Preventive Maintenance

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Mike Mills

Why is preventive maintenance important?

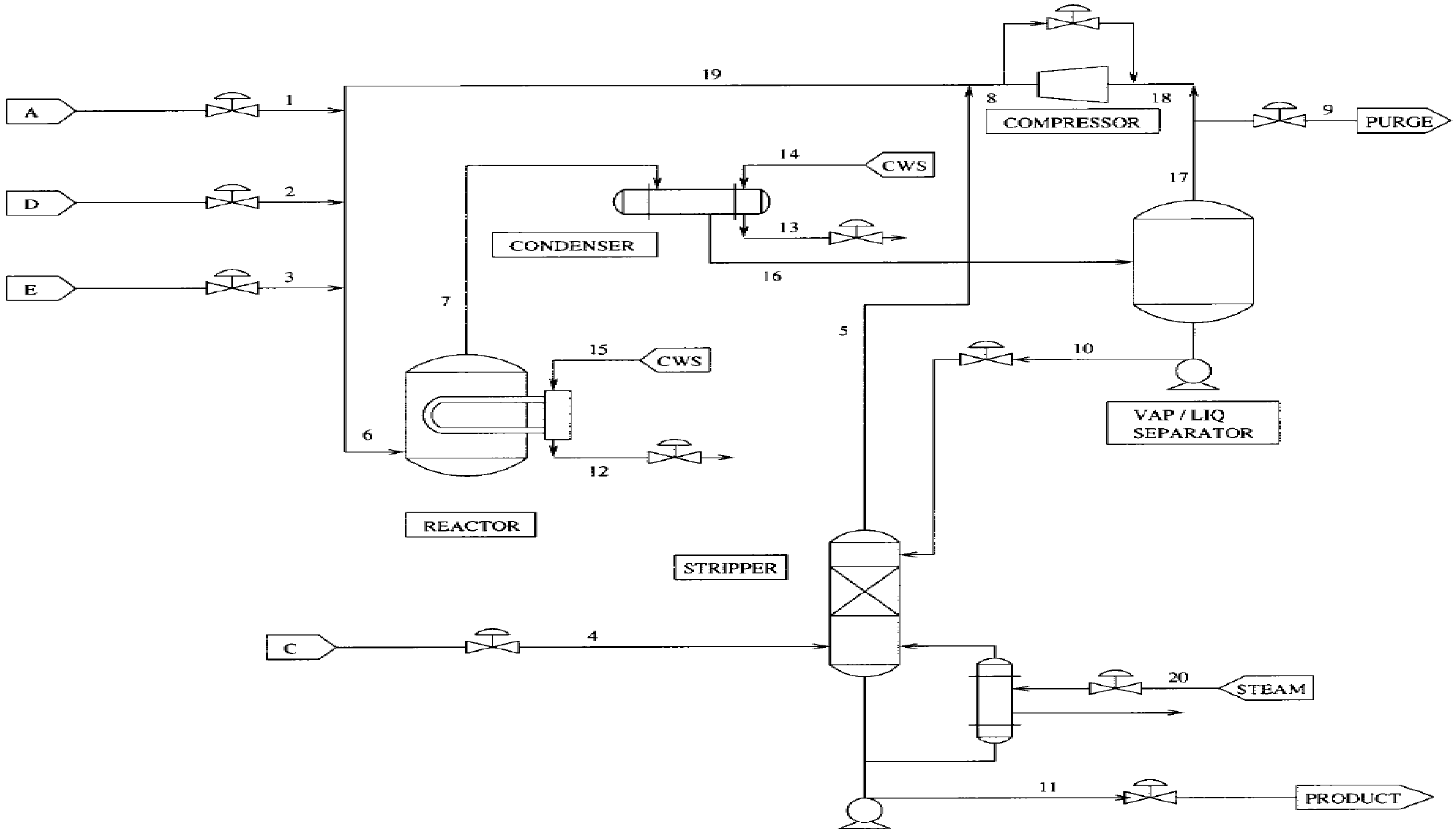
- Reduce equipment downtime
- Reduce environmental and workplace hazards

- To save money

Project overview

- Build preventive maintenance scheduler
  - Assess potential losses
  - Find frequency of failure
  - Determine optimal maintenance policy
- Assist in Data Formation and Collection
  - Fortran Program – Quang Nguyen
- Sample plant: Tennessee Eastman

Tennessee Eastman Process Plant



Theory

Maintenance types:

- Corrective (CM)
  - Event driven (repairs)
- Preventive (PM)
  - Time driven
  - Equipment driven
- Opportunistic

Equipment failure modes

- How does an equipment fail?
- Why does it fail?
- Preventive maintenance...

Equipment Data

- Equipment type
- Failure type
- Mean time between failure
- Time needed for CM
- Time needed for PM
- PM interval
- Economic loss
- CM cost
- PM cost
- Inventory cost

Equipment Types

- Valves
- Pumps
- Compressor
- Reactor
- Flash Drum
- Heat Exchangers
- Stripping Column

Failure Types

- Fatigue
- Corrosion
- Wear
- Overload
- Contamination
- Misalignment

NS2

Mean time between failure...

- Log of equipment for particular time period
- Literature / Assumptions-Probability

MTBF

Slide 10

NS2	Shouldn't this be MTBF??? Nico Simons, 4/13/2007

Failure frequency

Equation:

$$t = MTBF \cdot \ln\left(\frac{1}{1-P}\right)$$

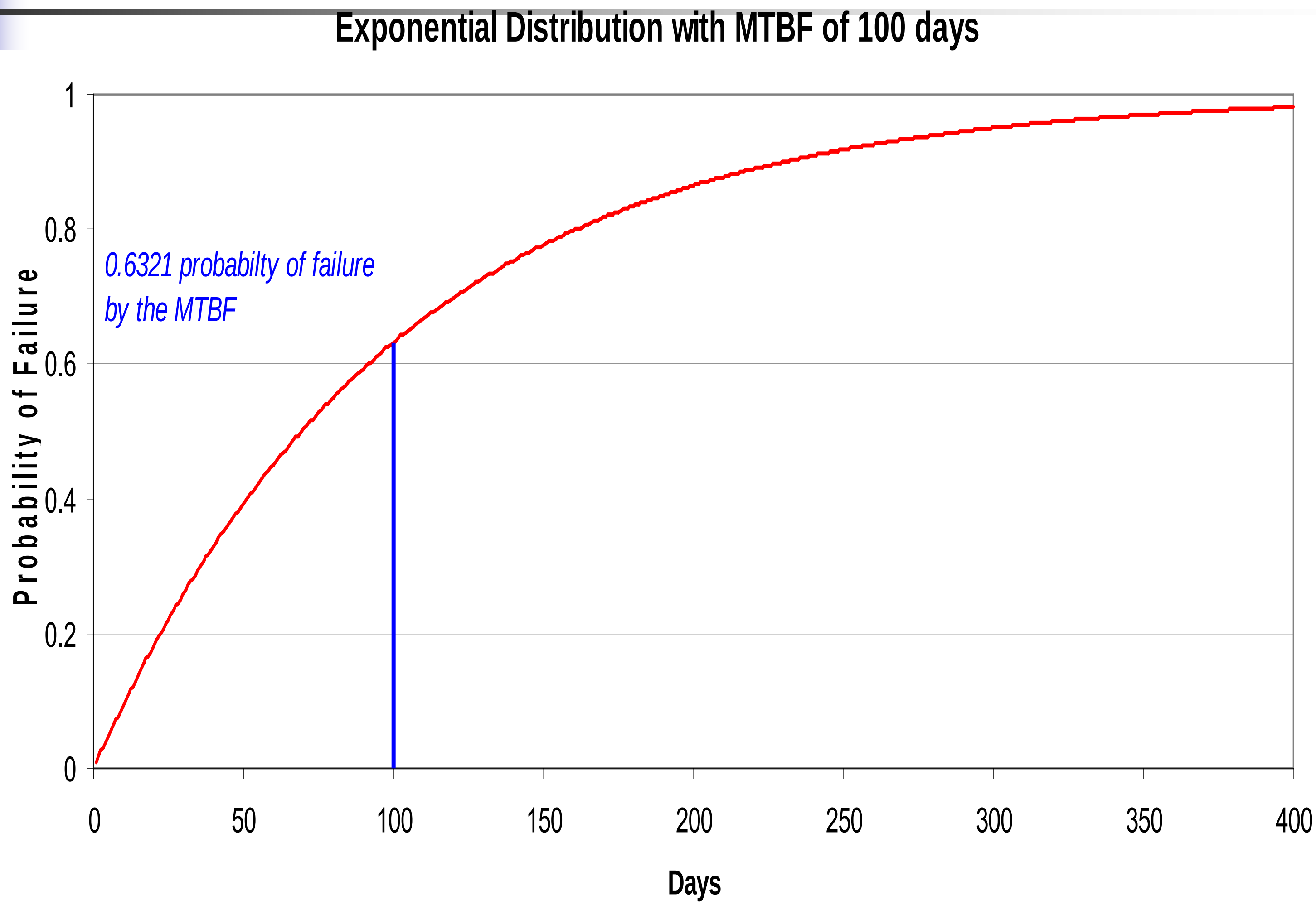
P = probability

t= time of failure

MTBF = mean time between failure

- Exponential distribution for all failures

Exponential distribution (graph)



Time Needed for CM & PM

- Why?
  - Calculating Labor Costs
  - Duration of Job
    - Scheduling

Preventative Maintenance Interval (PMI)

Based on MTBF

- High Frequency MTBF – Shorter PM Interval
- Low Frequency MTBF – Longer PM Interval

- Adjust to optimize cost
- Using a ratio of the MTBF

Economic Loss

- Losses occurred from reduced or halted process flows
- When CMs is performed
- Equipment with failure that has not been Repaired

CM Cost

- Economic Loss (EL)
- Labor Costs (LC)
- Inventory Cost (IC)

- CM = EL + LC + IC

PM Cost

- Economic Loss (EL)
- Labor Costs (LC)
- Inventory Cost (IC)
- PM Interval (PMI)

- PM = EL + LC + IC
  - Per PMI

Inventory Cost

- Inventory Cost – Opportunity Cost
  - $$IC = PC \cdot (1 + i)^{MTBF} - PC$$
    - PC = Parts Cost
    - i = Interest Rate for investing money
    - MTBF in years
    - Not Accounted for Currently

PM Scheduler/Model

- Monte Carlo Simulation
- Optimize occurrence of PMs
  - Taking in to account the distributions of failure
  - PMs cost < Amount saved
- Verify optimum with plots of total cost versus number of PMs

Monte Carlo Simulation

- Random Number Generation
  - Used to produce a random samples
  - Compile/Compute Data easily
  - Large sample size – represents system
  - Analyze the results
- Optimization
  - Change the parameters
  - Repeat the simulation

A Perfect Model

- Equipment Data control
  - Generate PM's automatically
  - Determines equipments importance
- Employee Management
  - # of Employee's based on Failures
  - Employee skill determines job selection
- Inventory Control and Management
- Detail Repair Cost for Each Job
- Repair Instructions

Design of First Simulation

- Familiar tools
- Excel
- @Risk

- Only six pieces of equipment

Excel Simulation!

Assumptions made:

- Unlimited resources
- Immediate detection of failure
- No PM down time
- Equipment failure ⟶ shut down
- Equipment restored to new

Input Values

- Mean time between failures
- Time needed for CM
- Time needed for PM
- Initial runtime of equipment
- PM interval
- PM cost
- Cost of repair
- Economic Loss

Excel Table

	Equipment Specs	Equipment Number	Name	ID Number	MTBF (hrs)	MTCM (hrs)	MTPM (hrs)	Runtime Star (hour)	PM (hrs)	PM Cost ($)	COF ($)	COD ($)/hr	Total Cost
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Simulation Process

During each hour for each piece of equipment:

1. Check current status of the equipment.
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21	0	21	3	0.67311809	0.312710721			2			1	0	0	8

Simulation Process

6. If runtime is greater than or equal to the time between PMs, mark equipment as PMed.
7. Determine equipment status.
8. If the equipment is still under repair or maintenance than decrement the downtime remaining.
9. Determine total downtime.

After simulation has run calculate total cost.

Excel Table

Equipment Specs	Equipment Number	Name	ID Number	MTBF (hrs)	MTCM (hrs)	MTPM (hrs)	Runtime Star (hour)	PM (hrs)	PM Cost ($)	COF ($)	COD ($)/hr	Total Cost
	1	Valve 1	V1	8	4	0	1	6	10	1000	606.6	$8,733,319

Number of Hours	Number of Days	Hour of the Day	Continous Runtime (hrs)	Generate Random Number	Failure Probability	Failed Y/N	Under Repair Y/N	Failure Count	PM Y/N	Under PM Y/N	PM Count	Downtime Remaining (hrs)	Total Downtime Remaining (hrs)	Total Hours of Downtime (hrs)
0	0	0	2	0.33333648	0.221199217			0			0	0	0	0
1	0	1	3	0.33333648	0.312710721			0			0	0	0	0
2	0	2	4	0.33333648	0.39346934	Yes	Yes	1			0	4	4	4
3	0	3	0	1	0		Yes	1			0	3	3	4
4	0	4	0	1	0		Yes	1			0	2	2	4
5	0	5	0	1	0		Yes	1			0	1	1	4
6	0	6	0	1	0			1			0	0	0	4
7	0	7	1	0.89994635	0.117503097			1			0	0	0	4
8	0	8	2	0.89994635	0.221199217			1			0	0	0	4
9	0	9	3	0.89994635	0.312710721			1			0	0	0	4
10	0	10	4	0.89994635	0.39346934			1			0	0	0	4
11	0	11	5	0.89994635	0.464738571			1			0	0	0	4
12	0	12	6	0.89994635	0.527633447			1	Yes	Yes	1	0	0	4
13	0	13	1	0.13051049	0.117503097			1			1	0	0	4
14	0	14	2	0.13051049	0.221199217	Yes	Yes	2			1	4	4	8
15	0	15	0	1	0		Yes	2			1	3	3	8
16	0	16	0	1	0		Yes	2			1	2	2	8
17	0	17	0	1	0		Yes	2			1	1	1	8
18	0	18	0	1	0			2			1	0	0	8
19	0	19	1	0.67311809	0.117503097			2			1	0	0	8
20	0	20	2	0.67311809	0.221199217			2			1	0	0	8
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0	0	0	2	0.33333648	0.221199217			0			0	0	0	0
1	0	1	3	0.33333648	0.312710721			0			0	0	0	0
2	0	2	4	0.33333648	0.39346934	Yes	Yes	1			0	4	4	4
3	0	3	0	1	0		Yes	1			0	3	3	4
4	0	4	0	1	0		Yes	1			0	2	2	4
5	0	5	0	1	0		Yes	1			0	1	1	4
6	0	6	0	1	0			1			0	0	0	4
7	0	7	1	0.89994635	0.117503097			1			0	0	0	4
8	0	8	2	0.89994635	0.221199217			1			0	0	0	4
9	0	9	3	0.89994635	0.312710721			1			0	0	0	4
10	0	10	4	0.89994635	0.39346934			1			0	0	0	4
11	0	11	5	0.89994635	0.464738571			1			0	0	0	4
12	0	12	6	0.89994635	0.527633447			1	Yes	Yes	1	0	0	4
13	0	13	1	0.13051049	0.117503097			1			1	0	0	4
14	0	14	2	0.13051049	0.221199217	Yes	Yes	2			1	4	4	8
15	0	15	0	1	0		Yes	2			1	3	3	8
16	0	16	0	1	0		Yes	2			1	2	2	8
17	0	17	0	1	0		Yes	2			1	1	1	8
18	0	18	0	1	0			2			1	0	0	8
19	0	19	1	0.67311809	0.117503097			2			1	0	0	8
20	0	20	2	0.67311809	0.221199217			2			1	0	0	8
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After simulation has run **calculate total cost.**

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Equipment Specs	Equipment Number	Name	ID Number	MTBF (hrs)	MTCM (hrs)	MTPM (hrs)	Runtime Star (hour)	PM (hrs)	PM Cost ($)	COF ($)	COD ($)/hr	Total Cost
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0	0	0	2	0.33333648	0.221199217			0			0	0	0	0
1	0	1	3	0.33333648	0.312710721			0			0	0	0	0
2	0	2	4	0.33333648	0.39346934	Yes	Yes	1			0	4	4	4
3	0	3	0	1	0		Yes	1			0	3	3	4
4	0	4	0	1	0		Yes	1			0	2	2	4
5	0	5	0	1	0		Yes	1			0	1	1	4
6	0	6	0	1	0			1			0	0	0	4
7	0	7	1	0.89994635	0.117503097			1			0	0	0	4
8	0	8	2	0.89994635	0.221199217			1			0	0	0	4
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10	0	10	4	0.89994635	0.39346934			1			0	0	0	4
11	0	11	5	0.89994635	0.464738571			1			0	0	0	4
12	0	12	6	0.89994635	0.527633447			1	Yes	Yes	1	0	0	4
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14	0	14	2	0.13051049	0.221199217	Yes	Yes	2			1	4	4	8
15	0	15	0	1	0		Yes	2			1	3	3	8
16	0	16	0	1	0		Yes	2			1	2	2	8
17	0	17	0	1	0		Yes	2			1	1	1	8
18	0	18	0	1	0			2			1	0	0	8
19	0	19	1	0.67311809	0.117503097			2			1	0	0	8
20	0	20	2	0.67311809	0.221199217			2			1	0	0	8
21	0	21	3	0.67311809	0.312710721			2			1	0	0	8

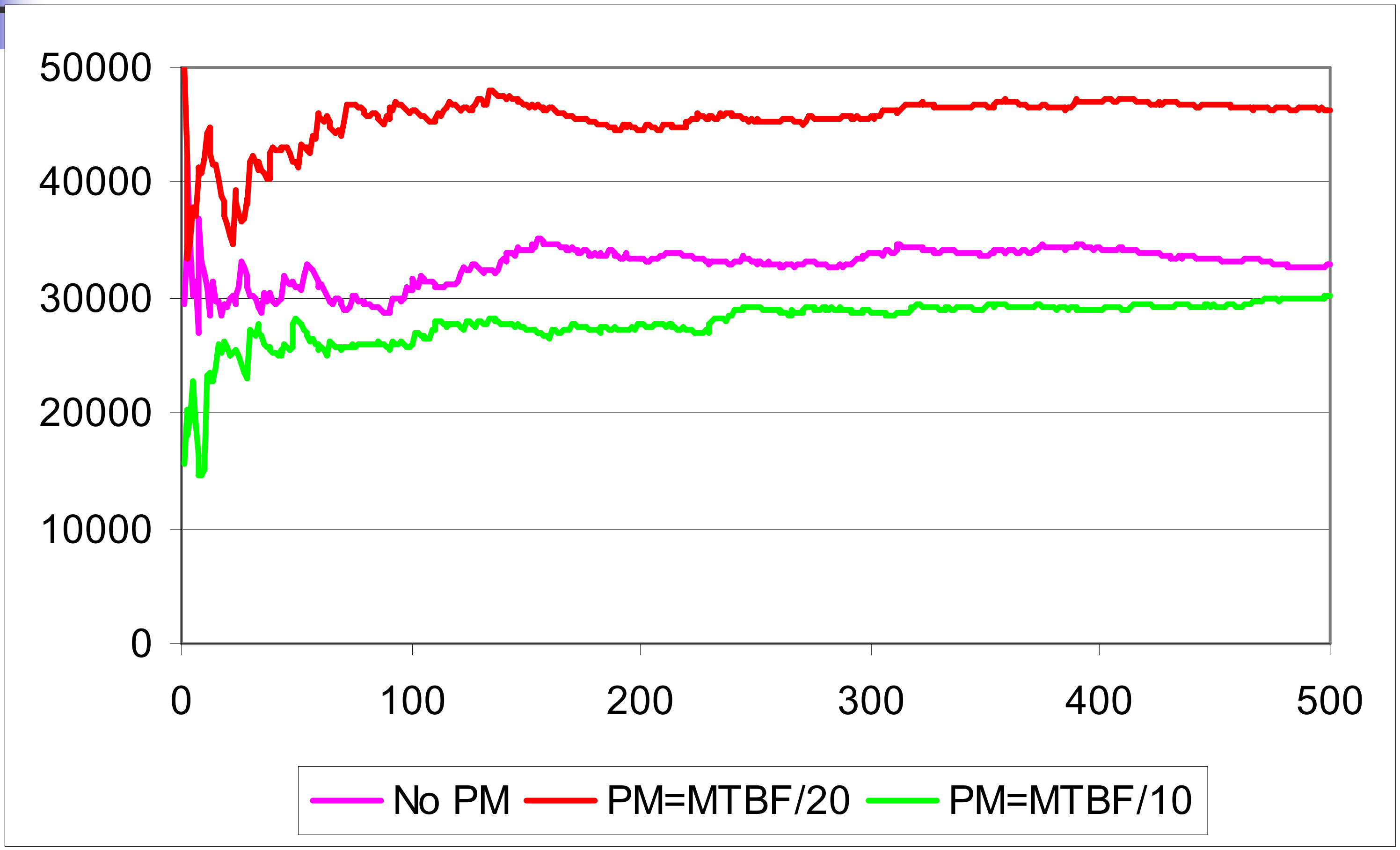
Running the Simulation

- Enter the equipment specifications
- Use @RISK and optimize values manually
- ... or use RISKOptimizer to optimize automatically
- Would be best to optimize one piece of equipment at a time

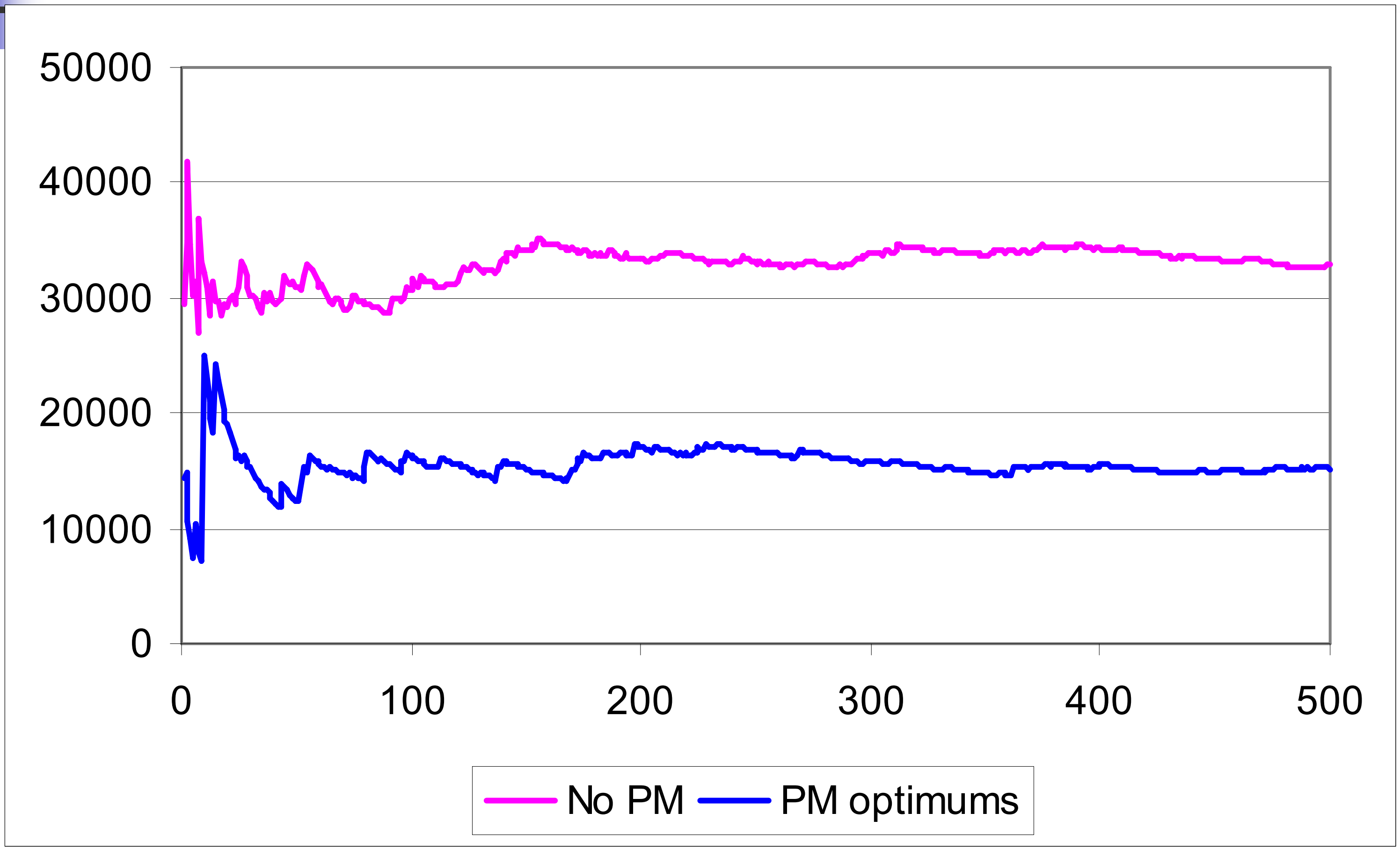
Methods

- Rough Estimates
- Determine Number of Samples Needed
- All PMs adjusted by common factor of each equipment's MTBF.
- From this rough optimum each PM is then optimized individually

Results – Rough Optimums



Results – Overall Optimums



Results Summary

- Average total cost using MTBF factor
  - No PMs – $32,883
  - MTBF/10 – $30,203
  - MTBF/20 – $46,373
- Individual PM optimums – $15,197
  - 3 valves – 8 PMs / year for each
  - Stripping column – <1 PM / year
  - Heat exchanger – 6 PMs / year
  - Pump – 22 PMs / year

Advantages of Excel Simulation

- Easy to see how the simulation works
- Detailed analysis of results via @Risk
- Automatic optimization via @Risk

Limitations of Excel Simulation

- Number of cells in a worksheet
- No labor limitation considerations
- No failure types or priorities
- Difficult to add advanced features
- Computation time
- Computation time
- Computation time

Switched to Fortran Program

- No limit on number of equipment
  - 7 types, 19 pieces (Piping not considered)
- Addition of labor limitations
  - To an extent (Salary)
- Multiple failure types and priorities
- Easier to add more advanced features
- <u>Significantly</u> faster than Excel

Rules

1. Repair is classified by priority

2. Categories are described by the time one can afford before there is an unacceptable loss

3. Preventive maintenance is scheduled at regularly recurring intervals

Rules

4. If corrective maintenance occurred before schedule PM, PM is suspended.
5. Each week corrective maintenance actions schedule is planned ahead
6. Preventive maintenance on all major equipment is performed at downtime to minimize downtime

Rules

7. Opportunistic maintenance, equipment dependencies, and delayed detection of failure are not considered
8. If there is an online backup of a piece of equipment determine the rules for when to switch to it

Priority Categories

- Priority categories are established using a double entry matrix

	Consequence of failure		
Probability of subsequent catastrophic failure	High	Medium	Low
High	1	2	3
Medium	2	3	4
Low	3	4	5

Levels of Failures for Maintenance Concerns (following Tischuk , 2002)

Priority Categories

- Probability of subsequent catastrophic failure is based on how often a failure is expected to occur
- Consequences of failures is based on production loss, environmental hazards, and workplace safety all of which are ultimately associated with revenue

Equipment Data Determinations

- Mean time between failure
- Time needed for CM
- Time needed for PM
- PM interval
- Economic loss
- CM cost
- PM cost
- Priority

MTBF

- Base on Average MTBF for type of equipment
  - Higher Probability – Smaller MTBF
  - Lower Probability – Larger MTBF

Time Needed for CM & PM

- CM
  - Assumption Based
    - Type of CM for each piece of equipment
- PM
  - Assumption Based
    - Type of PM for each piece of equipment
  - Safety work permits & simplicity of work

PMI

- Ratio of MTBF
  - ½ MTBF → 1/80 MTBF
    - Were Tested for Optimization
- Done with an infinite work for at no cost.

Economic Loss

- During CM - Cost per time
  - Based on Equipment Importance
- Un-repaired Equipment
  - Was 0.1% of the EL occurred during CM
- Cost per time x time = Economic loss

CM & PM Cost

- CM Cost
  - Simply Cost of the Equipment
- PM Cost
  - Based on the Type of Equipment
    - Lubrication
    - Cleaning a Compressor impeller so vibrations will be minimized

Priority

- Used for planning
  - CM completed from Priority 1 → 5
  - PM completed after CM from Priority 1 → 5
- Delays
  - CM is completed at the first of the next week
  - PM is rescheduled for exactly seven days later

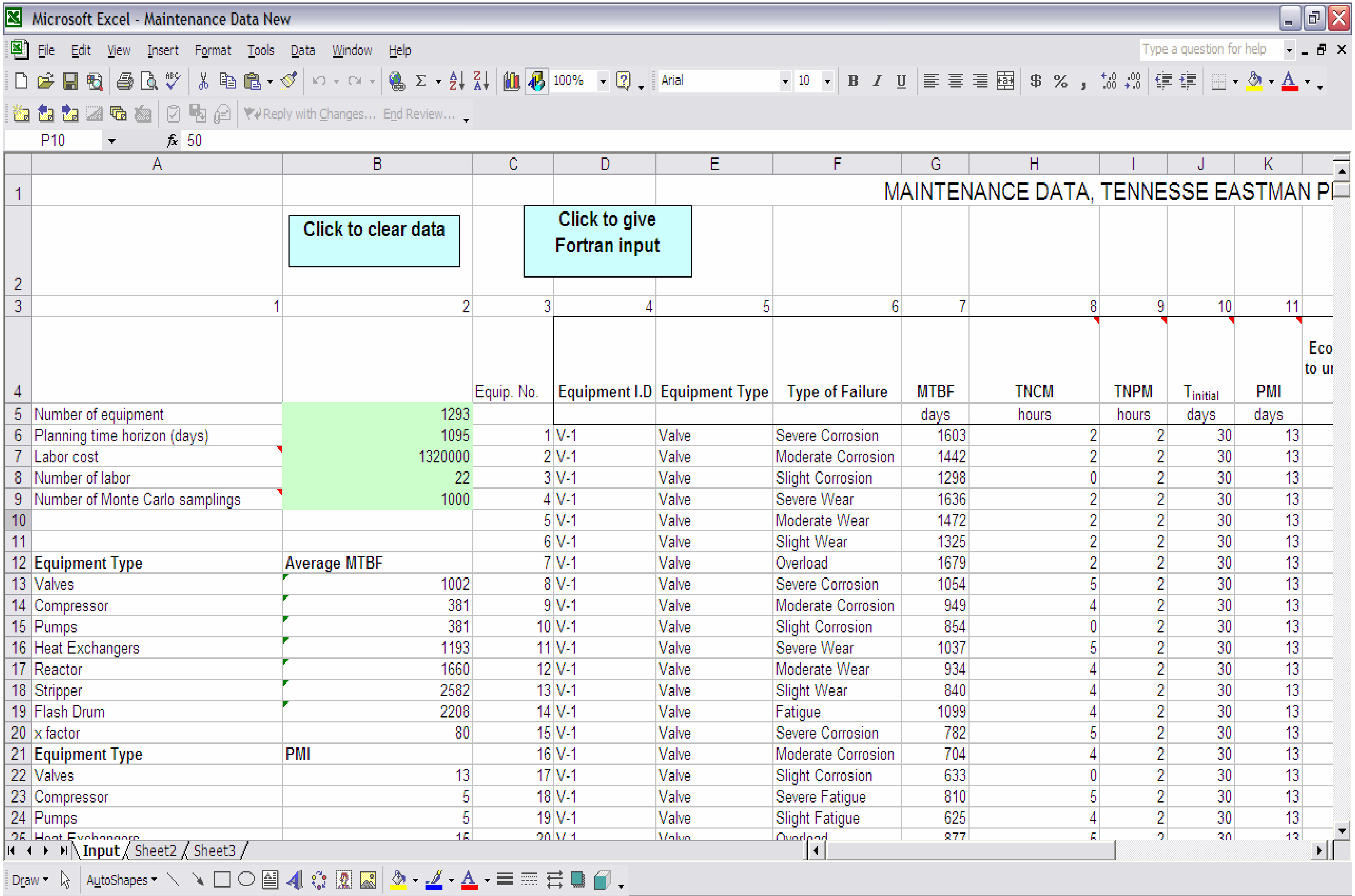
Priority (cont'd)

- If CM performed on equipment, next PM is ignored

- If CM is delayed more than 21 days, it is upgraded one level.

- After CM equipment is good-as-new.

Equipment Failure Spreadsheet



	A	B	C	D	E	F	G	H	I	J	K	
3	1	2	3	4	5	6	7	8	9	10	11	
4			Equip. No.	Equipment I.D	Equipment Type	Type of Failure	MTBF	TNCM	TNPM	$T_{initial}$	PMI	Eco to u
5	Number of equipment	1293					days	hours	hours	days	days	
6	Planning time horizon (days)	1095	1	V-1	Valve	Severe Corrosion	1603	2	2	30	13	
7	Labor cost	1320000	2	V-1	Valve	Moderate Corrosion	1442	2	2	30	13	
8	Number of labor	22	3	V-1	Valve	Slight Corrosion	1298	0	2	30	13	
9	Number of Monte Carlo samplings	1000	4	V-1	Valve	Severe Wear	1636	2	2	30	13	
10			5	V-1	Valve	Moderate Wear	1472	2	2	30	13	
11			6	V-1	Valve	Slight Wear	1325	2	2	30	13	
12	**Equipment Type**	**Average MTBF**	7	V-1	Valve	Overload	1679	2	2	30	13	
13	Valves	1002	8	V-1	Valve	Severe Corrosion	1054	5	2	30	13	
14	Compressor	381	9	V-1	Valve	Moderate Corrosion	949	4	2	30	13	
15	Pumps	381	10	V-1	Valve	Slight Corrosion	854	0	2	30	13	
16	Heat Exchangers	1193	11	V-1	Valve	Severe Wear	1037	5	2	30	13	
17	Reactor	1660	12	V-1	Valve	Moderate Wear	934	4	2	30	13	
18	Stripper	2582	13	V-1	Valve	Slight Wear	840	4	2	30	13	
19	Flash Drum	2208	14	V-1	Valve	Fatigue	1099	4	2	30	13	
20	x factor	80	15	V-1	Valve	Severe Corrosion	782	5	2	30	13	
21	**Equipment Type**	**PMI**	16	V-1	Valve	Moderate Corrosion	704	4	2	30	13	
22	Valves	13	17	V-1	Valve	Slight Corrosion	633	0	2	30	13	
23	Compressor	5	18	V-1	Valve	Severe Fatigue	810	5	2	30	13	
24	Pumps	5	19	V-1	Valve	Slight Fatigue	625	4	2	30	13	
25	Heat Exchangers	15	20	V-1	Valve	Overload	877	5	2	30	13	

Fortran Model

- CM Model
  - Without Resource Limitations
  - Resource Limitation
    - Number of Workers

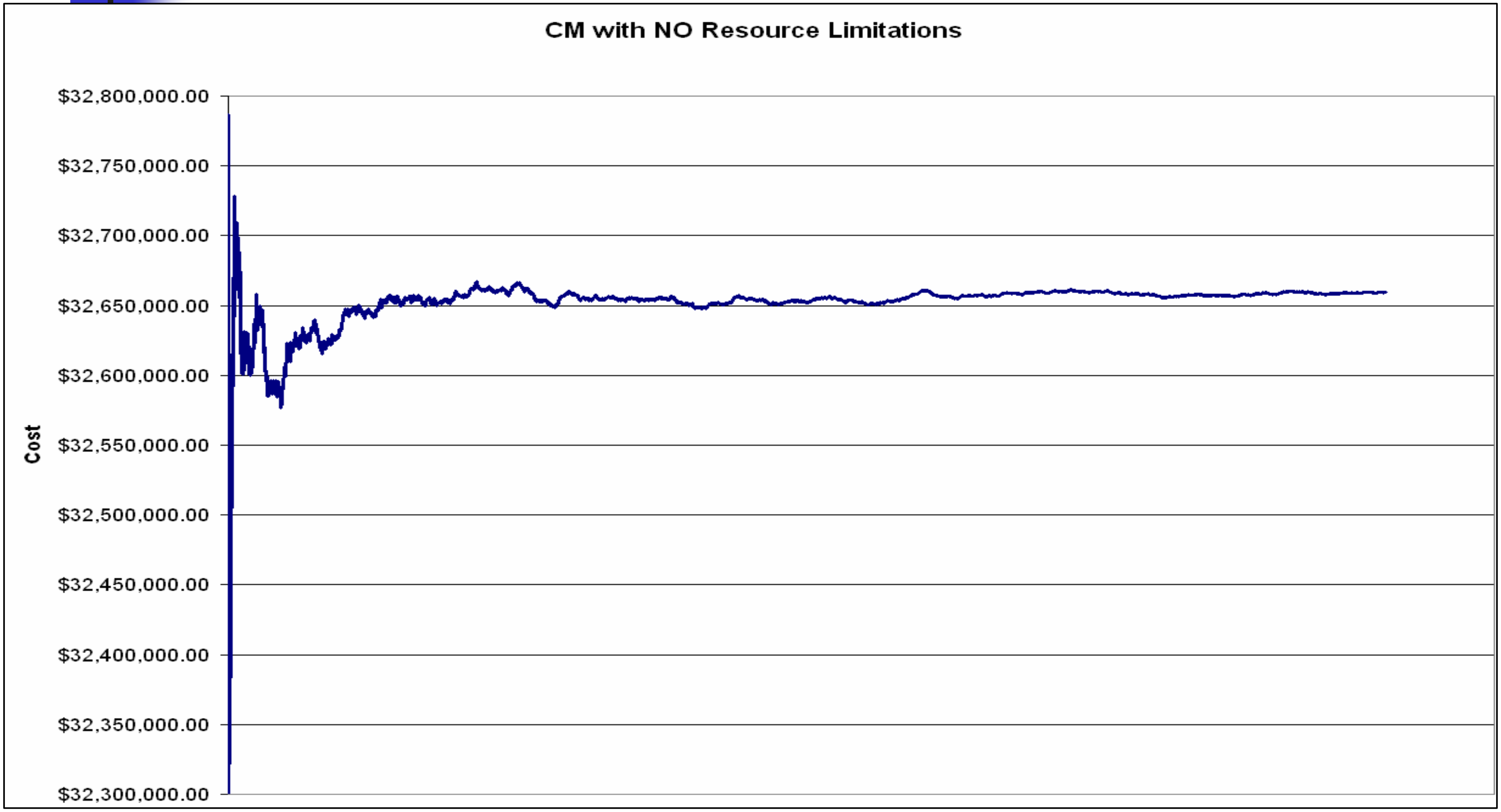
- CM & PM Model
  - Optimize
    - PMI
    - Number of Workers

- Will be analyzed at 1 & 3 years

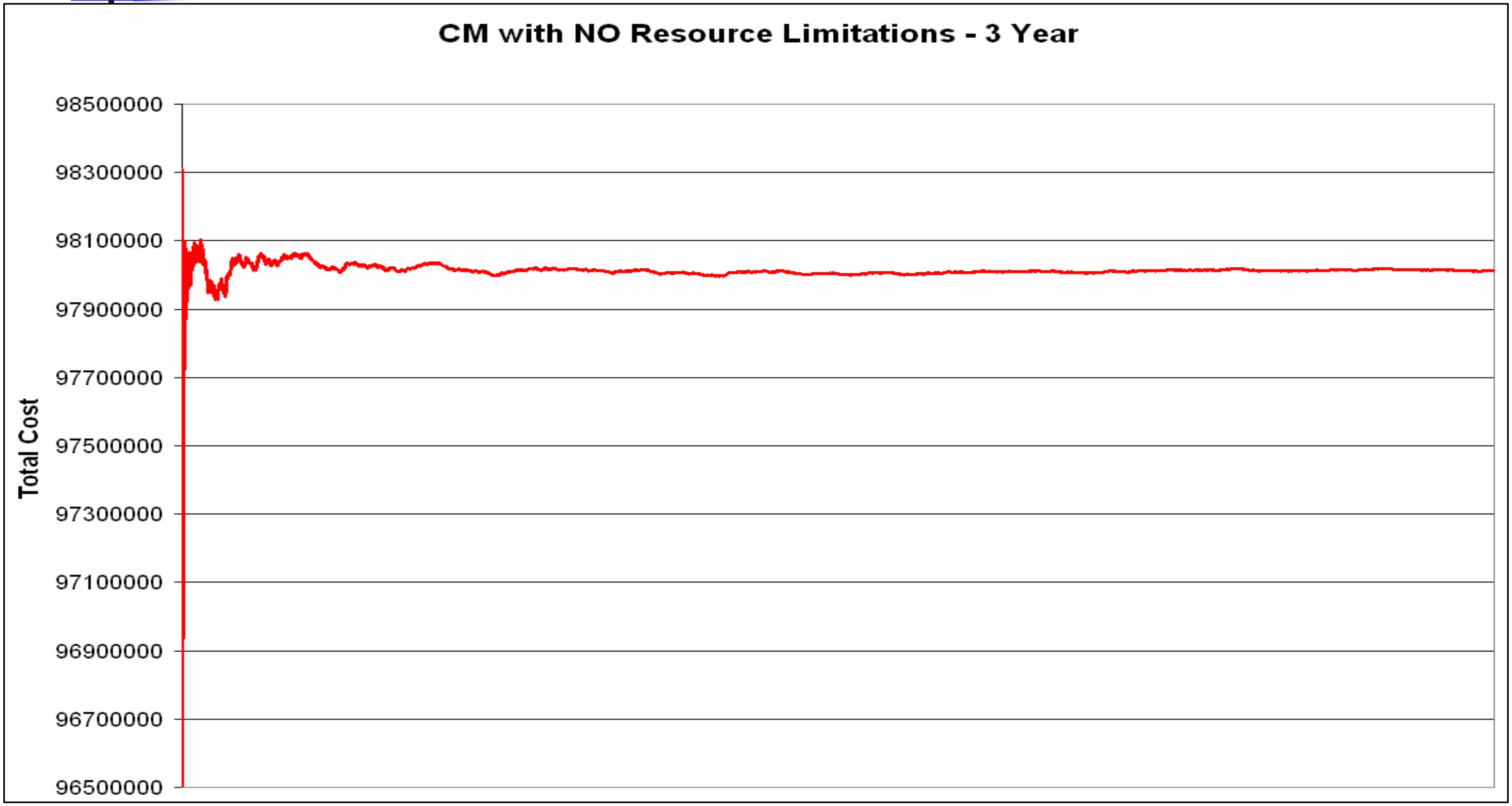
Fortran Model

- Does Not Consider...
  - Inventory Cost or Parts Available
  - Cost on an hourly/job basis
  - Employee Management
    - Which Job working
    - Employees are on Salary

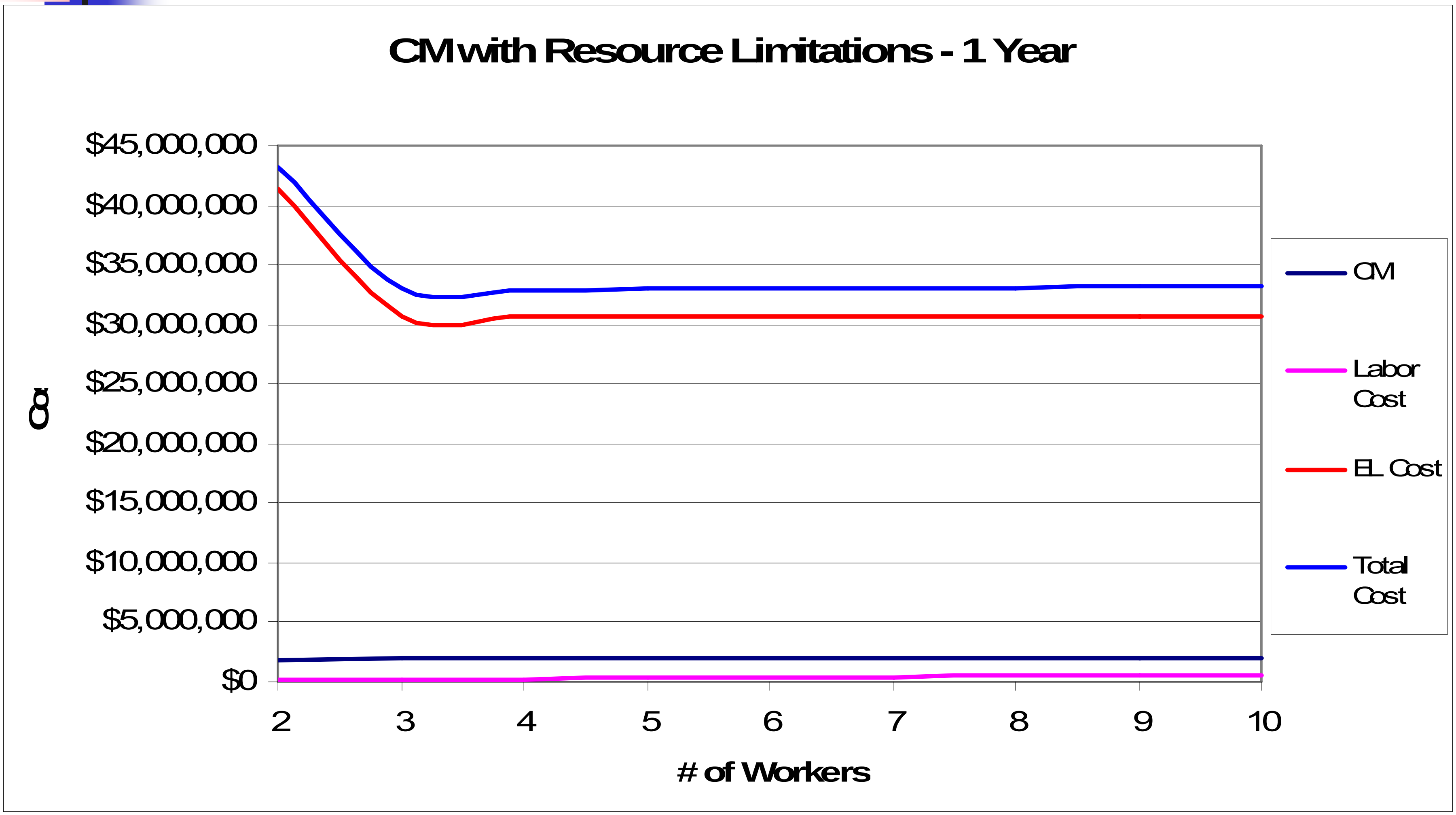
1 Year CM Model
No Resource Limitations



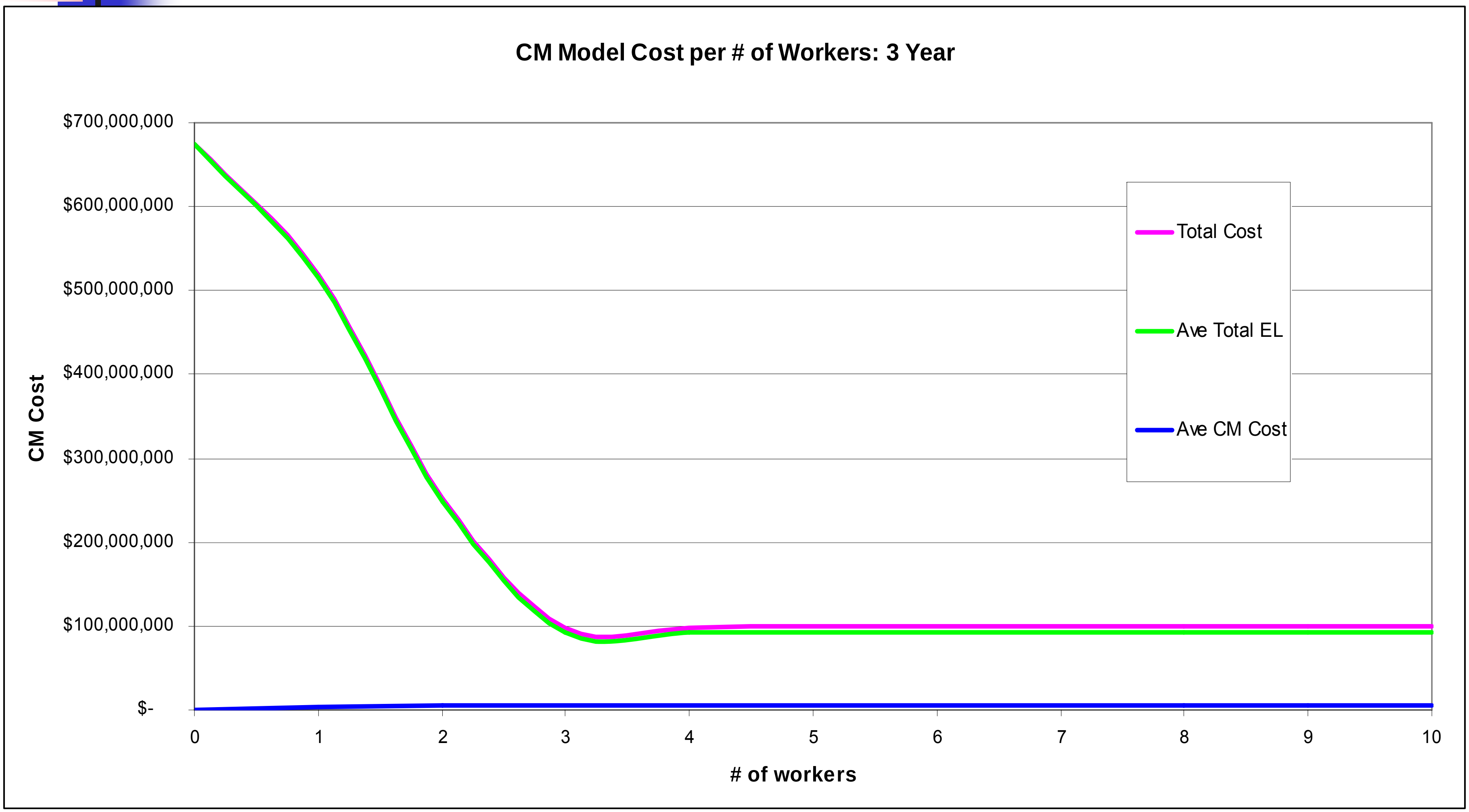
3 Year CM Model
No Resource Limitations



1 Year CM Model With Resource Limitations



3 Year CM Model With Resource Limitations



Comparison of the CM Models

	CM Models		
Years	Model	# of Workers	Total Cost
1	CM Model - No Resource Limitations	Infinite	$32,670,224
1	CM Model - With Resource Limitations	4	$32,892,092
3	CM Model - No Resource Limitations	Infinite	$98,026,767
3	CM Model - With Resource Limitations	3	$98,657,573

- 1 Year Difference $221,868
- 3 Year Difference $630,806

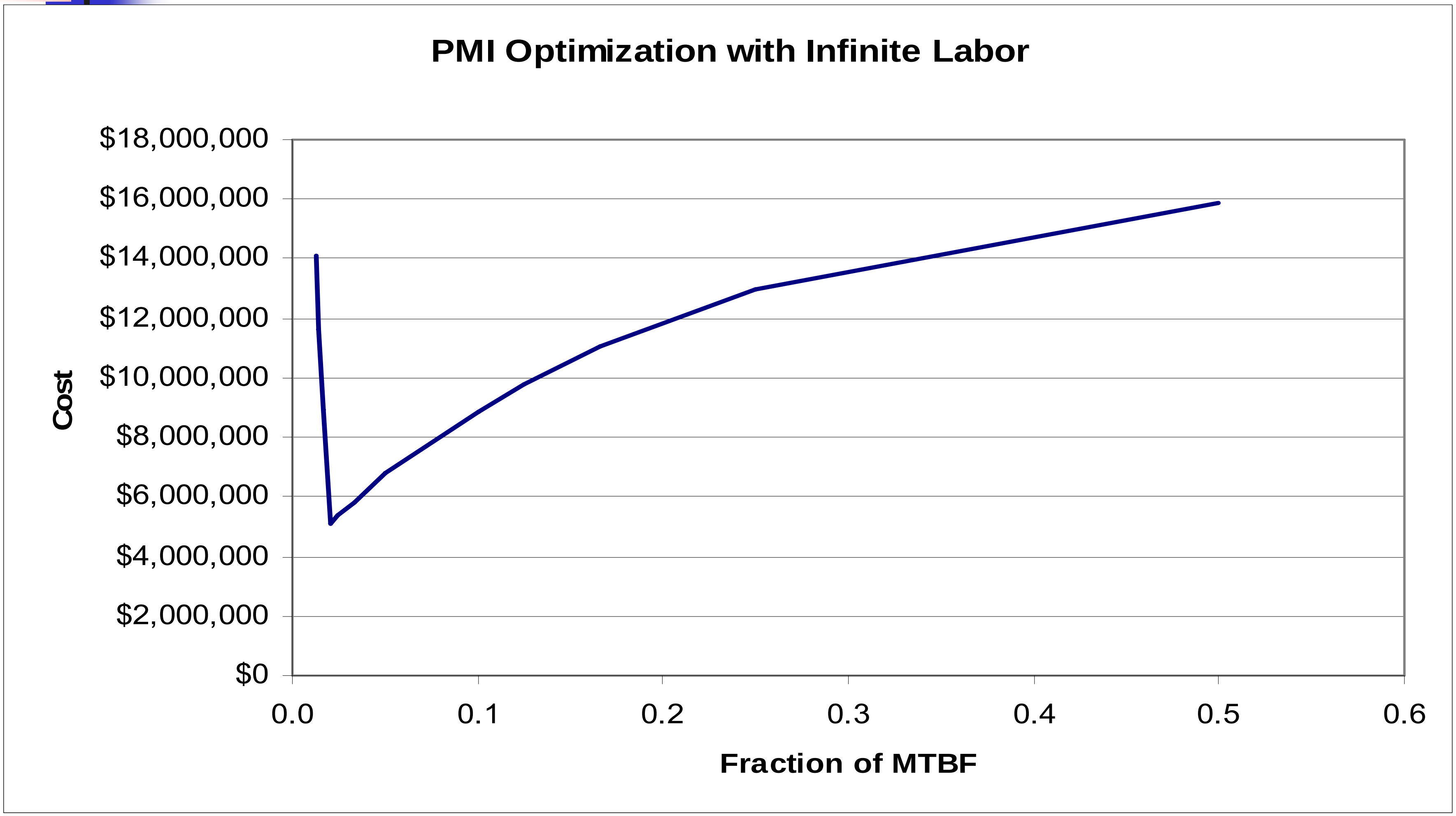
CM & PM Model – PMI optimization

- Use of Infinite Labor
  - No Labor Cost

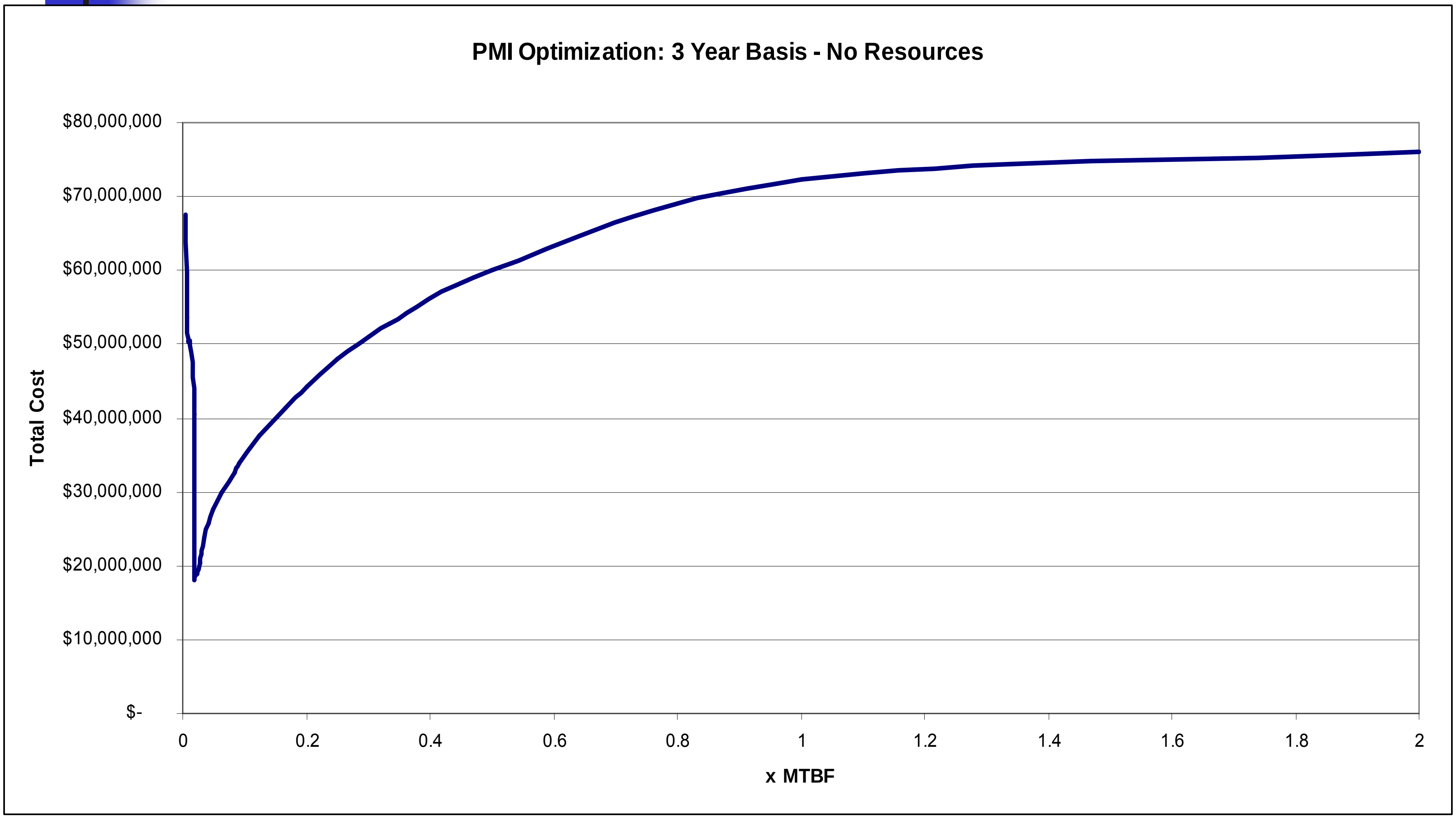
- Ran Model with PMI Ranges
  - Ranging from ½ → 1/80 the MTBF

- Low Cost??

PMI optimization – 1 Year



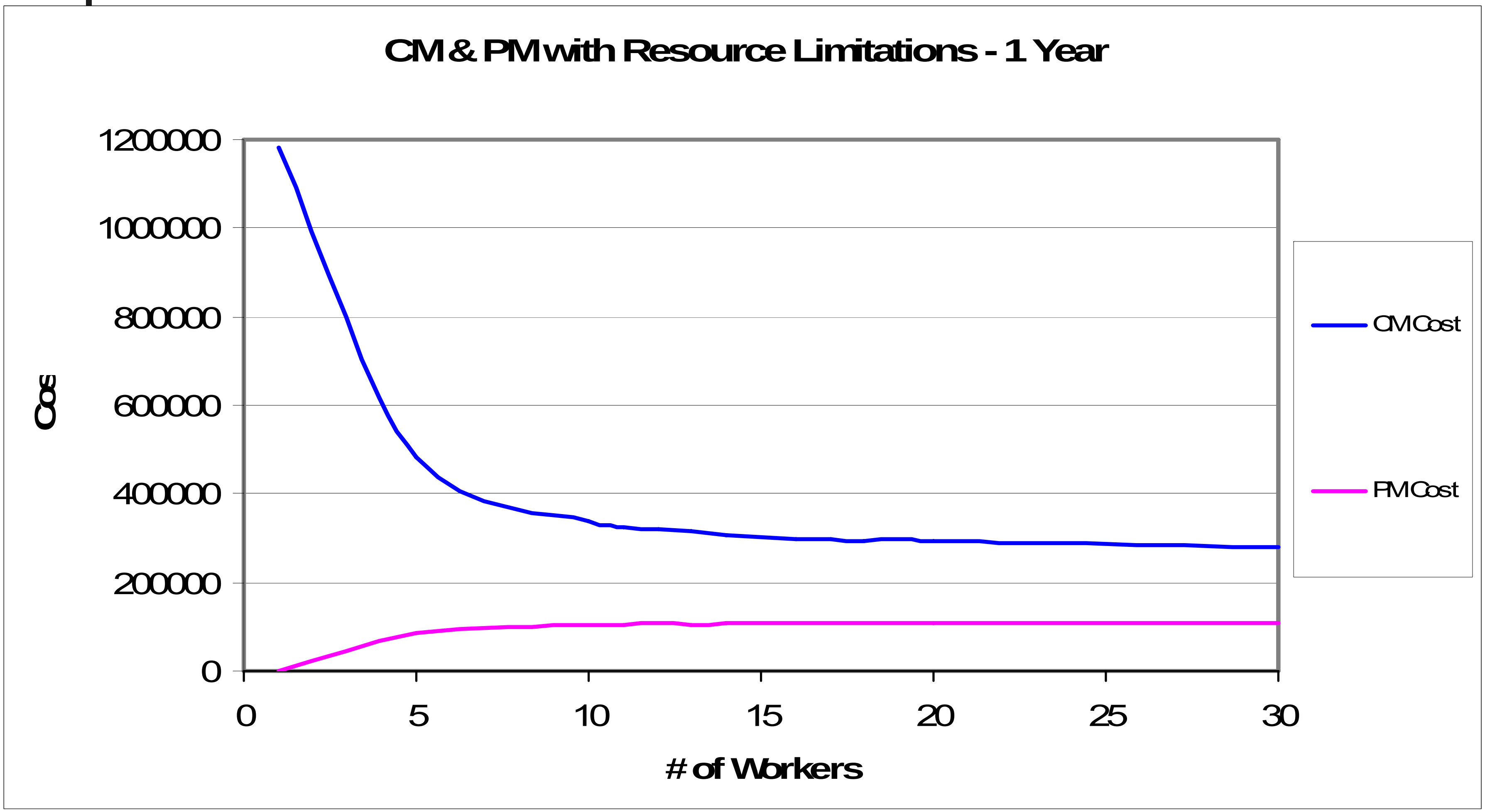
PMI optimization – 3 Year



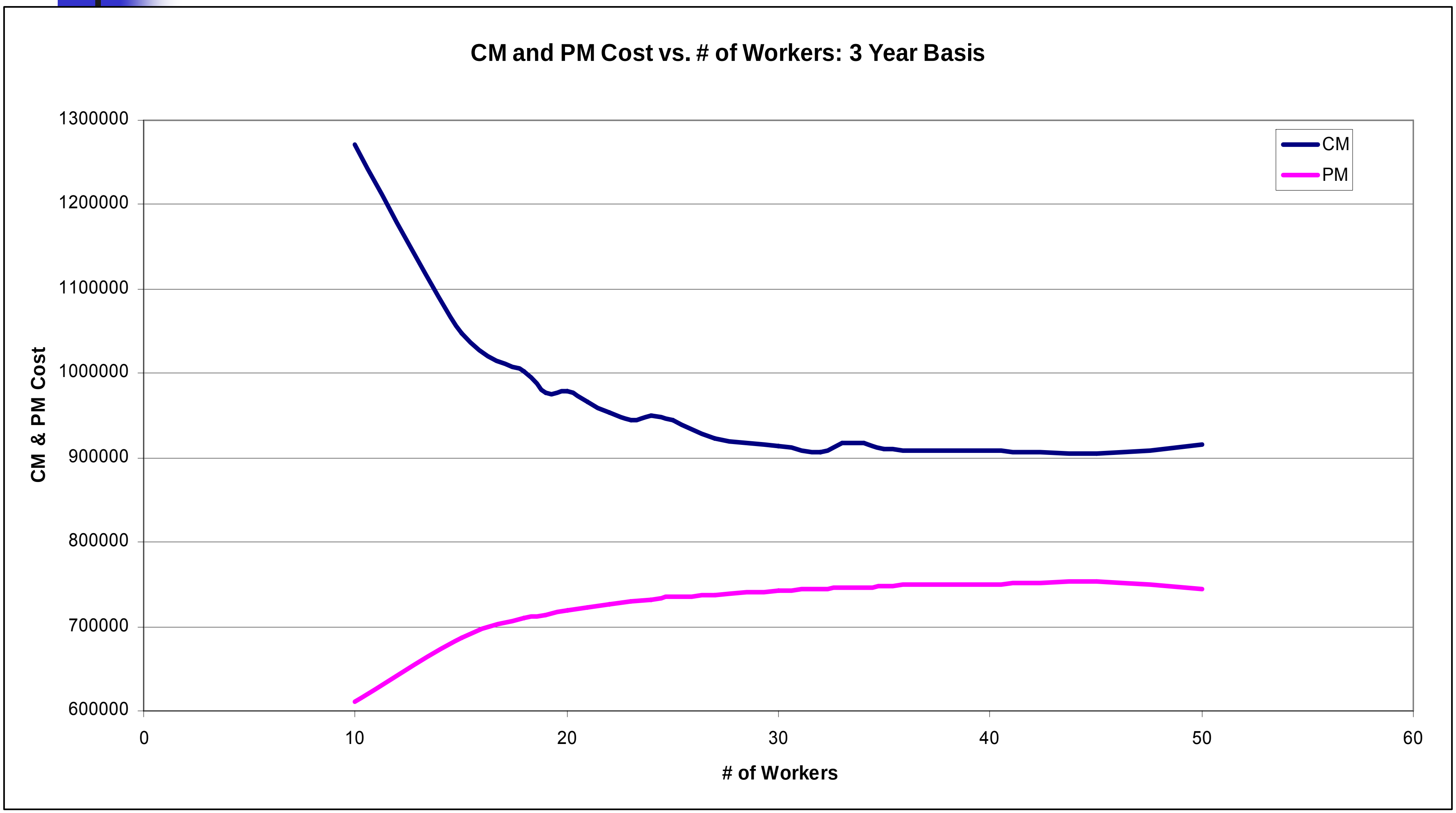
Workforce Optimization
CM & PM Model

- Use the Optimal PMI Found
- Vary the number of workers
- Low Costs??

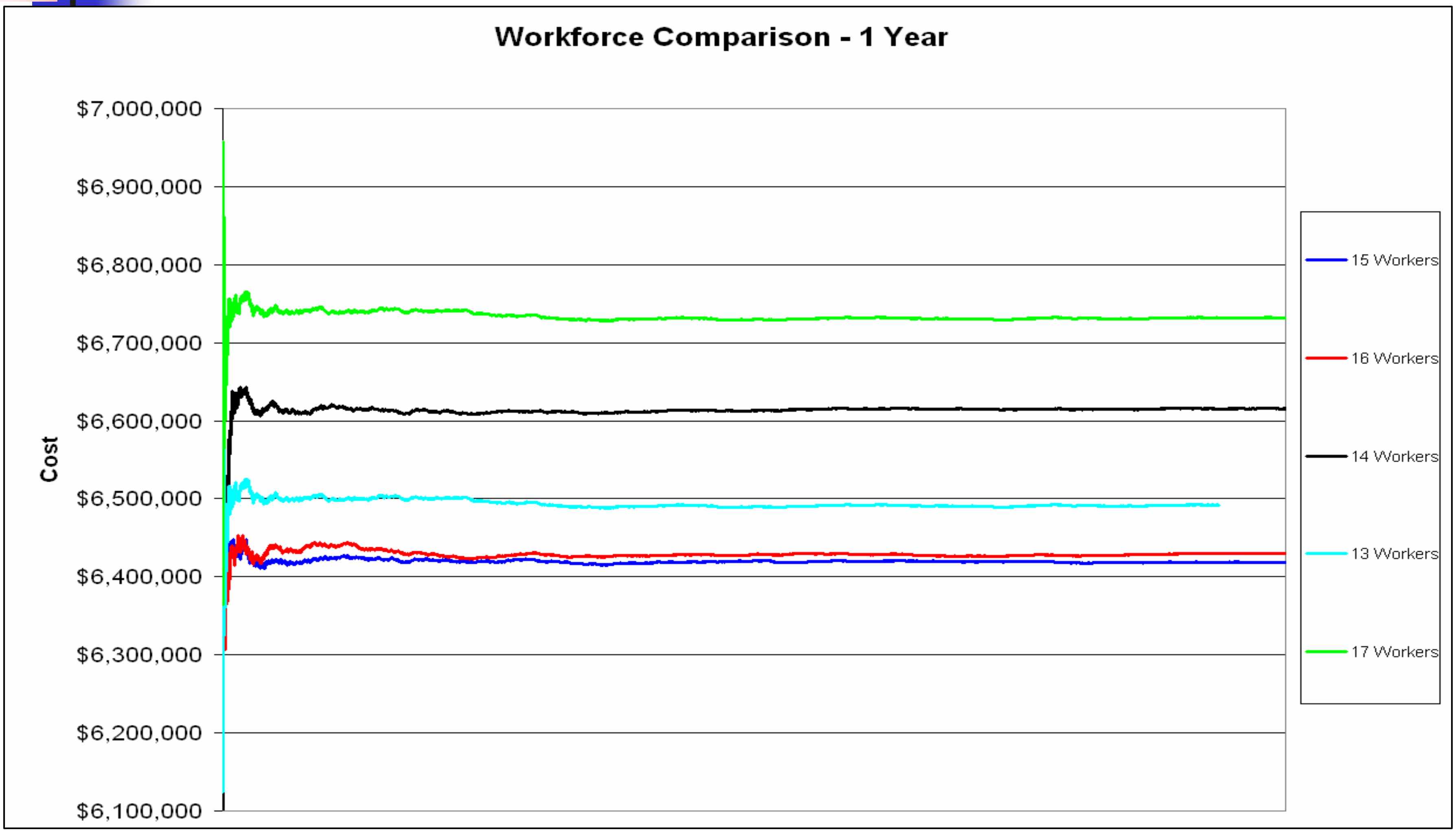
CM & PM Model (1-Year)
CM, EL, PM, & Total Costs



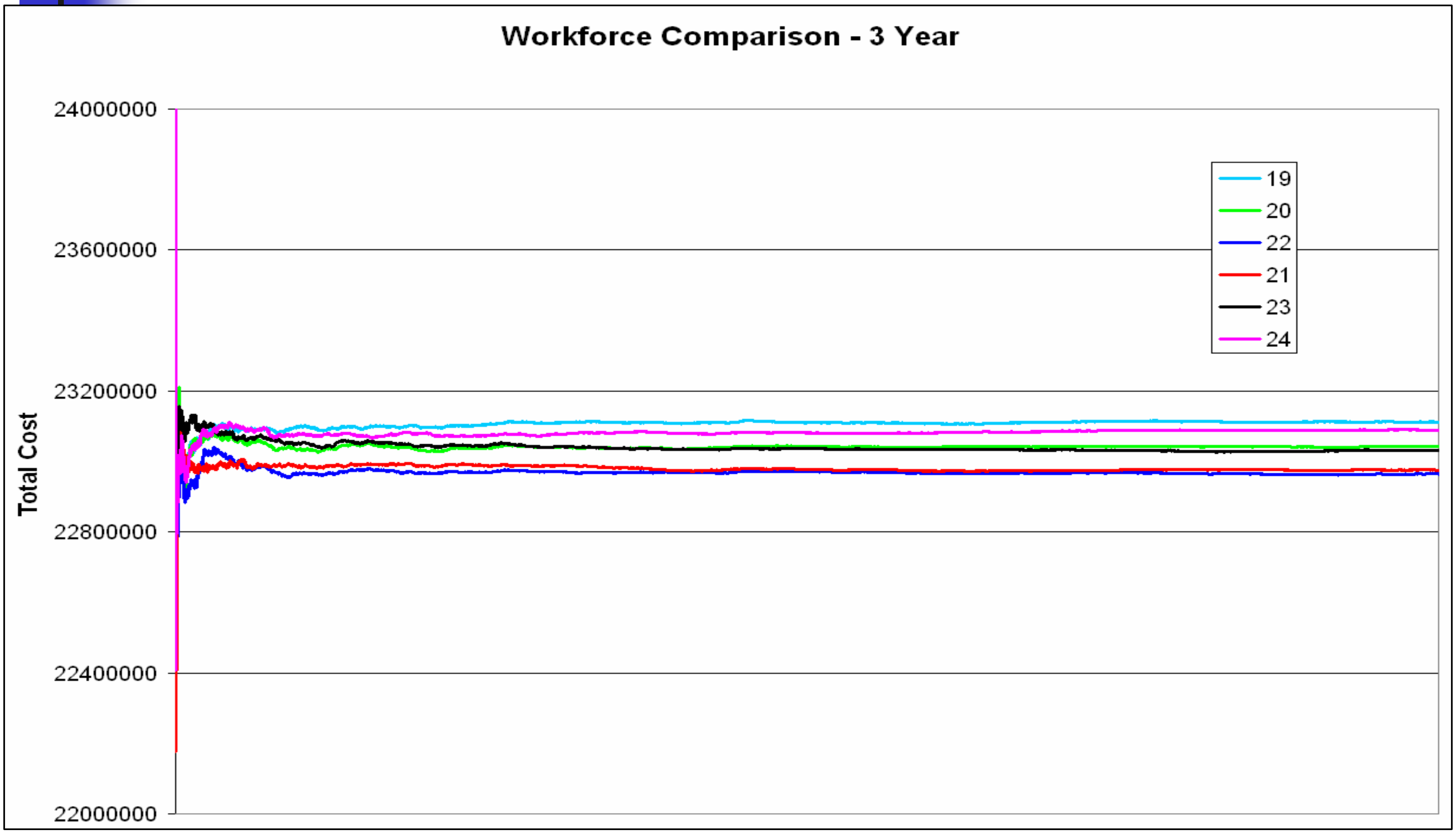
CM & PM Model (3-Year)
CM, EL, PM, & Total Costs



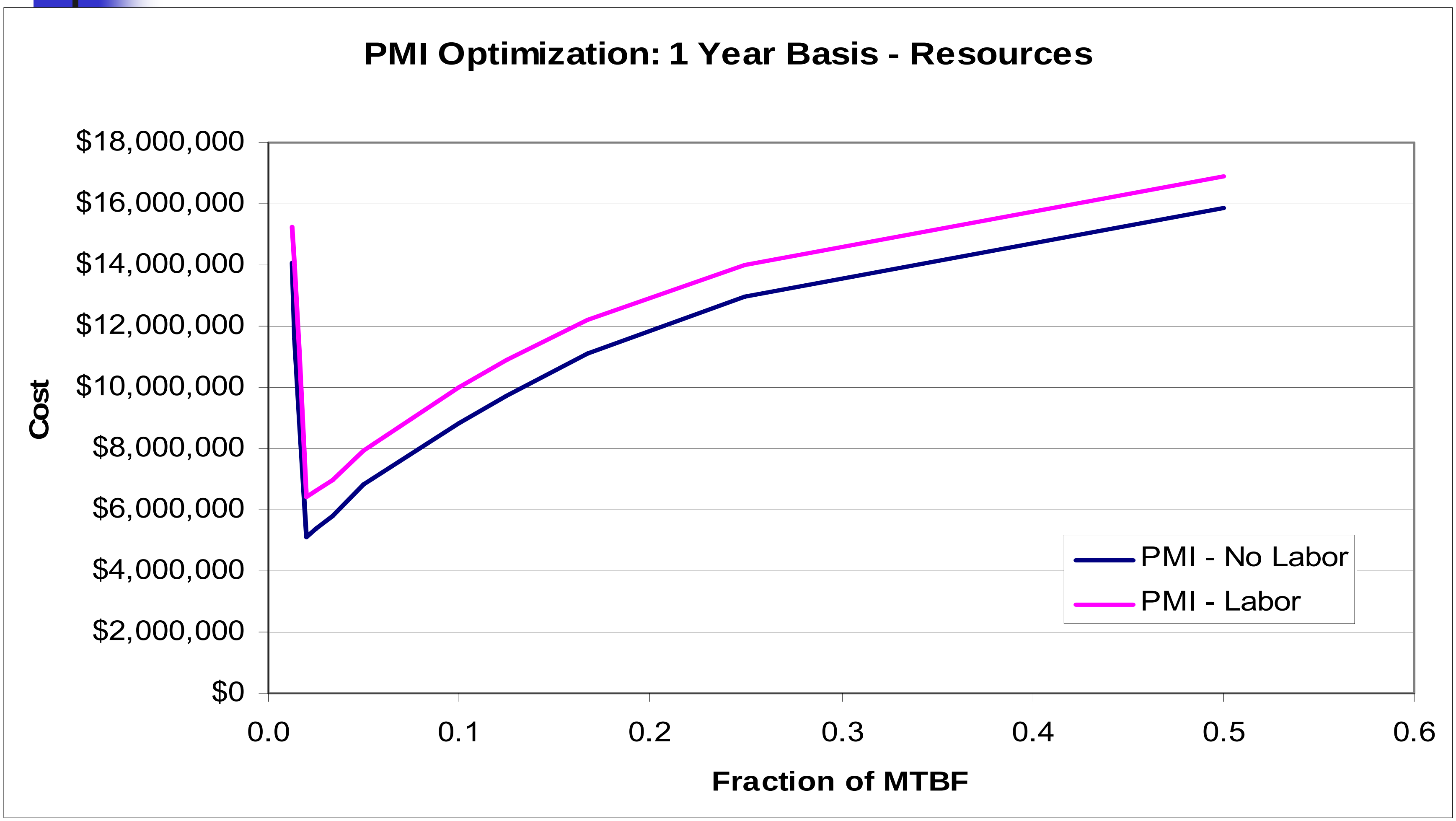
Verification of Number of Workers PM & CM Model (1 Year)



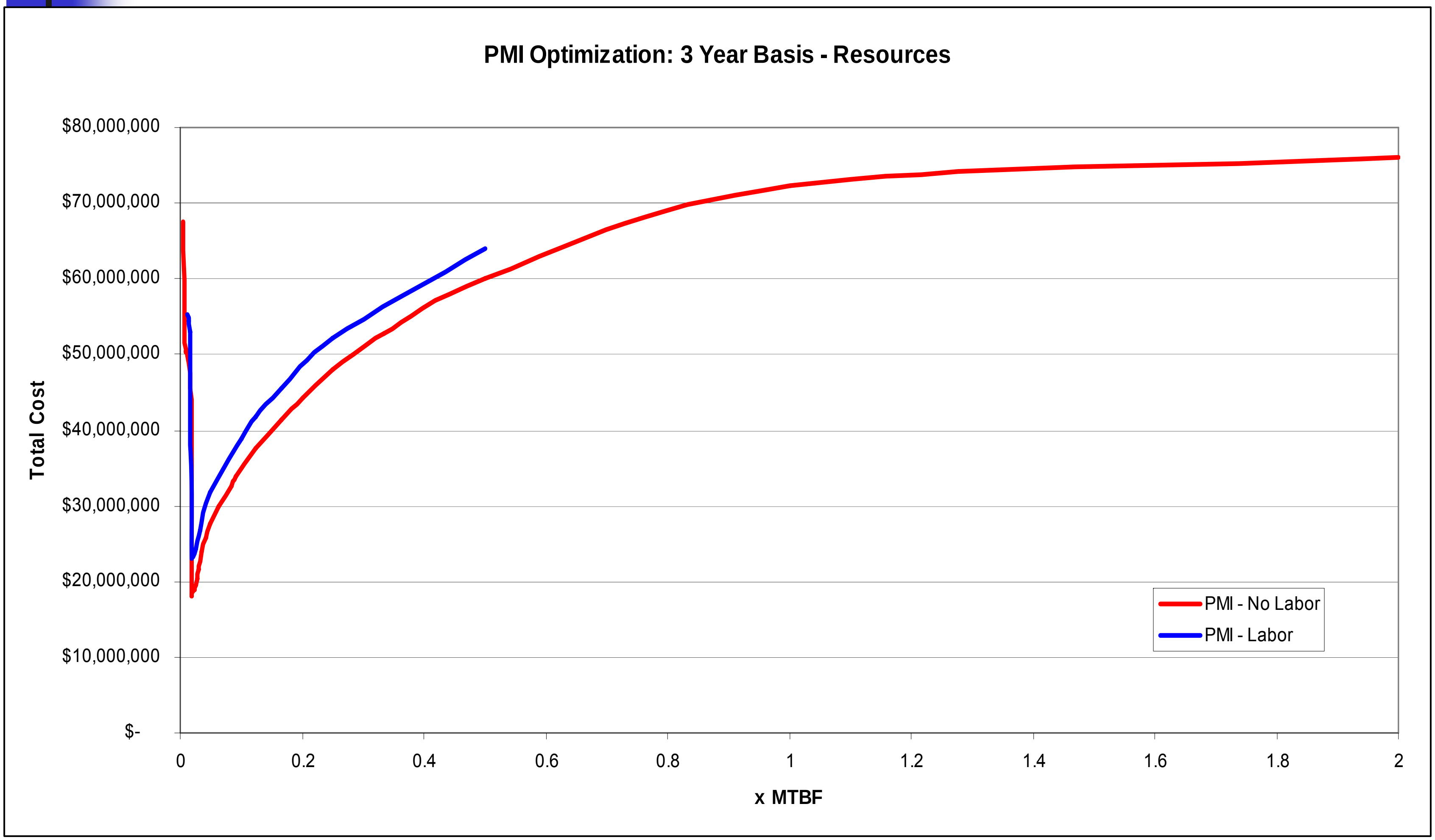
Verification of Number of Workers PM & CM Model (3 Year)



Does the PMI change based on a different work force?



Does the PMI change based on a different work force?



Model Comparison

	All Models		
Years	Model	# of Workers	Total Cost
1	CM Model - No Resource Limitations	Infinite	$32,670,224
1	CM Model - With Resource Limitations	4	$32,892,092
1	PM & CM Model	15	$6,421,160
3	CM Model - No Resource Limitations	Infinite	$98,026,767
3	CM Model - With Resource Limitations	3	$98,657,573
3	PM & CM Model	22	$23,027,813

- 1 Year Saving using PM Model
  - $26,470,932
- 3 Year Savings using PM Model
  - $75,629,760

Conclusions

- Easy to see PM significantly reduces Cost
  - Best CM Model vs. PM & CM Model
    - Savings of $26.5 million for 1 year
    - Savings of $75.6 millions for 3 year

- Improvements

Questions?

REFERENCES:

- Guidelines for process equipment reliability data with data tables. American Institute of Chemical Engineers. 1989.
- Guidelines for Design Solutions for Process Equipment Failures. American Institute of Chemical Engineers. 1998.