KEYNOTE LECTURE 3

DECISION SUPPORT SYSTEMS FOR CIVIL ENGINEERING CONSTRUCTION

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Abstract: Decision support systems have been developed and applied at all levels of civil engineering construction. This presentation will concentrate on two such applications. At the strategic level we will examine how competitive bidding models can help a contractor select the optimum price for a lump-sum construction contract. We will also examine the importance of cost uncertainty and the contractor's risk aversion on the optimum bid price. These are two factors that have traditionally been ignored even though they have a significant impact on how much the contractor should bid. At the operational level we will describe the discrete event simulation systems that have been developed at the University of Michigan, such as UM-CYCLONE, COOPS, STROBOSCOPE, and EZSTROBE, for modeling construction processes under uncertainty. The most modern of these, STROBOSCOPE and EZSTROBE, are used throughout the world for research, teaching, and practice, and are available from www.stroboscope.org. Applications of these systems to be presented include general earthmoving, dam construction, tunneling, and the scheduling of projects with repeating activities under uncertainty.



Profile of Professor Photios G. Ioannou

Photios G. Ioannou is Professor in the Department of Civil and Environmental Engineering at the University of Michigan, a Fellow of the ASCE, and a recipient of several awards including the Peurifoy Construction Research Award and the John O. Bickel Award from ASCE. Together with his former doctoral student J.C. Martinez are the designers and developers of the STROBOSCOPE Simulation System. He has also performed research in the development of other simulation systems, including UM-Cyclone, COOPS, EZStrobe, ProbSched, CPMAddon, and Chastrobe. His research is in construction engineering and management in the areas of simulation, tunneling, competitive bidding models, project finance, innovative project delivery systems, and project scheduling. His email address is photios@umich.edu and his homepage is https://www.ioannou.org

Decision Support Systems for Civil Engineering Construction



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Decision Support Systems (DSS)

- DSS are information systems that support decision-making.
- Target Organizational Levels in Construction Firms:
  - Top:
    - E.g., Decide the bid price for a lump-sum fixed-price project
  - Middle:
    - E.g., Design operations, choose resources, specify interactions
- DSS require
  - Computer systems – simple to special-purpose – often multiple
  - Human expertise

Two DSS Examples

- Example 1 - Top Level DSS:
  - Determine the Optimum Bid price for a Fixed-Price Contract
- Example 2 - Middle Level DSS:
  - Minimize Cost of Earthmoving for the Construction of Dam
  - Determine the optimum
    - Number of Trucks by Model
    - Number and type of Bridges to Cross River

Choose Bid for Fixed-Price Contract Lowest Responsible Bid Wins

- Uncertainties
  - Lowest bid by competitors
  - Cost of the project (if won)
- Risks
  - Bid is too High: Lose the contract
  - Bid is too Low: Win the contract and lose money on the job

Historical Bid Data & Statistics

- Bids of Opponents i on Past Projects j: b_{ij}
- Own Cost Estimate on Past Projects j: c_{0j}
- Historical Apparent Bid-To-Cost Ratios: $x_{ij} = b_{ij}/c_{0j}$
- Distributions of Apparent Bid-To-Cost Ratios: $f_X(x)$
- For example data & analysis (50 Building Projects) see:
  - Shaffer, L. R., and Micheau, T. W. (1971). "Bidding with Competitive Strategy Models." *Journal of the Construction Division*, ASCE, 97(1), 113–126, March 1, 1971, https://doi.org/10.1061/JCCEAZ.0000290.

Probabilistic Cost Estimating

- Actual Cost of Project (Random Var.): C
- Probabilistic Estimating gives: $E[C], Var[C], f_C(c)$
- Examples and analysis can be found in:
  - Diekmann, J. E. (1983). "Probabilistic Estimating: Mathematics and Applications." *J. of Constr. Eng. and Mgmt*, ASCE, 109(3), 297–308, Sept. 1, 1983, https://doi.org/10.1061/(ASCE)0733-9364(1983)109:3(297).
  - Spooner, J. E. (1974). "Probabilistic Estimating." *J. of the Constr. Div.*, ASCE, 100(1), 65–77, March 1, 1974, https://doi.org/10.1061/JCCEAZ.0000411.

Decision Variables

- Contractor A_0's Bid Price
  - b_0
    - A_0 wins when: $b_0 < B_{\min} = \min\{B_1, B_2, \ldots, B_n\}$
- Contractor A_0's Bid-to-Cost Ratio
  - $x_0 = (1 + m_0) = b_0 / E[C]$
    - A_0 wins when: $x_0 < X_{\min} = \min\{X_1, X_2, \ldots, X_n\}$

Random Variables At Bidding

- Bids of n Opponents
  - $B_i, \quad i = 1,2, \dots, n$
    - A_0 wins when: $b_0 < B_{\min} = \min\{B_1, B_2, \dots, B_n\}$
- Bid-to-Cost Ratios of n Opponents
  - $X_i = B_i / E[C], \quad i = 1,2, \dots, n$
    - A_0 wins when: $x_0 < X_{\min} = \min\{X_1, X_2, \dots, X_n\}$

Probability To Win

- $$P[A_0 \text{ wins} | b_0, x_0, f_C(c)] = P[b_0 < B_{\min}]$$
$$= P[(b_0/E[C]) < (B_{\min}/E[C])]$$
$$= P[x_0 < X_{\min}]$$
$$= 1 - F_{X_{\min}}(x_0)$$

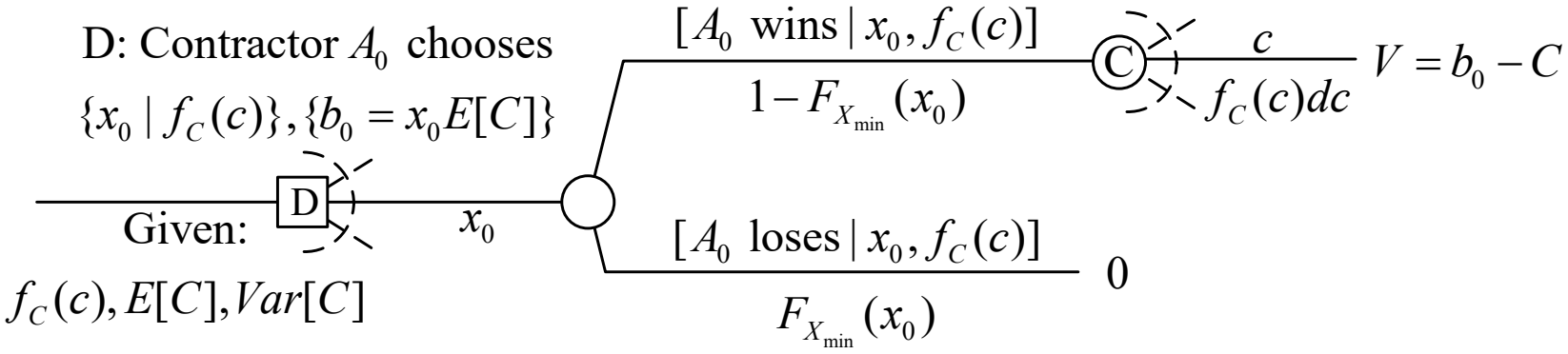
- Example 1: Friedman's Bidding Model:
  - $P[A_0 \text{ wins} | b_0, x_0, f_C(c)] = 1 - F_{X_{\min}}(x_0) = \prod_{i=1}^{n}[1 - F_{X_i}(x_0)]$
- Example 2: Gates' Bidding Model:
  - $P[A_0 \text{ wins} | b_0, x_0, f_C(c)] = 1 - F_{X_{\min}}(x_0) = 1/\{1 + \sum_{i=1}^{n} \frac{F_{X_i}(x_0)}{1 - F_{X_i}(x_0)}\}$

Random Variables If Project is Won

- Actual Cost of Project:
  - $C,\ E[C], Var[C], f_C(c)$

- Gross Profit:
  - $V = b_0 - C = x_0 E[C] - C$
  - $E[V|A_0 \text{ wins}, x_0, f_C(c)] = b_0 - E[C] = (x_0 - 1)E[C]$
  - $Var[V|A_0 \text{ wins}, x_0, f_C(c)] = Var[C]$

Decision Tree for Optimum Bid-to-Cost Ratio x_0^* & Bid b_0^*



Expected Value of Profit, $E[V]$

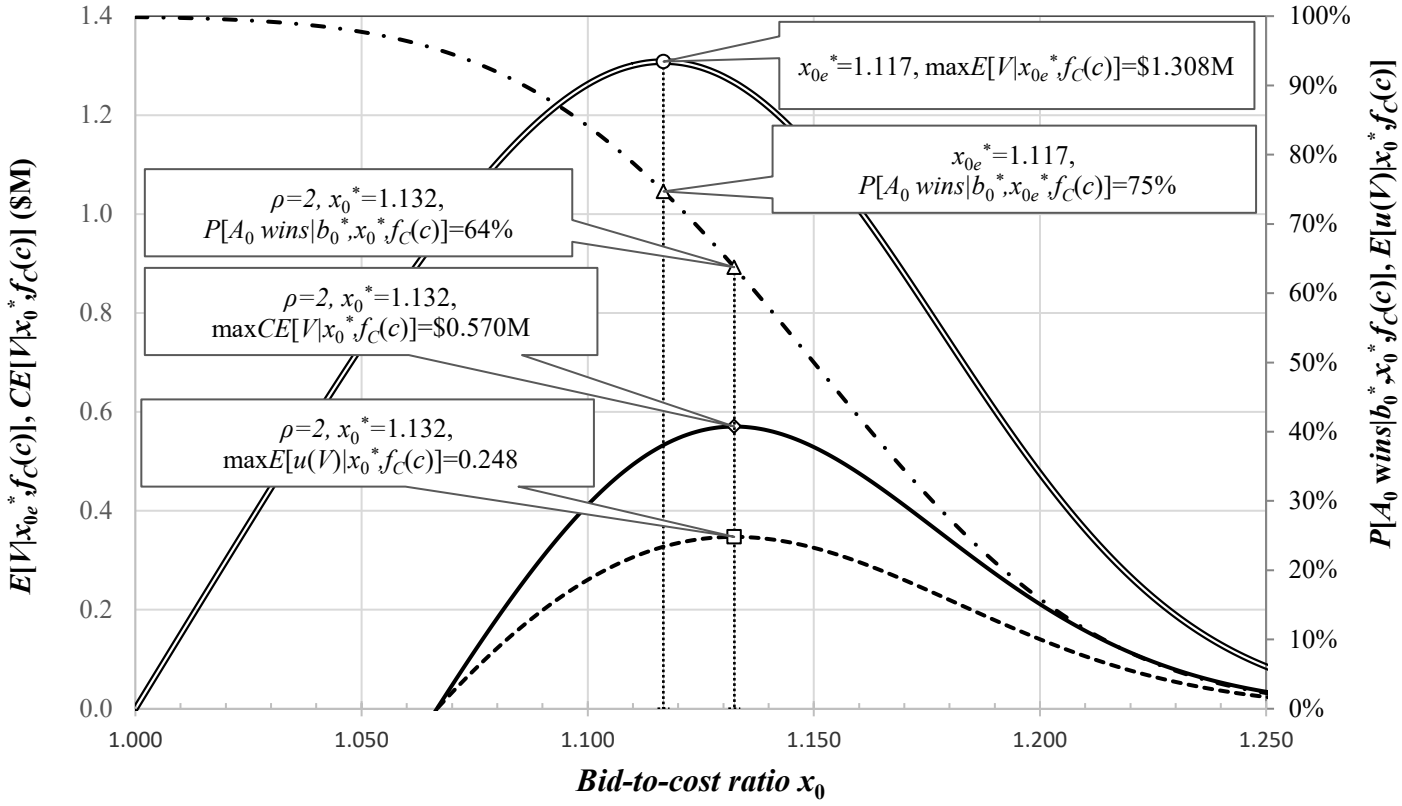
- Traditional Objective: Maximize Expected Value of Profit
  - $E[V|x_{0e}^*, f_C(c)] = \left[1 - F_{X_{\min}}(x_{0e}^*)\right](x_{0e}^* - 1)E[C]$

- Decision variables:
  - Bid-to-Cost Ratio: $x_{0e} = (1 + m_{0e}) = b_{0e}/E[C]$
  - Bid price: $b_{0e} = (1 + m_{0e})E[C] = x_{0e}E[C]$

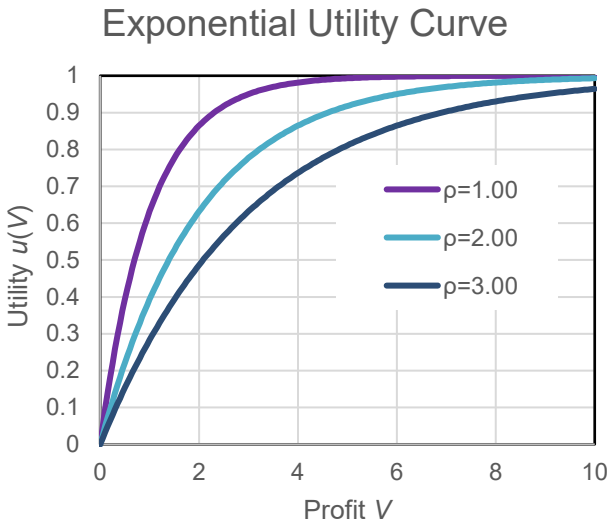
Numerical Example

- Project Cost if Won
  - $C \sim N(E[C] = \$15\text{M}, SD[C] = \sigma = \$2\text{M})$
- Minimum Opposing Bid-to-Cost Ratio:
  - $X_{\min} \sim N(E[X_{\min}] = 1.15, SD[X_{\min}] = 0.05)$

E[Profit], CE[Profit], P[Win] vs. x_0



Utility Curve for Profit, $u(V)$



- Exponential Utility Curve for Profit, V
  - $u(V) = 1 - e^{-V/\rho}$
- ρ = Risk Tolerance
  - Has same Units as Profit, V, (e.g., $M)
  - As Risk Tolerance increases, Risk Aversion decreases
  - $\rho \approx R$ when indifferent: $\$0 \sim (50\%, \$R\,; 50\%, -\$R/2)$

Expected Utility of Profit, $E[u(V)]$

- Objective: Maximize Expected Utility of Profit
  - $E[\mathrm{u}(V)|x_0^*, f_C(c)] = [1 - F_{X_{\min}}(x_0^*)] \int u\big((x_0^* - 1)c\big) f_C(c) dc$

- Closed-form for Exponential Utility Curve:
  - $E[u(V)|x_0, f_C(c)] = \left[1 - F_{X_{\min}}(x_0)\right] \times$
    $\left\{1 - \exp\left(-\{(x_0 - 1)E[C] - \frac{1}{2\rho} Var[C]\}/\rho\right)\right\}$

Certain Equivalent of Profit, $CE[V]$

- *CE* makes the Decision Maker indifferent between:
  - (a) Receiving the Certain Equivalent with certainty
  - (b) Facing the uncertain outcome of Profit

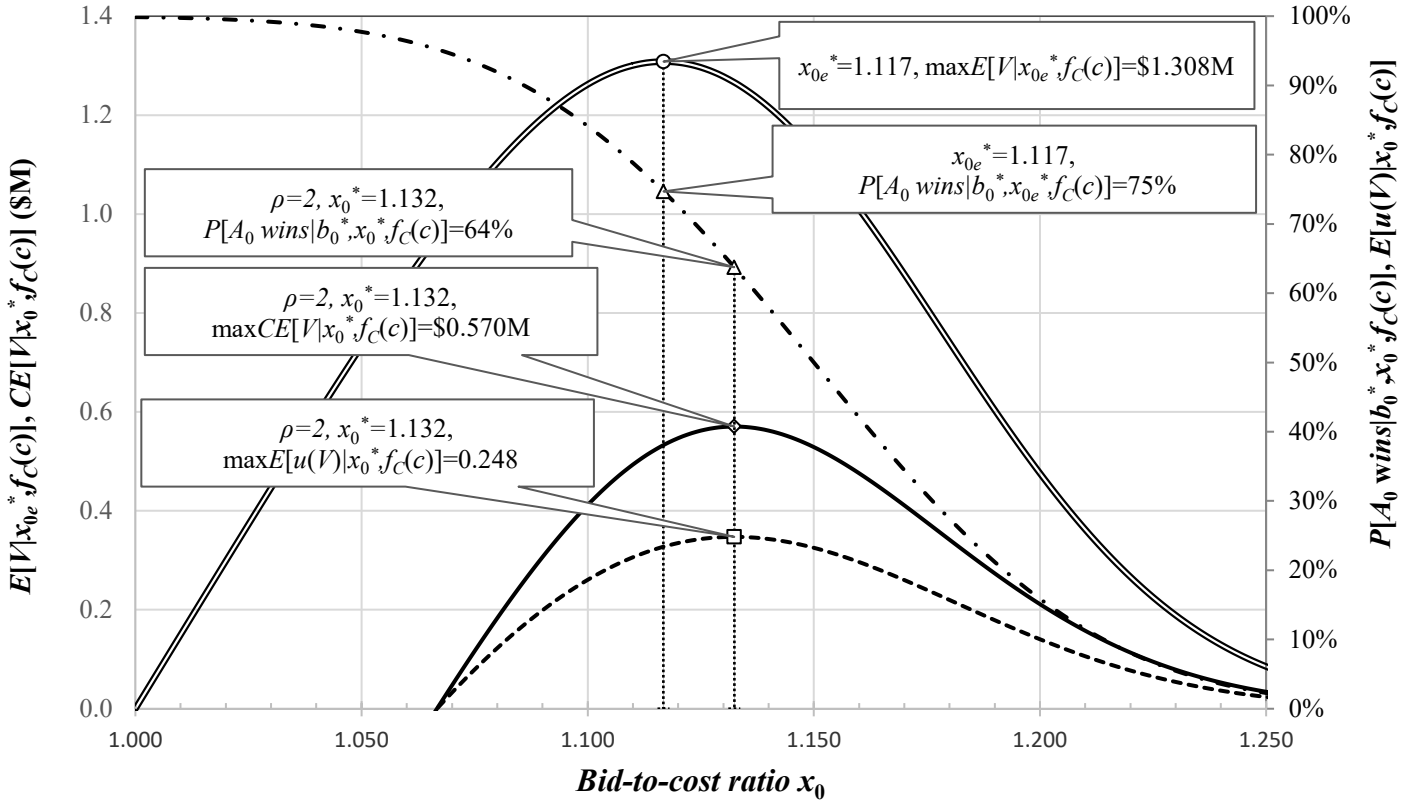
- Utility of Certain Equivalent = Expected Utility of Profit
  - $u(CE[V]) = E[u(V)]$

$CE[V]$ for Exponential Utility Curve

- $CE[V]$ is found using the inverse function of utility curve:
  - $CE[V] = -\rho \cdot \ln\{1 - E[u(V)]\}$

- Closed form when Profit V follows a Normal Distribution
  - $CE[V] = E[V] - \frac{1}{2\rho} Var[V]$
  - Very good approximation for other Profit distributions

E[Profit], CE[Profit], P[Win] vs. x_0



Delta Property of Exponential Utility

- Lottery = a gamble (random variable) whose outcomes are uncertain (e.g., Profit, V, or Cost, C)
- Delta Property:
  - Changing <u>all the outcomes</u> of a lottery V by Δ, changes the $CE[V]$ by the <u>same</u> amount Δ:
    - $CE[V + \Delta] = CE(V) + \Delta$
    - $CE[V] = CE(b_0 - C) = b_0 - CE(C)$ $\quad (i.e., b_0 \text{ is } \Delta)$

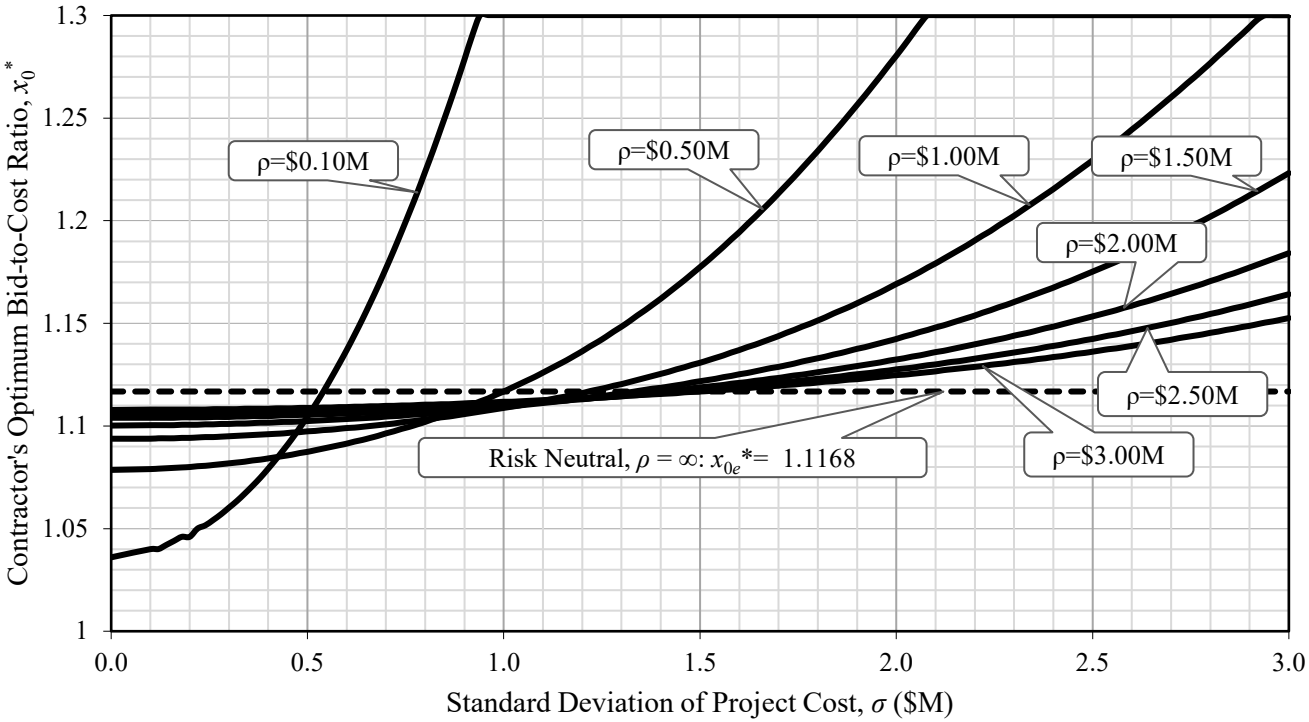
Risk Premium of a Profit Lottery, $RP[V]$

- $RP[V]$ is the amount of the expected profit $E[V]$
  - that a risk-averse contractor is giving up
  - when exchanging the uncertain profit lottery V
  - with its certain equivalent $CE[V]$
    - $RP[V] = E[V] - CE[V]$
- For Exp. Utility Curve and Normal Cost and Profit
  - $RP[V|A_0 \text{ wins }] = RP[C|A_0 \text{ wins}] = \frac{1}{2\rho} Var[C]$

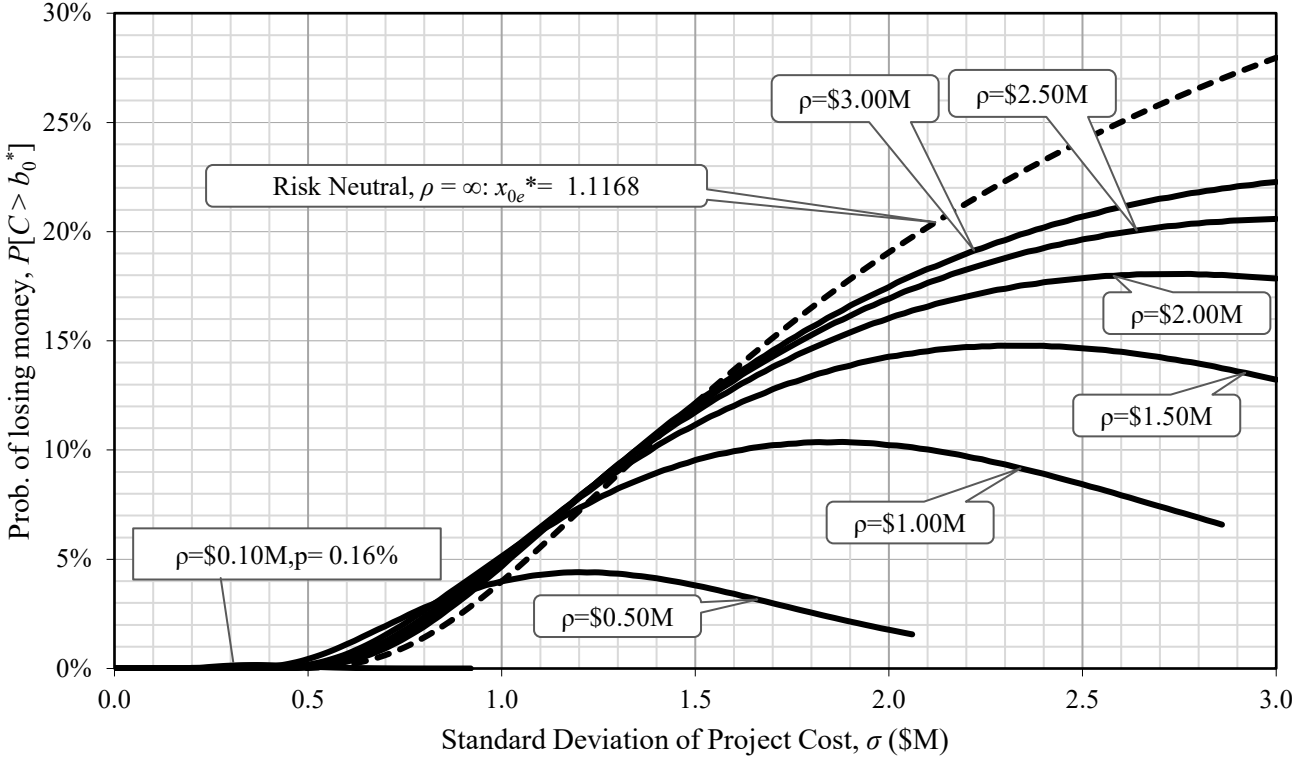
Example Parametric Analysis

- Analysis to compute optimum Bid-to-Cost Ratio x_0^*
- That maximizes Expected Utility $E[\mathrm{u}(V)]$
  - For 21,462 combinations of (σ, ρ)
    - $\sigma = SD[C]$ = standard deviation of project cost
    - ρ = contractor's risk tolerance

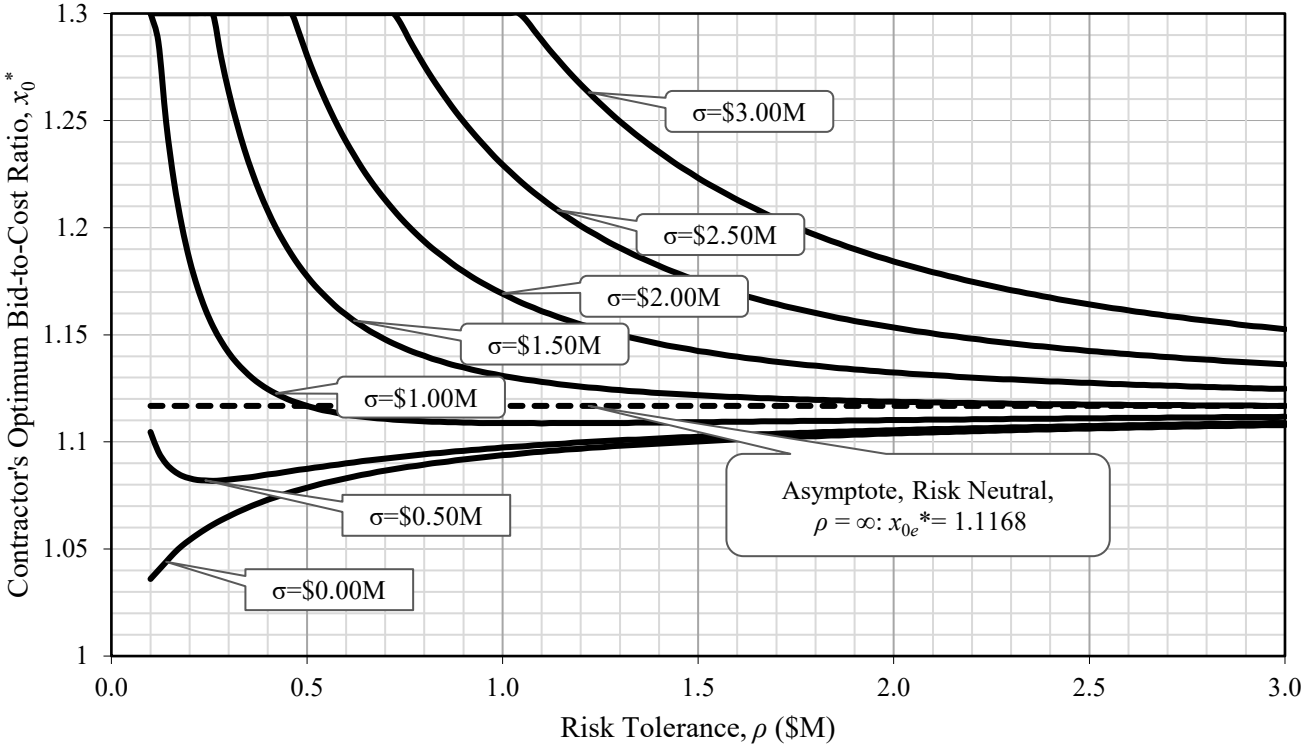
x_0^* vs. $\sigma = SD[C]$ given Risk Tolerance ρ



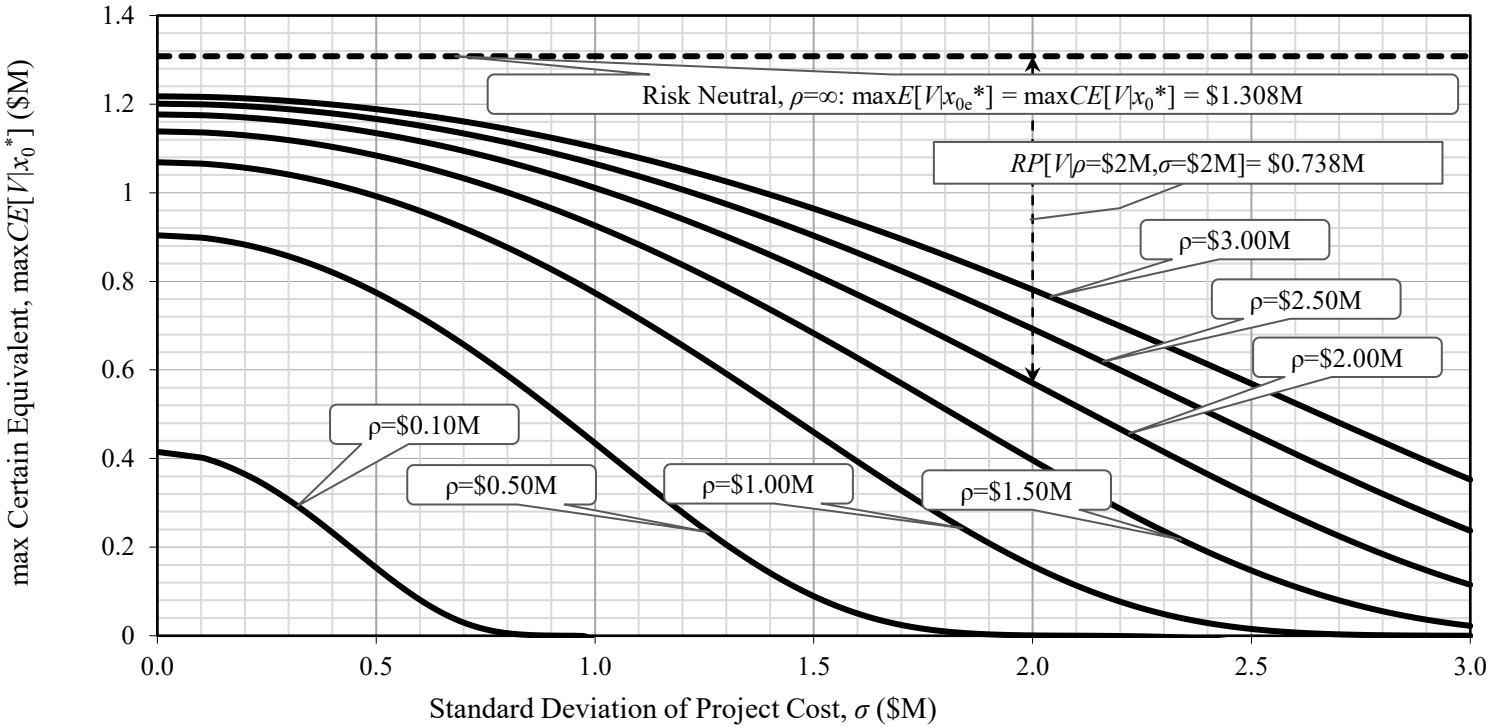
$P[Lose\ Money \mid x_0^*]$ vs. σ given ρ



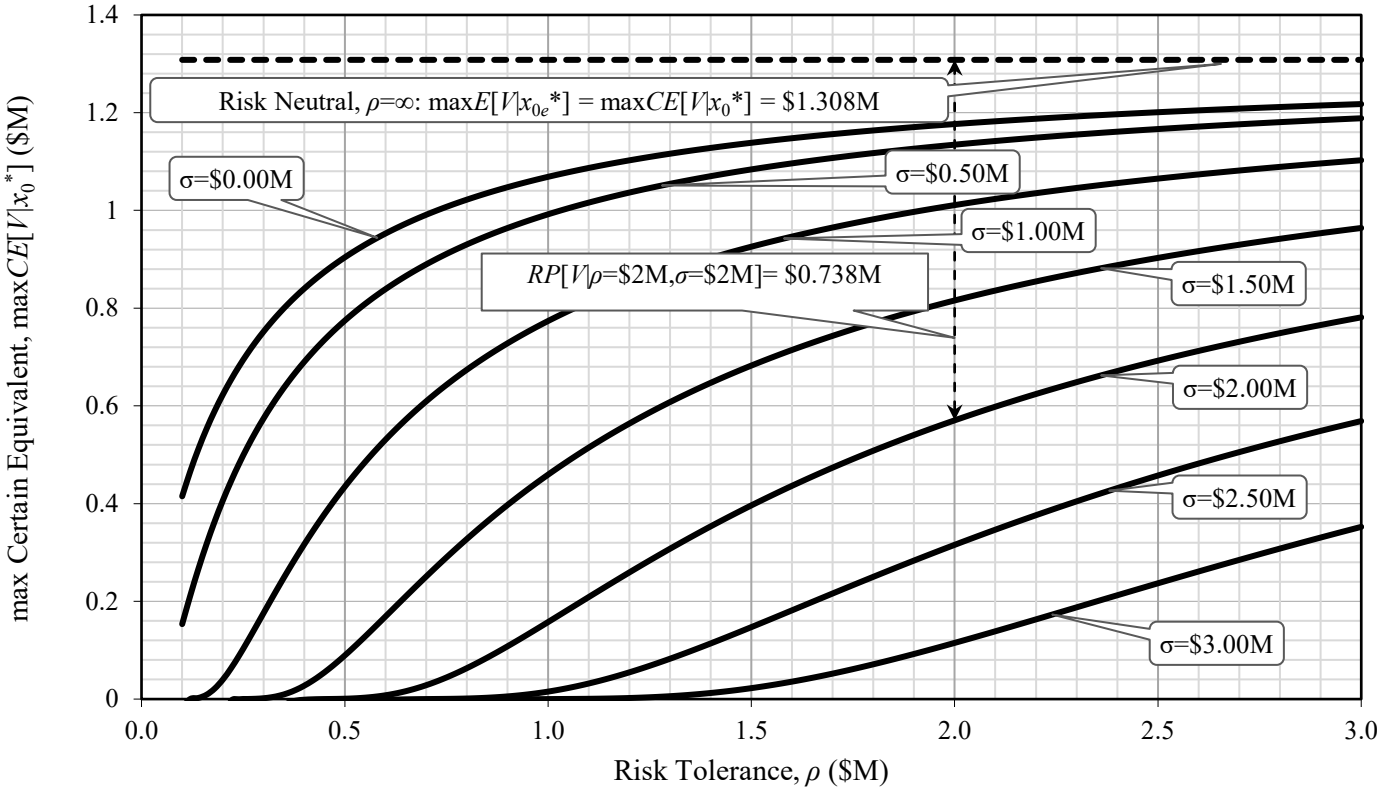
x_0^* vs. Risk Tolerance ρ given $\sigma = SD[C]$



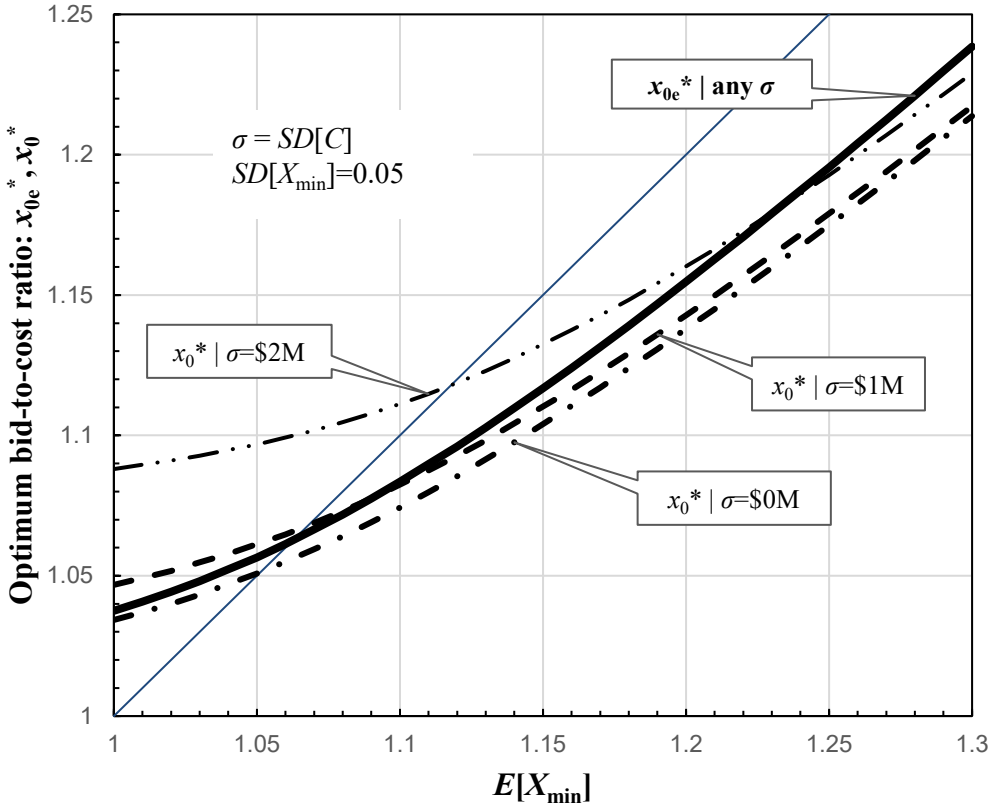
$\max CE[V|x_0^*]$ vs. $\sigma = SD[C]$ given ρ



$\max CE[V|x_0^*]$ vs. ρ given $\sigma = SD[C]$



Optimum x_0^* vs. $E[X_{min}]$ given $\sigma, \rho = \$2M$



CONCLUSIONS

- Uncertainty in Project Cost $\sigma = SD[C]$ and the Contractor's Risk Aversion ρ change optimum Bid for Fixed-Price Contracts **significantly**.
  - To find Optimum Bid, σ and ρ **must** be taken into account **explicitly**.
- Optimum Bid
  - **Must** maximize **Expected Utility of Profit**.
  - **Not** just maximize Expected Value of Profit.
- Bidding Decision Model - Should at least:
  - Select model for P[Win] (e.g., Friedman, Gates, Carr, Ioannou)
  - Estimate the mean and standard deviation of Project Cost
  - Encode Risk Tolerance
  - Compute optimum Bid Price to maximize *Expected Utility of Profit*.

Discrete-Event Construction Simulation Systems at the University of Michigan

- Systems to model construction processes under uncertainty
  - UM-CYCLONE – R.I. Carr, P.G. Ioannou
  - COOPS – L.Y. Liu, P.G. Ioannou
  - STROBOSCOPE – J.C. Martinez, P.G. Ioannou
    - EZSTROBE – J.C. Martinez, P.G. Ioannou
    - ProbSched – J.C. Martinez, P.G. Ioannou
    - ChaStrobe – C. Srisuwanrat, P.G. Ioannou

UM-CYCLONE

- Developers: R.I Carr, P.G. Ioannou (1989)
- Objective: Teach construction simulation at UM
- Language: FORTRAN, PASCAL
- OS: DOS
- Paradigm: Activity Scanning, Activity Cycle Diagrams
- Nodes: Queue, Combi Activity, Normal Activity, Consolidation
- Links: Plain, Probabilistic
- Resources: Generic, represented by a number in queues only
- Status: No longer used or maintained.

COOPS

- Developers: L.Y. Liu, P.G. Ioannou (1992)
- Objective: Object-oriented simulation (teaching and research)
- Language: ACTOR (COOPS has own Graphical User Interface)
- OS: Windows 3.11
- Paradigm: Activity Scanning, Activity Cycle Diagrams, Objects
- Nodes: Queues, Combis, Normals, Consolidations, Routers, Flags
- Links: Objects, Plain, Probabilistic
- Resources: Objects with special properties
- Status: No longer used or maintained.

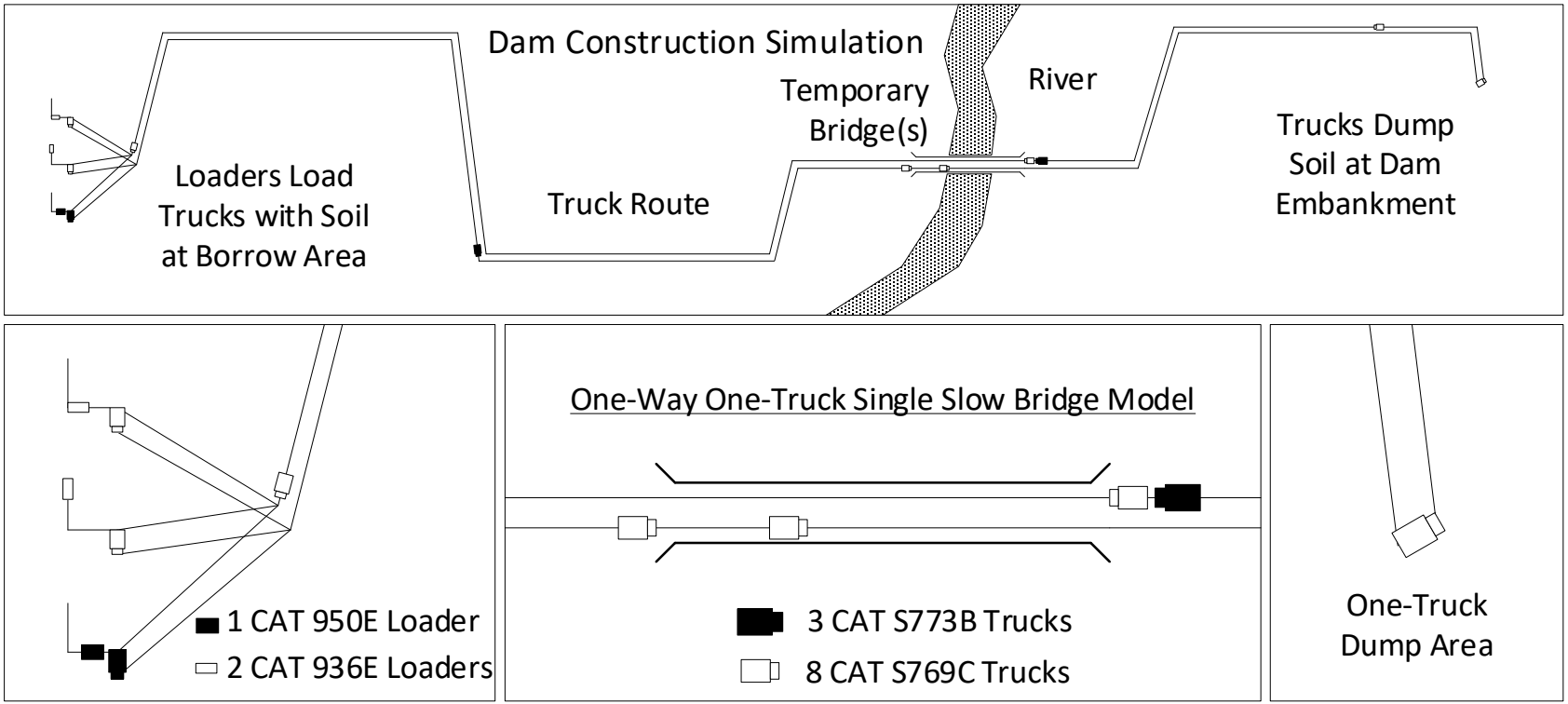
STROBOSCOPE

- Developers: J.C. Martinez, P.G. Ioannou (1996-present)
- Objective: General-purpose object-oriented simulation language
- Language: C++ & Visio for Graphical User Interface
- OS: Windows
- Paradigm: Activity Scanning, Activity Cycle Diagrams, Objects
- Nodes: Queues, Combis, Normals, Consolidators, Forks, Dynaforks, Assemblers, Disassemblers
- Links: Named Objects, Match Resources, Probabilistic/Decisions
- Resources: Generic, Characterized, Compound
- Complete language: Statements, Functions, Variables, Math, Add-ons.

EZSTROBE

- Developers: J.C. Martinez (primary), P.G. Ioannou (1997-present)
- Objectives:
  - Graphical simulation system – no language to learn
  - Simulation network shows complete model (WYSIWYG)
- GUI: Visio (input/output) – VBA custom programming
- Engine: STROBOSCOPE (also shows simulation output)
- Paradigm: Activity Scanning, Activity Cycle Diagrams
- Resources: All resources are generic of type “ezs”
- Nodes: Queues, Combis, Normals, Forks
- Links: Draw links, Release links, Flow links, Branch links

Example STROBOSCOPE Simulation Model
EARTHMOVING FOR A DAM



Loader Data

Model	CAT 950E	CAT 936E
Machines available	1	2
Bucket Size (m^3)	2.4	2
Soil loaded in loader's bucket, S (m^3)	Bucket Size * N[1,0.04]	Bucket Size * N[1,0.05]
Time to load a bucket of soil in truck (min)	0.43+0.035S	0.40+0.05S
Cost ($/hr)	130	90

Truck Data

Model	CAT 773B	CAT 769C
Capacity (m^3)	34.1	23.6
Mass when empty (kg)	39,396	31,178
Flywheel Power (kW)	485	336
Transmission efficiency	0.84	0.82
Retarding power (kW)	526	434
Max. speed (km/hr)	62	75
Actual speed (km/hr)	Calc. spd *N[1,0.02]	Calc. spd *N[1,0.03]
Dumping time (min)	1.12	1
Maneuvering time (min)	0.72	0.6
Time to cross bridge (min)	2.5	1.5
Cost ($/hr)	300	230

Haul and Return Road Segments

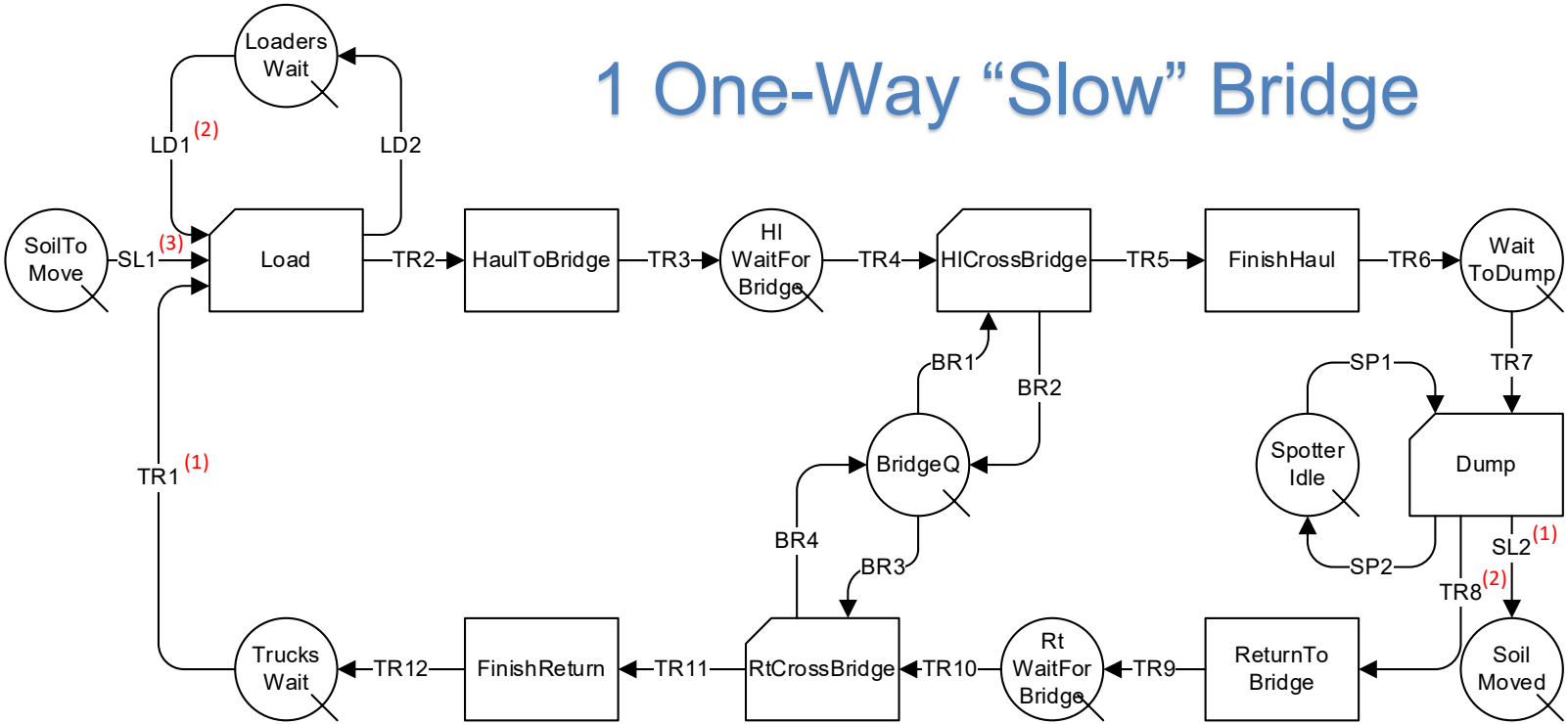
Road Segment	Length	Grade	Rolling Resistance
Borrow area to Bridge (descending)	2.3 km	-4%	7%
Bridge to Dam Embankment (ascending)	1.7 km	6%	4%

Material Data

Volume of Soil to Move	500,000 m^3
Soil Density	1690 kg/m^3

STROBOSCOPE SIMULATION NETWORK

1 One-Way “Slow” Bridge



Resource Types & Properties

```
GENTYPE   Soil;   GENTYPE Bridge;  GENTYPE   Spotter;

CHARTYPE Loader    BucketSize LoadVariability FixedLdTm VarLdTmFact CostPerHr;
/                      m3           SD           min       min/m3       $/hr
SUBTYPE  Loader S936E   2          0.05         0.40       0.05         90;
SUBTYPE  Loader S950E 2.4          0.04         0.43       0.035       130;

CHARTYPE Truck       Cap Emass Powr Eff RetPwr MxSpd SpdV DmpT MvT CstHr XTm;
/                     m3   kg   kw   %   kw  m/sec   SD  min  min $/hr  min
SUBTYPE   Truck S769C 23.6 31178 336 0.82 434 75/3.6 0.03 1.0  0.6  230  1.5;
SUBTYPE   Truck S773B 34.1 39396 485 0.84 526 62/3.6 0.02 1.12 0.72 300  2.5;

SAVEPROPS Truck AmtLoaded RollRes Grade;
```

Loading the Trucks (Amount & Time)

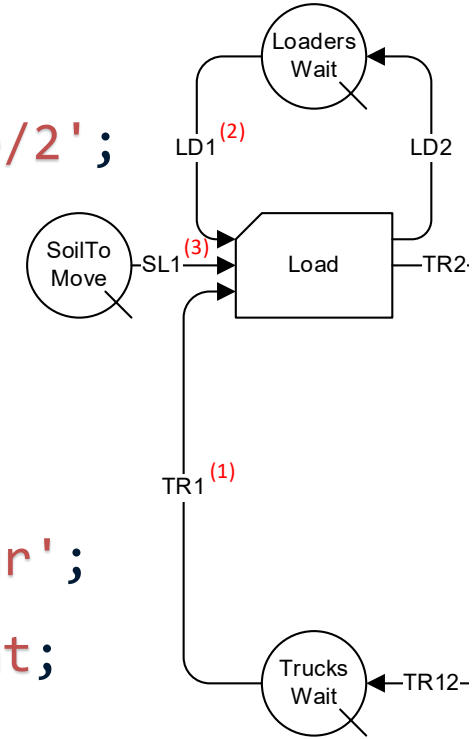
```
DRAWUNTIL SL1 'Load.Soil.Count >=
 Load.Truck.Capacity - Load.Loader.BucketSize/2';

DRAWAMT SL1 'Load.Loader.BucketSize *
 Normal[1,Load.Loader.LoadVariability]';

DRAWDUR SL1 'Load.Loader.FixedLdTm +
 SL1.LastAmtDrawn * Load.Loader.VarLdTmFact';

DURATION Load 'Load.Truck.MvT + SL1.SumDrawDur';

ONRELEASE TR2 ASSIGN AmtLoaded Load.Soil.Count;
```



Engineering Calculations for Truck Speed

```
VARPROP Truck EffectiveGrade 'RollRes + Grade';

VARPROP Truck EffectivePow
    '(EffectiveGrade>=0 ? Powr*Eff : RetPowr)*1000'; / Watts

VARPROP Truck Force '(Emass + AmtLoaded * SoilDensity)
                     *Abs[EffectiveGrade] * 9.8’; / Newton

VARPROP Truck Speed 'Min[EffectivePow/Force, MxSpd]’; /  m/s

VARPROP Truck SpeedVar  'Speed * Normal[1,SpdV]’; /  m/s
```

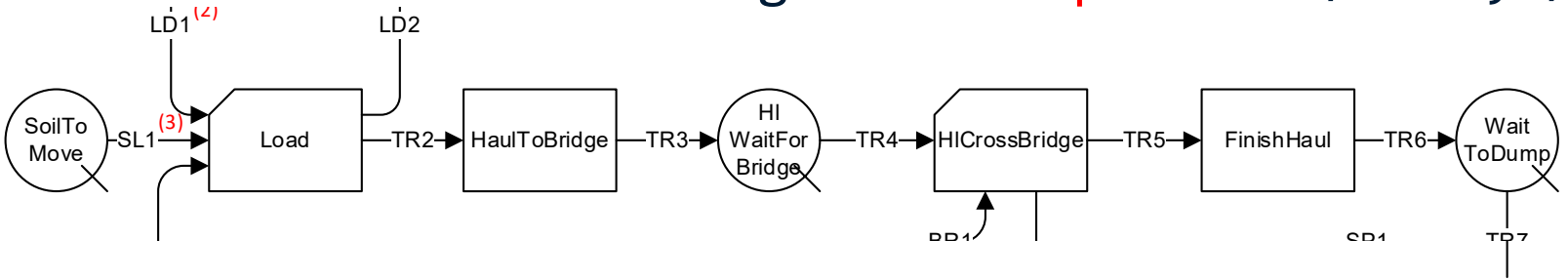
Soil & Road Data: Speed & Travel Time

```
ONRELEASE TR2 ASSIGN AmtLoaded  Load.Soil.Count;

ONRELEASE TR2 ASSIGN RollRes    0.07;

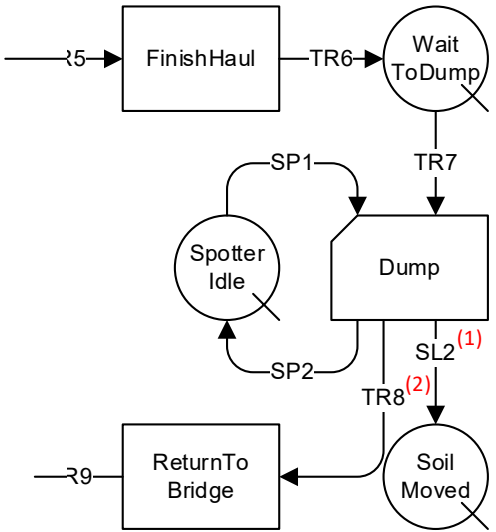
ONRELEASE TR2 ASSIGN Grade     -0.04;

DURATION HaulToBridge 'DistSourceToBridge /
                       HaulToBridge.Truck.SpeedVar / 60’; / min
```

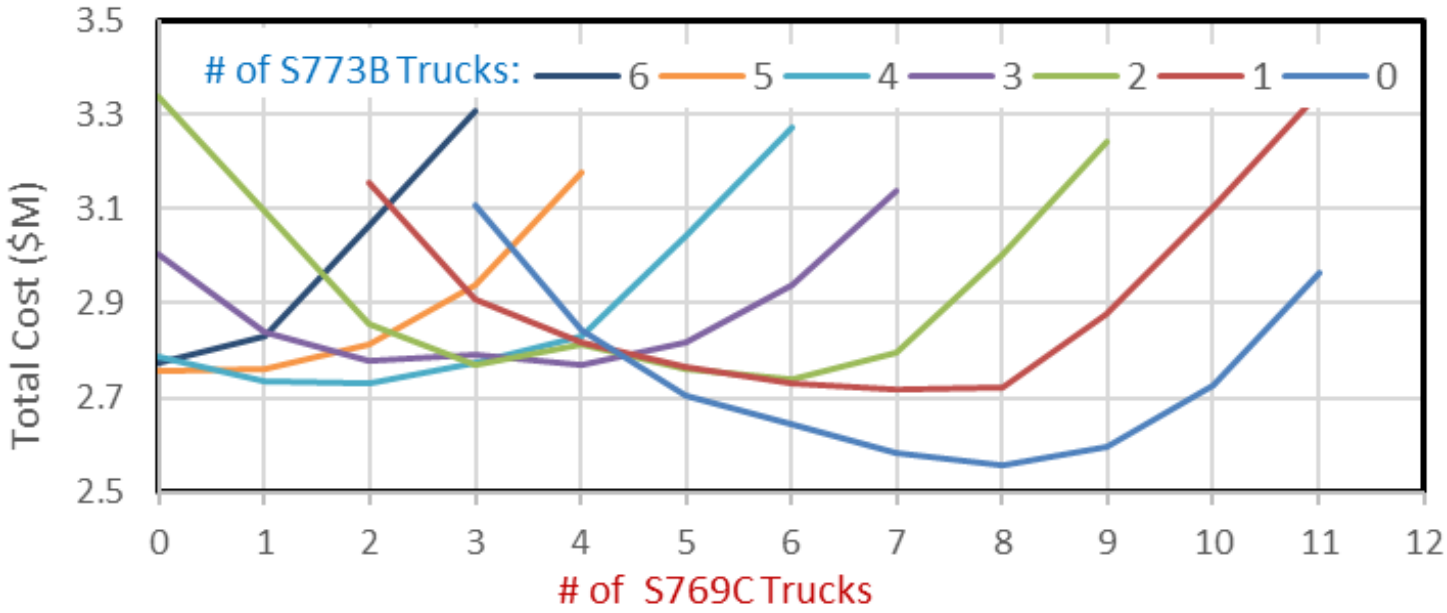


Dumping at the Dam Site

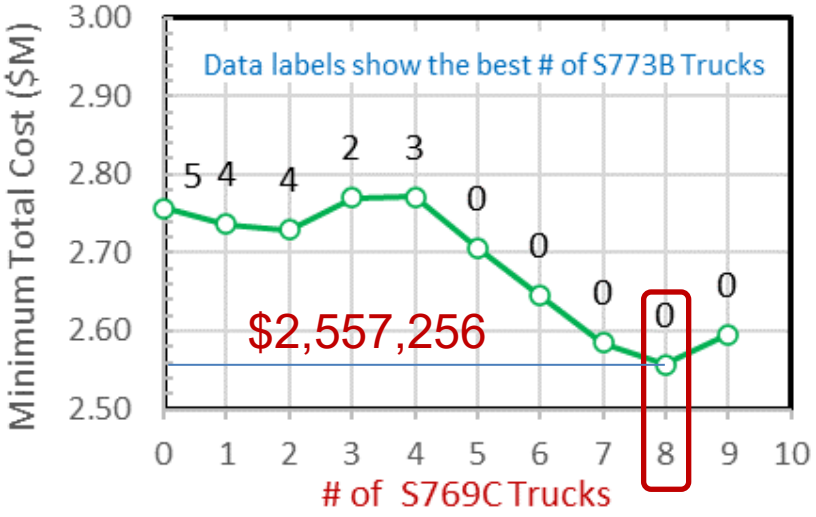
```
DURATION    Dump    'Dump.Truck.DumpTm';
RELEASEAMT  SL2     'Dump.Truck.AmtLoaded';
```

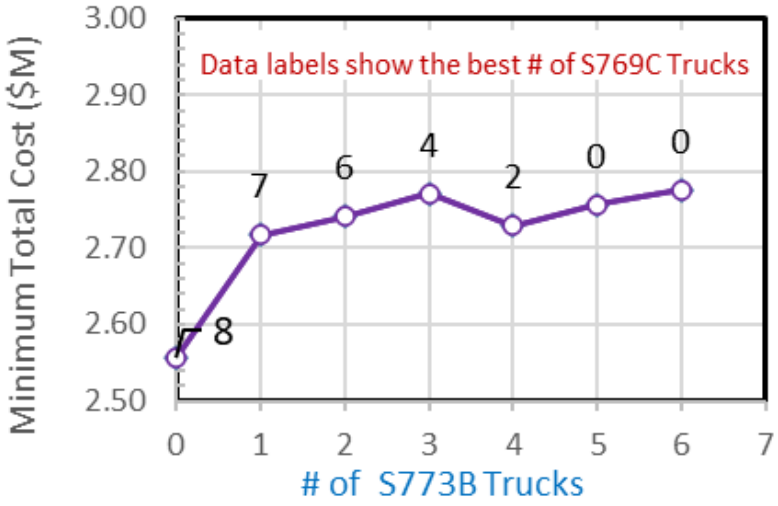


Sim. Results: 1 One-Way “Slow” Bridge



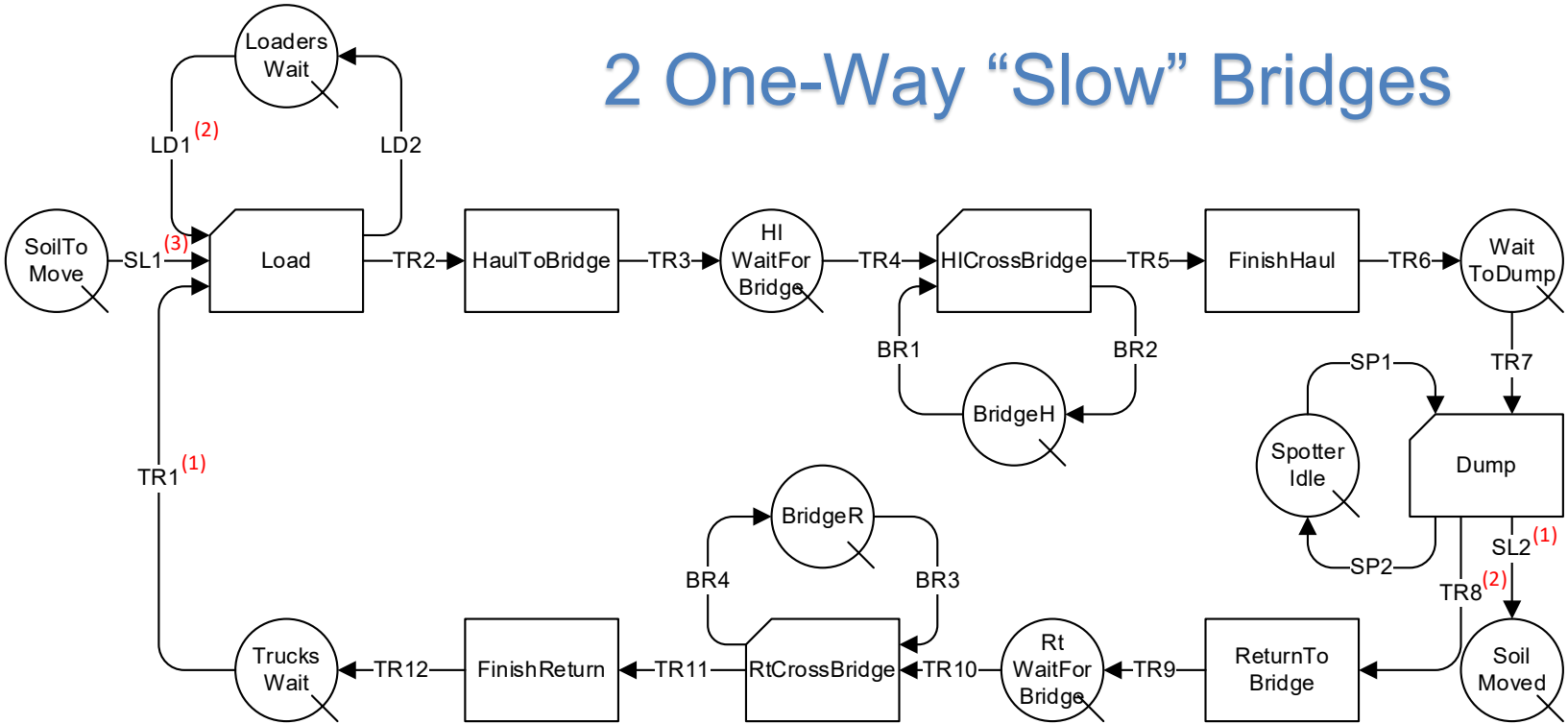
Sim. Results : 1 One-Way “Slow” Bridge



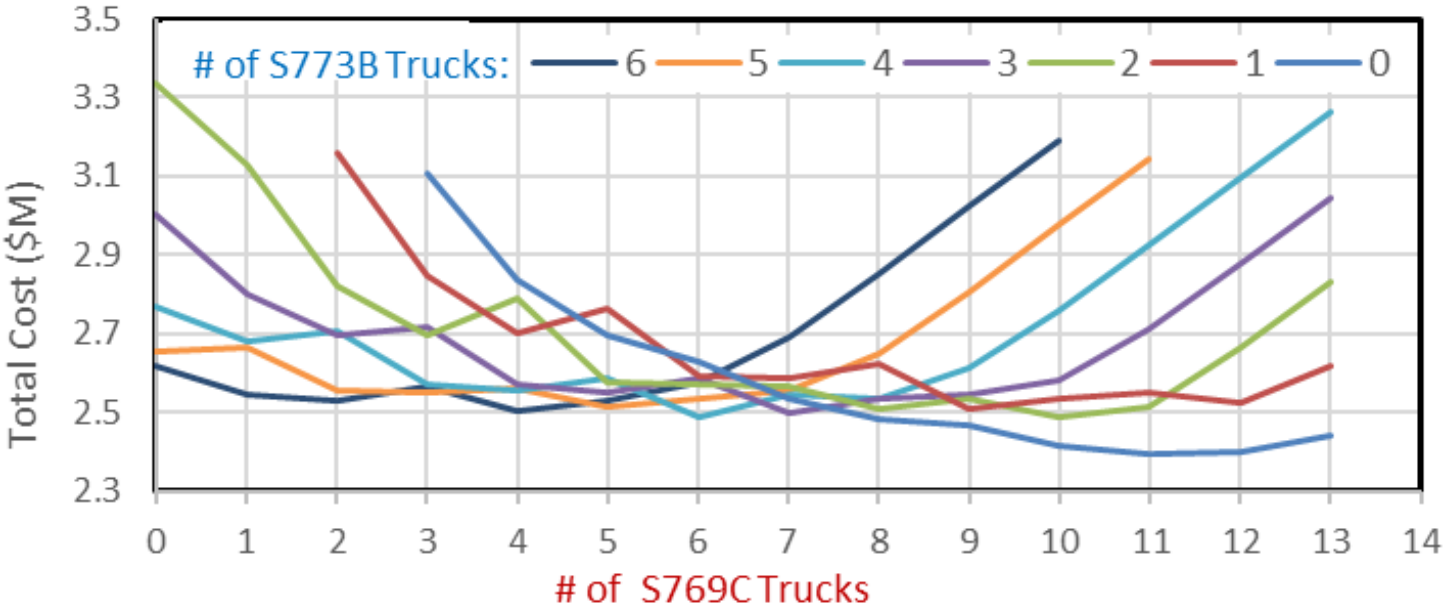


STROBOSCOPE SIMULATION NETWORK

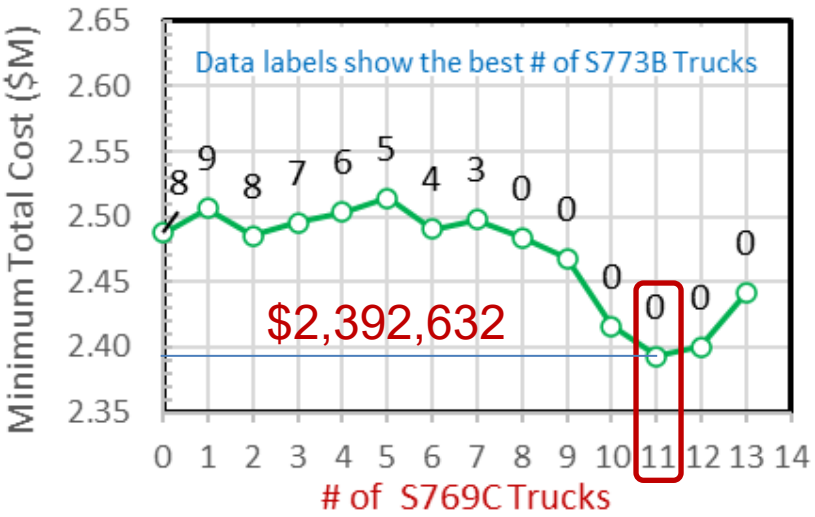
2 One-Way "Slow" Bridges

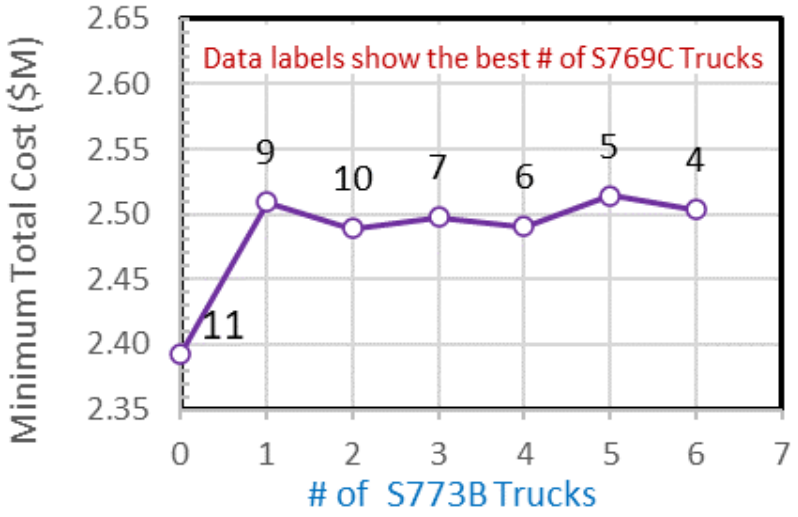


Sim. Results: 2 One-Way “Slow” Bridges



Sim. Results : 2 One-Way “Slow” Bridges

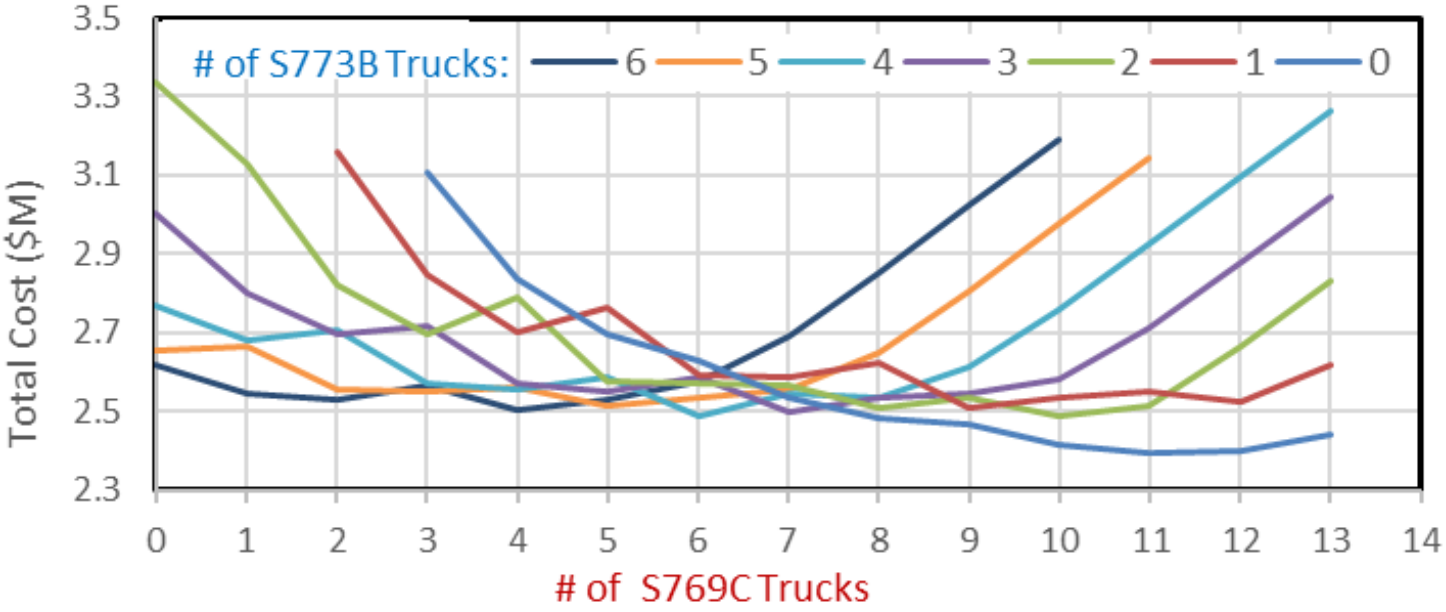




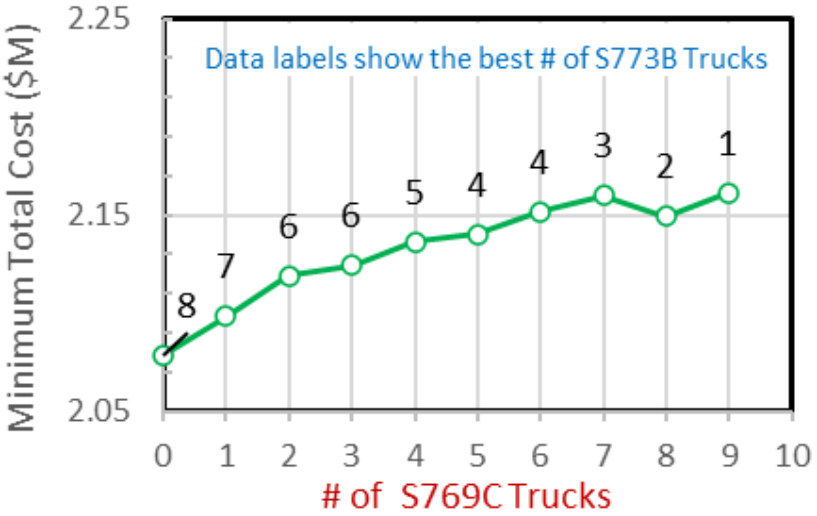
ΔC = Cost with1 Slow Bridge - Cost with 2 Slow Bridges

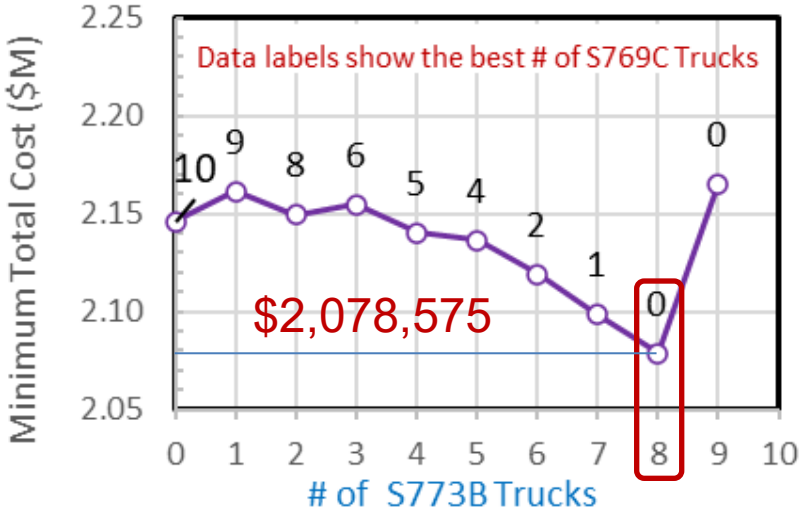
ΔC = $2,557,256 - $2,392,632 = $164,624

Sim. Results: 2 One-Way Multi-Truck “Fast” Bridges



Sim. Results : 2 One-Way Multi-Truck “Fast” Bridges





ΔC = Cost with 2 Slow Bridges - Cost with 2 Fast Bridges

ΔC = $2,392,632 - $2,078,575= $314,057

Decision Tables

- C1 = Cost of 1st Slow Bridge C2 = Cost of 2nd Slow bridge
- CF = Cost of 2 Fast Bridges

	If CF > $478,681+C1	If CF < $478,681+C1
If C2 > $164,624	1 Slow Bridge Cost: $2,557,256 + C1 Trucks: 8 x S769C + 0 x S773B	2 Fast Bridges Cost: $2,078,575 + CF Trucks: 0 x S769C + 8 x S773B

	If CF > $314,057 + C1 + C2	If CF < $314,057 + C1 + C2
If C2 < $164,624	2 Slow Bridges Cost: $2,392,632 + C1 + C2 Trucks: 11 x S769C + 0 x S773B	2 Fast Bridges Cost: $2,078,575 + CF Trucks: 0 x S769C + 8 x S773B

DSS - CONCLUSIONS

- Decision Support Systems are invaluable aids for making difficult decisions at the top and middle levels of a construction firm.
- DSS come in many forms, from spreadsheets to special-purpose dedicated computer programs.
- Decisions are often unique and complex:
  DSS may require multiple software that work together.
- In addition to software the correct use of DSS requires expertise.
- Final responsibility lies with the decision maker – not the software.



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Thank you!
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