EVALUATING FLEXIBLE MANUFACTURING SYSTEMS

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ABSTRACT

Many firms are considering Flexible Manufacturing Systems as a means for increasing productivity, quality and profitability. In this paper a methodology for properly comparing and evaluating FMS's is presented. The appropriate financial criteria are presented. Mathematical models of different FMS's are presented. The important stochastic variables are determined. The principles of stochastic dominance, risk preference and the value of information; and a decision analysis cycle are used to evaluate the FMS's.

EVALUATING FLEXIBLE MANUFACTURING SYSTEMS

1. Introduction

Manufacturing ranks among the principal real-wealth producing activities of most industrialized countries (Herroelen and Lambrecht [1984]). Manufacturing industries have always been very interested in using the newest in automation equipment and techniques, to increase productivity and profitability. In recent years, the state of automation technology has reached a stage where the bottleneck is no longer the transformation operation (that is, the transforming of inputs into outputs) but is now the control operation and the transfer operation (that is, the scheduling, control and transfer of the work-in-process between transformation operations). At the same time, breakthroughs in electronics technology, robotics technology and the continued reduction in the cost of computer hardware, are providing the means for automating both the control and the transfer components of manufacturing processes. The final goal in this process of increasing automation is, of course, the fully automated factory. Our current position in this evolutionary process is the flexible manufacturing system - the building block for our fully automated factories. (Ranky [1983]).

A Flexible Manufacturing System (FMS) can be described as a set of transformation stations on which a variety of parts are automatically processed and between which parts are automatically transported. FMS's are considerably more complex that this definition suggests. An overview of the technology, and descriptions of FMS's can be found in several articles. (See, for example, Proceedings of the First International Conference on FMS, [1982]). A summary of much of the theoretical work that is currently being done on FMS's can be found in the Proceedings of the First ORSA/TIMS Conference on FMS, [1984], and in recent articles in the Journal of Manufacturing Systems [1982 on].

Many firms have either introduced or are considering flexible manufacturing technology. (Suri and Whitney [1984]) These firms see FMS as a means for increasing productivity, profitability and quality as well as a means of maintaining a competitive edge in the market place. Unfortunately, many researchers have reported that traditional approaches to the financial justification of FMS's tend to discourage their adoption. (See, for example, Kaplan [1983], Burstein and Talbi [1984], Gold [1982], and Suresh and Meredith [1984].) Researchers such as Michael and Millen [1984] suggest that traditional financial evaluation models are more suited to meet short-term profitability goals rather than long-term strategic goals. While there is probably more truth to this suggestion than many people would like to believe, we will show that when traditional financial evaluation models are properly used, they do indeed, encourage the adoption of FMS's.

The most important property of a FMS is its flexibility. Flexibility has three components. (1) There is the flexibility to produce a variety of products using the same machines as well as the flexibility to produce the same product on different machines. (This allows firms to easily increase or decrease production capacity.) (2) There is the flexibility to produce new products on existing machines, and (3) is the flexibility of the machines to accomodate changes in the design of products. When evaluating FMS's, these components of flexibility must be accurately modelled. In this paper, we define random variables (with appropriate probability density functions) to represent the components of flexibility. These random variables are combined with other stochastic and deterministic variables, to form models of FMS's.

These models are put in a "decision analysis framework" so that the FMS's can be analyzed and compared.

There are two kinds of manufacturing systems that can be considered -- assembly systems and forming systems. Assembly systems assemble components into final products while forming systems actually form components or final products. This paper evaluates only assembly manufacturing systems because assembly activities are similar in most manufacturing firms. (The basic assembly activities consist of picking up components, positioning them and subsequently joining them together. Forming systems, on the other hand, are more diverse. Typical forming activities are milling, cutting, grinding, drilling, electro-chemical operations and so on.) Our objective is to show how traditional financial evaluation models should be used when selecting the "best" of a number of FMS's.

In what follows Section 2 briefly describes the traditional financial evaluation models that will be used -. namely the net present value and annuity equivalent, the internal rate of return, and the payback period. In section 3 mathematical models for six flexible manufacturing systems are presented. (The systems differ in the "amount" of flexibility that they have.) Section 4 reviews the "decision analysis framework" used, while section 5 illustrates the complete methodology with a worked example. Section 6 summarizes the results in this paper and describes possible extensions.

2. Traditional Financial Evaluation Models

Many financial models can be used to help evaluate projects. The Net Present Value (NPV), the Profitability Index (PI), and the Internal rate of return (IRR) are the more "sophisticated" ones since they explicitly consider the time value of money. Although there are numerous "unsophisticated" models, the best known are the Average Rate of Return (AROR) and the Payback period (PB). Based on a survey of major U.S. companies, Gitman and Forrester [1977] report that there are strong preferences for sophisticated financial evaluation models. The study reveals that 53.6 percent of the companies used IRR, 9.8 percent NPV, and 2.7 percent used PI. Only 33.9 percent of the companies used either AROR (25.0%) or PB (8.9%) as their primary technique. In addition, they indicate that the use of time discounting (principally the IRR) has been increasing over time.

The Net Present Value (NPV) is the difference in the present value of the after-tax cash inflows and outflows. That is:

$$NPV = \sum_{t=1}^{n} \frac{NCI_t}{(1 + k)^t} - \sum_{t=1}^{n} \frac{I_t}{(1+k)^t}$$

where NCI_t = after-tax cash inflow generated by the project in period t,

I_t = investment in period t,

n = useful life of the project,

k = the appropriate discount rate.

If the NPV is positive (that is, inflows exceed outflows), the project should be accepted. Since it would be incorrect to compare the NPV's of projects having different lives, each project's NPV should be converted to an Annuity Equivalent (AE), and the AE's of the projects should be compared. The larger the AE the more attractive the project. (The AE method assumes that each project is continually replaced at the end of its useful life by a project of like profitability. This essentially converts the fixed life investment to an equivalent infinite life investment.)

By definition, the IRR of a project is that rate which equates the present value of the after-tax cash inflows with the present value of the after-tax cash outflows. That is:

$$\sum_{t=1}^{n} \frac{NCI_t}{(1 + IRR)^t} - \sum_{t=1}^{n} \frac{I_t}{(1 + IRR)^t} = 0$$

The IRR recognizes the time value of money and considers the anticipated revenues over the entire life of a project. Companies should accept any project offering an IRR in excess of the opportunity cost of capital.

Companies frequently require that the initial outlay on a project will be recoverable within some specified cutoff period. The payback (PB) period of a project is found by counting the number of years it takes before cumulative forecasted cashflows equal the initial investment. That is, find the value of PB that satisfies

$$\sum_{t=2}^{PB} NCI_t - I_t = I_1 - NCI_1$$

where PB = payback period of the project,

$I_1 - NCI_1$ = initial investment.

The PB for the project is then compared to a prespecified cutoff period decided by the firm. If PB exceeds the prespecified period, the project will not be undertaken. The problem with this method is that it gives equal weight to all cash flows before the cutoff date. (The time value of money is not taken into account.) It also ignores all cashflows after the payback period and, does not differentiate between projects requiring different initial investments. Merritt and Sykes [1963] note that "It (payback) has harshly, but not unfairly, been described as the "first bait" test, since it concentrates on the recovery of the bait (the initial investment) paying no attention to the size of the fish (the ultimate profitability), ...".

Although the NPV and the IRR give equivalent results with regard to independent conventional projects, they will not rank projects the same. For the problem in this paper (the firm must choose the best FMS from among a number of alternatives) the NPV is the appropriate criterion. (The NPV reflects the absolute magnitude of the project while the IRR does not. In addition the NPV implicitly assumes reinvestment of the interim proceeds at the cost of capital, while the IRR assumes reinvestment at the project's own rate of return. The reinvestment assumption is important if we assume a changing cost of capital in future years. Under such a condition, the IRR rule will break down because the comparison of a single-rate of return with a series of different short-term discount rates is meaningless. Finally, when a project with nonconventional cashflows is considered, a real-valued IRR may not exist, or more than one IRR exist.)

Despite the obvious advantages of the NPV over IRR and PB, all of them will be examined in this paper. We do so since management has a very strong preference for the IRR over NPV. Moreover, many corporations still use PB in combination with IRR for project evaluation. (See, for example, Gitman and Forrester [1977] or Schall et al [1978].) It appears that the preference for IRR is in part psychological since it is set out in terms of percentages. However, the intuitive appeal of the IRR should not be permitted to obscure the fundamental fact that when mutually exclusive projects are to be evaluated, the appropriate criterion is the AE, not IRR.

We now formulate a financial model which will be used to evaluate alternative manufacturing systems. The inputs to this model consist of demand variables, engineering variables and financial variables. The outputs are the NPV and AE, IRR, and PB for each manufacturing system. Define the following variables.

A) Exogenous Variables

NP_t - number of different assemblies to be manufactured in year t

$MS_{i,1}$ - total market size for assembly i in year 1 (in units demanded per year), $i=1,2,3,\ldots,NP_1$

$MSHARE_i$ - share of the assembly i market for the firm

$MGROW_i$ - annual market growth rate for assembly i

I_t - investment in year t, $t=1,2,3,\ldots$

N - useful life of the project (for NPV calculations)

D - life of the project for depreciation purposes

WT_t - total wage costs in year t

$SP_{i,t}$ - selling price for assembly i in year t

TX - tax rate

k - risk free interest rate

B) Endogeneous Variables

$MS_{i,t}$ - total market size for assembly i in year t

$VS_{i,t}$ - annual sales of assembly i in year t by the firm

REV_t - total revenues in year t

DEP_t - total depreciation in year t

BV_t - book value of the project in year t

$ATCF_t$ - after tax cash flow in year t

C) Relationships Between Variables

$$MS_{i,t} = MS_{i,t-1}\ (1+MGROW_i)$$

$$VS_{i,t} = MS_{i,t} * MSHARE_i$$

(1) $$REV_t = \sum_{i=1}^{NP_t} VS_{i,t}\ SP_{i,t}$$

(2) $$DEP_t = \frac{2}{D}\left(\sum_{j=0}^{t-1} I_j - \sum_{j=0}^{t-1} DEP_j\right)$$

$$BV_o = 0$$

$$BV_t = BV_{t-1} - DEP_t + I_t$$

(3) $ATCF_t = (REV_t - WT_t)(1-TX) + DEP_t\, TX - I_t$

(4) $NPV = \sum_{t=1}^{N} \frac{ATCF_t}{(1+k)^t} + \frac{BV_N}{(1+k)^N}$

(5) $AE = \frac{NPV}{1 - \frac{1}{(1+k)^N}}$

IRR is calculated from

(6) $\sum_{t=1}^{N} \frac{ATCF_t}{(1 + IRR)^t} + \frac{BV_N}{(1 + IRR)^N} = 0$

PB satisfies

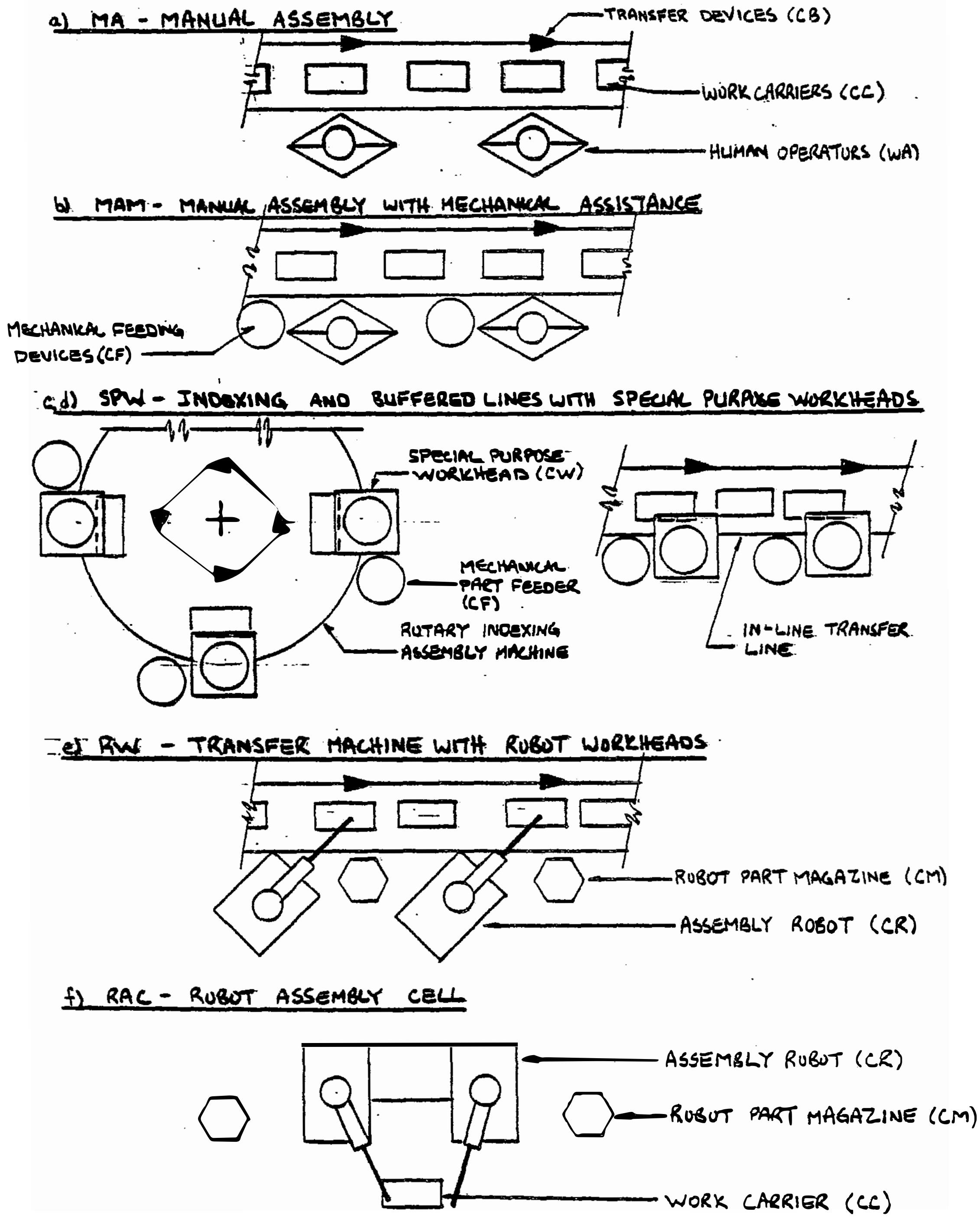
(7) $\sum_{t=1}^{PB} [(REV_t - WT_t)(1-TX) - I_t] = 0$

For simplicity it is assumed that the risk free rate k (used to discount the cash flows) is constant over the life of the project. Assume that the total cost per year is made up of labour costs and investment costs. That is fixed or overhead costs are ignored. Depreciation is calculated using the double declining balance method (equation 2). Finally, notice that the last term in the NPV and IRR equations is the discounted book value of the project at the end of its useful life.

3. MATHEMATICAL MODELS FOR FLEXIBLE ASSEMBLY MANUFACTURING SYSTEMS

Six assembly manufacturing systems will be considered - namely, manual assembly (MA), manual assembly with mechanical assistance (MAM), rotary or in-line indexing machines with special purpose workheads and free transfer lines with special purpose workheads (SPW), free transfer lines with robot workheads, (RW), and robot assembly cells, (RAC). Figure 1 shows these manufacturing systems. The mathematical models that we use for these manufacturing systems are based on the models developed by Boothroyd [1981], [1982]. Consider the production of a family of assemblies where each assembly consists of a number of parts. The assembly is produced on one of

Figure 1 6 Assembly Manufacturing Systems



the above assembly systems. The assembly system has a number of stations, and at each station NS parts are assembled. Define the following variables.

A) Exogenous Variables

(i) TIMES (seconds)

TA - time to assemble one part manually

TM - time assemble one part manually with mechanical assistance

TW - time to assemble one part with special purpose workhead (non-programmable automation)

TR - time to assemble one part with robot workhead (programmable automation)

TD - downtime at a station due to a defective part

(ii) EQUIPMENT COSTS

CB - cost per station of transfer device on manual assembly system

CT - cost per station of transfer device on automated assembly system

CC - cost of carrier (pallet)

CF - cost of mechanical feeding device for manual and non-programmable assembly systems

CM - cost of part magazine (feeding device) for robot systems

CW - cost of special purpose workhead

C1 - basic cost of robot

C2 - additional cost of robot per degree of freedom

CG - cost of robot gripper

(iii) PLANT VARIABLES

PE - plant efficiency (fraction of available time worked)

PQ - part quality (fraction of defective parts to acceptable parts)

NR - number of assembly workers per station on automated assembly systems

NOS -number of supervisors on an assembly system

HR - number of production hours per shift

WA - annual cost of one assembly worker

WS - annual cost of one supervisor

(iv) PRODUCTION VARIABLES

NS_i - the number of parts assembled at each station for assembly i

NA_i - number of parts in assembly i, i=1,2,..., NP.

NT_i - number of parts in assembly i that are different from assemblies 1,2,...,i-1

$ND_{i,t}$ - number of part design changes for assembly i in year t

B) Endogenous Variables

TP_i - the average production time for a non-defective assembly i

NSR - number of stations required in the assembly system

SH - number of production shifts for assembly system

We now make the following assumptions. Assume that a number of different assemblies are to be produced in year t. The number of assemblies (NP_t), the number of parts (NA_i) in each assembly i (i=1,2,...,NP), and the production requirements for each assembly ($VS_{i,t}$), are all unknown. The manufacturing system consists of a number of stations. Each station has a "workhead" - either a manual operator (WA), a special purpose workhead (CW), or a robot (CR). The work-in-process is mounted on a work carrier or pallet (CC), and is transferred from one station to the next by a transfer device (CB or CT). The production schedule is as follows. Set up and produce the entire year's requirements for assembly 1. Then change over for assembly 2 and produce the entire year's requirements for assembly 2. Continue for the entire family of assemblies. Up to three shifts can be used to produce the total requirements for all assemblies. After all the required assemblies have been produced the workers and supervisors are transferred to other areas of the plant. (Hence there are no costs for hiring and firing workers).

During the life of an assembly, a number of parts may be redesigned (for marketing considerations). When this happens some of assembly equipment must be changed - specifically the carriers CC, partfeeders CF, robot grippers CG, robot part magazines CM, and the special purpose workheads CW. The number of parts in assembly i that will have to be redesigned in year t ($ND_{i,t}$), will usually be unknown.

The assembly manufacturing system produces a family of assemblies. If non-programmable automation is used, then a different assembly system is required for each assembly. The more flexible assembly systems can be changed over to manufacture all assemblies. (The transfer devices, the robots and the assembly operators would be reused. However, the work carriers CC, the mechanical feeding devices CF, the robot part magazines CM and the robot grippers CG would have to be changed.) In addition, some of the assemblies may have common parts. When this happens some assembly equipment; namely - the automatic feeding devices CF, robot grippers CG and robot part magazines CM can be reused.

The above assumptions have been made to simplify the mathematical models so that the overall problem is easy to understand. For example, producing the entire year's requirements in a single run, overlooks inventory lot sizing considerations, production scheduling, etc. Conceptually, it is a straightforward task to add more variables and make other assumptions so that the models are more appropriate for a particular firm. This is done in section 6.

1. MA - MODEL FOR MANUAL ASSEMBLY (Figure 1(a))

Select the required number of shifts SH, and the number of parts to be assembled in each station NS_i for each assembly i (i=1,2,...,NP), so that there is sufficient capacity to meet the production requirements.

That is:

(8) $\sum_{i=1}^{NP} VS_i * TP_i \leq HR * PE * SH$

where

(9) $TP_i = NS_i * TA(1+PQ)$

(Every TP seconds, on average, a good assembly will be produced by the assembly machine.) The number of stations required (NSR) in this manual assembly system is

(10) $NSR = \max [NA_i/NS_i]$ (i=1,1,..., NP).

Assume that there is one operator at each station and that each operator has access to two work carriers (CC) on the conveyor (to allow for minor delays) and that each station has a transfer device (CB). Finally, notice that only the work carriers have to be changed when the assembly system changes over to a different assembly.

The initial investment for a manual assembly system is, therefore,

(11) $I_1 = NSR(NP*2*CC+CB)$.

The total annual labour costs can be calculated from,

(12) $WT = \frac{WA \sum_{i=1}^{NP} NA_i \ VS_i \ TP_i}{3600 \ HR * PE}$

(The year subscript t, has been supressed for clarity.)

Example 1 - model MA

Consider the manual assembly manufacturing system described by the data in Appendix 1. Suppose that it will produce two types of assemblies (NP=2) over the next four years. The relevant demand data is:

Assembly i	$MS_{i,1}$ a	$MSHARE_i$ b	$MGROW_i$ c	$VS_{i,1}$ d=a*b	$VS_{i,2}$ e=d(1+c)	$VS_{i,3}$ f=e(1+c)	$VS_{i,4}$ g=f(1+c)	NA_i
1	750000	0.17	0.10	127500	140250	154275	169702.5	6
2	900000	0.17	0.10	153000	168300	185130	203643	10

As well, TA=10 seconds/part, PQ=0.05, PE=0.95, HR=2000 hours/shift, TX=0.40 and k=0.20. Suppose the assembly system works for one shift (SH=1) and, for both assemblies, one part is assembled at each station ($NS_1=NS_2=1$), and all assemblies are sold for $0.65. On average a good unit is produced every TP=TA*NS*(1+PQ)=10.5 seconds (equation 9). Each year the system will run for:

year, t	1	2	3	4
$TP(VS_{1,t}+VS_{2,t})/3600$	818.13 hr.	899.94	989.93	1088.92

which is much less than the capacity of a shift (HR*PE=1900 hours/shift). From equation 12 the annual labour costs (WT_t) are; $140921.05 in year 1, 155013.16 in year 2, 170514.47 in year 3, and 187565.92 in year 4. The initial investment (equation 11) required is I_1=10(2*2*1500+7000) = $130000. Using equations 1,2 and 3 to calculate revenues, depreciation and after tax cash flows gives:

Year, t	REV_t	I_t	DEP_t	$ATCF_t$
1	$182325	$130000	(2/10)(130000) =$26000	-$94757.63
2	200557.5	0	.2(130000-26000) = 20800	35646.60
3	220613.25	0	16640	36715.27
4	242674.58	0	13312	38389.99
		130000	76752	

The book value at the end of year 4 is the total investment less the accumulated depreciation, or $53248. Substituting these results into equations 4 to 7 gives:

$$NPV = -94757.63/1.2 + 35646.6/(1.2^2) + 36715.27/(1.2^3) + 38389.99/(1.2^4) + 53248/(1.2^4)$$

$= \$11229.86$

$AE = \$21689.86$, $IRR = 0.275$, $PB \approx 3\ 1/2$ years.

At a discount rate of 20%, the manual assembly system is a profitable investment.

2. MAM - MODEL FOR MANUAL ASSEMBLY WITH MECHANICAL ASSISTANCE (Figure 1(b))

The difference between this model and the previous model is that mechanical feeding devices are available at each station to speed up the assembly process. (A different feeding device is required for each different part. When a part is redesigned, a new feeding device is required.) The equations are as above, except:

(13) $TP_i = NS_i*TM*(1+PQ)$,

(14) $I_1 = NSR*(NP*2*CC+CB) + CF*\sum_{i=1}^{NP} NT_i$.

Example 2 - model MAM

Suppose we wish to produce the same assemblies as in example 1. However they are to produced for five years on a manual assembly system with feeding devices. From the data in Appendix 1 we see that assembly 1 has 6 unique parts ($NA_1=6$, $NT_1=6$) while assembly 2 has 10 parts, 2 of which are the same as parts used in assembly 1 ($NA_2=10$, $NT_2=8$). Suppose, as in example 1, SH=1, $NS_1=NS_2=1$ and the selling price is \$0.65 per assembly. Then TP=8.4 seconds (equation 13), and the annual labour costs (equation 12) are \$112736.84 in year 1, 124010.53 in year 2, 136411.58 in year 3, 150052.74 in year 4 and 165058.01 in year 5. The initial investment cost (equation 14) is

$I_1 = 130000 + 7000(6+8) = \$228000$.

Suppose that both assembly 1 and 2 will have one part redesigned each year. (That is, $ND_{i,t}=1$ for i=1,2 and t=2,3,4,5.) Then $I_2=CF*(1+1)=\$14000$, $I_3=14000$, $I_4=14000$, and $I_5=14000$. Using equations 1,2 and 3 gives:

Year, t	REV_t	I_t	DEP_t	$ATCF_t$
1	$182325	$228000	$45600	-$168007.1
2	200557.5	14000	39280	47640.18
3	220613.25	14000	34224	50209.40
4	242674.58	14000	30179.2	53644.79
5	266942.03	14000	26943.4	57907.77
		284000	176226.6	

The book value at the end of year 5 is $107773.4. Substituting these results into equations 4 to 7 gives:

NPV = $14587.82, AE = $24389.35

IRR = 0.244, PB = 4.2 years.

3a. SPW - MODEL FOR ROTARY AND IN-LINE INDEXING ASSEMBLY MACHINES (Fig 1(c))

These assembly machines are non-programmable. A dedicated machine is required for each different assembly produced. This is because each assembly requires different special purpose workheads, different work carriers and different part feeders. Each station in the assembly machine assembles one part only. Obviously, for such "hard automation" to be profitable, the volumes must be large enough to adequately utilize dedicated assembly machines.

For each assembly i, (i=1,2,....,NP) and for each year t select $SH_{i,t}$, so that there is sufficient capacity to meet the demand requirements. (In what follows, we suppress the year subscript t for clarity.) That is

$$VS_i*TP_i/3600 =< HR*PE*SH$$

where $TP_i=TW+NA_i*PQ*TD$. (15)

Each station in the assembly machine consists of work carriers CC, a feeding device CF, and a special purpose workhead CW (all of which must be changed if a part is redesigned) and a transfer devices CT. The initial investment required for assembly machine i is:

(16) $I_{i,1} = NA_i*(CC+CF+CW+CT)$.

The labour costs consist of operator and supervisor costs. One operator runs 1/NR stations on the assembly machine and one supervisor monitors 1/NOS assembly machines. The annual labour cost for machine i, is:

(17) $WT_i = (NR*NA_i*WA+NOS*WS)*(VS_i*TP_i/3600)/(HR*PE)$.

The initial investment in all NP indexing assembly machines is

$$I_1 = \sum_{i=1}^{NP} I_{i,1}$$

while the total annual labour cost is

$$WT = \sum_{i=1}^{NP} WT_i.$$

3b. SPW - MODEL FOR IN-LINE FREE TRANSFER (BUFFERED) ASSEMBLY MACHINES WITH SPECIAL PURPOSE WORKHEADS (Figure 1(d)

If the number of parts in assembly i (NA_i) is large, downtime due to defective parts, can be excessive when rotary and in-line indexing assembly machines are used. In this case an in-line assembly machine with buffer inventories between the stations will be used. Then, when a station produces a defective part, the other stations will not be forced down. They will use a good part from the buffer inventories.

Once again a separate non-programmable machine is required for each different assembly. Boothroyd [1982] recommends the in-line free transfer assembly machine be used whenever $NA_i >= 10$ and that the size of the buffer inventories (BI) be approximately $\lceil 0.5*TD/TW \rceil$ where $\lceil X \rceil$ is the smallest integer greater than or equal to X. He shows that a good assembly is produced every TW+PQ*TD seconds (on average) on these assembly machines.

For each assembly i, where $NA_i >= 10$ (i=1,2,...,NP), select the required number of shifts SH_i such that $VS_i*TP_i/3600 =< HR*PE*SH_i$, where TP_i=TW+PQ*TD. The initial investment for assembly machine i is,

(18) $I_{i,1}=NA_i*(CC+CF+CW+CT+BI*CC)$,

and the annual labour cost is,

(19) $WT_i=(NR*NA_i*WA+NOS*WS)*(VS_i*TP_i/3600)/(HR*PE)$.

(If a part is redesigned then a feeding device (CF) and a special purpose workhead (CW) will have to be changed.)

Example 3 - model SPW

Consider again the problem of examples 1 and 2. Suppose that the two assemblies are to be produced on assembly machines with special purpose workheads. Assembly 1 has 6 parts and will be produced on the non-buffered assembly machine of model 3a. Assembly 2, with 10 parts, will be produced on the buffered assembly machine of model 3b. The assemblies are to be produced for six years. Each assembly will have one part redesigned each year. A capacity check shows that both machines will be run for one shift only.

For assembly 1, TP_1=5+6*0.05*30=14 seconds. The annual demands are 127500 units in year 1, 140250 in year 2, and 154275, 169702.5, 186672.75 and 205340.03 in years 3 to 6. The required initial investment is $I_{1,1}$= 6(1500+7000+10000+16000) = $207000 with additional investments of (CF+CW)=$26000 in each successive year because of the redesigned parts. The labour cost in year 1 is

WT =(0.333*6*40000+0.25*55000)*(127500*14/3600)/(2000*0.95)=$24444.58 . Similarly, the labour costs in years 2 to 6 are 26889.04, 29577.95, 32535.74, 35789.31 and 39368.25.

For assembly 2, TP_2=5+0.05*30=6.5 seconds. The demands are 153000, 168300, 185130, 203643, 224007.3 and 246408.03 units per year. The initial investment is $I_{2,1}$=10(1500+7000+10000+16000+3*1500)=$390000 with additional investments of $26000 each year (because of part design changes). The annual labour costs are $13619.12, 14981.04, 16479.14, 18127.06, 19939.76 and 21933.74.

Using equations 1,2 and 3 to calculate revenues, depreciation and after tax cash flows gives:

Year, t	REV_t	I_t	DEP_t	$ATCF_t$
1	$182325	$207000+390000 =597000	(2/10)*597000 =119400	-$462683.22
2	200557.5	52000	105920	85580.45
3	220613.25	52000	95136	90788.10
4	242674.58	52000	86508.8	97810.59
5	266942.04	52000	79607.04	106570.60
6	293636.24	52000	74085.63	117,034.80
		857000	560657.47	

The book value at the end of year 6 is $296342.53. Substituting these results into equations 4 to 7 gives;

NPV = -\$45162.05, AE = -\$67902.44

IRR = 0.158, PB ≈ 5.6 years.

At a discount rate of 0.20 these assembly machines are not profittable. Obviously much larger volumes are required to justify non-programmable dedicated machines.

4. RW - MODEL FOR IN-LINE FREE TRANSFER (BUFFERED) ASSEMBLY MACHINE WITH ROBOT WORKHEADS (Figure 1(e)

This assembly machine is the same as the in-line free transfer machine with special purpose workheads (model 3b) except that the workheads are now programmable. That is, the robot workheads can be reprogrammed for different tasks. (In that sense this assembly system is similar to manual assembly with mechanical assistance - model 2, because the human operators can also do different tasks.) The cost of each robot is CR where CR=C1+DF*C2. C1 is the basic cost of a robot and C2 is the additional cost per degree of freedom of the robot. It is reasonable to assume that four degrees of freedom are required for assembly line robots.

Select the required number of shifts SH, and the number of parts to be assembled at each station NS_i, for each assembly i, i=1,2,...,NP such that there is sufficient capacity to meet the production requirements. That is, $\sum_{i=1}^{NP} VS_i*TP_i/3600 =< HR*PE*SH$ where $TP_i=NS_i*(TR+PQ*TD)$. The number of stations required in the assembly machine is, $NSR=\max[NA_i/NS_i]$, i=1,2,...,NP. Again we have buffers of size $BI=\lceil 0.50*TD/TR \rceil$ located between all stations. The required initial investment is

(20) $I_1=NSR*(CR+CT) + CM*\sum_{i=1}^{NP} NT_i + (CG+CC(1+BI))* \sum_{i=1}^{NP} (NA_i/NS_i)$.

If design changes are made then the robot part feeders (CM) and the robot grippers (CG) need to be changed. Labour costs consist, as in model 3b, of operator and supervisor costs. (Notice that if assembly i has NA_i parts and NS_i parts are assembled at each station, then NA_i/NS_i stations are required to complete the assembly.) Therefore the annual labour costs are;

(21) $WT = \sum_{i=1}^{NP} ((NA_i/NS_i)*NR*WA+NOS*WS)*(VS_i*TP_i*NS_i/3600)/(HR*PE)$.

Example 4 - model RW

This time we will produce the two assemblies, for the next seven years, on a single transfer line with robot workheads. In addition, a new assembly will be introduced in year 4. This assembly will have NA_3=8 parts (of which NT_3=6 are different). Initially the total market demand is 700000 units and, like the other assemblies, that demand will grow by 10% each year. All three assemblies will have a part redesigned each year. Annual production requirements are:

year, t	1	2	3	4	5	6	7
$VS_{1,t}$	127500	140250	154275	169702	186672	205340	225874
$VS_{2,t}$	153000	168300	185130	203643	224007	246408	271049
$VS_{3,t}$				700000*0.17=119000	130900	143990	158389
NS_1	2	2	2	2	2	2	2
NS_2	2	2	2	2	2	2	2
NS_3				2	2	2	2
$\Sigma VS_i*TP_i/3600$	1169	1286	1414	2051	2257	2482	2730
SH	1	1	1	2	2	2	2

where $TP_1=TP_2=2(6+0.05*30)=15$ seconds.

Clearly 1 shift is required in years 1 to 3 and 2 shifts are required thereafter. (Recall that the capacity of a shift is HR*PE=1900 hours.) The maximum number of stations required is NSR=max(6/2,10/2)=5 and so the required initial investment (from equation 20) is

$CR=50000+4*10000=90000$, $BI=\lceil 0.5*30/6 \rceil = 3$,

$I_1=5(90000+16000)+5000(6+8)+(1700+1500*4)*(6/2+10/2)=\$661600$.

Additional investments of 2(CM+CG)=$6400 are required in years 2 and 3 because of part design changes in assemblies 1 and 2. With the introduction of assembly 3 in year 4 new part feeders (CM), grippers (CG) and carriers

(CC) are needed. The new investment is NT_3*CM+(NA_3/NS_3)*(CG+CC(1+BI)) = $60800 plus $6400 for part design changes in assemblies 1 and 2. Finally additional investments of $9600 are required in years 5,6 and 7 because of part design changes in all 3 assemblies.

Using equations 21, 1, 2 and 3 to calculate labour costs, revenues, depreciation and cash flows gives:

Year,t	REV_t	LAB_t	I_t	DEP_t	$ATCF_t$
1	$182325	$83954.28	$661600	132320	-$549649.57
2	200557.5	92349.70	6400	107136	101379.08
3	220613.25	101584.67	6400	86988.8	99812.67
4	320024.58	146728.10	67200	83031.04	69990.30
5	352027.03	161400.91	9600	68344.83	132113.60
6	387229.74	177541.00	9600	56595.87	138851.59
7	425952.71	195295.10	9600	47196.69	147673.24
			770400	581613.23	

The book value at the end of year 7 is $188786.77. Substituting these results into equations 4 to 7 gives;

NPV = -$102629.75, AE = -$142359.74

IRR = 0.122, PB = 6 years.

At a discount rate of 0.20 this assembly machine is not a profittable investment.

5. RAC ROBOT ASSEMBLY CELL (Figure 1(f)

The robot assembly cell uses two robots. Each of these sophisticated robots has six degrees of freedom. While one robot is assembling a part, the other robot can change grippers and pick up the next part. If the assembly cell is carefully designed, the average time to complete a good assembly i, is TP_i=NA_i*(TR/2+PQ*TD). As always, select SH such that

$$\sum_{i=1}^{NP} VS_i*TP_i/3600 =< HR*PE*SH.$$

(Of course if there is insufficient capacity over 3 shifts, a second assembly cell would be needed.) The required initial investment is:

(22) $I_1=2*CR+\sum_{i=1}^{NP}(CC+NT_i*(CM+CG))$

If a part is redesigned then the part feeder (CM) and robot gripper (CG) will have to be changed. If one supervisor is assigned to monitor each robot assembly cell, the annual labour cost is:

(23) $WT=WS*\sum_{i=1}^{NP}(VS_i*TP_i/3600)/(HR*PE)$.

Example 5 - model RAC

Now we will produce the assemblies discussed in example 4, in a robot assembly cell. The average assembly times are $TP_1=6(6/2+0.05*30)=27$ seconds, $TP_2=45$ and $TP_3=36$. A capacity check shows:

Year, t	1	2	3	4	5	6	7
$VS_{1,t}$	127500	140250	154275	169702	186672	205340	225874
$VS_{2,t}$	153000	168300	185130	203643	224007	246408	271049
$VS_{3,t}$				119000	130900	143990	158389
$\Sigma VS_{i,t}*TP_i/3600$	2869	3156	3471	5008	5509	6060	6666
SH	2	2	2	3	3	2 mach 2 shift	2 mach 2 shift

Notice that in years 6 and 7 there is insufficient capacity with one assembly cell, and so a second assembly cell is needed. From equation 22 the required initial investment is (CR=50000+6*10000=$110000);

$I_1=2*110000+1500+6(1700+1500)+1500+8(1700+1500)=\$267800$,

with additional investments of $6400 in years 2,3 and 4 because of part design changes in assemblies 1 and 2. In year 4 assembly 3 is introduced, necessitating an investment of $NT_3*(CM+CG)+CC=\$20700$. An additional investment of $9600 is required in year 5 because of part design changes in the three assemblies. In year 6 a new robot assembly cell is required at cost

$I_6=2*CR+\sum_{i=1}^{3}(CC+NT_i(CM+CG)) = \$288500$.

As well, part design changes require an investment of $9600 for the original cell. Finally in year 7 an additional investment of 2*$9600 is required because of part changes. Equations 23, 1, 2 and 3 can be used to calculate labour costs, revenues, depreciation and cash flows.

Year, t	REV_t	LAB_t	I_t	DEP_t	$ATCF_t$
1	$182325	$60400	$267800	53560	-$173221
2	200557.5	66442	6400	44128	91720.5
3	220613.25	73074	6400	36582.4	96756.5
4	320024.58	105432	27100	34685.92	115529.9
5	352027.03	115979	9600	29668.74	143896.3
6	387229.74	127579	298100	83354.99	-108967.6
7	425952.71	140337	19200	70523.99	180379.0
			634600	352504.04	

The book value at the end of year 7 is $282095.96. Substituting these results into equations 4 to 7 gives;

NPV = $181455.89 , AE = $251701

IRR = 0.556, PB ≈ 1.8 years.

Obviously the robot assembly cell is an excellent investment for this situation.

3. DECISION ANALYSIS METHODOLOGY

The application of decision analysis often takes the form of an iterative procedure called the Decision Analysis Cycle (see Figure 2). The procedure is divided into three phases. In the first (deterministic) phase, the variables affecting the decision are defined and a model showing the relationships between the variables is developed. The importance of each variable is also determined. In the second (probabilistic) phase uncertainty (that is, probabilities) is encoded on the more important variables. The associated probability distribution of the outcome variable is then determined. Then, the principles of stochastic dominance are used to determine the "best" decision from the probability distributions of the outcome variable for each alternative. The third (informational) phase uses the results of the first two phases to determine the economic value of eliminating uncertainty in each of the important variables. If there are profitable sources of information, then the decision should be to gather the

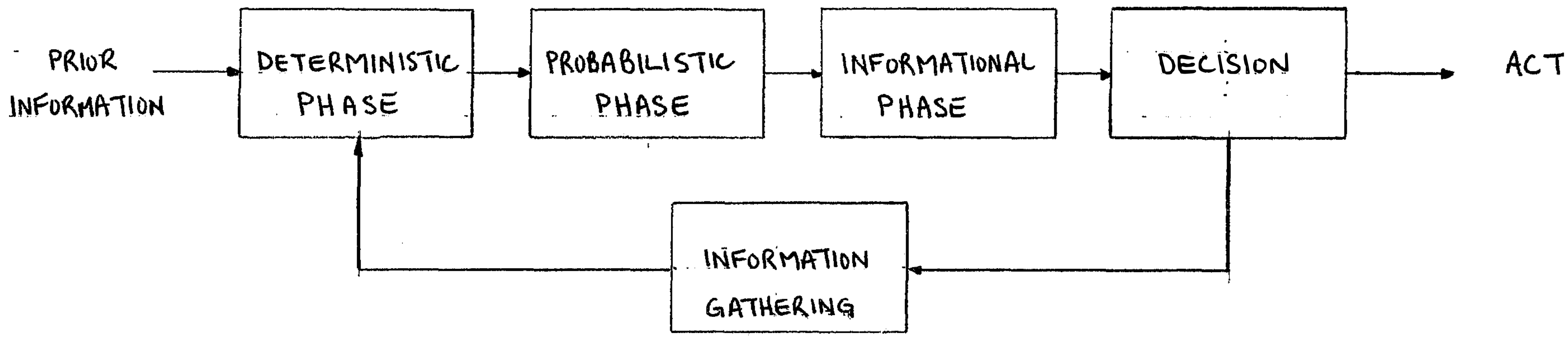


FIGURE 2 - The Decision Analysis Cycle
(p. 9, Howard and Matheson [1983]

new information. Hence the design and execution of the information-gathering program follow. Often the new information requires revisions to the original analysis and so the first three phases are repeated. (Usually the modifications are slight.) This iterative procedure is repeated until there are no longer any profitable sources of new information. At this point the final decision is made. (Based on pp. 8-9 of Howard and Matheson [1983].)

4. SELECTING THE ASSEMBLY MANUFACTURING SYSTEM

We will now use the decision analysis methodology of section 3 and the models of section 2, to select the "best" assembly manufacturing system.

i) Deterministic Phase

The variables affecting the decision and the models relating these variables were developed in section 2. First we will determine the annuity equivalents (AE), internal rates of return (IRR) and paybacks (PB) for the five assembly systems under the "most likely" conditions. To do this, the decision maker's specialists are asked for the most likely values of all the variables. Suppose that the data in Appendix 2 are the most likely values for the variables. The results of using these estimates in the models developed above, are presented in Tables 1 and 2. Since the appropriate criterion is the Annuity Equivalent (AE), a Free Transfer Line with Robot Workheads (RW) should be used. The second best system is the Robot Assembly Cell (RAC). Notice that if the criterion is IRR or PB then a Manual Assembly system (MA) would be selected. Second choice would be RW. Clearly, using the wrong criterion will lead to the wrong assembly system.

Of all the variables defined in section 2, sixteen are stochastic variables, in that at the time the decision is to be made, they cannot be estimated exactly. Another eighteen variables are called deterministic

Table 1
Results of Deterministic Phase - Results Under Most Likely Conditions

Assembly System	AE	IRR	PB
1. MA - Manual Assembly	$251670	44%	3.4 years
2. MAM - Manual Assembly with Mechanical Assistance	285819	22	> 5
3. SPW - Assembly Machines with Special Purpose Workheads	-678363	4	> 6
4. RW - Assembly Machines with Robot Workheads	845477	23	5.06
5. RAC - Robot Assembly Cell	352684	18	6.16

Table 2 - Ranking FMS's From Table 1

	Criterion		
Ranking	AE	IRR	PB
1 - Best	RW	MA	MA
2	RAC	RW	RW
3	MAM	MAM	MAM
4	MA	RAC	RAC
5 - Worst	SPW	SPW	SPW

variables because they can be accurately estimated. Finally there are three output variables - namely AE, IRR and PB. We now wish to study the sensitivities of the output variable AE, to each of the stochastic variables. By so doing, we can determine which of the stochastic variables are the more important ones. If the output variable is sensitive to changes in a stochastic variable, then that stochastic variable is called an important stochastic variable. If the output variable is not sensitive to changes in a stochastic variable, then the stochastic variable will be treated as a deterministic variable. To illustrate; suppose the decision-maker's experts gave the most likely values and ranges shown in Appendix 2. Table 3 shows the resulting sensitivities. These sensitivities were calculated as follows. A stochastic variable was set to its low value and all other variables were set to their most likely values. Using the models of section 2, AE's were calculated for all five assembly systems. The average AE, $\overline{AE}$; the mean absolute deviation, MAD, of AE; and the ratio MAD/$\overline{AE}$ were then calculated. (This ratio is a measure of risk per unit of return.) The stochastic variable was then set to its high value and the procedure was repeated. The average(MAD/$\overline{AE}$) is then calculated. Those stochastic variables which produced a large average(MAD/$\overline{AE}$) are called important stochastic variables because they have an important effect on the variabilities of the AE's for the five assembly systems. The stochastic variables which produced a small average(MAD/$\overline{AE}$) do not have an important effect on the variability of the AE's and so can be treated as deterministic variables. From Table 3 one can see that the most important stochastic variable is the annual demand for the assemblies, MS. Other stochastic variables such as market share, MSHARE, and market growth, MGROW, which affect the annual demand, are also very important. (These three variables emphasize the great importance of demand, in the selection of the best FMS.) Next in importance are the project lives and the risk-free interest rate, IR; followed by the number of new assemblies introduced each year, NAP, and the number of annual part design changes, ND. Finally there are other production variables such as assembly times, part quality, etc. Notice that the important stochastic variables are either variables which measure the "required flexibility" of the assembly system, or are financial variables. (Recall that flexibility has three components - flexibility to meet changing demands (MS, MSHARE, MGROW); flexibility to accomodate new products (NAP); and flexibility to modify products (ND).)

In summary, in the deterministic phase a model was developed, a most likely case was analyzed, and the important stochastic variables were identified.

ii) The Probabilistic Phase

Since some of the variables are stochastic, the output variable, AE, for each assembly system will also be stochastic. To encode the uncertainty in all of the important stochastic variables, probability density functions(pdf's) are estimated for each of them. These pdf's are obtained by asking appropriate questions of the experts within the firm and, if necessary, from outside the firm. (Actually it is usually easier to estimate the cumulative density function (cdf). See, for example, Spetzler and Stael von Holstein [1975].) By systematically substituting all possible combinations of variable values into the models, the pdf for AE for each of the five assembly systems can be calculated. A systematic representation of this procedure is given in Figure 3. Each path represents one particular setting of all the variables. Two points should be made here. First; care should be taken when deciding which variables are stochastic and which are

Table 3

Deterministic Phase Results - Sensitivities of AE's to Stochastic Variables

Variable	Most Likely Case	Range Low	Range High	Average (MAD/AE) *100	Rank
NP	5	3	5	11.78	10
NAP	1	1	2		
	0	0	1	25.10	4
	1	1	1		
	0	0	0		
MS	750000	500000	900000		
	900000	700000	1000000	69.15	1
	700000	450000	1000000		
	550000	350000	650000		
	300000	200000	400000		
	500000	400000	600000		
	300000	200000	400000		
	800000	600000	900000		
	750000	600000	850000		
MGROW	0.10	0.07	0.10	8.27	11
MSHARE	0.17	0.15	0.17	18.27	6
Project Lifes	MA = 4 yr	4	7		
	MAM =5	5	8	32.22	2
	SPW =6	6	9		
	PW = 7	7	10		
	RAC =8	8	12		
TX	0.40	0.35	0.45	12.76	9
k	0.10	0.08	0.12	31.25	3
TA	10 sec	9	10	30.66	
TM	8	7	8	29.22	7
TW	5	4	5	2.98	
TR	6	5	6	17.45	
TD	30	27	30	4.11	
PE	0.95	0.95	0.98	6.27	12
PQ	0.05	0.035	0.05	13.59	8
ND	1	1	2	23.88	5

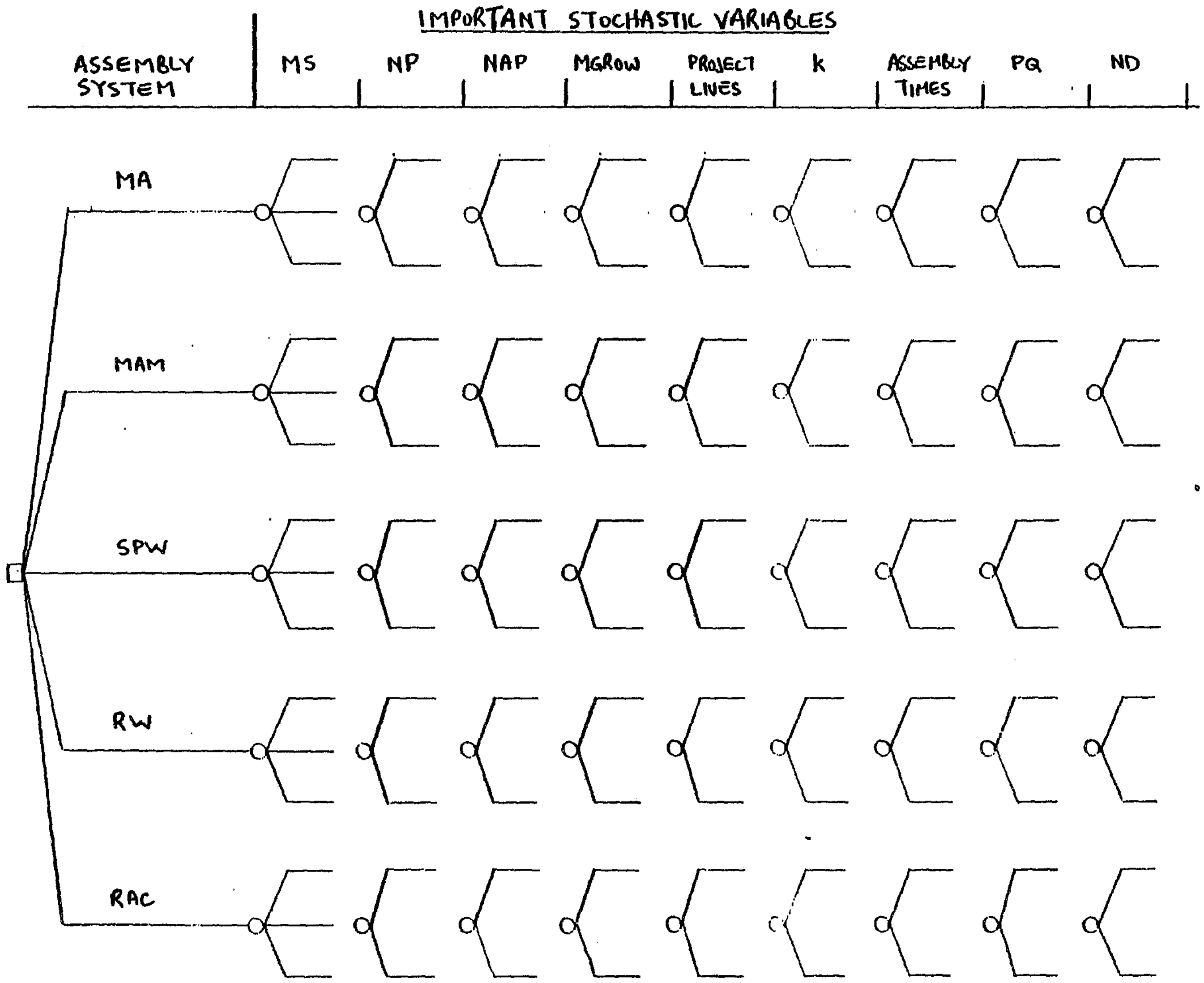


Figure 3 Decision Tree Structure ($5 \times 3 \times 2^8 = 3840$ branches)

deterministic, because the tree grows very rapidly when there are large numbers of stochastic variables. Second, we usually estimate a cumulative density function for each stochastic variable and then approximate the cumulative by two, three or four values. Two values are used if the deterministic phase shows that the variable is an important stochastic variable. If the variable is a very important stochastic variable then three or four values are used. Again as few values as possible are used to keep the decision tree manageable. Based on the results of the sensitivity analysis done in the deterministic phase (Table 3) we will use three branches for the annual demand MS, and two branches for NP, NAP, MGROW, Project Lives, k, TA, TM, TW, TR, PQ and ND. The variables PE, TD and TX will be deterministic variables because they have a smaller effect on the variability of the AE's and because they are relatively easy to estimate. Note that another analyst might have used fewer stoc astic variables (say MS, Lifes, IR, NAP, ND, and NP) with more branches for each variable. In general one should use as many stochastic variables and branches as the computer resources permit. (There are 3840 branches in our decision tree.)

We can now determine the cumulative density function of the annuity equivalent, AE, for each of the five manufacturing systems. Using the pdf's from Appendix 3, our computer program calculated the cdf's shown in Figure 4. Looking, for example, at the cdf for the robot assembly machine we see that there is a 50 - 50 chance that the annuity equivalent will be above or below $750000, and there is a 20% chance that AE will exceed $1.25 million. To order the manufacturing systems from best to worst (based on the cdf's) we will use the following two step procedure. First; use first-order, second-order and third-order stochastic dominance (SD) to order the systems. (See Appendix 4 for a review of stochastic dominance.) Second; if SD doesn't

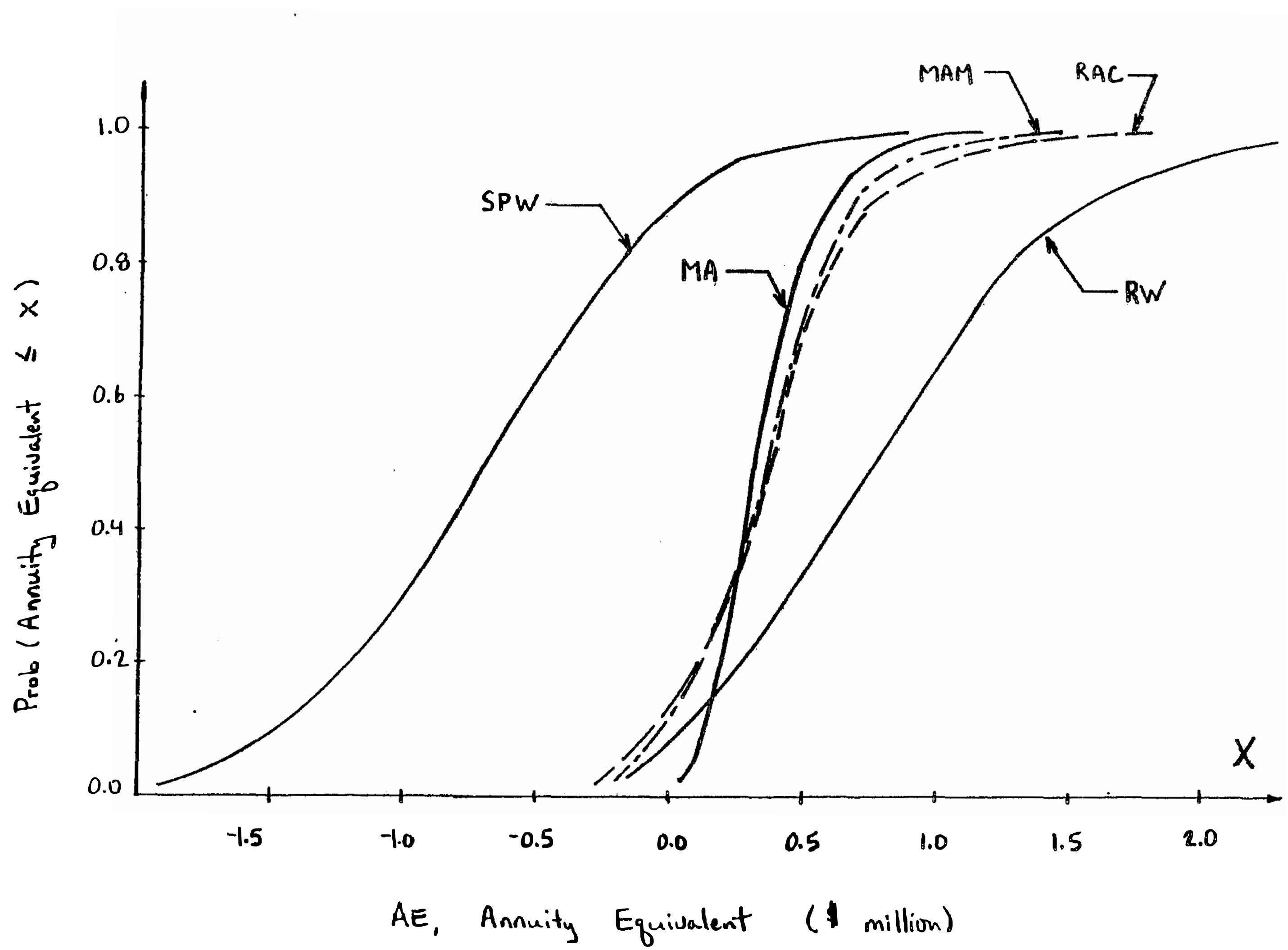


Figure 4 Cumulative Density Functions of Annuity Equivalents for Five Assembly Manufacturing Systems

exist between some systems, estimate the risk attitude of the decision-maker and use this to order the remaining systems. From Figure 4, we see that the assembly machine with special purpose workheads, SPW, is the worst manufacturing system (using the principle of first-order SD). It appears that RW, the assembly machine with robot workheads, is the best system. Unfortunately, we cannot use SD to prove this. Since SD does not exist for RW, MA, MAM and SPW we need to estimate the risk attitude of the decision-maker.

Risk preference is the decision-maker's attitude toward risk. It should be measured independently of any specific project and is usually encoded in the form of a preference curve. Suppose, for the sake of illustration, that our decision-maker has the preference curve shown in Figure 5. This means that he is indifferent between a lottery with equal chances of winning $3 million or losing $2 million, and the status quo. (0.5*U(3) + 0.5*U(-2) = 0.5 + 0 = U(0) .) That is, he accepts a certain value smaller than the expected value of the lottery. For any lottery there is some riskless value, called the certainty equivalent, which would make the decision-maker indifferent. When the certainty equivalent is less than the expected value of the lottery (as it usually is) we say that the decision-maker is risk averse. As a consequence of a set of risk preference axioms, the decision-maker's rating of any lottery can be computed by multiplying the preference value of any possible value in the lottery by the probability of that value and then summing over all possible values. This rating is called the expected preference of that lottery.

Table 4 calculates the expected preferences for the five assembly systems. The first two columns describe the pdf of AE (obtained from Figure 4) for the robot assembly cell. The next column gives the preference values

Table 4 - Calculation of Expected Preferences For Five Assembly Systems

RAC - Robot Assemby Cell

Maximum AE = 1,916,085
Minimum AE = - 419,789.3
Interval Width = 116,793.6

AE (Midpoint)	Probability	Preference	Prob. * Pref.
- 361,391	0.00309	0.41891	0.00129
- 244,598	0.00900	0.44477	0.00400
- 127,804	0.02533	0.47016	0.01191
- 11,011	0.05928	0.49507	0.02935
105,783	0.12412	0.51953	0.06448
222,577	0.15298	0.54353	0.08315
339,370	0.15915	0.56709	0.09025
456,164	0.14750	0.59021	0.08706
572,958	0.10853	0.61290	0.06652
689,751	0.07448	0.63518	0.04731
806,545	0.05201	0.65704	0.03417
923,339	0.03269	0.67850	0.02218
1,040,132	0.02640	0.69955	0.01847
1,156,926	0.01303	0.72022	0.00938
1,273,719	0.00541	0.74051	0.00401
1,390,513	0.00242	0.76042	0.00184
1,507,307	0.00204	0.77996	0.00159
1,624,100	0.00164	0.79914	0.00131
1,740,894	0.00035	0.81797	0.00029
1,857,688	0.00052	0.83647	0.00043

Extended Preference = 0.57900

Similarly

Assembly System	Annuity Equivalent Mean	Variance	Expected Preference	Certainty Equivalent	Rank
MA	$365093	3.650E+10	0.5716	361,982	3
MAM	363141	8.357E+10	0.5705	356,459	4
SPW	-659597	2.808E+11	0.3454	-681,874	5
RW	891049	3.696E+11	0.6673	862,123	1
RAC	407069	9.770E+10	0.5790	399,259	2

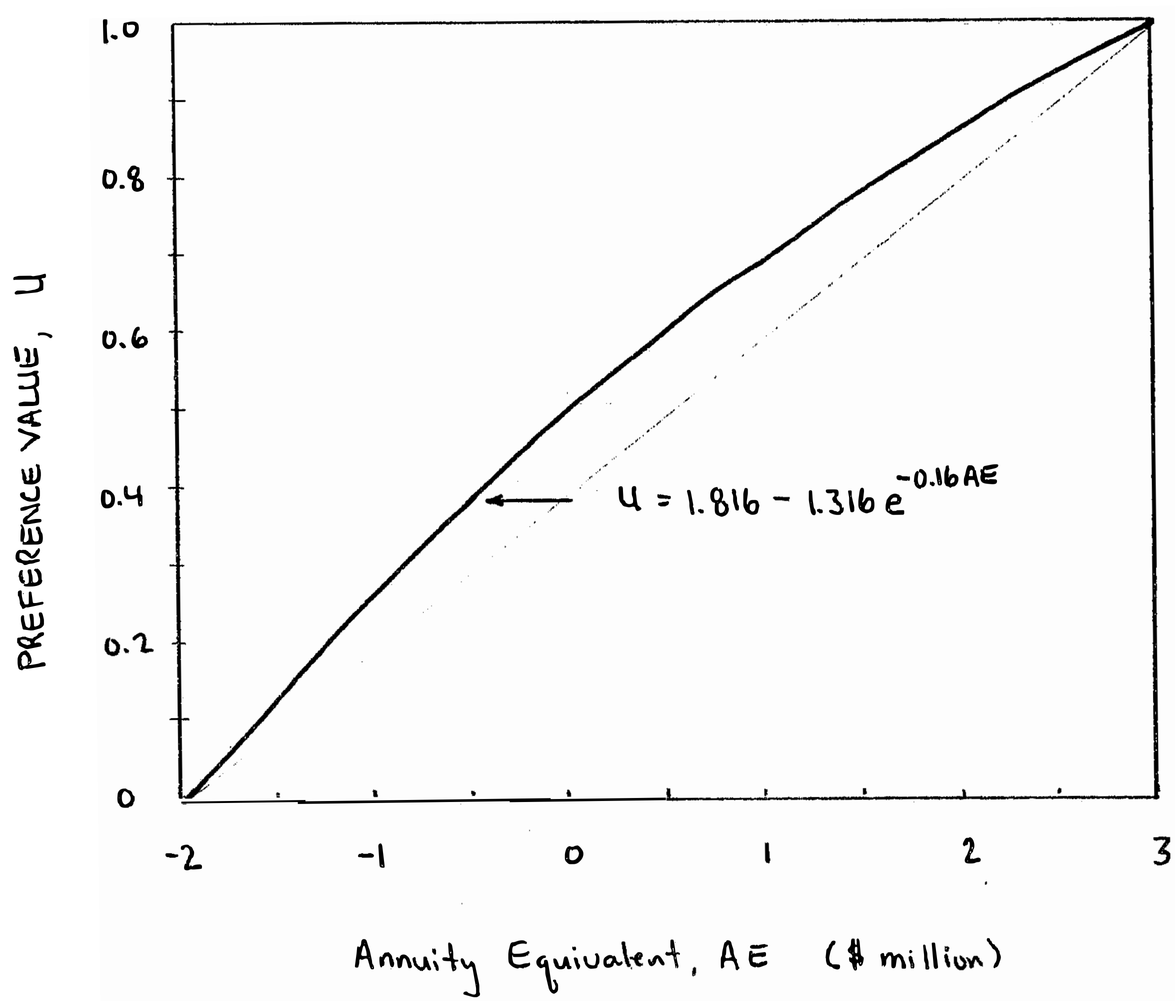


Figure 5 A Typical Preference Curve For $-2 \leq AE \leq 3$ ($ million)

(obtained from Figure 5) for the AE's of the first column, from which the expected preference can be calculated. If the decision-maker's risk preference is accurately described by the preference curve of Figure 5, the best assembly system is the assembly machine with robot workheads, followed by the robot assembly cell, manual assembly, manual assembly with mechanical assistance and the assembly machine with special purpose workheads. (It is interesting to note that the same ranking would have been obtained if the criterion was the expected annuity equivalent. This is because this decision-maker is not very risk averse.

ii) Informational Phase

In this phase the uppermost question is; "Should more information be gathered before the final decision is made?". The value of gathering additional information can be measured by evaluating a revised decision tree. A special case is the case of perfect information - that is, the value of an important stochastic variable will be known exactly after perfect information is gathered. The value of perfect information provides an upper limit on the amount of resources that can be expended, in further studies and analysis, to reduce the uncertainty in a variable. The higher the value of perfect information, the more important the variable. The value of information is the difference in the output variable between the best decision without information and the best decision with new information. The information has no value if it results in the same decision as in the without information case.

In the example we have been discussing the value of perfect information is zero for all the important stochastic variables (considered alone). Eliminating the uncertainty in any one stochastic variable does not change the decision. The best assembly system is still RW. However with perfect information about MS and MGROW (that is - the total demand) the best FMS might be RAC. The value of perfect information about MS and MGROW is

AE(perfect information about MS and MGROW) - AE(no information)

= \$908450.87 - \$891049.5 = \$17401.37

where the first term is obtained by revising the original decision tree and the second term is the expected AE of the best decision from the original tree.

iv) Decision

If all uncertainty could be eliminated about future demands, at a cost of less than \$17401.37 then it would be profitable to do the necessary studies. A study which would eliminate part of the uncertainty would be worth less. It is unlikely that such studies could be done for less than \$17401.37. Hence they shouldn't be undertaken. Rather the final decision should be made. In this example the "best" decision is to use a robot assembly machine (RW) to manufacture all assemblies.

6. Summary and Extensions

The problem in this paper was to select the "best" flexible manufacturing system for a particular situation. There was a considerable amount of uncertainty about the amount of flexibility that was required (demands, new products, and product changes), about the financial considerations (discount rate, project lives) and about the production variables (assembly times, quality, etc.). Simple mathematical models of five potential FMS's were developed. The important stochastic variables were identified, and estimates for all variables were obtained from experts. Cumulative density functions of the annuity equivalent for each potential FMS were evaluated and the "best" FMS was selected (using stochastic dominance or the appropriate preference curve). An example was worked and it showed that the "overwhelming best" FMS was a robotic assembly line, while the next best FMS was a robotic assembly cell.

We have illustrated the proper way to evaluate alternative flexible manufacturing systems. It is considerably more work than a simple cost - benefit analysis or a deterministic payback calculation. However it does provide valuable insight into the amount of flexibility that is required, the important decision variables, and the value of doing studies and gathering additional information. In another project we are investigating the general conditions under which certain types of FMS's are "best". We believe that this paper and our other work show that traditional financial evaluation models, if properly used, do encourage the adoption of robotic FMS's.

Possible extensions to this work would be:

i) Add lot-sizing and sheduling considerations to the mathematical models for the five FMS's. (It should be noted that these considerations would make the robotic assembly line, and the robotic assembly cell even more attractive.)

ii) Take account of the correlation between the stochastic variables; especially between the demands for various assemblies, and between demands and the financial varibles.

iii) Consider mixed manufacturing systems. For example, use a robotic assembly cell for assemblies 1, 2 and manual assembly for assembly 3, etc.

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Appendix 1 Data For Examples 1 To 4

Assembly, i	NA_i	NT_i	Initial Market Size, $MS_{i,1}$	$ND_{i,t}$
1	6 parts	6 parts	750000 assemblies/year	1 t=1,2,3,...
2	10	8	900000	1
3	8	6	700000	1

$MSHARE_i$ = 0.17 i=1,2,3
$MGROW_i$ = 0.10 i=1,2,3
$SP_{i,t}$ = $0.65 per assembly i=1,2,3 t=1,2,3,...

Assembly Machine	Life	Assembly Time
MA - Manual	4 years	TA = 10 seconds/part
MAM - Manual with mech. assistance	5	TM = 8
SPW - Special purpose workheads		
i) Non-buffered	6	TW = 5 TD = 30 seconds
ii) Buffered	6	TW = 5 TD = 30
RW - Robot assembly line (Buffered)	7	TR = 6 TD = 30
RAC - Robot assembly cell	8	TR = 6 TD = 30

Costs
CB = $7000
CT = 16000
CC = 1500
CF = 7000
CM = 5000
CW = 10000
C1 = 50000
C2 = 10000
CG = 1700

Plant Variables
PE = 0.95
PQ = 0.05
NR = 0.333 operators/station
NOS = 0.25 supervisors/machine
HR = 2000 hours/shift/year
WA = $40000 per year
WS = $55000 per year

Financial Variables
TX = 0.40
k = 0.20
D = 10 years

Appendix 2 Most Likely Values and Ranges for Variables Defined in Section 2

1. Deterministic Variables (Most Likely Values)

CB = $7000
CT = 16000
CC = 1500
CF = 7000
CM = 5000
CW = 10000
C1 = 50000
C2 = 10000
CG = 1700
WA = 40000
WS = 55000
HR = 2000
NR = 0.333
NOS = 0.25
D = 10
$SP_{i,t}$ = $0.65 i=1,2,...,9 t=1,2,... (For simplicity, the selling price for all assemblies is the same.)

Assembly, i	NA_i	NT_i
1	6 parts	6 parts
2	10	8
3	8	6
4	12	8
5	7	6
6	8	6
7	8	6
8	8	6
9	8	6

2. Stochastic Variables

Variable		Most Likely Value	Range Low	Range High
NP_1 = number of different assemblies to be manufactured in year 1		5	3	5
NAP_t = number of new assemblies to be manufactured in year t	t=2	...1	...1	...2
	t=3	...0	...0	...1
	t=4	...1	...1	...1
	t=5	...0	...0	...0
$MS_{i,1}$ = total annual demand for item i in year 1	i=1	750000	500000	900000
	i=2	900000	700000	1000000
	i=3	700000	450000	1000000
	i=4	550000	350000	650000
	i=5	300000	200000	400000
	i=6	500000	400000	600000
	i=7	300000	200000	400000
	i=8	800000	600000	900000
	i=9	750000	600000	850000
$MGROW_i$	i=1,2,...,9	0.10	0.07	0.10
$MSHARE_i$	i=1,2,...,9	0.17	0.15	0.17
Project Lifes	MA	4 years	4	7
	MAM	5	5	8
	SPW	6	6	9
	PW	7	7	10
	RAC	8	8	12
TX = Tax Rate		0.40	0.35	0.45
k = Risk-free interest rate		0.10	0.08	0.12

TA	10 seconds	9	10
TM	8	7	8
TW	5	4	5
TR	6	5	6
TD	30	27	30
PE	0.95	0.95	0.98
PQ	0.05	0.035	0.05
$ND_{i,t}$ = Annual Part Design Changes	1* i=1,2,...,9 t=1,2,3,4,5	1	2

*Each assembly will have 1 part design change every year, for 5 years, beginning in the next year after it is introduced.

Appendix 3 Probability Distributions For Important Stochastic Variables

Variable	(Value ; Probability), (Value ; Probability), ...	
NP_1	(5 ; 0.6)	(4 ; 0.4)
NAP_t	(1,0,1,0 ; 0.6)	(2,1,1,0 ; 0.4)
$MS_{i,1}$	(Most Likely Value from Appendix 2 ; 0.5)	
	(Low Value ; 0.3)	
	(High Value ; 0.2)	
$MGROW_i$	(0.10 ; 0.50)	(0.07 ; 0.50)
Project Lifes	(4,5,6,7,8 ; 0.5)	(7,8,9,10,12 ; 0.5)
k	(0.10 ; 0.60)	(0.12 ; 0.40)
TA,TM,TW,TR	(10,8,5,6 ; 0.6)	(9,7,4,5 ; 0.4)
PQ	(0.05 ; 0.60)	(0.035 ; 0.4)
ND	(1,1,... ; 0.60)	(2,2,... ; 0.40)

Appendix 4 Stochastic Dominance

The notion of stochastic dominance, SD, is quite old and was traced by Bawa [1982] to the work of Bernoulli in 1713. However, it was not until the beginning of the 1970's that SD was widely accepted. (See, for example, Hadar and Russell [1969], Hanoch and Levy [1969] and Rotschild and Stiglitz [1970].)

In its most general form, SD makes no assumptions about the probability distributions of the outcomes. Futhermore, when employing SD, one is not required to place excessive restrictions on the form of the decision-maker's risk preference curve. There are three SD criteria, corresponding to three classes of preference curves.

1. FSD, First-Order Stochastic Dominance. Let F(X) and G(X) be the cumulative density functions for the outcomes X of the two manufacturing systems F and G. Then system F will be preferred to system G by FSD if $F(X) \leq G(X)$ for all X and, for at least one value of X ($X=X_0$) the strict inequality holds $F(X_0) < G(X_0)$. FSD assumes only that decision-makers prefer more to less. Figure 6a shows an example of FSD. It is obvious that F dominates G because the cumulative of F always lies to the right of G.

2. SSD, Second-Order Stochastic Dominance. SSD compares areas under the cumulative density functions. System F is said to dominate system G by SSD if $\int_{-\infty}^{X} [G(t)-F(t)]dt > 0$ for all X, with at least one strict inequality. SSD assumes only that the decision-maker is risk averse. That is risk preferences are nondecreasing and that total preference must increase at a decreasing rate. (If U(X) is the risk preference curve, then $U' \geq 0$ and $U''<0$.) Figure 6b illustrates SSD. Over the entire range of X the cumulative area

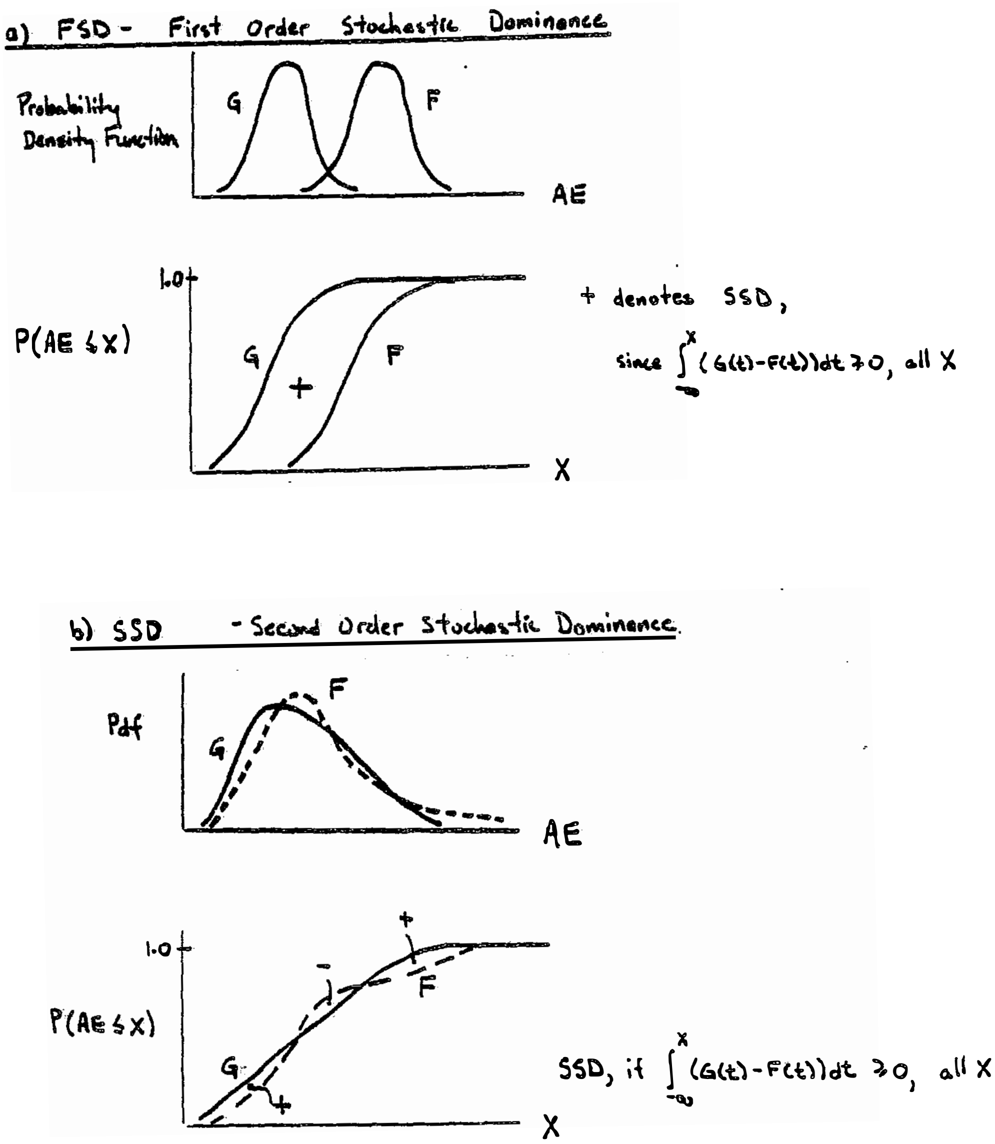

Figure 6 Principle of Stochastic Dominance

between the two density functions is positive (or zero), and so SSD concludes that all risk averse decision-makers prefer system F to G.

3. TSD, Third-Order Stochastic Dominance. F dominates G by TSD if $E[F] \geq E[G]$ and $\int_{-\infty}^{X}\int_{-\infty}^{V}[G(t)-F(t)]dtdV \geq 0$, for all X, with at least one strict inequality. In addition to the two assumptions made for SSD, one more assumption is necessary for TSD - namely that the preference curve exhibit decreasing absolute risk aversion. (That is $U''' \geq 0$.)

FSD is the strongest criterion, followed by SSD and TSD. This means that dominance by FSD implies dominance by SSD and TSD. Dominance by SSD implies dominance by TSD. (For a detailed discussion of SD see, for example, Hanoch and Levy [1969].) In short, SD is an important and powerful result. For the problems we are dealing with we will usually be able to use FSD and SSD to select the "best" FMS - a decision which is appropriate for all risk averse decision-makers.

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