Cost and Schedule Interrelationships

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Acknowledgements

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Overview

- **This presentation summarizes a study performed on cost and schedule interrelationships for the Independent Program Assessment Office (IPAO)**
  - **Performed Research on Cost and Schedule Relationships**
  - **Developed Excel-Based Cost Modeling Capability to Implement**
    - **Funding profiles with cost caps**
    - **Cost impacts on schedule**
    - **Schedule impacts on cost**
    - **Effect of specific functions on funding profiles, such as testing**

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Cost and Schedule Are Correlated

- **Cost and schedule are highly correlated**
  - **If the schedule slips, i.e., the project takes longer than anticipated to complete, then its cost will increase**
    - **"Burn rate"**
    - **"Standing army" must be paid**
- **Cost and schedule are mathematically correlated**
  - **A program with a longer schedule generally has higher cost**
  - **A program with a short schedule generally has lower cost**
    - **Unless a program has a compressed schedule**
- **Many models are not currently well-equipped to handle cost and schedule jointly**
  - **Cost and schedule are often analyzed independently of one another**

The Importance of Considering Cost and Schedule Interactions

- Because cost and schedule are interrelated, and changes in schedule have a significant impact on cost, there is a need to model these phenomena
- In 2006, IPAO initiated a task to determine the effects of schedule changes and funding constraints on cost
  - Effect of schedule increases on cost
  - Effect of schedule compression on cost
  - Effect of cost caps that constrain funding

Cost Penalties/Benefits Due to Changes in Schedule

- **Previous work includes**
  - Schedule algorithm in the Microgravity Experiments Cost Model, which indicates
    - Schedule growth penalizes cost at the 20% growth level and above
    - Ratio of schedule growth to cost growth is approximately 50%
  - Matt Schaffer's DOD experience, which indicates a ratio of schedule to cost growth of approximately 33%-50%

Schedules – Is the Glass Half-Empty or Half-Full?

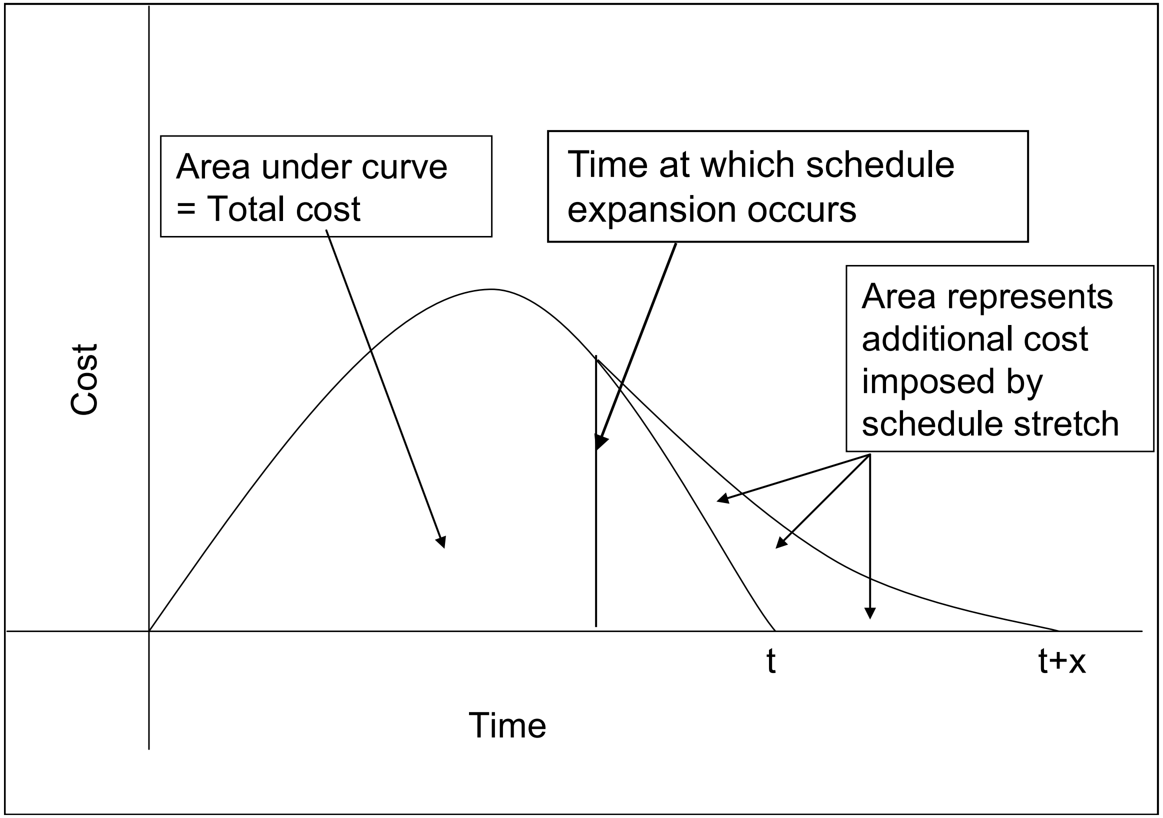
- Some available research indicates that "most" schedules are longer than optimal (built-in pessimism)
  - Some programs have been able to cut cost by optimizing schedule
    - Delta 180 program cut both cost and schedule by more than 50%
    - Rossi XTE had significant cost and schedule savings
- However, the data do not seem to bear this out in the general case
  - Most programs incur schedule overruns
    - 85% of the missions analyzed for this study had schedule overruns
      - In a previous study for Goddard Space Flight Center, 80% of missions analyzed experienced a schedule overrun
  - If most schedules were pessimistic, the schedule overrun rate would not be as high as historical experience indicates

Systems Level Vs. Detailed Analysis

- Applicability of prior research on this subject is limited to system-level analysis
- For more detailed analysis (such as how changes in specific schedule activities impact funding profiles and cost), specific time-phased analysis is needed
- Schedule impacts are a function of (at least) two variables
  - Increase in schedule length
  - Time at which schedule increase occurs

Cost Penalties/Benefits Due to Changes in Schedule - New Theoretical Research

- **When schedule increases, cost increases due to a stretching of the funding profile**

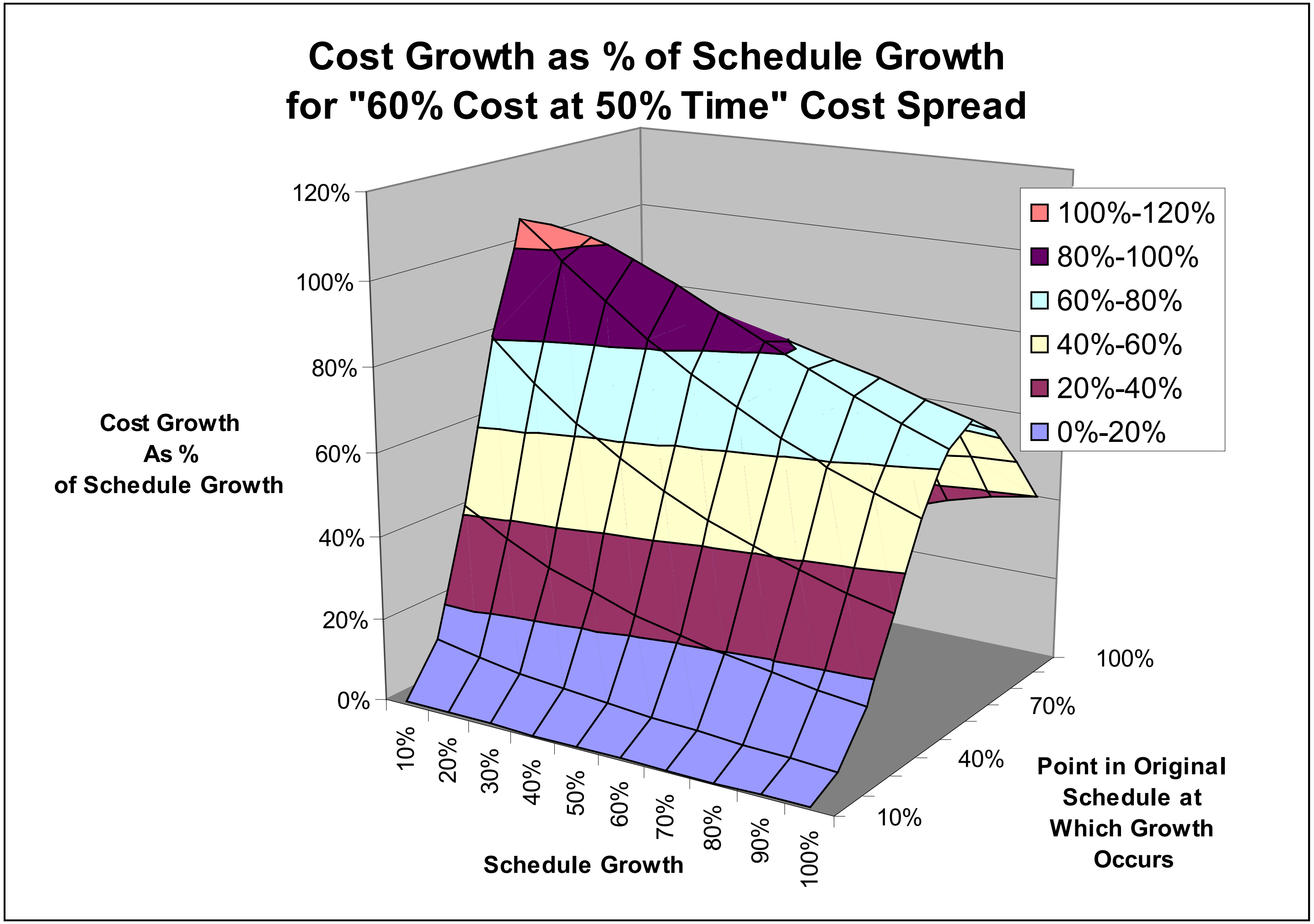


Cost Penalties/Benefits Due to Changes in Schedule - New Theoretical Research

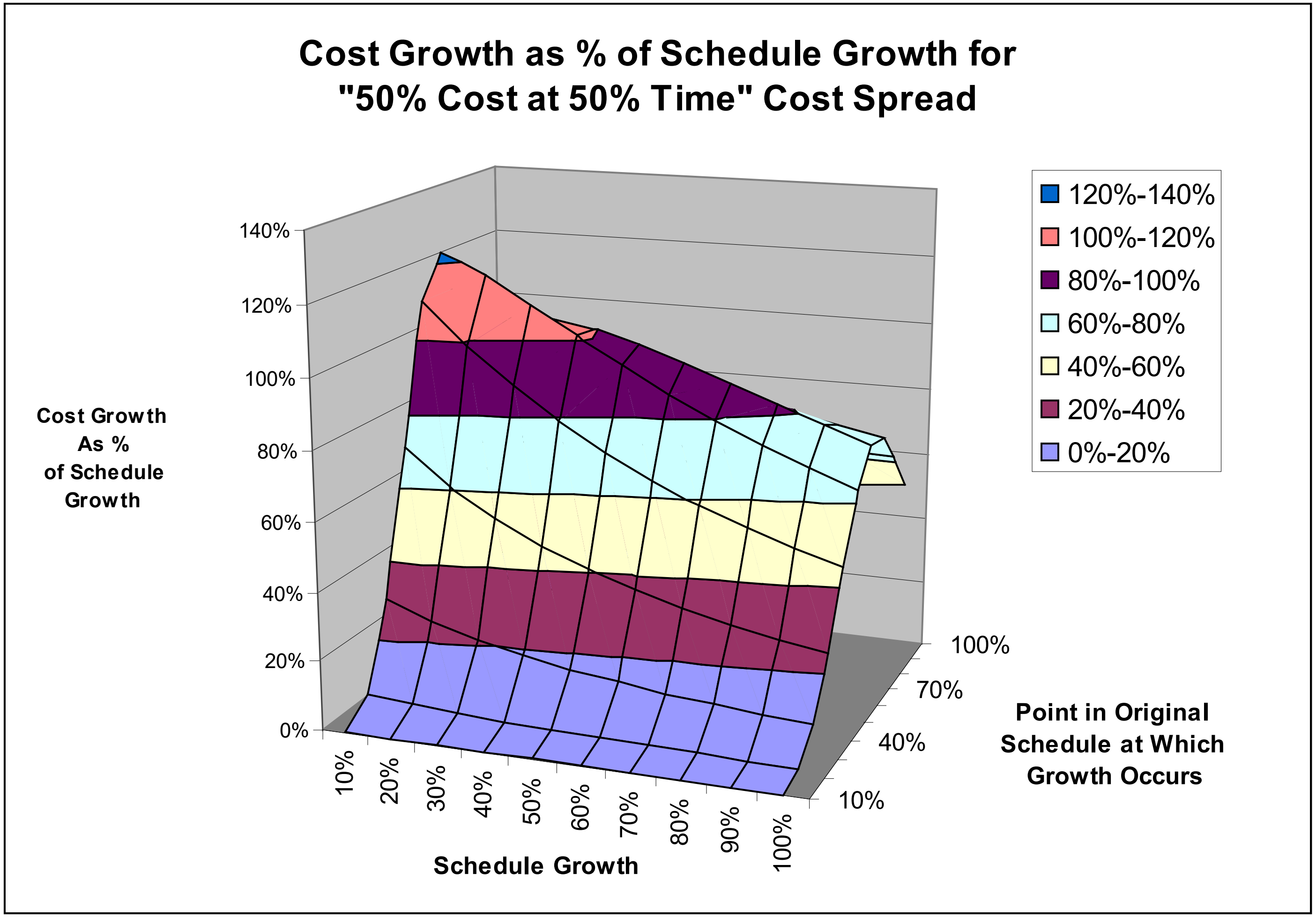
- **For example, if a beta distribution is used for time-phasing, a 10% schedule increase that occurs at time *z* will increase the total cost by the amount in the equation below**

$$\int_0^z \frac{x^{p-1}(1-x)^{q-1}}{B(p,q)}dx + \int_z^{1.1} \frac{x^{p-1}(1.1-x)^{q-1}}{B(p,q)1.1^{p+q-1}}dx$$

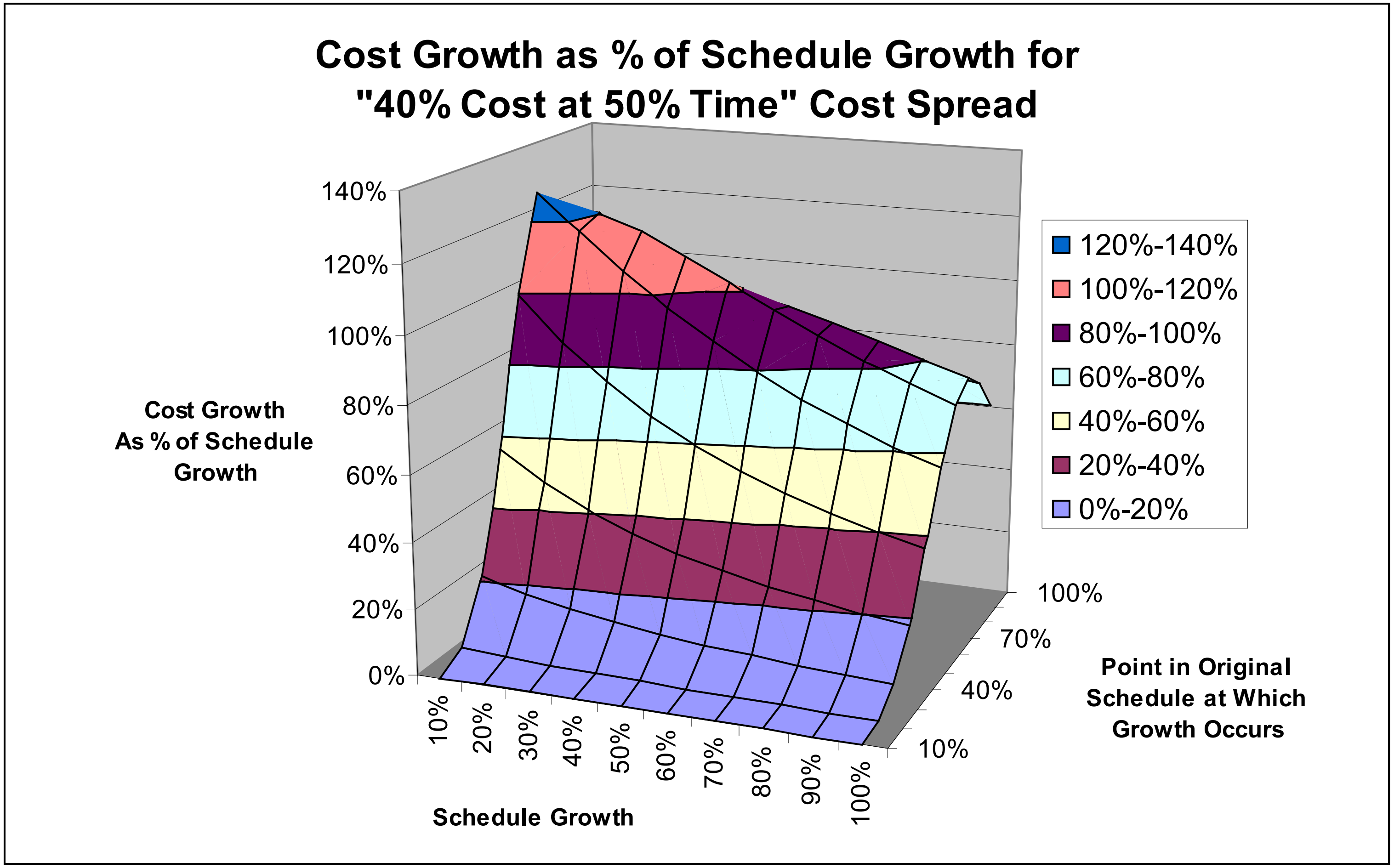
Cost Penalties/Benefits Due to Changes in Schedule- New Theoretical Research



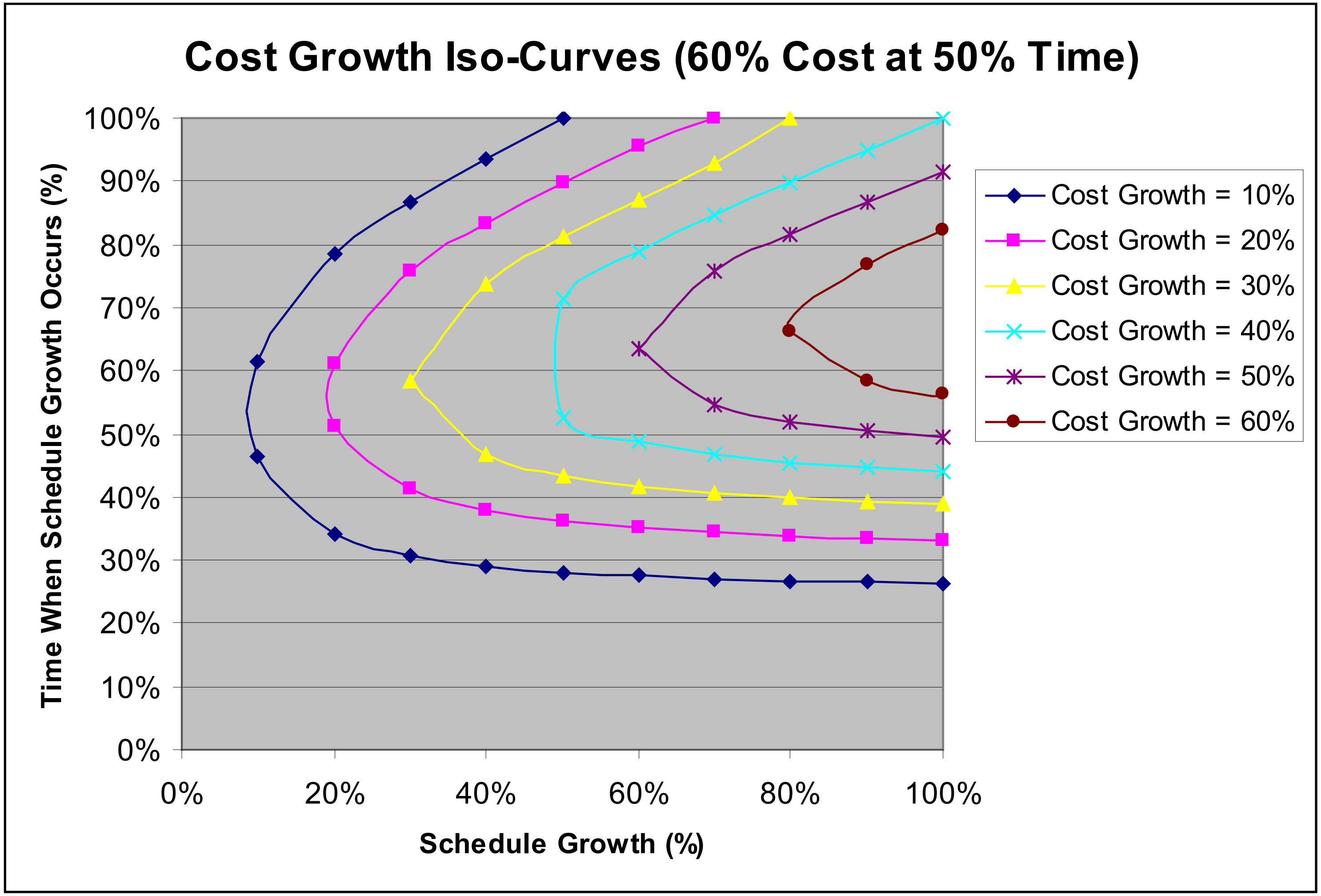
Cost Penalties/Benefits Due to Changes in Schedule - New Theoretical Research



Cost Penalties/Benefits Due to Changes in Schedule - New Theoretical Research



Cost Penalties/Benefits Due to Schedule Increases in 2-D



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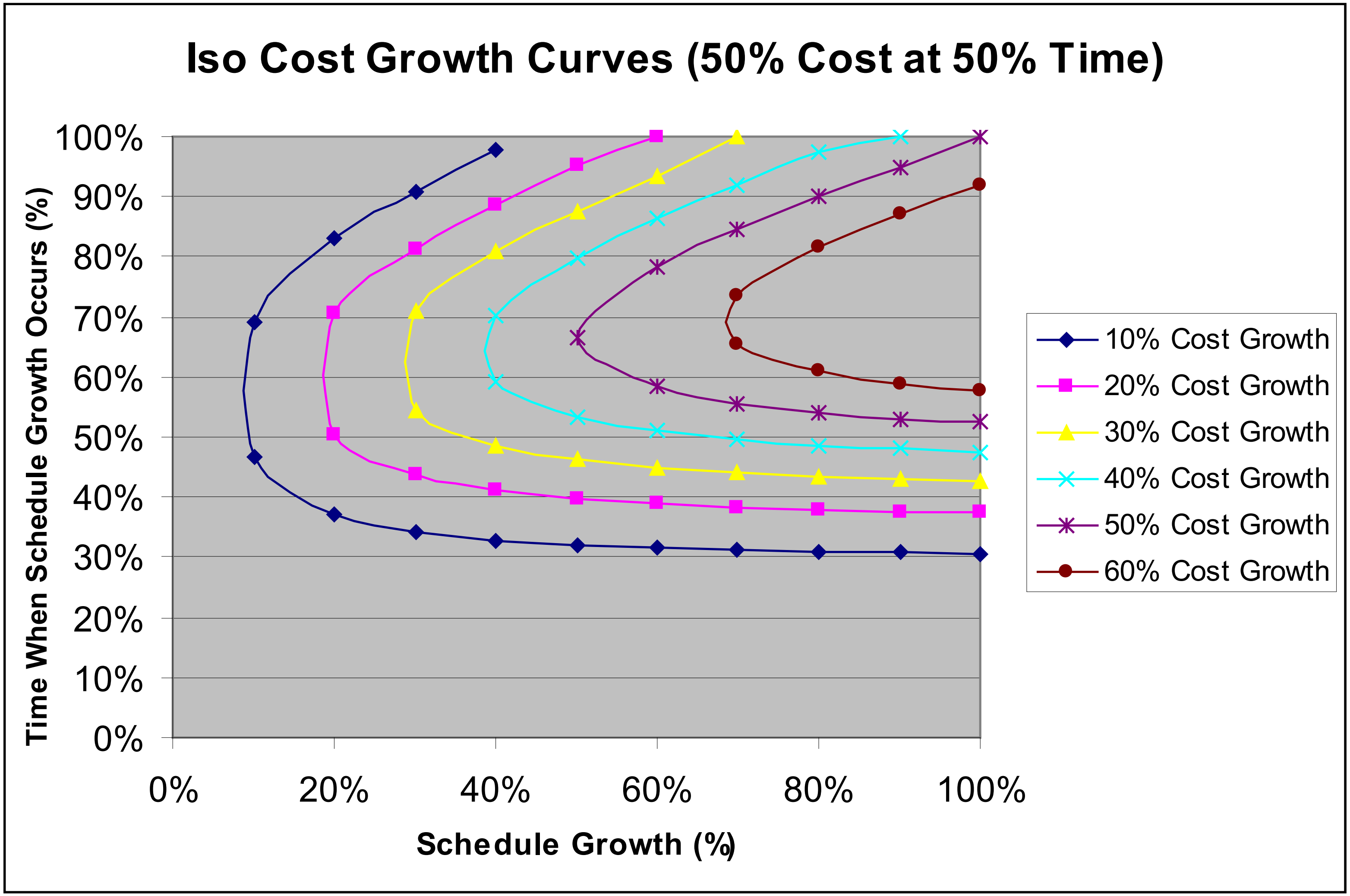

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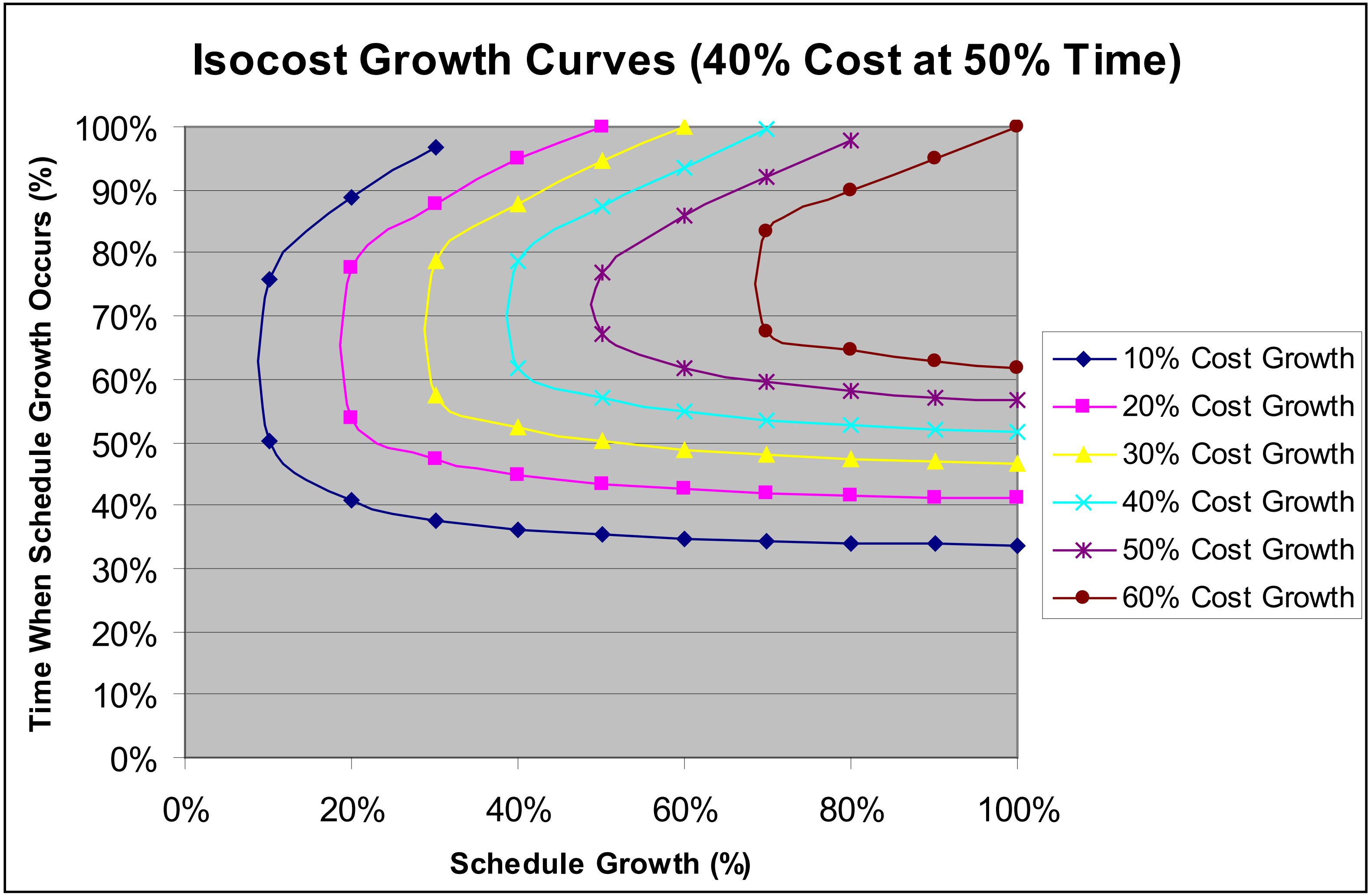

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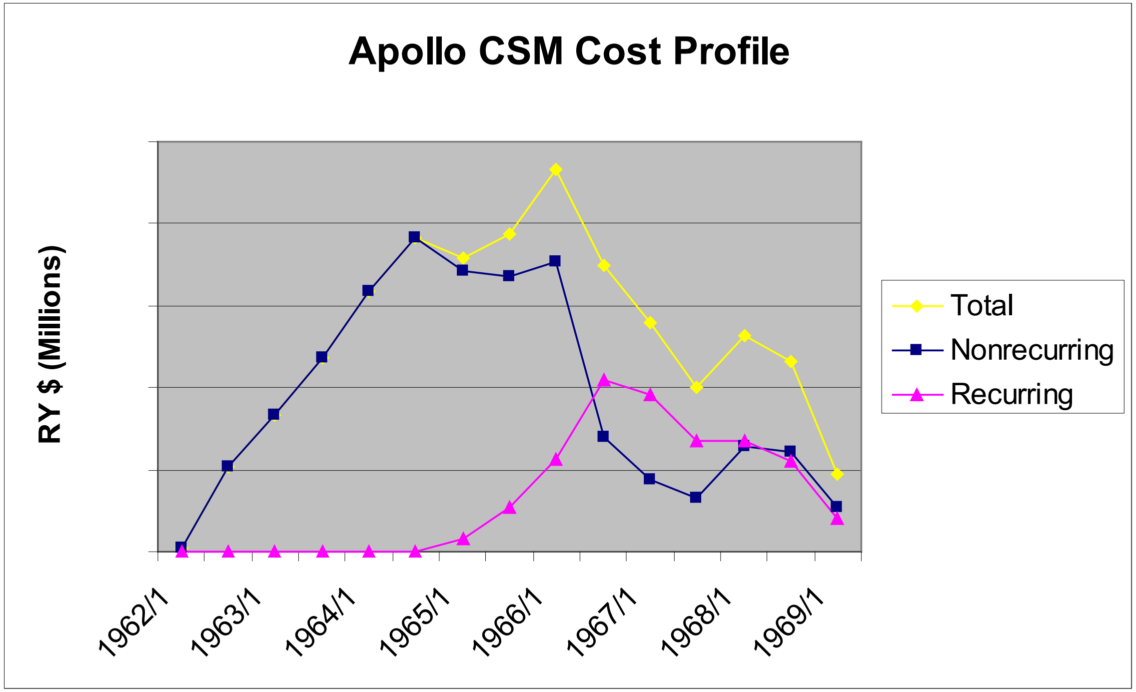
Cost Penalties/Benefits Due to Changes in Schedule - Conclusions

- **Conclusions from Theoretical Research**
  - **Cost growth is most sensitive to schedule growth (as a % of schedule growth) when**
    - **Schedule growth is small**
    - **Schedule growth occurs in the middle of the schedule (at peak funding)**
      - **Validates hypotheses made (but unverified) by previous research**
    - **Cost profile is back-loaded (peak occurs in out years)**

Cost Profiles and Smoothness

- **Changes in schedule will likely result in jagged, non-smooth changes in cost profiles, unlike the beta distribution**



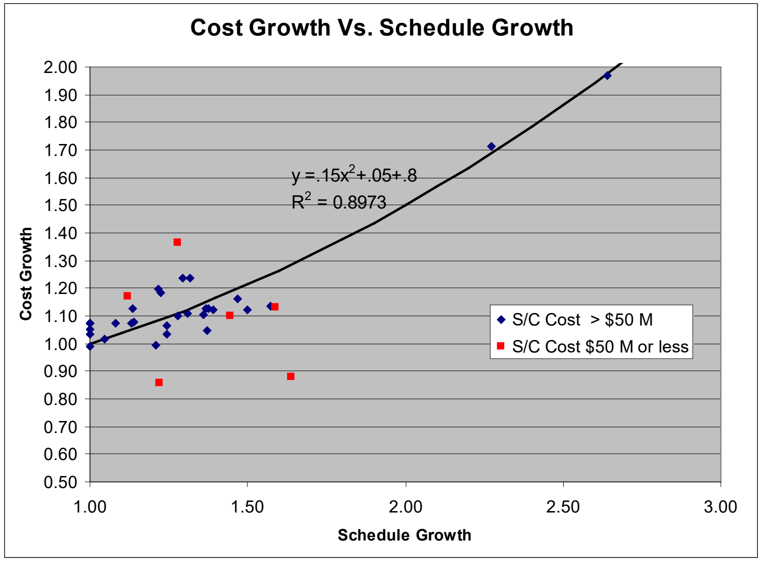
Cost Penalties/Benefits Due to Changes in Schedule - New Empirical Research

- **Collected cost and schedule growth information for over 40 NASA missions.**

ACE	GRACE	OSO-8
ACTS	HEAO-1	Saturn V
AE-3	Hessi	Shuttle Orbiter
AMPTE-CCE	HETE-II	SORCE
Aqua	HST	Spitzer Space Telescope
Aura	ICESAT	Stardust
C GRO	IMAGE	SWAS
CONTOUR	Landsat-1	Swift
Dawn	Landsat-7	TDRS-H
Deep Impact	Lunar Orbiter	Terra
DMSP-5D	Lunar Prospector	TIMED
EO-1	Magellan	TIROS-M
FAST	MAP	TIROS-N
FUSE	Mars Exploration Rovers	TRACE
GALEX	Mars Observer	TRIANA
Galileo	Mars Odyssey	VCL
Genesis	Messenger	Viking Orbiter

Cost Penalties/Benefits Due to Changes in Schedule - Best Fit

- **Relationship of cost growth to schedule growth is nonlinear**
  - **Ratio varies from 30 – 50%**
- **Removed small missions (less than $50 million) from the analysis**
  - **Limited applicability to missions IPAO analyzes**
  - **No clear relationship between cost and schedule for these missions**



Cost Penalties/Benefits Due to Changes In Schedule - Best Fit

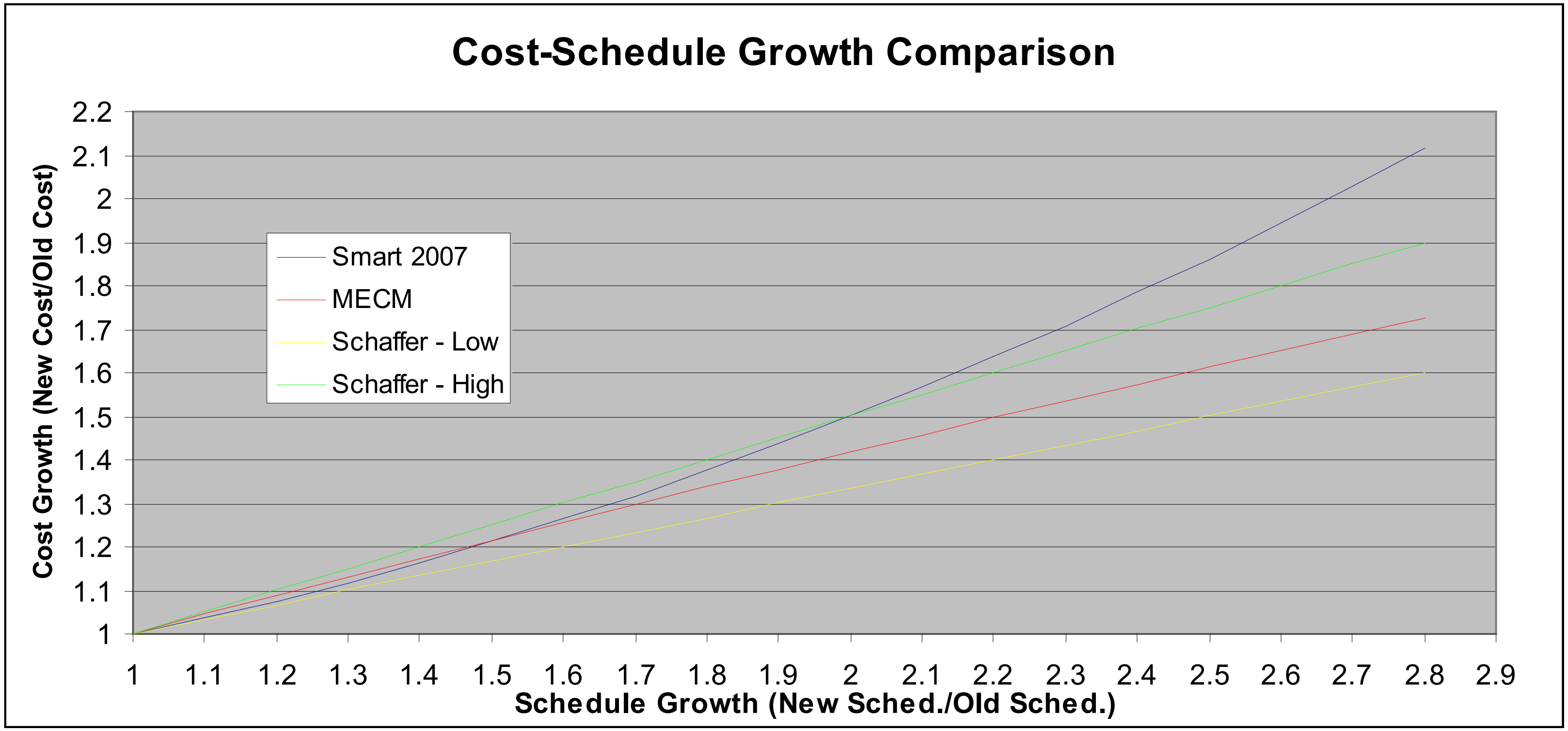
- **If Schedule Increases, (i.e., New Schedule Duration > Old Schedule Duration), Cost Growth is given by**

$$Cost\ Growth\,(\%) = 0.15\left(Schedule\ Growth\,(\%) + 1\right)^2 + .05\left(Schedule\ Growth(\%) + 1\right) - 0.2$$

- **For example a schedule growth equal to 47% translates to a cost growth of 0.15*(1.47)2+0.05*1.47-0.2 = 0.20, or 20%, which is 42% of the schedule growth.**

Schedule Increase	Cost Increase
20%	8%
30%	12%
50%	21%
75%	35%
100%	50%

Cost Penalties/Benefits Due to Changes In Schedule - Comparison



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Cost Penalties/Benefits Due to Changes in Schedule - Crosscheck

- The theoretical results may not match real-world data, since changes in schedule can result in discontinuous changes
  - Means change in the funding profile may not equal that implied by theory
- Compared theoretical results to empirical data based on a case-by-case analysis of cost and schedule growth data by milestone (ATP, PDR, CDR, Delivery, and Launch)
  - Relative results of the theory are confirmed by the data, but the assumption that schedule changes are continuous results in consistent underestimation of the effects of schedule increases on cost by about 50%
- Conclusion
  - Use theoretical analysis for schedule analysis, but apply a 2.0 continuity adjustment factor

Cost Penalties/Benefits Due to Schedule Decreases – Previous Work

- **Previous research includes the Microgravity Cost Experiments Model (MECM)**
- **In MECM if schedule contracts, (i.e., New Schedule Duration < Old Schedule Duration), cost grows according to the following equation**

$$Cost\ Growth(\%) = \frac{0.055 * \left(100\left(1 - 1.2\frac{New\ Schedule}{Old\ Schedule}\right)\right)^{1.952} - 0.52 * 20^{0.924}}{100} \quad if\ \frac{Old\ Schedule}{New\ Schedule} < 1.2, and$$

$$Cost\ Growth(\%) = \frac{0.52\left(100\left(1.2\left(\frac{New\ Schedule}{Old\ Schedule}\right) - 1\right)\right)^{0.924} - 0.52 * 20^{0.924}}{100} \quad otherwise$$

Cost Penalties/Benefits Due to Schedule Decreases ("Compression")

- **There are limited data available on schedule compressions**
- **Considered two alternatives**
  - **Faster, Better, Cheaper NASA policy in the 1990s likely resulted in several missions with compressed schedules**
    - **Looked at missions included in Dave Bearden's CoBRA model and in the GSFC Mission Cost Risk Assessment Model (MCRAM)**
    - **For missions below-the-trend, looked at what it would take to get back to the "average" for that mission's complexity level**
      - » **But "Faster, Better, Cheaper" missions tended to skimp on both cost ("Cheaper") and schedule ("Faster") so did NOT find a meaningful trend**

Cost Penalties/Benefits Due to Schedule Decreases – The Apollo Connection

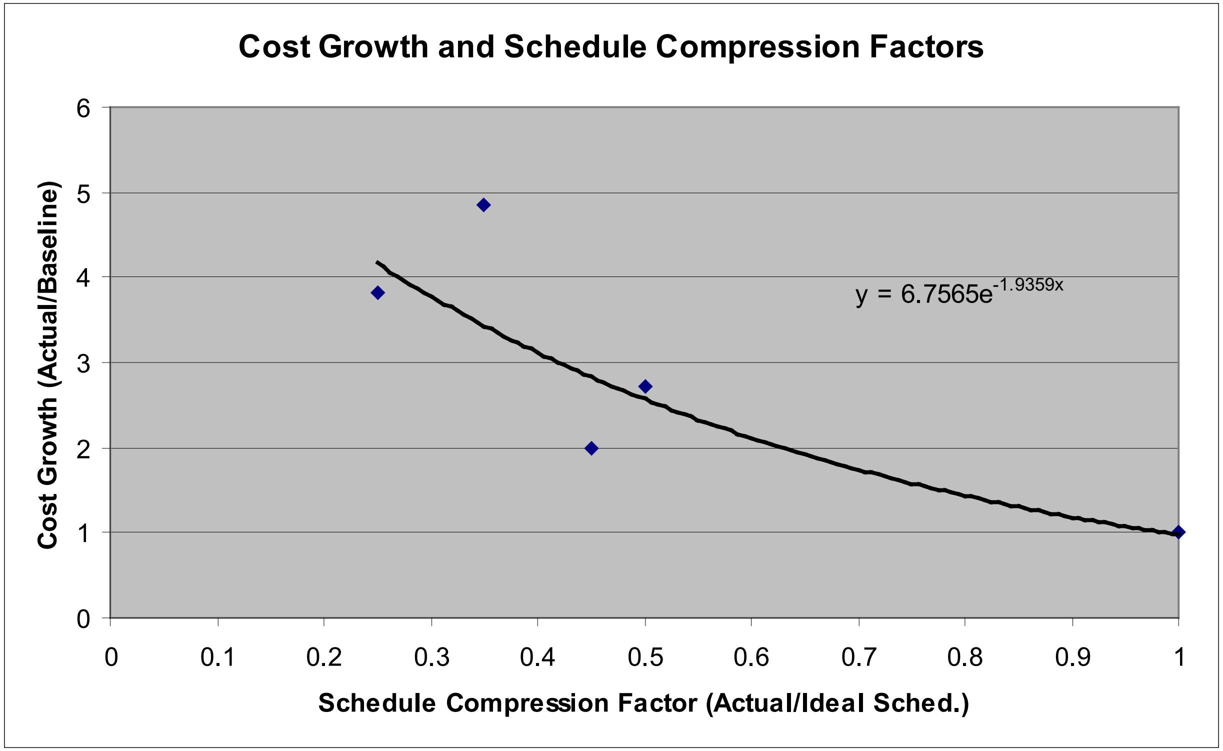
- During the "Space Race" of the 1960s, the Apollo and Saturn programs were schedule driven
  - Ambitious and successful effort to beat the Soviet Union in putting a man on the moon
  - When schedule drives the program, schedules are compressed compared to the optimal or ideal schedule
    - Can result in large cost increases, particularly if the schedule is highly compressed
  - As noted by Burgess (Burgess 2004), large programs typically are highly front-loaded, with 80% of the cost spent at the halfway point in the overall schedule
  - The Apollo and Saturn stages, rather than begin front-loaded to a large degree, were more evenly distributed, and in some cases, cumulative spending did not reach the 50% mark until after the schedule midpoint
    - Using this notion, which is that an ideal schedule for the Saturn stages and Apollo spacecraft should have expended 80% of the cost at 50% time, we can develop a schedule compression and cost growth comparison

Cost Penalties/Benefits Due to Schedule Decreases – The Apollo Connection

- **A beta function with $\alpha = 1.42$ and $\beta = 3$ has the property that 80% of the cost is expended at 50% time**
  - **50% compression is required in order for 50% of the cost to be spent by the 50% point in the schedule.**

Mission	% Cost At 50% Time	Schedule Compression (Actual/Ideal Sched.)	Cost Growth Ratio (Actual/Baseline)
S-II	50%	0.45	2
S-IVB	44%	0.35	4.86
CSM	41%	0.25	3.81
LM	55%	0.5	2.73

Cost Growth as a Function of Schedule Compression



$$Cost\ Growth\,(\%) = 6.7565e^{-1.9359*\frac{New\ Sched}{Old\ Sched}} - 1$$

Comparison with the Microgravity Experiments Cost Model

- According to the MECM equations, a schedule compression equal to 50% will increase cost by 65%
  - Much lower than the equation derived using Apollo and Saturn data
    - However in MECM schedule reductions by as much at 17% result in cost decreases rather than increases
  - The notion that schedule and cost constraints can both be compatible
    - May work for simple missions and small experiments such as the missions MECM was designed to estimate
  - However for spacecraft this notion was largely disproved during the "Faster, Better, Cheaper" policy of the 1990s where cost and schedule constraints typically resulted in an uncomfortably high failure rate
    - As many as 25% of missions resulted in catastrophic failure, cancellation, or significant impairment

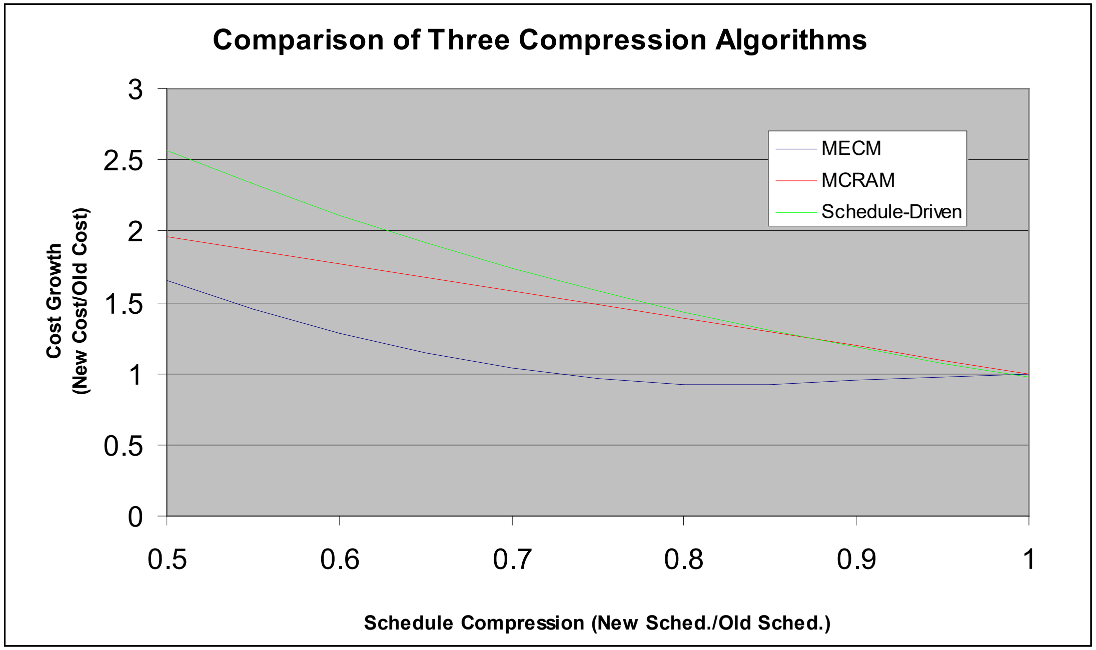
Comparison with the Mission Cost Risk Analysis Model (MCRAM)

- **As another comparison, Goddard Space Flight Center's Mission Cost Risk Assessment is a multivariate equation that uses mission complexity, cost, schedule, and other parameters to predict the probability of mission success (Smart, 2002)**
- **Cost and schedule tradeoffs can be analyzed with this model**
  - **For a high level of mission success, the cost growth necessary to maintain a high level of mission success, for a given schedule compression is**

$$Cost\ Growth\,(\%) = 1.9276 - 1.9277\left(\frac{New\ Sched}{Old\ Sched}\right)$$

Comparison Summary

- Note that the Apollo-based algorithm is based on highly complex missions
- MCRAM is based on a large 55-mission database of medium complexity earth orbiting and planetary spacecraft
- The MECM model is designed to estimate experiments, which are low in complexity

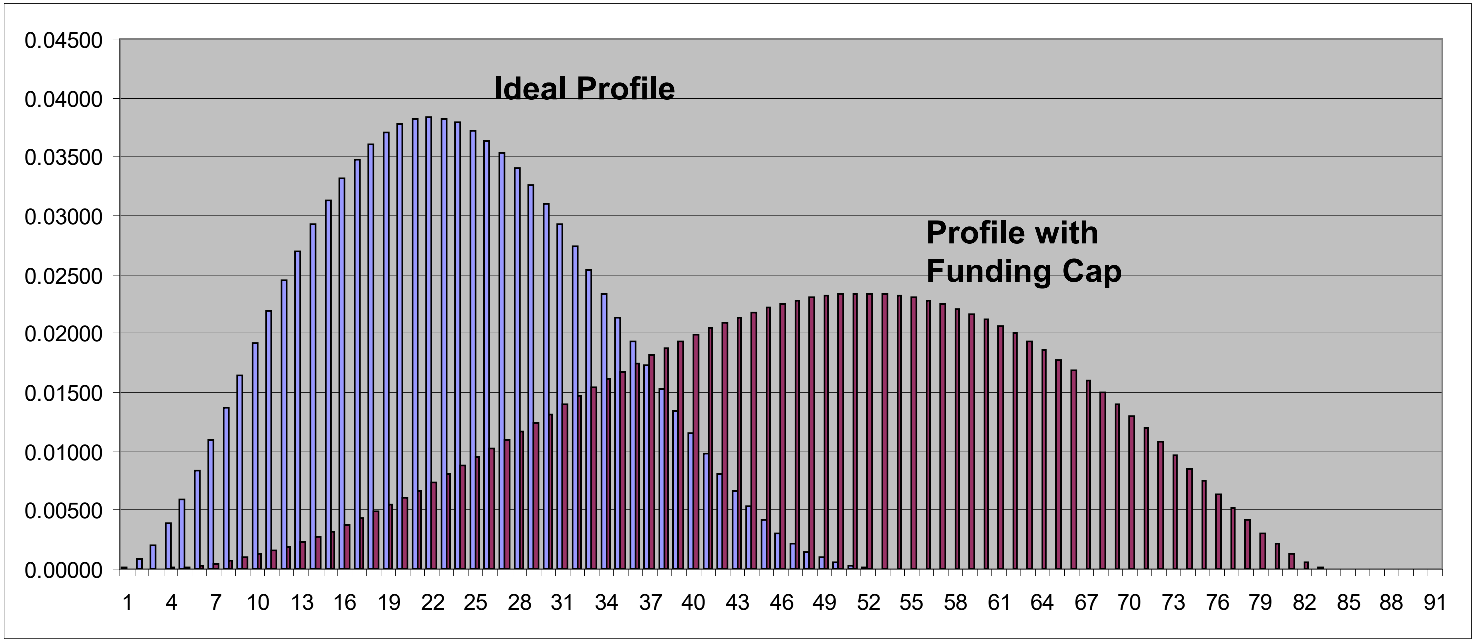


Funding Peak Constraints and Schedule Growth

- **For each project, there is an ideal funding schedule, one that ramps up as the design work gets underway, and then ramps down as fabrication and assembly nears completion and testing ensues**
- **For large programs, the ideal funding peak may exceed the budget for an entire directorate, which requires funding caps that constrain expenditures**
  - **This constraint is non-optimal, leading to delays in activities**
  - **The funding profile peak will be delayed and may shift the profile from being front-loaded to back-loaded**
    - **Results in schedule and cost increases**

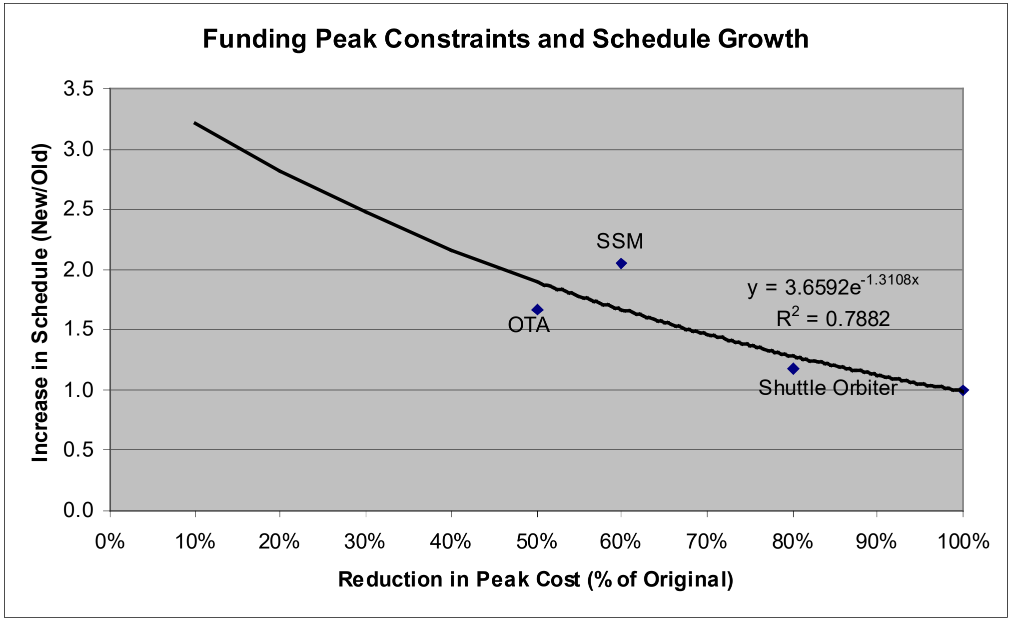
Funding Peak Constraints and Schedule Growth Example

- **Funding Profiles Before and After Cap Is Applied**



Funding Peak Constraints and Schedule Growth Algorithm

- **Two prominent missions that experienced significant schedule growth due to funding constraints were Shuttle Orbiter and the Hubble Space Telescope (Emhart PRC, 1988)**
  - **Both elements of HST, SSM and OTA experienced large schedule increases due to funding constraints**

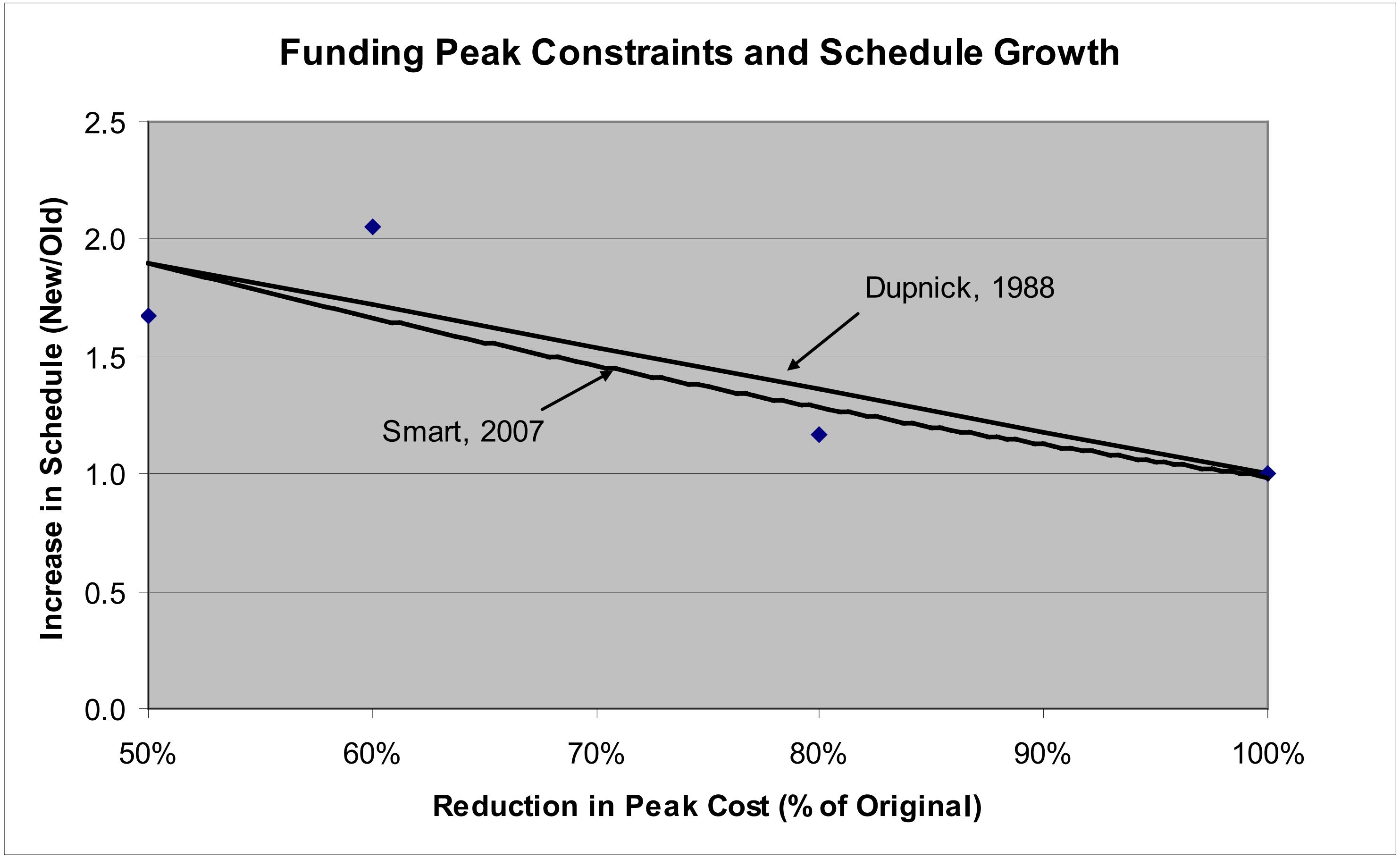


Funding Peak Constraints and Schedule Growth Algorithm

$$Schedule\,Growth\,(\%) = 3.6592\; e^{\left(-1.3108 * \left(1 - \%Reduction\ in\ Peak\ Funding\right)\right)} - 1$$

- For example, if the reduction in peak funding is 30%, the predicted increase in schedule is 46%
- While based on a small data set, funding constraints for major programs are not an everyday occurrence
- Despite this small data set, this equation closely agrees with an equation developed by Edwin Dupnick, (Dupnick, 1988)
  - Dupnick’s equation was based on his experience with “modest-sized” NASA programs at JSC

Funding Peak Constraints and Schedule Growth Comparison



Excel Implementation

- Implemented algorithms in Excel
- User has capability to assess the cost impact of
  - Schedule expansions
  - Schedule compressions
  - Funding caps
- Developed easy-to-use user interface

Funding Profiles with Cost Caps

- **Based on Beta distribution**
  - **Includes ability to set beta distribution parameters and number of periods**
  - **Also includes**
    - **Ability to set annual spending caps**
    - **Ability to set when first month begins during a fiscal year**
    - **Ability to constrain cap-imposed profile to peak either before or after the unconstrained profile**
    - **If cap is too small (annual cap times the number of years in the phasing is less than 120% of the total cost), user is presented with a dialog box informing them of this situation**
  - **In addition, the user can change specific schedule times for preliminary design, detailed design, fabrication and assembly, and testing, and re-calculate the funding profile and compare with the original funding profile, and determine the effect on overall cost and schedule**
    - **Determine the impact of schedule changes on cost using the algorithms described in this presentation**

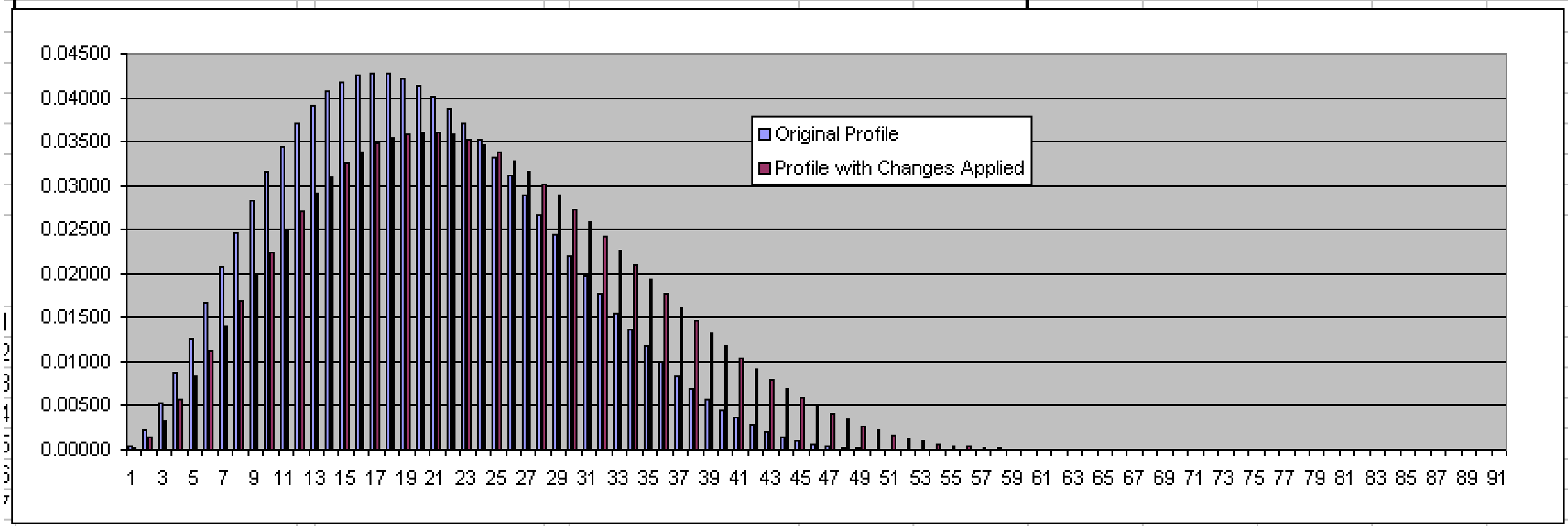
Funding Profiles Screenshot

Cost ($M) =	1000	Complexity	High	
P Value =	1.79	Q Value =	4	
Beginning Month =	6	Schedule Length =	54	Months
Funding Cap?	Yes	Cap Per Year (M$) =	400	
Expand	Entire Schedule	By	10	Months
Preliminary Design	10%	6.4	Months	
Detailed Design	40%	25.6	Months	
Fabrication and Assembly	40%	25.6	Months	
Test and Integration	10%	6.4	Months	
New Cost	1143.280656	New Schedule	64	Months

Apply Schedule Changes

Apply Cost Cap

Reset



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Summary

- Developed algorithms for effect of schedule expansion, schedule compression, and funding caps on cost
- Effect of schedule expansion based on largest data set and has a theoretical framework
  - Also has richest history
- Other algorithms based on limited data, more study warranted
  - Results agree with prior work
  - Results agree with intuition
  - Research serves as a framework for more in-depth study
- Automated algorithms in Excel

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Demo

Demonstration of Excel Tool