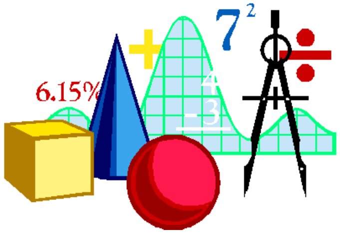
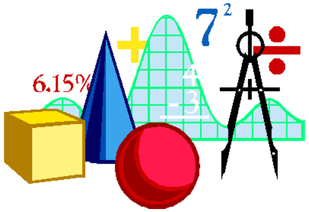


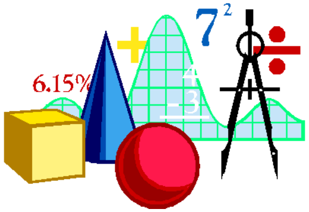
McKinney Associates Capabilities Discussion of System Models & Modeling, Simulation & Analysis (MS&A)

14 January 2016



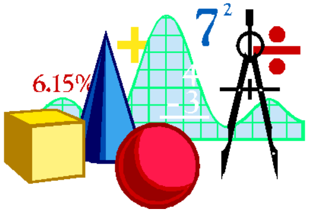
McKinney Associates Overview

- McKinney Associates has been providing innovative, optimized modeling, simulation & analysis (MS&A) solutions for complex systems since 1993. Leon McKinney, the founder and president of McKinney Associates, has 34 years of experience in system concept synthesis, design, performance assessment, optimization, and mission analyses, including significant work on classified projects. He had an 11-year career with McDonnell Douglas Space Systems in California before founding McKinney Associates in 1993.
- Mr. McKinney has participated on a wide range of advanced projects, with an emphasis on space access and hypersonics programs, including AMLS, TAV, Copper Canyon, NASP, STAS, ALS, NLS, ABLV, SLI, RMLS, NGLT, CAV, X-43, X-51, FALCON, HIFIRE, ALASA, TBG, XS-1 and others
- Mr. McKinney has also participated on a wide range of strategic and tactical projects for the Department of Defense, the National Reconnaissance Organization, the Ballistic Missile Organization, and the Strategic Defense Initiative, including Shuttle, Shuttle Launch Dispenser, Peacekeeper, SICBM, Trident, AMaRV, DSV, HEDI, Smart MaRV, MSTART, and many classified programs. Mr. McKinney has also been involved in a number of other national security projects, including support of National Intelligence Estimate and Foreign Technology Assessment activities.



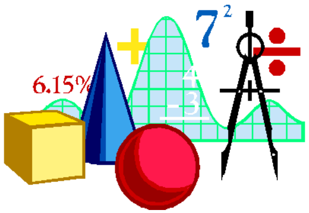
McKinney Associates Overview

- Mr. McKinney currently provides system analysis support to many government agencies and contractors, and served as Executive Director of the first US Hypersonics Industry Team from 2009 thru 2011, an industry consortium that promoted development of high-speed systems for the U.S
- McKinney Associates' regular interaction with federal executive branch agencies including the Executive Office of the President, Department of Defense and NASA, as well as the members and committee staff of the Congress allows timely programmatic and policy assessments to clients.
- In addition to our aerospace and defense experience, McKinney Associates also has extensive experience in environmental & regulatory affairs and public works engineering. McKinney Associates MS&A projects involving storm water and flood control systems has resulted in savings of millions of dollars for local governments – one MS&A project alone saved over $35 million, 90% of the original estimated cost.



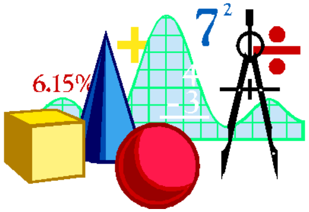
McKinney Associates Overview

- **McKinney Associates’ primary areas of MS&A have been:**
  - **Traditional system performance modeling & optimization**
    - **Assemble and/or develop vehicle models (weights, aero, propulsion, guidance, etc)**
    - **Assemble and/or develop vehicle & mission constraints models (boundary conditions, in-path static or dynamic, roving events, etc)**
    - **Optimize performance (range, weight, cost, etc) – “Point Designs” – using traditional system performance tools (OTIS, POST, GVSIM, NPSS, etc.)**
  - **N-Dimensional Design Space modeling & optimization**
    - **Assemble and/or develop vehicle models (weights, aero, propulsion, guidance, etc)**
    - **Assemble and/or develop vehicle & mission constraints models (boundary conditions, in-path static or dynamic, roving events, etc)**
    - **Optimize performance (range, weight, cost, etc)**
    - **THEN – create N-dimensional Response Model(s) (RMs) that allow targeting for the overall “best” class of system concept answers – NOT point-designs but concepts that incorporate trades of technology vs cost- and schedule-risktion**
    - **Tools used include SAS-JMP, @Risk, Evolver, Genetic Algorithms (Gas), and proprietary algorithms**



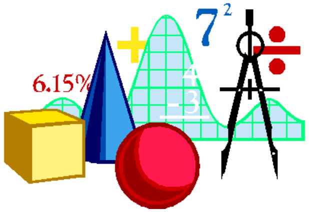
Response Models (RMs)

- RMs Are Mathematical Models Of Complex Physical Systems That Replicate Results Of Simulation Of The Physical Systems
- RMs Provide System Sensitivities To Changes In Design Variables But Serve A Broader Purpose
- RMs Capture The Characteristics Of A Physical System As A Mathematical System So That Various Numerical Analysis Methods Can Be Applied
  - Different from just running a large number of simulation cases, which typically result in determining system responses via nth-order interpolation table-lookup
  - RMs provide equations for system responses to design variables changes
- Ideally, RMs Allow Avoiding Running Large Numbers Of Simulation Cases - Beyond 2-3 System Design Variables, The Number Of Cases Required For Sufficient Fidelity Rises Geometrically:
  - NC = NVPDV ^ NDV, where NC = number of cases, NVPDV = number of values per design variable, NDV = number of design variables
  - For 2 design variables, if the goal is to produce a matrix of cases for interpolation with reasonable fidelity, at least 5 values for each design variable should be used
  - For 2 design variables the number of required cases is 25 (NC = NVPDV^NDV = 5^2 = 25)
- For Example, A 5-Design Variable System Model With 5 Values For Each Design Variable, The Number Of Cases is 5^5 or 3,125 Cases
- But More Important Than Reducing The Number Of System Simulation Cases Is That RMs Provide Insight Into N-Dimensional Design Space Topology And Allow A Wide Variety Of Numerical Analysis Methods: Constrained Optimization Techniques w/ Cost & Penalty Functions , etc.



RMs and MS&A Interactions

- **RMs Tend To Evolve During MS&A Studies:**
  - **System models, with design parameters and their ranges, and system model responses almost always change as the study progresses**
  - **Key is learning how to fine-tune response model design parameters to efficiently produce high-fidelity response models to which application of numerical analysis methods is straight-forward**
  - **McKinney Associates uses Central Composite Design (CCD), Neural Network Designs (NND) RMs and RMs developed using proprietary algorithms**
- **CCDs produce response equations which are 2nd-degree polynomials of all the design variables**
- **NNDs produce response equations which are 1st-degree linear combinations of transcendental "Squish" functions, where each Squish(X) = 1 / { 1+exp(-X) }, and the X is in turn a linear combination of all the design variables**
- **Sometimes CCDs and NNDs fail to provide system response models with the desired fidelity – Then models are developed for all combinations of all design variables**
- **Proprietary algorithms can be brought to bear on the problems**



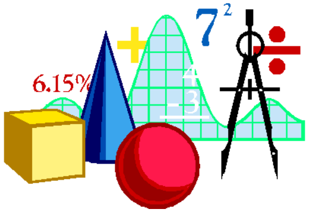
Representative Analysis Results
3-Stage Missile Range

Neural Network Range Response Equation

- To achieve adequate fidelity, the neural network required 12 “hidden nodes” (one of the key parameters in neural networks that control fidelity)
- The 12 “hidden nodes” represented by 12 Squish functions (:H1 Formula, :H2 Formula, :H3 Formula, etc
- The Range Response Eqn is a linear combination of the 12 Squish functions

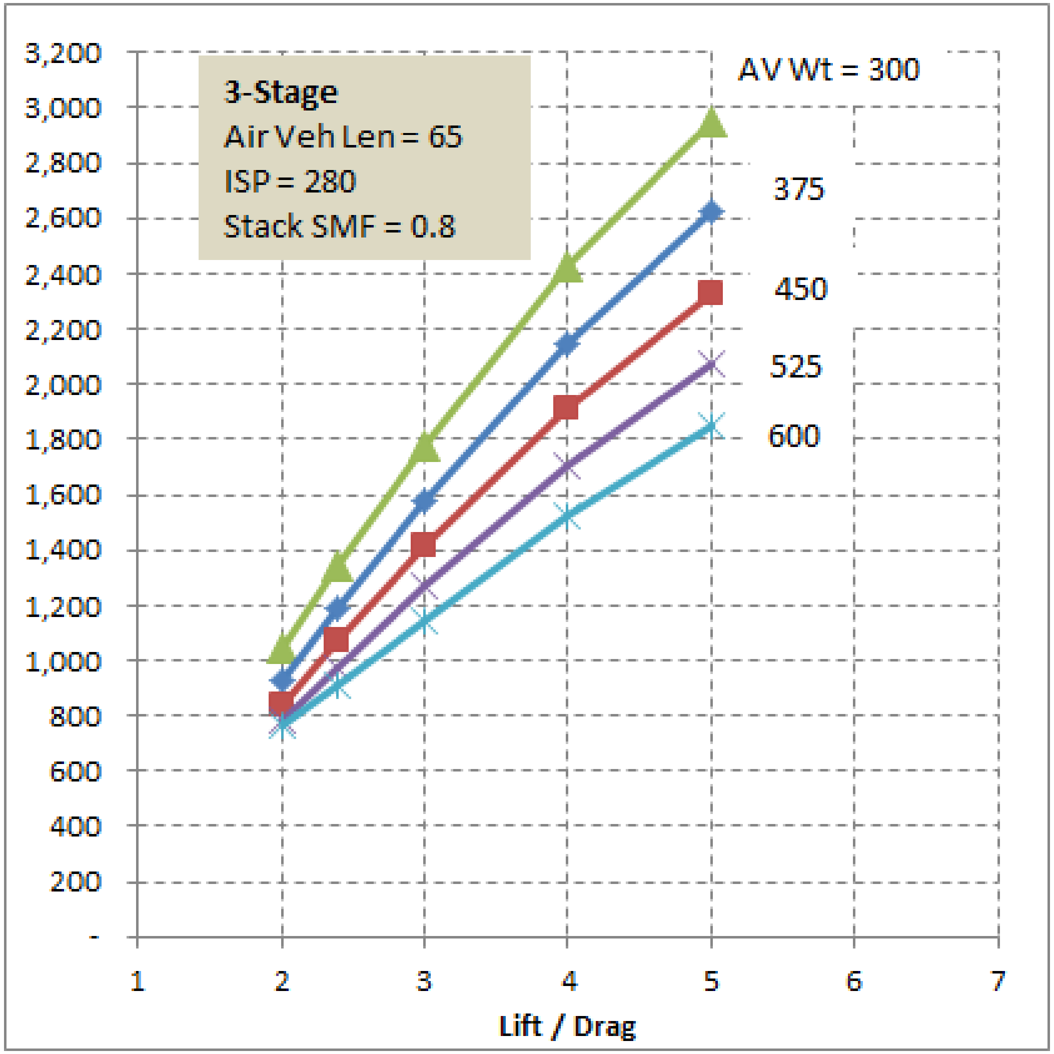
Range Response Eqn (Neural Net Model) =	(1.02445193353531 + 0.938555018969049 * :H1 Formula + -2.49970906621305 * :H2 Formula + -0.631407253209197 * :H3 Formula + 0.344985129548897 * :H4 Formula + 0.72655209625983 * :H5 Formula + 0.223993766954954 * :H6 Formula + 0.905576360109712 * :H7 Formula + -0.161477064241789 * :H8 Formula + -0.665053318232658 * :H9 Formula + 1.26116221173489 * :H10 Formula + 0.315009651193269 * :H11 Formula + -0.539715999014605 * :H12 Formula) * 1511.74357113955 + 2315.32222222222

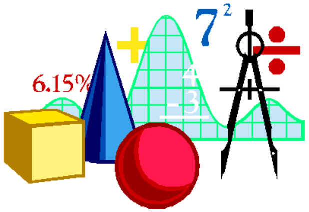
H1 =	Squish(0.614950204999226 + 0.29408719765595 * ((:AirVehWt - 450) / 120.141426095044) + 0.295668858478454 * ((:AirVehLen - 65) / 8.00942840633627) + 0.32838488311483 * ((:CDfactor - 0.835485) / 0.28678959823148) + 1.68075139058011 * ((:CLfactor - 1.4662145) / 0.503294459840257) + -0.403885592986331 * ((:StackIsp - 280) / 24.0282852190088) + -0.634700770705714 * ((:StackSMF - 0.799999999999999) / 0.0800942840633628))



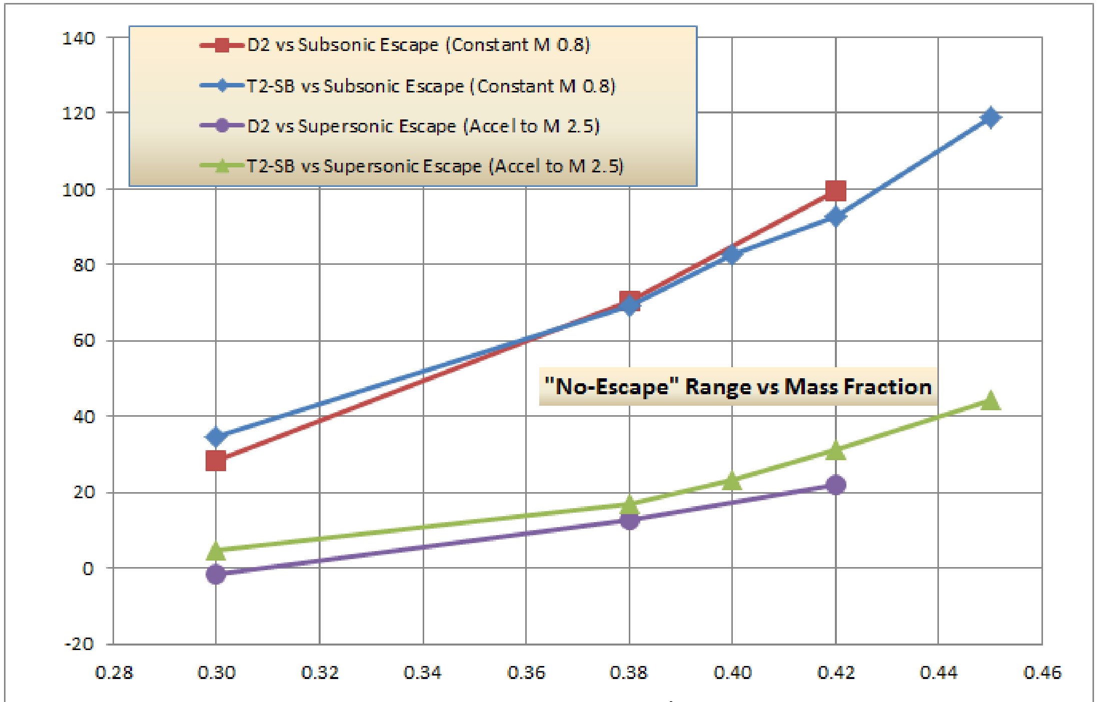
Representative Analysis Results
3-Stage Missile Range

Range as
f(AV Weight & L/D)
Stack ISP & SMF Fized
AV Length Fixed

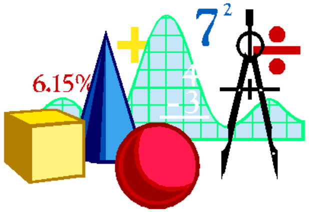




Representative Analysis Results
A2A Missile vs A/C “No-Escape”

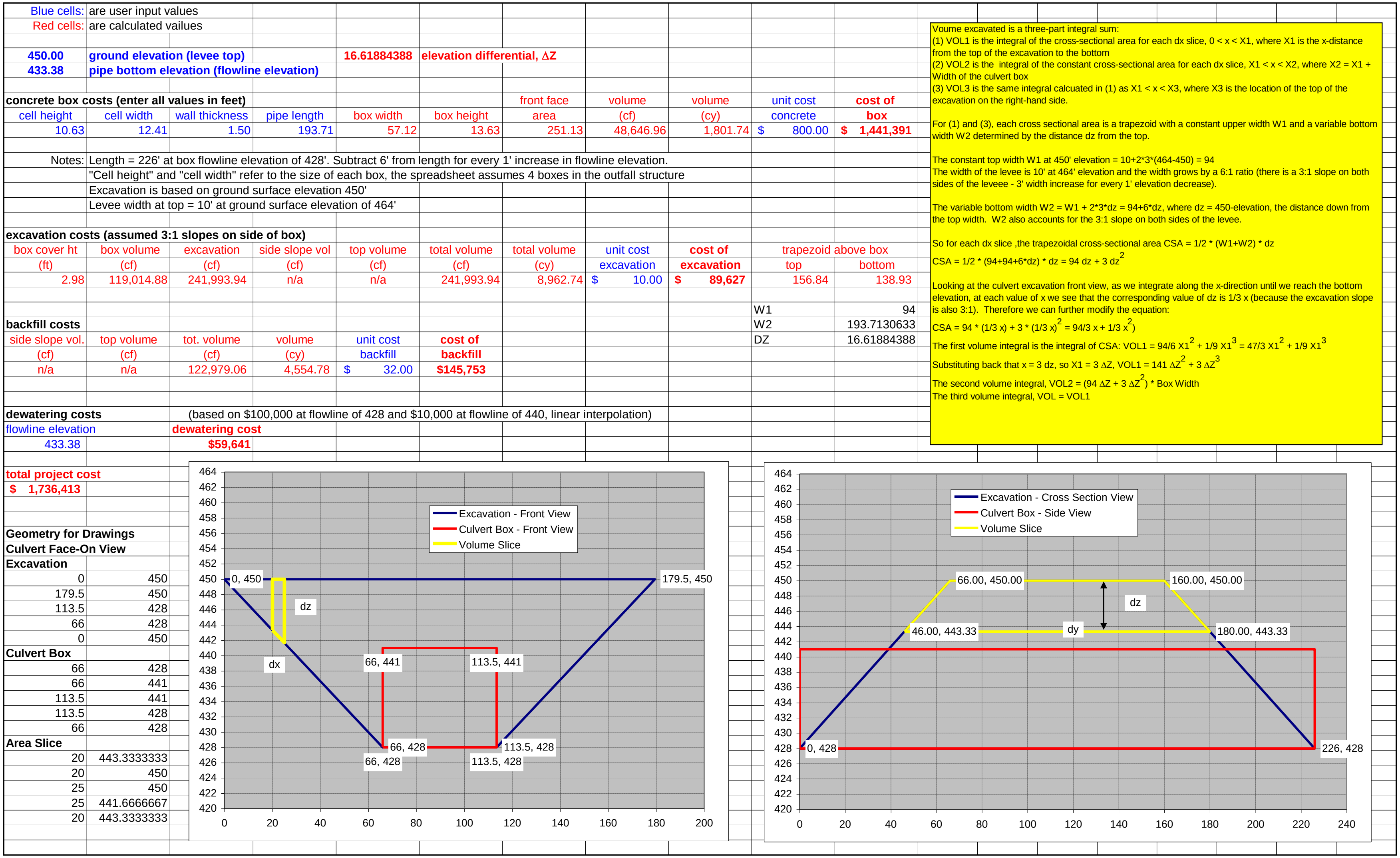


"No-Escape" Range							
Subsonic Escape (Const M 0.8)				Supersonic Escape (Accel to M 2.5)			
D2 AMRAAM-Like		**T2-Strongback**		**D2 AMRAAM-Like**		**T2-Strongback**	
Propellant Fraction	NE Range	Propellant Fraction	NE Range	Propellant Fraction	NE Range	Propellant Fraction	NE Range
0.30	28.34	0.30	34.48	0.30	(1.56)	0.30	4.92
0.38	70.38	0.38	69.25	0.38	12.62	0.38	16.91
0.42	99.62	0.40	82.66	0.42	22.00	0.40	23.45
		0.42	92.66			0.42	31.37
		0.45	118.72			0.45	44.47



Non-Aerospace Example: Missouri River Levee Culvert

McKinney Associates developed a comprehensive culvert model with significantly higher fidelity than what had previously been used



Blue cells:	are user input values		
Red cells:	are calculated vailues		
450.00	**ground elevation (levee top)**	**16.61884388**	**elevation differential, ΔZ**
433.38	**pipe bottom elevation (flowline elevation)**		

concrete box costs (enter all values in feet)

cell height	cell width	wall thickness	pipe length	box width	box height	front face area	volume (cf)	volume (cy)	unit cost concrete	**cost of box**
10.63	12.41	1.50	193.71	57.12	13.63	251.13	48,646.96	1,801.74	$ 800.00	**$ 1,441,391**

Notes: Length = 226' at box flowline elevation of 428'. Subtract 6' from length for every 1' increase in flowline elevation.
"Cell height" and "cell width" refer to the size of each box, the spreadsheet assumes 4 boxes in the outfall structure
Excavation is based on ground surface elevation 450'
Levee width at top = 10' at ground surface elevation of 464'

excavation costs (assumed 3:1 slopes on side of box)

box cover ht (ft)	box volume (cf)	excavation (cf)	side slope vol (cf)	top volume (cf)	total volume (cf)	total volume (cy)	unit cost excavation	**cost of excavation**	trapezoid above box top	trapezoid above box bottom
2.98	119,014.88	241,993.94	n/a	n/a	241,993.94	8,962.74	$ 10.00	**$ 89,627**	156.84	138.93

W1	94
W2	193.7130633
DZ	16.61884388

backfill costs

side slope vol. (cf)	top volume (cf)	tot. volume (cf)	volume (cy)	unit cost backfill	**cost of backfill**
n/a	n/a	122,979.06	4,554.78	$ 32.00	**$145,753**

dewatering costs (based on $100,000 at flowline of 428 and $10,000 at flowline of 440, linear interpolation)

flowline elevation	**dewatering cost**
433.38	**$59,641**

total project cost
$ 1,736,413

Voume excavated is a three-part integral sum:
(1) VOL1 is the integral of the cross-sectional area for each dx slice, 0 < x < X1, where X1 is the x-distance from the top of the excavation to the bottom
(2) VOL2 is the integral of the constant cross-sectional area for each dx slice, X1 < x < X2, where X2 = X1 + Width of the culvert box
(3) VOL3 is the same integral calcuated in (1) as X1 < x < X3, where X3 is the location of the top of the excavation on the right-hand side.

For (1) and (3), each cross sectional area is a trapezoid with a constant upper width W1 and a variable bottom width W2 determined by the distance dz from the top.

The constant top width W1 at 450' elevation = 10+2*3*(464-450) = 94
The width of the levee is 10' at 464' elevation and the width grows by a 6:1 ratio (there is a 3:1 slope on both sides of the leveee - 3' width increase for every 1' elevation decrease).

The variable bottom width W2 = W1 + 2*3*dz = 94+6*dz, where dz = 450-elevation, the distance down from the top width. W2 also accounts for the 3:1 slope on both sides of the levee.

So for each dx slice ,the trapezoidal cross-sectional area CSA = 1/2 * (W1+W2) * dz

$CSA = 1/2 * (94+94+6*dz) * dz = 94\ dz + 3\ dz^2$

Looking at the culvert excavation front view, as we integrate along the x-direction until we reach the bottom elevation, at each value of x we see that the corresponding value of dz is 1/3 x (because the excavation slope is also 3:1). Therefore we can further modify the equation:

$CSA = 94 * (1/3\ x) + 3 * (1/3\ x)^2 = 94/3\ x + 1/3\ x^2)$

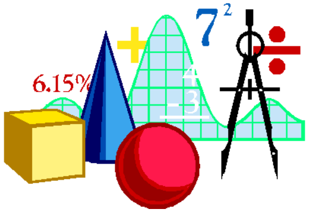
The first volume integral is the integral of CSA: $VOL1 = 94/6\ X1^2 + 1/9\ X1^3 = 47/3\ X1^2 + 1/9\ X1^3$

Substituting back that x = 3 dz, so X1 = 3 ΔZ, $VOL1 = 141\ \Delta Z^2 + 3\ \Delta Z^3$

The second volume integral, $VOL2 = (94\ \Delta Z + 3\ \Delta Z^2) * \text{Box Width}$
The third volume integral, VOL = VOL1

Geometry for Drawings
Culvert Face-On View

Excavation	
0	450
179.5	450
113.5	428
66	428
0	450
Culvert Box	
66	428
66	441
113.5	441
113.5	428
66	428
Area Slice	
20	443.3333333
20	450
25	450
25	441.6666667
20	443.3333333



Non-Aerospace Example: Missouri River Levee Culvert

RISK Optimizer

McKinney Associates developed a system model – using the client’s software package (ICPR) – that incorporated all independent and dependent variables, and, most importantly, the nonlinear constraints.

Max Elevation for Culvert Top	450.00	(Upstream)	
Fall (Upstream to Downstream)	-1.00		
Min Elevation for Culvert Bottom	427.60	(Downstream)	
Max Span	192.00		
Min Span	144.00		
Span / Rise Ratio	1.17		
		Baseline Optimum Values	
Culvert Span	148.87	148.8747	**Independent Variable 1**
Culvert Rise	127.61		
Elevation	433.38	433.3812	**Independent Variable 2**
Max Elevation Allowed	437.87		
Margin Below Max Elevation	4.48		
Min Elevation Allowed	428.60		
Margin Above Min Elevation	4.78		
Length	196.71		
Minimum Elevation	443.00		**Constraint 1**

Starting with the system model, McKinney Associates produced Response Surface Models (RSMs) that predicted actual system responses with a very high degree of fidelity (< 0.5%)

Response Surface Model 1 : 210.639867592597 + -0.0189293452221367 * SPAN + 0.54228795406796 * ELEVATION + (SPAN - 168) * ((ELEVATION - 432.927692307692) * 0.00225415796128196)

[For Max Stage @ Node UP2BOX]

Max-Stage (ft) : 442.820

Response Surface Model 2 : 43.2671413976985 + 0.0085218402110504 * SPAN + -0.0943492971901012 * ELEVATION + (SPAN - 168) * ((ELEVATION - 432.927692307692) * -0.000390184389356899)

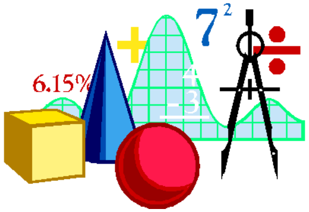
[For Total Costs]

Project Cost ($M) : $ 3.650

Concrete Box Cost	**$**	**1,441,391**	39.6%
Excavation Cost	**$**	**89,627**	2.5%
Backfill Cost	**$**	**145,753**	4.0%
Dewatering Cost	**$**	**59,641**	1.6%
Culvert Total Cost	**$**	**1,736,413**	47.8%
Channel Widening Land Cost	**$**	**1,899,449**	52.2%
Total Cost	**$**	**3,635,862**	
Difference from RSM Value	**$**	**(14,142)**	
% Difference from RSM Value		**-0.39%**	

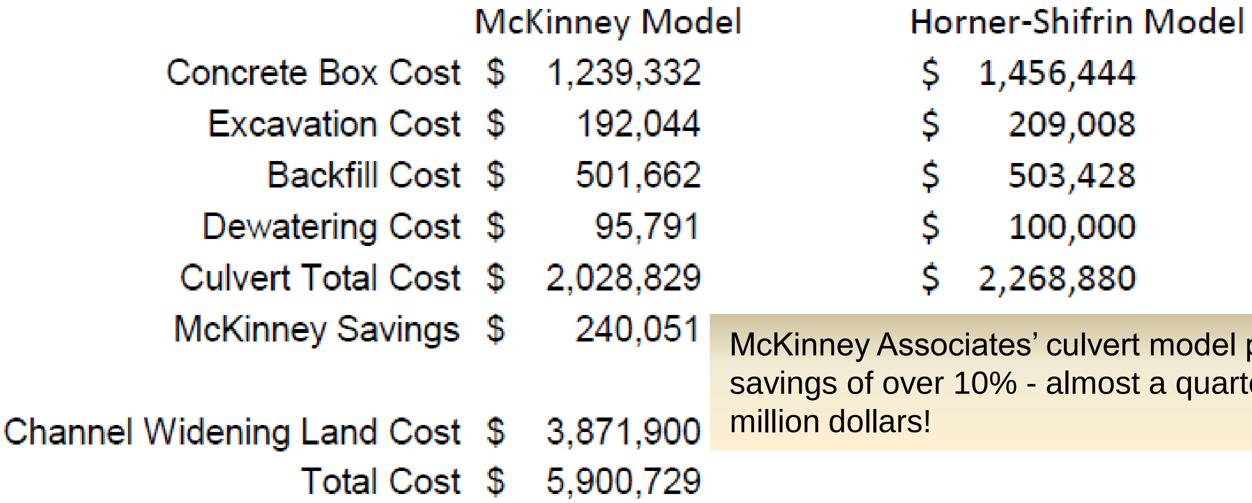
		Orig Width	New Width	
FEESP-JOIN Channel Section Length	2,650.00	660	660	**ft**
JOIN-CASINO Channel Section Length	980.00	660	1080	**ft**
CASINO-UP2BOX Channel Section Length	2,960.00	660	1080	**ft**

Channel Δ Acreage	37.99	**acres**
Channel Δ Acreage Cost / Acre	50.00	**$K**



Non-Aerospace Example: Missouri River Levee Culvert

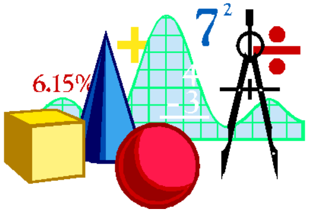
McKinney Associates had no authority to optimize the remainder of the system, but identified substantial potential cost savings in optimization of the total system beyond the designated culvert and the direct-feed channels



	McKinney Model	Horner-Shifrin Model
Concrete Box Cost	$ 1,239,332	$ 1,456,444
Excavation Cost	$ 192,044	$ 209,008
Backfill Cost	$ 501,662	$ 503,428
Dewatering Cost	$ 95,791	$ 100,000
Culvert Total Cost	$ 2,028,829	$ 2,268,880
McKinney Savings	$ 240,051	
Channel Widening Land Cost	$ 3,871,900	
Total Cost	$ 5,900,729	

McKinney Associates’ culvert model produced savings of over 10% - almost a quarter of a million dollars!

Non-Aerospace Example: Missouri River Bottoms Detention Basin Optimization



From January 1999 report to City of Chesterfield: "…In summary, this optimization process has reduced the planned land acquisition from 168.6 acres, at a cost of $43.12 M, to only 18.4 acres, at a cost of $5.01 M – a savings of $38.11 M, or 88%…"

OPT_ICPR RESULTS

SUMMARY

Watershed	Initial Land Required	Cost	Final Land Required	Land Savings	Land Savings (%)	Cost	Cost Savings	Cost Savings (%)
2, 6 & 7	132.17	$ 34,530,883	10.28	121.89	92.2%	$ 2,629,012	$ 31,901,872	92.4%
3 & 4	31.30	$ 7,697,052	8.12	23.18	74.0%	$ 2,376,041	$ 5,321,011	69.1%
5	5.10	$ 888,624	0.02	5.08	99.6%	$ 3,485	$ 885,139	99.6%
Totals	**168.57**	**$ 43,116,559**	**18.42**	**150.15**	**89.1%**	**$ 5,008,538**	**$ 38,108,022**	**88.4%**

WATERSHEDS 2, 6 &7

				Iteration 3				
Pond/Node	Cost ($/ft^2)	Initial Size	Cost ($)	Size	Land Savings	Cost ($)	Savings ($)	Savings (%)
N6-15P	4	2.2	$ 383,328	0.55	75.0%	$ 95,832	$ 287,496	75.0%
N6-16P	4	3.5	$ 609,840	0.875	75.0%	$ 152,460	$ 457,380	75.0%
N6-24P	6	4.4	$ 1,149,984	1.1	75.0%	$ 287,496	$ 862,488	75.0%
N6-37P	5	9.6	$ 2,090,880	2.4	75.0%	$ 522,720	$ 1,568,160	75.0%
N6-57P	6	0.55	$ 143,748	0.1375	75.0%	$ 35,937	$ 107,811	75.0%
N6-60C	10	2.9	$ 1,263,240	0.2417	91.7%	$ 105,285	$ 1,157,955	91.7%
N6-68P	6	3	$ 784,080	0.25	91.7%	$ 65,340	$ 718,740	91.7%
N6-RES1	5	21.9	$ 4,769,820	0.6083	97.2%	$ 132,488	$ 4,637,332	97.2%
N6-RES2	5	5	$ 1,089,000	0.4167	91.7%	$ 90,757	$ 998,243	91.7%
N7X-62P	8	10	$ 3,484,800	1	90.0%	$ 348,480	$ 3,136,320	90.0%
NRT-10	6	38.48	$10,057,133	1.0689	97.2%	$ 279,368	$ 9,777,765	97.2%
NRT-9	6	22.64	$ 5,917,190	0.6289	97.2%	$ 164,369	$ 5,752,821	97.2%
NS7-2P	8	8	$ 2,787,840	1	87.5%	$ 348,480	$ 2,439,360	87.5%
		132.17	$34,530,883	10.28	92.2%	$ 2,629,012	$31,901,872	92.4%

WATERSHEDS 3 & 4

				Final Iteration				
Pond/Node	Cost ($/ft^2)	Initial Size	Cost ($)	Size	Land Savings	Cost ($)	Savings ($)	Savings (%)
N3-RES1	3	3	$ 392,040	0.01	99.7%	$ 1,307	$ 390,733	99.7%
N4-18P	4	3	$ 522,720	0.1661	94.5%	$ 28,941	$ 493,779	94.5%
N4-26P	6	4.2	$ 1,097,712	0.01	99.8%	$ 2,614	$ 1,095,098	99.8%
N4-RES1	5	3	$ 653,400	0.2164	92.8%	$ 47,132	$ 606,268	92.8%
N4-RES2	5	2.1	$ 457,380	0.01	99.5%	$ 2,178	$ 455,202	99.5%
N4-RES3	5	3	$ 653,400	3	0.0%	$ 653,400	$ -	0.0%
N4-RES4	8	6	$ 2,090,880	4.7	21.7%	$ 1,637,856	$ 453,024	21.7%
N4-RES5	6	7	$ 1,829,520	0.01	99.9%	$ 2,614	$ 1,826,906	99.9%
		31.30	$ 7,697,052	8.12	74.0%	$ 2,376,041	$ 5,321,011	69.1%

WATERSHED 5

				Final Iteration				
Pond/Node	Cost ($/ft^2)	Initial Size	Cost ($)	Size	Land Savings	Cost ($)	Savings ($)	Savings (%)
N5-10C	4	2.1	$ 365,904	0.01	99.5%	$ 1,742	$ 364,162	99.5%
N5-RES6	4	3	$ 522,720	0.01	99.7%	$ 1,742	$ 520,978	99.7%
		5.10	$ 888,624	0.02	99.6%	$ 3,485	$ 885,139	99.6%