Performance Evaluation Surface

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Abstract

The performance evaluation surface relates total cost over a system lifetime to eleven key performance factors. A system dynamics model is developed to project initial costs and trends over the system lifetime. A quadric surface (equation with all linear, quadratic, and two factor interaction terms) is fit to a complete factorial design of model runs. These runs span the practical range of factor values. The equation is a generalized cost model that gives a first-cut total cost projection for any product or service.

Performance Evaluation Surface

Overview

The performance evaluation surface relates total cost over a system lifetime to eleven key performance factors. A system dynamics model is developed to project initial costs and trends over the system lifetime. A quadric surface (equation with all linear, quadratic, and two factor interaction terms) is fit to a complete factorial design of model runs. These runs span the practical range of factor values. The equation is a generalized cost model that gives a first-cut total cost projection for any product or service.

Purpose

Information technology equipment prices have been decreasing at a 20 to 30 percent annual rate for many years. There has also been a reduction in operations and maintenance costs . In this environment, operations and maintenance costs are a function of the age of the installed equipment base. To adequately project future costs, one must take account of these trends with a dynamic model. In this report we present a general dynamic model of total future system cost as a function of the following key factors:

- Equipment purchase price
- Equipment price reduction rate
- Equipment lifetime
- Annual operations and maintenance cost percentage of initial equipment price
- Annual decrement in operations and maintenance costs
- Annual growth rate in installed base
- Installed base age
- Interest rate
- Procurement cost as a percentage of equipment price
- Salvage value as a percentage of new equipment price
- System lifetime or planning period

Present information technology hardware prices can easily be obtained from vendors. What is needed is a cook-book way of projecting total system costs from the easily obtained hardware costs and historic trend data. The model calculates a total average annual cost multiplier of the present equipment price as a function of time. This dimensionless ratio can be applied to any initial equipment price. It is similar to the annuity table values that calculate total mortgage costs over its lifetime.

To span the practical factor space, multiple runs of the model were performed. A complete factorial design was employed to efficiently span the factor space. Then a quadric surface equation was fit to the run results. The equation can be used to estimate total costs for factor values within the fitted range. The fitted range spans the practical parameter space and projects performance nine years into the future. Two and three dimensional plots of the equation documents the sensitivity of cost to individual factors, and pairs of selected factors. The optimal equipment turnover rate can also be calculated from the equation.

Figure 1 is the complete PES model. It is divided into capital investment, operations and maintenance, unit age distribution, cash flow calculation, and per unit age distribution sectors. Inputs to the model are on the left, and final output performance measures are at the bottom right in the cash flow sector. There are three accumulators (boxes) in the first three sectors, one for each age category. Each sector is described in a following paragraph.

The conserved flow in the unit age distribution sector is units of equipment. The installed equipment base is divided into three age categories. New equipment enters the newest third age category (accumulator box U1). The rate of purchase of new equipment (NewUnits) is set to the rate at which equipment becomes obsolete plus any unit growth rate (UnitGrowthR). The later is a percentage of the total installed base (Units=U1+U2+U3). "Life3" is one third of the specified equipment lifetime. Note that the reciprocal of equipment lifetime is equipment turnover rate. Each month the reciprocal of "Life3" proportion of accumulator units move to the next accumulator (UR1=U1/Life3). In the oldest third accumulator "U3" the units become obsolete (Obsolete=U3/Life3). A similar process occurs in both the capital investment and operations sectors. The same three age categories are maintained. In the capital investment sector the flow is dollars investment in units. The accumulators represent the total investment in units of that age category. Similarly in operations and maintenance, the accumulators represent the monthly operation and maintenance costs for units in that age category. Since operations and maintenance costs are based on initial unit investment cost, and the technology at the time of purchase (OM costs change with time at "OMred" rate) , we must keep track of the age categories.

The conserved flow in the capital investment sector is dollars investment in units. A specified annual rate of equipment price reduction (PriceRed) is assumed to hold over the simulation period. This same historical rate trend is also held over the time existing equipment was installed. This assumption is needed to calculate the initial investment in each age category at the start of the simulation. Initially equipment age is assumed to be uniformly distributed over the installed baseline months (specified in Base input). The total investment (Investment=Inv1+Inv2+Inv3) is assumed to be amortized over the equipment lifetime (Life). Each month there is an amortization charge of investment divided by equipment life in months. New equipment is procured at the present equipment price (EquipPrice). A procurement cost percentage (ProcCostPct) is added to this cost to handle contracting, shipping, and installation charges.

The conserved flow in the operations and maintenance sector is monthly dollar cost of operations and maintenance. Operations and maintenance are specified as a percentage of equipment investment dollars (OMinit = 50% of investment dollars per year at operating point). An annual rate of improvement in operations and maintenance is also specified (OMred). The operations and maintenance costs for a given unit are specified at its purchase and continue at the same rate throughout its lifetime.

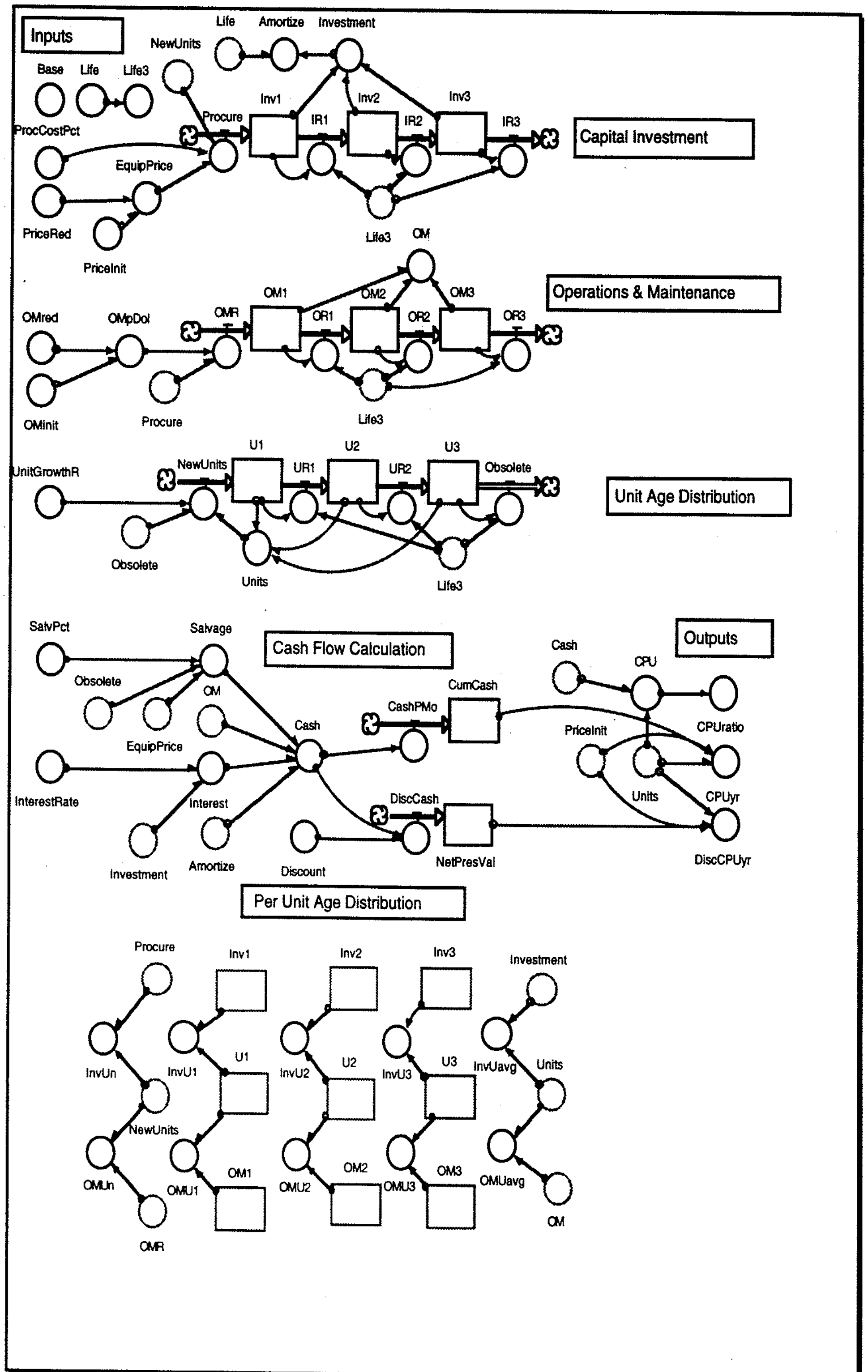


Figure 1. Complete PES Model

The cash flow sector also calculates the output measures of effectiveness. Monthly cash flow is the sum of amortization, operations and maintenance, interest on investment, minus cash from salvage of equipment. Salvage is a specified proportion of new equipment price. In an environment with 20 to 30 percent annual reductions in equipment price, basing salvage on initial purchase price would lead to unrealistically high values. Since investment is fully amortized over the equipment lifetime, interest is paid on an average of one half the investment. Cash flow is accumulated from the start of the simulation in "CumCash". The discounted net present value of all cash flows is accumulated in "NetPresVal". A discount rate of 10% per year was used. Three measures-of-effectiveness are calculated as a function of time:

- CPUyr = the average annual total cost per unit divided by the unit equipment price at the start of the simulation
- DiscCPUyr = the discounted average annual total cost per unit overthe simulation period divided by the unit equipment price at the start of the simulation
- CPUratio=total cost per unit at the present time divided by total cost per unit at the start of the simulation

The first "CPUyr" measure is used for the following sensitivity runs and surface plots. The same analysis could be applied to the other two measures. An initial unit equipment price (PriceInit) of $1000 per unit was used for the model runs. Since all the output measures are divided by this price, they are dimensionless ratios and can be applied to any initial equipment price. The second measure gives greater weight to early simulation cash flows and takes into account the time value of money. The first two measures are averages over the entire simulation, while the last is a ratio of monthly cost at the simulation time to cost at the start of the simulation. Note that the total cost at the start of the simulation includes amortization, interest, operations and maintenance. The "CPUratio" is more sensitive to cost changes and would be of greater use in developing fee-for-service algorithms.

The per unit age distribution sector presents Investment per unit and operations and maintenance per unit calculations as a function of age. This model considered three age categories. Later work will compare the accuracy benefits of more categories to the increased complexity and computation times required. In figure 1 age increases from left to right. The first column gives present investment per unit and operations and maintenance per unit. The next three columns give investment per unit and operations and maintenance per unit in the newest, middle, and oldest third age category. The final column gives average investment per unit and operation and maintenance per unit over all age categories.

Model results

The model was run at the following set of factor values:

- Equipment price reduction rate 15 % per year
- Initial unit equipment purchase price $1000
- Equipment lifetime 48 months
- Annual operations and maintenance cost percentage of initial equipment price 50%
- Annual decrement in operations and maintenance costs 0% per year
- Annual growth rate in installed base 0 % per year
- Installed base age 60 months
- Interest rate 10 % per year
- Procurement cost as a percentage of equipment price 4%
- Salvage value as a percentage of new equipment price 15%
- System lifetime or planning period 108 months

Figure 2 plots investment per unit of equipment and annual operations and maintenance per unit of equipment versus simulation time. Both values decrease at a constant percentage rate through out the simulation. Since the percentage reduction is applied to a constantly decreasing value, the absolute value of the reduction decreases through time. The results are averages over all age categories. Note that investment per unit exceeds the initial unit equipment price of $1000. This is due to the installed base being purchased before the start of the simulation at higher prices.

Figure 3 shows investment per unit by age category versus simulation time. New units are those purchased at a continuously decreasing price throughout the simulation. The percentage price reduction is constant. The age categories represent thirds of the equipment lifetime. The average age in the first third is one sixth of the equipment life. Thus this category contains units that were purchased on the average of one sixth of the equipment lifetime before the simulation time. The average age for the middle third is one half the equipment lifetime. Finally, the average age for the oldest third is five sixths of the equipment lifetime. The investment cost per unit of the oldest third age category is that used for obsolete units.

Figure 4 is a similar plot for operations and maintenance per unit. Note operations and maintenance costs for all age categories decreases at a constant percentage rate through time. The difference between the age categories is a measure of model accuracy. More categories would lead to greater accuracy at the price of greater complexity and longer execution times.

Figure 5 shows monthly cash flow versus simulation time. The two largest components of cash flow are operations and maintenance and amortization. Note procurement costs are not directly included in cash flow. They are amortized over the equipment life time. The amortization charge is included in the cash flow. Interest is only paid on the unamortized balance which averages one-half the investment.

Figure 6 plots the other two components of cash flow. Monthly salvage value is an income cash flow while interest cost is an expense. Note salvage value from obsolete equipment pays a significant part of the interest costs on unamortized investment. This occurs even at a low salvage proportion of 15% of the new equipment price.

Finally, figure 7 gives the three measures-of-effectiveness versus simulation time. Both the "CPUyr" and "DiscCPUyr" ratios start out greater than unity. These are ratios of total annual cost to initial equipment purchase price. Total annual cost includes operations and maintenance charges in addition to investment recovery charges. The 10% discount rate reduces future costs and thus the "DiscCPUyr" cost ratio is below the "CPUyr'" cost ratio. The first two measures average costs over the entire simulation period. Conversely the "CPUratio" is a ratio of total monthly cost at simulation time to total monthly cost at the start of the simulation. This more sensitive measure would be of more use in fee-for-service algorithms.

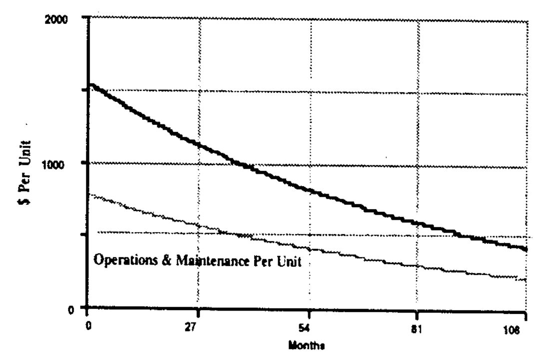


Figure 2 Investment and Annual Operations and Maintenance Per Unit versus Time

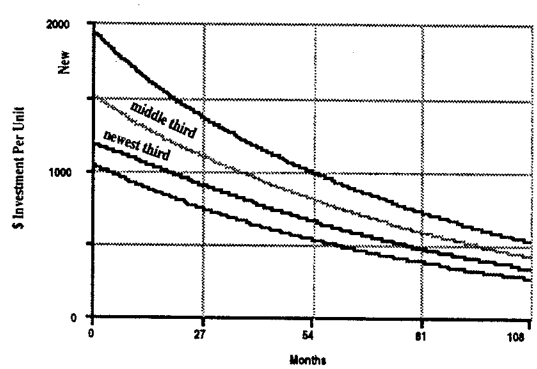


Figure 3. Investment Per Unit By Age Category Versus Time

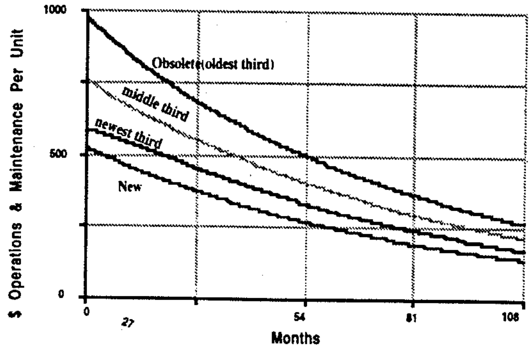


Figure 4. Operations and Maintenance Per Unit By Age Category Versus Time

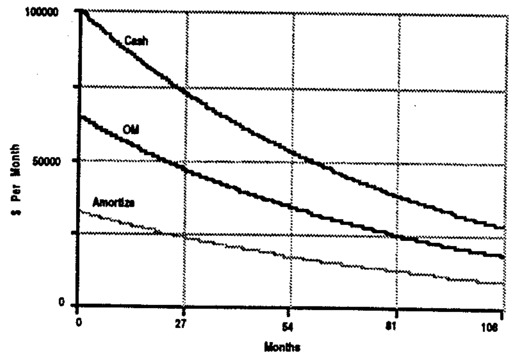


Figure 5. Monthly Cash Flow Components Versus Time

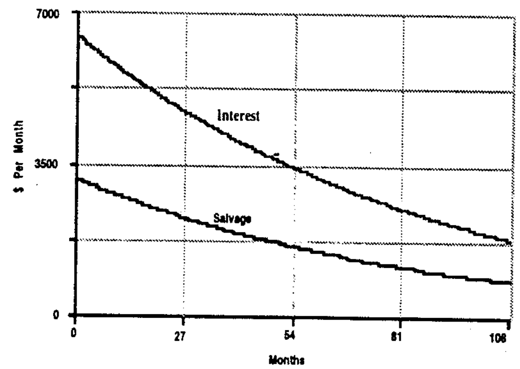


Figure 6. Monthly Interest and Salvage Versus Time

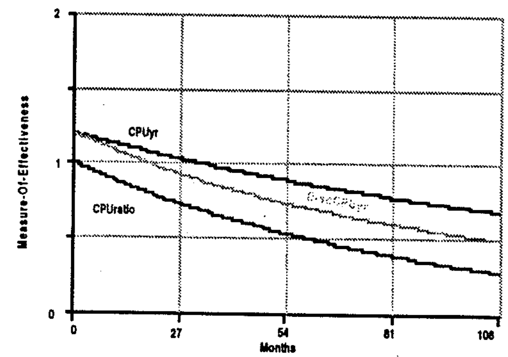


Figure 7. Cost Per Unit Performance Measures Versus Time

Cost multiplier surface

A complete factorial design of six factors at three levels was developed (729 runs). The factor level values used are given in parenthesis and the equation variable name in brackets

- [price] Equipment price reduction rate (0,15,30 % per year)
- [life] Equipment lifetime (24,48,72 months),[life]
- [omin] Annual initial operations and maintenance cost percentage of initial equipment price (10,50,90 %)
- [unit] Annual growth rate on installed base units (-10,0,10 % per year)
- [base] Maximum installed base age (24,60,96 months)
- [plan] System lifetime or planning period (36,72,108 months)

The center value for each factor is the operating point. With this number of factors the number of possible combinations is very large. To overcome this problem, all factors except the one or two of interest are set to their operating point values. Initially all linear, quadratic, and two factor interaction terms were included in the quadric surface equation. After fitting, the "t" significance of each term was evaluated. To simplify the equation all terms with a "t" probability of greater than .0001 were eliminated. The first quadric surface equation is :

Annual Cost Multiplier Of Initial Equipment Price =

$$.92 - .029\ \text{price} - .003\ \text{base} - .013\ \text{life} + .04\ \text{unit} + .006\ \text{omin} + .001\ \text{unit}^2$$

$$+ .0004679\ \text{price}^2 + .0000379\ \text{plan}^2 + .0000507\ \text{base life} - .0002453\ \text{base unit} + .0003824\ \text{base price}$$

$$+ .00006101\ \text{base omin} - .00004432\ \text{base plan}$$

+.0003237 life price +.00006675 life omin -.001 unit price -.000449 unit omin -.000382 unit plan

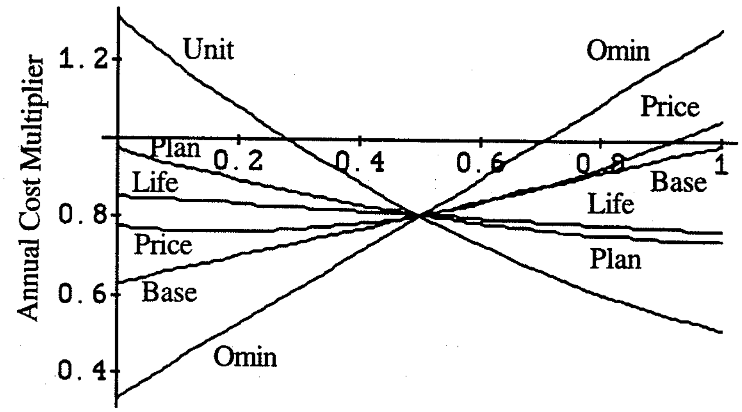
+.0001127 price omin -.000276 price plan

-.00003721 plan omin

93.2% of the data variability is explained by this equation. There are many significant two factor interactions. When calculating single factor sensitivity, all other factors are set at their operating point values. Thus all two factor interactions just affect the overall mean level. The only single factor sensitivity plots that are curved are those with squared terms. The squared term factors are unit growth rate, price reduction rate, and planning period.

Individual factor sensitivity

For individual factor sensitivity analysis, the cost multiplier is calculated as the individual factor is varied over its range, while all other factors are set to their operating point values. The results of this process for the fit surface equation is presented in figure 8. Note that the cost sensitivity curves all intersect at the operating point value at the midpoint of the variable ranges. The abscissa axis is in proportion of variable range given below the plot. The relative cost sensitivity of factors is given by the slope of the sensitivity curve. Note curvature of the planning period, price reduction, and unit growth rate factors. As previously mentioned each of these factors has a squared term in the quadric surface equation. The negative gradient direction (optimal cost reduction strategy) varies with factor value for these factors. We note the cost multiplier decreases at a reduced rate as the planning period is extended from 36 months to 108 months. There is a significant linear increase in cost multiplier as installed base equipment age is increased from 24 to 96 months. Note equipment age is assumed to be uniformly distributed over the installed base time period. Cost multiplier is relatively insensitive to equipment lifetime; though there is a slight (<10%) reduction of cost with increases in equipment lifetime from 24 months to 72 months. As unit growth increases from negative ten percent per year to plus ten percent per year, cost multiplier is significantly reduced, though at a decreasing rate. This is due to reduction in the overall equipment age and the resulting reduction in operations and maintenance cost requirements of the newer equipment. There is a significant linear increase in cost with a higher percentage of annual operations and maintenance cost per initial dollar invested. Cost initially is reduced but then increases as the price reduction rate increases from zero to thirty percent per year. At higher price reduction rates the old installed base has a higher value. This adversely affects amortization, operations and maintenance, and interest cost until the older equipment is replaced.



36 £ [Plan] Planning Period (months) £ 108
0 £ [Price] Equipment Price Reduction (% per year) £ 30
24 £ [Base] Installed Base (months) £ 96
24 £ [Life] Equipment Life (months) £ 72
-10 £ [Unit]Unit Growth Rate (% per year) £ 10
10 £ [Omin] Operations & Maintenance Multiplier (%) £ 90

Figure 8. Individual Variable Change At Operating Point

Two factor interactions

The quadric surface equation had many two factor interactions. Here the effect of one factor on cost is dependent on the value of the other factor. This subsection gives three dimensional cost multiplier plots for some significant two factor interaction terms in the quadric surface equation. Figure 9 plots cost multiplier as a function of planning period (system lifetime) and equipment price reduction rate. At no change in price, annual cost is relatively insensitive to planning period (system lifetime). At high price reduction rates, the longer the planning period, the smaller the costs. Over most of the plot region, average annual costs are increased with greater price reduction rates due to greater investment in installed base. At high price reduction rates and small planning periods, average annual costs are greater than the equipment investment at the start of the simulation (cost multiplier >1). The price reduction rate is assumed to be constant over the past installed base age in addition to the entire planning period. The higher the price reduction rate, the larger the installed base investment, and corresponding operations and maintenance costs. Through time the original installed base becomes obsolete and cost is reduced with increasing price reduction rates. Thus for a 108 month planning period, average period cost is reduced with an increase in price reduction rate from zero to ten percent per year.

Figure 10 plots cost multiplier as a function of planning period and installed base age. The older the equipment base, the higher the average annual cost multiplier. The longer the planning period (system lifetime), the lower the average annual costs. The rate of annual cost reduction is reduced as the planning period is increased.

Figure 11 plots cost multiplier as a function of planning period and unit growth rate. Higher unit growth rates reduce the average age of the installed equipment base. This reduces investment costs (the operating point price reduction rate is 15% per year) and the associated operations and maintenance costs. At a 10% unit growth rate even a 36 month planning period system has a lower average annual cost (cost multiplier<1) than initial equipment investment. For positive unit growth rates the longer the planning period the greater the reduction in annual costs. At negative unit growth rates less obsolete equipment is replaced with new less costly equipment. Hence cost does not decrease with planning period.

Figure 12 plots cost as a function of planning period and operations and maintenance multiplier. The later is the percentage of initial equipment price that is annually spent on operations and maintenance. Cost directly increases with this percentage. Cost also is reduced with longer planning periods. The cost reduction with planning period is greater with higher operations and maintenance percentages.

Figure 13 plots cost multiplier as a function of equipment price reduction and installed base age. The greater the installed base, the greater is the cost multiplier. At high installed base ages, cost increases with equipment price reduction rate due to the larger investment in the initial installed base. At low base ages, cost is reduced with greater equipment price reductions.

Figure 14 plots cost as a function of equipment price reduction and equipment life. At no equipment price reduction (constant price), cost is reduced by long equipment lifetimes (low turnover). At high rates of price reduction cost is reduced by short equipment life times (high turnover). Note higher costs for greater price reduction rates are due to the larger investment in installed equipment base.

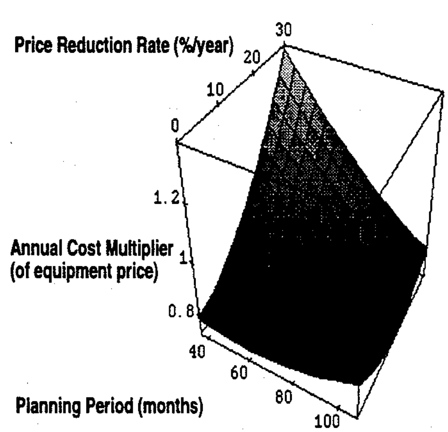


Figure 9. Cost Multiplier Versus Planning Period and Equipment Price Reduction

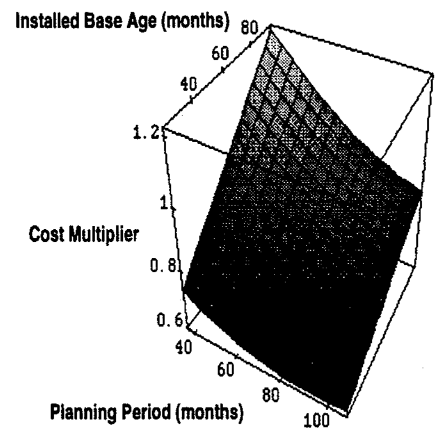


Figure 10. Cost Multiplier Versus Planning Period and Installed Base Age

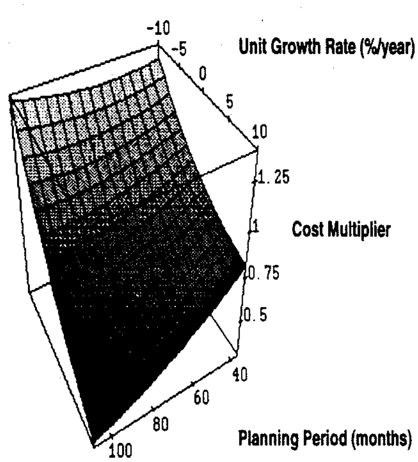


Figure 11. Cost Multiplier Versus Planning Period and Unit Growth Rate

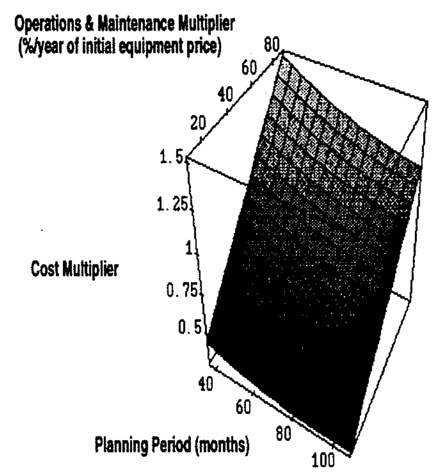


Figure 12. Cost Multiplier Versus Planning Period and Operations and Maintenance *

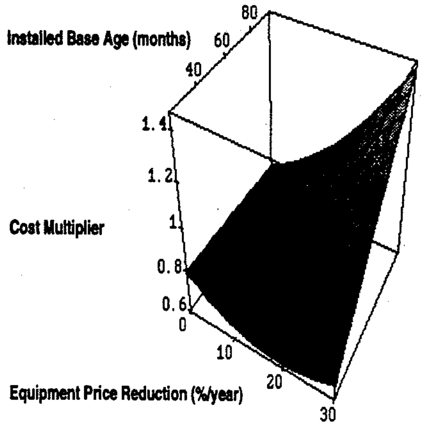


Figure 13. Cost Multiplier Versus Equipment Price Reduction and Installed Base Age

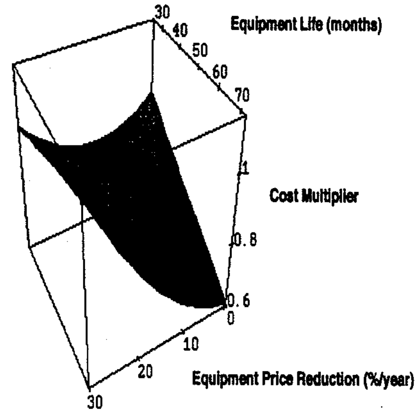


Figure 14. Cost Multiplier Versus Equipment Price Reduction and Equipment Life

Conclusions

Total life cycle costs can be projected from initial equipment price and parameter values for all key factors. Two equations relating annual total cost to equipment price and key factors were developed. These equations can be applied over the practical range of key factor values. The sensitivity of total annual cost to individual factors and pairs of factors was documented. This technique provides a simple first-cut cost projection in the fast changing information technology marketplace.

The developed equations were based on a quadric surface fit to runs of a system dynamics model of the process. Recently I obtained the analytic solution to the differential equations. The model was based on common accounting practice and an assumed uniform installed base equipment age distribution. It projects costs as a function of time and existing price and operation and maintenance trends. The impact of the age of the installed equipment base on total annual cost is documented. The total annual cost versus time plots aid in determining fee-for-service through time.