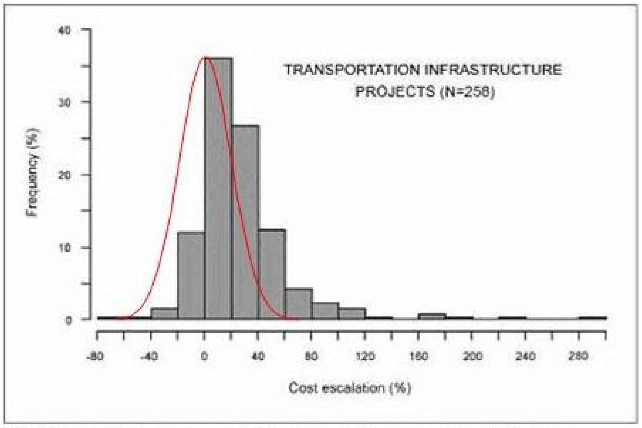
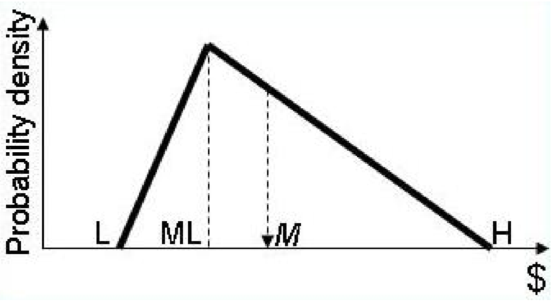


FIGURE 1. Inaccuracy of cost estimates in 258 transportation infrastructure projects (fixed prices).

the actual asymmetric and mean-shifted distribution with the normal distribution having CoV ~ 20%. Flyvbjerg et al. have also proven that project delays and cost overruns show no tendency of reduction in time, could not be attributed to historical reasons, lack of managerial experience or to technical difficulties, and suggested an extravagant hypothesis "…that a pattern of highly misleading forecasts of costs and patronage could not be explained by technical issues and were best explained by lying".

When a reasonably large project is conceived, the planner suggests "average" task durations and costs from his own or historical experience. It could be expected and confirmed by Central Limit Theorem (http://en.wikipedia.org/wiki/Central_limit_theorem) that, after many generations of projects, especially in construction of buildings, bridges, roads etc., all task estimates will become rational and milestone distributions will show almost normal results. This expectation, however, has never materialized which demonstrates the "reality" of asymmetric distributions of project costs and durations, and calls for new analytical models.

In the mean time, risk practitioners use the empirical approach of multiple expert interviews to determine possible asymmetric delays of tasks and their combinations. The existing analytical methodology (for example, U. S. Air Force Cost Risk and Uncertainty Analysis Handbook, Jul. 2007) prescribes asymmetric distribution functions to each task or WBS element. Asymmetry introduces individual task risk by skewing Median M to exceed Most Likely values ML as the following figure shows:



Triangular distributions are chosen for simplicity, and the values L, H and ML are defined in multiple expert interviews. Though widely criticized for "driving with a rear-view mirror" the expert opinion methodology has proven efficient in predictions of cost overruns/delays based on historical data. The expert opinion-based methodology of *predicting* currently unknown project details is time consuming (needs averaging over many interviews), and does not incorporate specificity of the current project.

This paper presents a new analytical model that starts from normally distributed tasks (WBS elements) and ends up with asymmetric and mean-shifted distribution of project duration and cost. The general idea is that cost overruns and delays depend on currently unknown details of project tasks that may be calculated from average task correlation functions. The asymmetry of a milestone (or Summary Task) distribution is defined by random correlations of associated tasks or sub-tasks, with the sub-task distributions fully symmetric. The mathematical environment adequate for calculations of this task-to-task correlation function is embodied in the formalism of quantum mechanical "wave functions". It turns out that the correlation function (and probability density) of randomly delayed tasks is larger than that of randomly shortened tasks.

Why Quantum Mechanics?

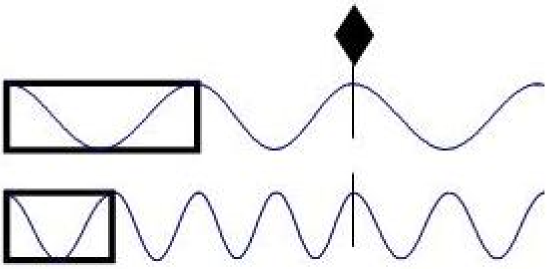
Quantum mechanics is the physics of elementary particles: electrons, photons, neutrons, etc. The attempts to treat the electron as a little ball bearing-like entity circling around a nucleus and determine its kinematics (location and velocity) were not self-consistent, and physicists realized quickly that electron behavior is better described in probabilistic terms.

This paper's fundamental premise is that probability distributions of schedule (WBS) tasks and milestones is better suited by probabilistic treatment of elementary particles rather than by conventional probabilistic analysis of risks and costs of industrial projects. The starting point of the new model is that human productivity cannot be predicted with arbitrary high accuracy, no matter how precise are the work condition limitations. This idea invokes the "uncertainty principle" and application of wave function formalism, especially the concept of interference, to project tasks and WBS elements. Interference can be *destructive* or *constructive. It is destructive* when waves cancel each other out, and *constructive* when wave amplitudes align. In this paper, relations between task uncertainty and project risk are proposed as being naturally described better by the interference of quantum mechanical wave functions than by classical random deviations. Readers more accustomed to presenting task durations and costs as blocks of time or $ and interested in how elementary particles are described with optical and quantum mechanical waves, may start from http://en.wikipedia.org/wiki/Interference.

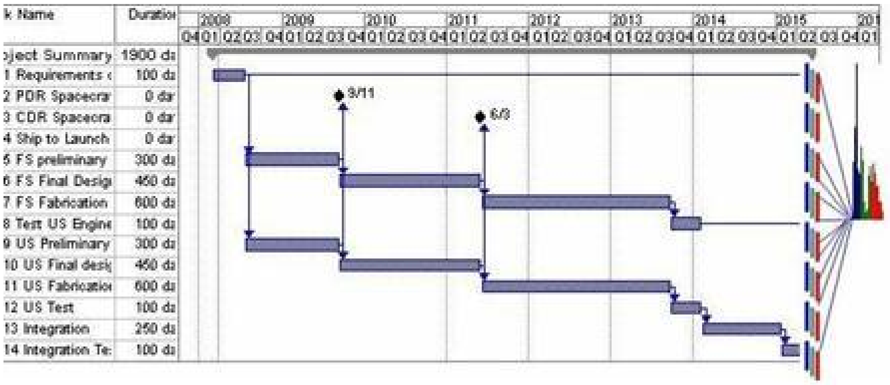
The basic difference between classical and quantum mechanical probabilities may be described from the comparison of an electron propagating from point A to point B and scattered along the way by a plurality of random obstacles with a classical ball bearing passing through the same path and scattered by the same obstacles (a typical classical example is the scattering of artillery shells on the target). In the classical example, a deviation of each individual hit from the Mean is related to the uncertainty from multiple factors (mass of powder, cannon position, wind etc.). It is believed that if all these uncertainties are removed or accounted for, the shells would hit the target with arbitrary high accuracy. Electron scattering behaves more like this: before taking a specific path, the electron sends out its "precursor" wave testing for all possible scattering alternatives, and ultimately propagates along the path of the maximum of the wave interference pattern, that is, along the path of the most *constructive* interference. The accuracy of interference pattern parameters is defined by the "uncertainty principle".

The Quantum Model

For the purpose of finding interference (correlation) between the tasks, each task is presented by a sinusoidal wave function, with one or more periods squeezed into the task duration. The milestone is modeled as a collective image of all associated tasks. Wave functions of all tasks propagate to the milestone, and are "focused" (arrive at the same phase) to the milestone:



The following figure is a graphical presentation of the quantum model:



Fields “emitted” by all tasks are focused onto the milestone and each task (each wavelength) contributes to the field intensity at the milestone spot.

The milestone image (a diffraction pattern of task wave functions) is similar to diffraction images of other optical or quantum objects. Each project task is identified as a particle *"i"*, and the wave associated with it is a wave function

$$\psi_i \sim \cos(2\pi t / D_i)$$

where ***D*** $\boldsymbol{D_i}$ is task duration (cost and duration of WBS elements are suggested to be proportional to each other), “*t*” is project time.

Probability density ***P*** is calculated as the square of the sum of all task wave functions

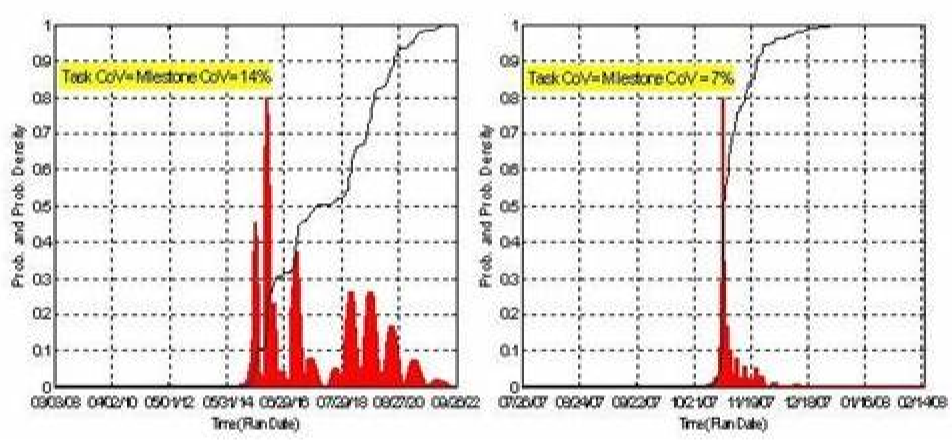
$$P = (\sum \psi_i)^2$$

To account for deviations of task durations (costs) from their Means, a plurality of project samples with duration (or cost) of each project task normally distributed around its Mean value is created by Monte Carlo simulations. To provide optimum image contrast, milestone and task coefficient of variations (CoVs) have to be of the same order of magnitude. Without task variations, milestone image would be defocused (spread over the full time axis), in contrast with classical model of small task variations causing exact position of the milestone.

Thus, the only substantial difference between the classical and quantum models is the treatment of the milestone. In the classical model, the milestone is a point on the time axis corresponding to the end of latest task of the project sample with random task durations. In the quantum model, the milestone is an image (superposition) of all task wave functions with random phases.

For readers interested in the algorithm details, the milestone image with task CoVs = 0 is a Fourier transform of a periodic function having a discrete spectrum defined by non-varying task durations. For CoV > 0, the milestone image is formed by a continuous spectrum of varying task durations with a "pulse" Fourier transform which duration is inversely proportional to spectral width (CoV) of tasks.

The milestone image plays the same role in the quantum model that the distribution of hitting points on the time axis plays in conventional Monte Carlo simulations. However, the quantum image of fully symmetric task distributions is naturally asymmetric which provides, even without user input, some measure of expected project delay and cost increase. Basically, the delay is defined by the project schedule structure itself (task durations and links). Typical quantum modeling results for two different projects are shown in the following figure:

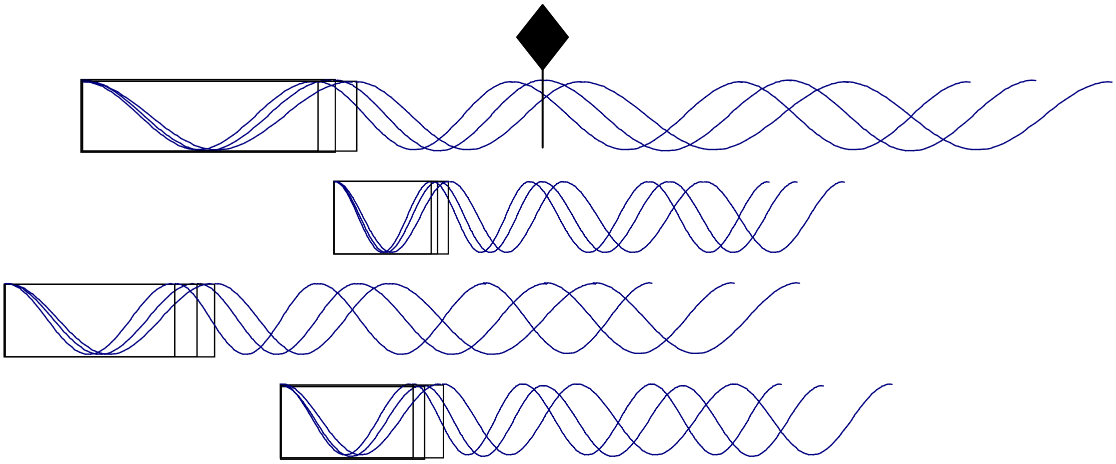


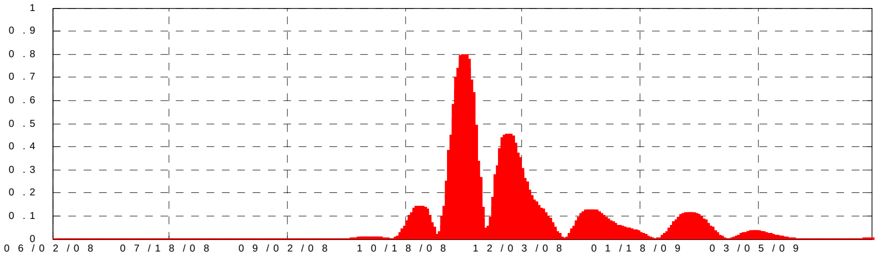
The probability density presented by a non-monotonic diffraction image is different from a bell-like, almost normal classical distribution. Image details (length in time, periodicity etc.) depend on the milestone structure (number of tasks, their durations, links and distances to milestone). Non-monotonic time behavior emphasizes random correlations of tasks and groups of tasks.

Quantum imaging provides natural quantitative relationships between Risk and Uncertainty (task *uncertainties* are converted into milestone *risk)*. Qualitatively, Risk is understood as a uni-directional manifestation of Uncertainty towards poor project outcome. The Quantum model introduces risk as a systematic shift of milestone probability as a function of task uncertainty. The "unit" of project risk corresponds to a phase shift caused by random variation of duration or cost directly transferred to the milestone. The mathematical object describing risk is the milestone *Correlation Function* of task wavefunctions. For further references to Numerical Inverse Fourier Transform (NIFT) of random functions see for example, Autocorrelation of Random Processes (http://cnx.org/content/m10676/latest/).

How It Works

The following Figure qualitatively demonstrates how the quantum algorithm works:

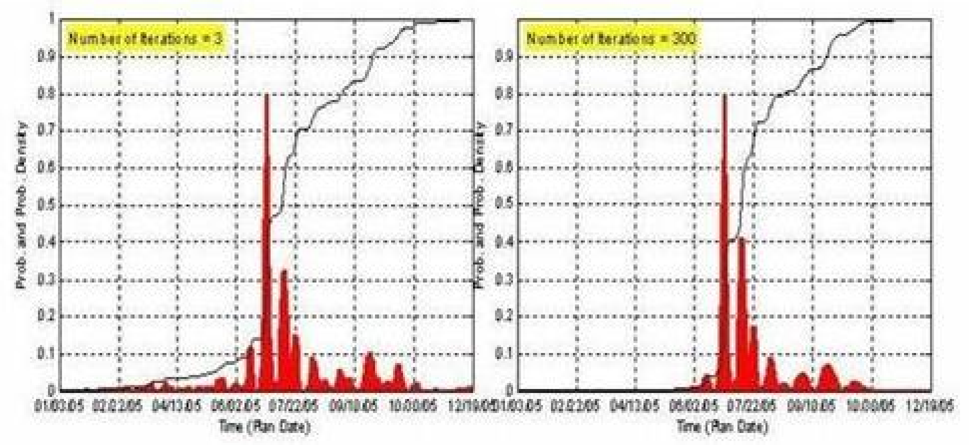




The figure presents a simple project with 4 tasks reporting to a milestone; each task is described by a wave function, and the wave functions of all tasks are summed in phase at the milestone. In the process of Monte Carlo simulations, the task durations randomly fluctuate, and each task phase is shifting back and forth relative to the milestone. After all waves (300 project samples in the figure above) are superimposed, the resulting interference pattern (shown in red) exhibits a maximum at the milestone and strong asymmetry (skewed right), because wave functions of elongated tasks correlate stronger than wave functions of shortened tasks.

Iterations, Signal and Noise

The number of *Iterations* defines the number of Monte Carlo simulation samples. In terms of signal-to-noise ratio, NIFT is more efficient than conventional Monte Carlo analysis that leaves only one hitting point on the time axis after each simulation cycle; in NIFT, random harmonics are summed along the full time axis. Still, the number of iterations defines signal-to-noise:



Qualitatively, the high intensity peak near the milestone corresponds to all N harmonics summed almost in phase:

$$I \sim N^2$$

Far from the milestone, harmonics amplitudes are added randomly, providing intensity

$$I \sim N$$

Thus, for large number of iterations N, signal-to-noise ratio

$$\frac{S}{N} \sim \sqrt{N}$$

These relations well-known in optics, laser physics and radio/microwave antennae design show the origin of sharp and narrow milestone peaks in quantum modeling.

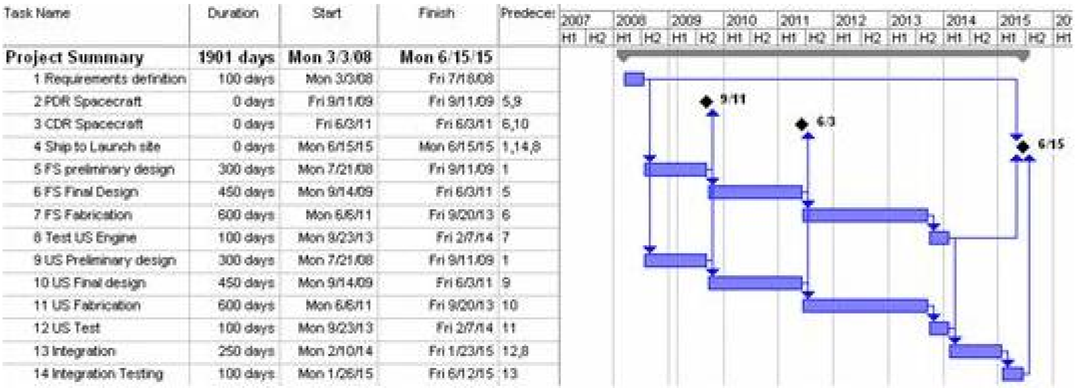
Quantum Model Parameters

In the “fundamental” state, each task wave function is characterized by two parameters: period $\boldsymbol{D_i}$ (duration) and phase at the milestone. These parameters may be independently changed to describe different external inputs.

Task CoV Input

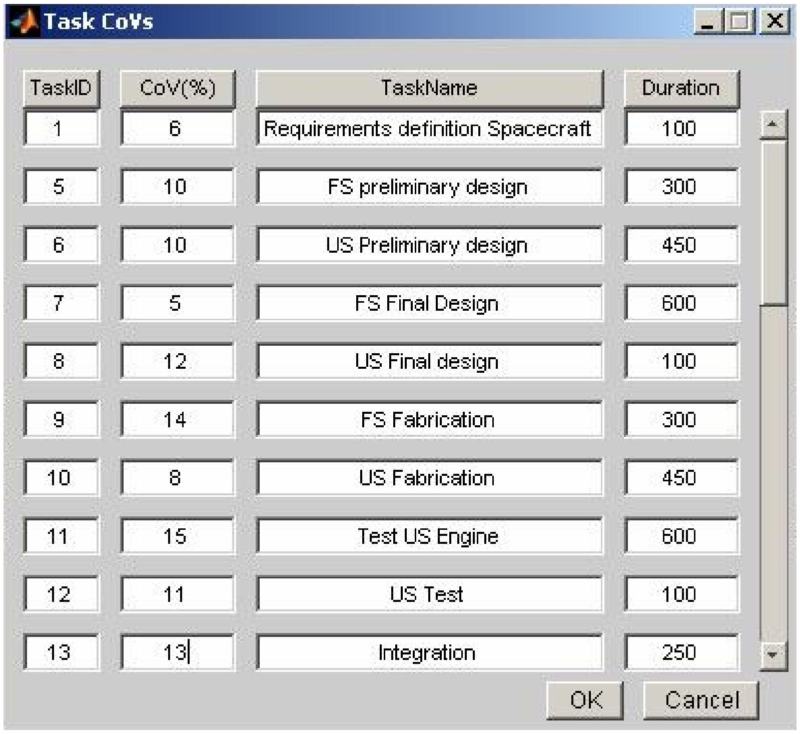
For the user of the quantum model, task uncertainty (CoV) is the single external variable. In essence, this is the major difference between the classical and quantum models for practical applications: the quantum model needs only the task CoV input while the classical model would require at least two parameters, Low and High values for each task duration (if the Most Likely coincided with the planned duration). The following example demonstrates how different inputs of task CoVs affect the model results.

The file describes manufacturing, testing and launch of a new satellite and rocket engine:



Task Name	Duration	Start	Finish	Predece:
Project Summary	**1901 days**	**Mon 3/3/08**	**Mon 6/15/15**	
1 Requirements definition	100 days	Mon 3/3/08	Fri 7/18/08	
2 PDR Spacecraft	0 days	Fri 9/11/09	Fri 9/11/09	5,9
3 CDR Spacecraft	0 days	Fri 6/3/11	Fri 6/3/11	6,10
4 Ship to Launch site	0 days	Mon 6/15/15	Mon 6/15/15	1,14,8
5 FS preliminary design	300 days	Mon 7/21/08	Fri 9/11/09	1
6 FS Final Design	450 days	Mon 9/14/09	Fri 6/3/11	5
7 FS Fabrication	600 days	Mon 6/6/11	Fri 9/20/13	6
8 Test US Engine	100 days	Mon 9/23/13	Fri 2/7/14	7
9 US Preliminary design	300 days	Mon 7/21/08	Fri 9/11/09	1
10 US Final design	450 days	Mon 9/14/09	Fri 6/3/11	9
11 US Fabrication	600 days	Mon 6/6/11	Fri 9/20/13	10
12 US Test	100 days	Mon 9/23/13	Fri 2/7/14	11
13 Integration	250 days	Mon 2/10/14	Fri 1/23/15	12,8
14 Integration Testing	100 days	Mon 1/26/15	Fri 6/12/15	13

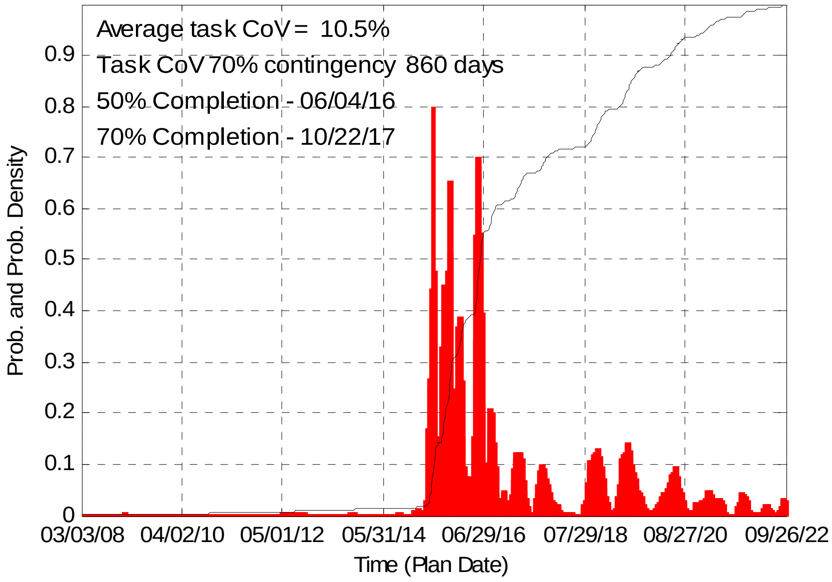
The table below is a set of task CoVs,



TaskID	CoV(%)	TaskName	Duration
1	6	Requirements definition Spacecraft	100
5	10	FS preliminary design	300
6	10	US Preliminary design	450
7	5	FS Final Design	600
8	12	US Final design	100
9	14	FS Fabrication	300
10	8	US Fabrication	450
11	15	Test US Engine	600
12	11	US Test	100
13	13	Integration	250

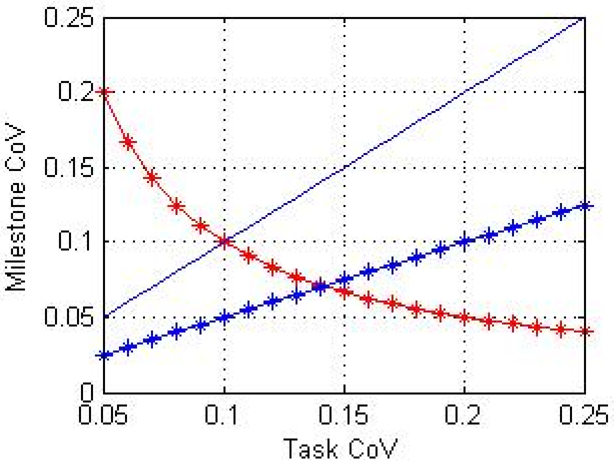
and the following figure presents probability density and S-curve for milestone 4 (Ship to Launch Site). Similar to figures shown above, probability density is strongly asymmetric, and the S-curve predicts about 2.5 years launch delay from the originally planned date of 6/15/15.

CoV input defines both frequencies and phases of task wave functions; the frequency variations are emphasized by the increase of wave function periods filling task durations. The limit of very small task CoV corresponds to “quasi-classical limit” with task details known with very high accuracy.



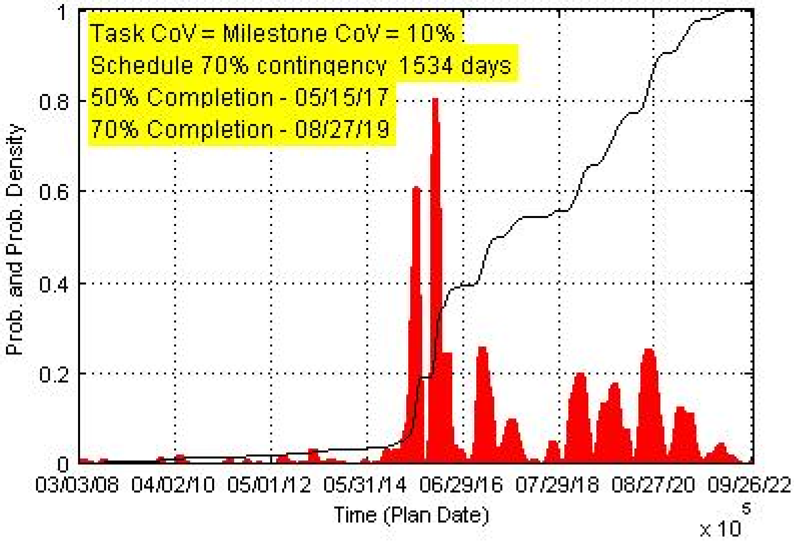
Schedule (or WBS cost) Risk

Another feature of the quantum model – its ability to make reasonable assessment of expected delays or excessive costs without any user input – is based on the conformity of quantum analysis to classical statistics. This conformity takes the form of ensuring the equality of CoVs at the intersection of a classical statistics line representing 100% correlation among task distributions and the quantum "decreasing at a decreasing rate" (hyperbolic) function phenomenon for a similar relationship. This determination of the quantum task distribution default CoV setting is meant to serve as a reference point for comparison with user-driven calculations of Task CoV input as in the table above. The following figure shows the relations between task CoVs and milestone CoVs in classical (blue lines) and quantum (red line) models:



Classical straight line and quantum hyperbolic function both depend on schedule structure. For any project, classical straight lines lay between fully correlated tasks (equal CoVs of tasks and milestone, thin blue line) and totally independent tasks (task CoV exceeds milestone CoV, marked blue line). The calibrated quantum image has to satisfy classical and quantum models simultaneously which is possible only at the intersections of red and blue curves. For different schedules, the CoV number could vary from ~2% (late stage) to ~ 15% (early stage) projects.

Probability density and S-curve based on the default task duration distribution CoV setting of 10% calculated for the intersection of classical and quantum models are shown for the Example project below:



Essentially, this figure calibrates task Coefficient of Variation (Standard Deviation-to-Mean ratio) e.g. calculates structurally-rational CoV value. *CoV = 10%* means that 99% of all Monte Carlo project samples have task durations varying within ~ 20% of their Means. If conventional Monte Carlo simulations were conducted with task CoVs ~ 10%, the result would be not a strongly asymmetric, irregular probability density but an almost normal distribution centered around planned date of June 15, 2015, with less than 200 days standard deviation.

Milestone contingency of ~ 1,500 days is "Schedule risk" calculated from the quantum mechanical task-to-task correlation function. It creates, without external input, a reference point for comparison with user-driven calculations of Task CoV input.

Risk Register Input

Finally, the quantum model uses Risk Register input, by filling the table of risk categories with relative values of risk Likelihood and Consequence (figure below):

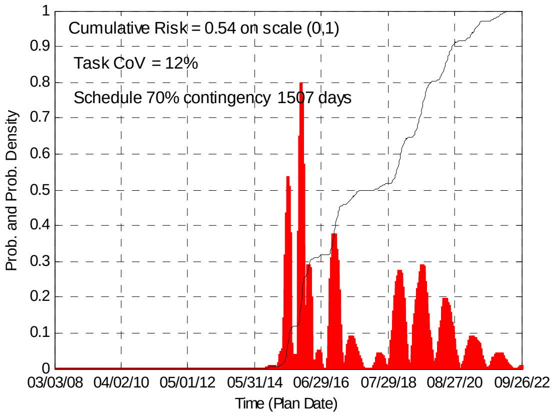
Cost risks

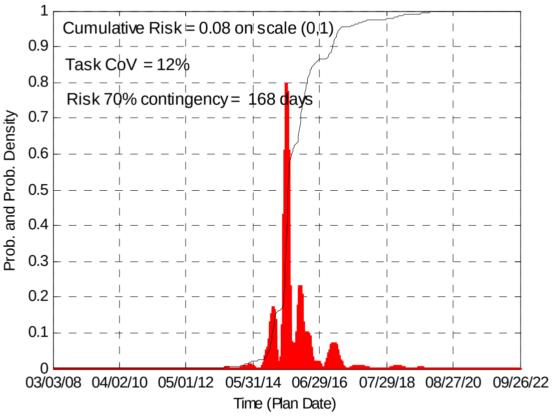
☑ Funding stability
☐ Supplier financial viability
☐ Other

Performance Risks

☐ Immature Technology - TRL was too low or assessed too high
☐ Requirements volatility
☐ High percent new design required
☐ Extent to which existing hardware or software can be reused
☐ Activities take longer because they are more complicated than estimated

With risk register input, wave function frequencies are not changing but their phases are adjusted and equal 0 for “green”, or very small risk and pre-set maximum for “red”, or very large risk. Thus, there are two types of adjustment available in the quantum approach: CoV adjustments and Likelihood & Consequence adjustments via the Risk Register. For these semi-qualitative external risk inputs, the Risk Register provides, similar to the classical procedure, S-curve and probability density. Two different examples from two different Risk Register inputs are shown below, both with CoVs equal to 12% with the one on the left describing rather large risk (mostly red cells from the Risk Register) and the one on the right illustrating very small risk (mostly green cells). These two graphs illustrate the model difference between very small CoV (resulting in very narrow but asymmetric distribution) and very small risk (rather wide but fully symmetric distribution).





Conclusion: Application to Planning and Execution

Risk practitioners involved in classical risk assessment and familiar with multiple expert interviews with often diverging opinions, might appreciate the user-independent Schedule (WBS) Risk procedure establishing a reference point for milestone contingency and taking no longer than 15-20 minutes. Further quantum analysis of Task CoV input and Risk Register input needs fewer interviews and, in a majority of cases, provides results of comparable predictive power.