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APPENDICES

APPENDIX A

TABLE A-1

PROGRAM LISTING FOR TESTING THE MODEL WITHOUT SPACE FACTOR

MODEL

```

MAX d4      ! max final output
ST
d4-d3<0
d3-d2<0
d2-d1<0

```

```

d1-8992m1=0
d2-6337m2=0
d3-2078m3=0
d4-1947m4=0

```

```

m1-x1<0
m2-x2<0
m3-3x3<0
m4-x4<0

```

```

x1<7
x2<4
x3<7
x4<7

```

```

x1>1
x2>1
x3>1
x4>1

```

```

m1<5
m2<5
m3<6
m4<7

```

```

end
gin d1
gin d2
gin d3
gin d4
gin x1
gin x2
gin x3
gin x4
gin m1
gin m2
gin m3
gin m4

```

REPORT SOLUTION

```

LP OPTIMUM FOUND AT STEP      13
OBJECTIVE VALUE =    12468.0000

```

SET	M3 TO <=	6 AT	1, BND=	0.1168E+05	TWIN=-0.1000E+31	28
SET	M1 TO >=	2 AT	2, BND=	0.1168E+05	TWIN= 8992.	34
SET	M2 TO <=	2 AT	3, BND=	0.1168E+05	TWIN= 0.1168E+05	41
SET	M3 TO >=	6 AT	4, BND=	0.1168E+05	TWIN= 0.1039E+05	43
SET	M2 TO >=	2 AT	5, BND=	0.1168E+05	TWIN=-0.1000E+31	44

NEW INTEGER SOLUTION OF 11682.0000 AT BRANCH 5 PIVOT 44
 BOUND ON OPTIMUM: 11682.00
 DELETE M2 AT LEVEL 5
 DELETE M3 AT LEVEL 4
 DELETE M2 AT LEVEL 3
 DELETE M1 AT LEVEL 2
 DELETE M3 AT LEVEL 1
 ENUMERATION COMPLETE. BRANCHES= 5 PIVOTS= 44

LAST INTEGER SOLUTION IS THE BEST FOUND
 RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 11682.00

VARIABLE	VALUE	REDUCED COST
D4	11682.000000	-1.000000
D3	12468.000000	0.000000
D2	12674.000000	0.000000
D1	17984.000000	0.000000
M1	2.000000	0.000000
M2	2.000000	0.000000
M3	6.000000	0.000000
M4	6.000000	0.000000
X1	2.000000	0.000000
X2	2.000000	0.000000
X3	2.000000	0.000000
X4	6.000000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	786.000000	0.000000
3)	206.000000	0.000000
4)	5310.000000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	5.000000	0.000000
10)	0.000000	0.000000
11)	0.000000	0.000000
12)	0.000000	0.000000
13)	0.000000	0.000000
14)	2.000000	0.000000
15)	5.000000	0.000000
16)	1.000000	0.000000
17)	6.000000	0.000000
18)	1.000000	0.000000

19)	1.000000	0.000000
20)	5.000000	0.000000
21)	3.000000	0.000000
22)	3.000000	0.000000
23)	0.000000	0.000000
24)	1.000000	0.000000

NO. ITERATIONS= 45
BRANCHES= 5 DETERM. = 1.000E 0

TABLE A-2

PROGRAM LISTING FOR TEST MODEL WITH SPACE FACTOR

MODEL

MAX d4 ! max final output

ST

d2-d1<0

d3-d2<0

d4-d3<0

d1-8992m1=0

d2-6337m2=0

d3-2078m3=0

d4-1947m4=0

m1-x1<0

m2-x2<0

m3-3x3<0

m4-x4<0

x1<7

x2<4

x3<7

x4<7

x1>1

x2>1

x3>1

x4>1

m1<5

m2<5

m3<6

m4<7

s1-0.5x1>0

s1-m1>0

s2-0.5x2>0

s2-0.5m2>0

s3-0.5x3>0

s3-0.2m3>0

s4-0.5x4>0

s4-m4>0

s1+s2+s3+s4<10

end
gin d1
gin d2
gin d3
gin d4
gin x1
gin x2
gin x3
gin x4
gin m1
gin m2
gin m3
gin m4

REPORT SOLUTION

LP OPTIMUM FOUND AT STEP 13
OBJECTIVE VALUE = 12468.0000

SET	X1 TO <=	1 AT	1, BND=	8992.	TWIN=	0.1162E+05	26
SET	M2 TO <=	1 AT	2, BND=	6337.	TWIN=-	0.1000E+31	28
SET	X4 TO <=	3 AT	3, BND=	5841.	TWIN=-	0.1000E+31	30

NEW INTEGER SOLUTION OF 5841.00000 AT BRANCH 3 PIVOT 30
BOUND ON OPTIMUM: 11615.10

DELETE	X4 AT LEVEL	3					
DELETE	M2 AT LEVEL	2					
FLIP	X1 TO >=	2 AT	1 WITH BND=	11615.098			
SET	M2 TO >=	2 AT	2, BND=	0.1148E+05	TWIN=	6337.	32
SET	M3 TO >=	6 AT	3, BND=	0.1129E+05	TWIN=	0.1039E+05	34
SET	M4 TO <=	5 AT	4, BND=	9735.	TWIN=-	0.1000E+31	36

NEW INTEGER SOLUTION OF 9735.00000 AT BRANCH 6 PIVOT 36
BOUND ON OPTIMUM: 10390.00

DELETE	M4 AT LEVEL	4					
DELETE	M3 AT LEVEL	3					
DELETE	M2 AT LEVEL	2					
DELETE	X1 AT LEVEL	1					
ENUMERATION COMPLETE. BRANCHES=			6	PIVOTS=	36		

LAST INTEGER SOLUTION IS THE BEST FOUND
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 9735.000

VARIABLE	VALUE	REDUCED COST
D1	17984.000000	0.000000
D2	12674.000000	0.000000

D3	12468.000000	0.000000
D4	9735.000000	-1.000000
X1	2.000000	0.000000
X2	2.000000	0.000000
X3	2.000000	0.000000
X4	5.000000	0.000000
M1	2.000000	0.000000
M2	2.000000	0.000000
M3	6.000000	0.000000
M4	5.000000	0.000000
S1	2.800000	0.000000
S2	1.000000	0.000000
S3	1.200000	0.000000
S4	5.000000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	5310.000000	0.000000
3)	206.000000	0.000000
4)	2733.000000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	0.000000	0.000000
11)	0.000000	0.000000
12)	0.000000	0.000000
13)	5.000000	0.000000
14)	2.000000	0.000000
15)	5.000000	0.000000
16)	2.000000	0.000000
17)	1.000000	0.000000
18)	1.000000	0.000000
19)	1.000000	0.000000
20)	4.000000	0.000000
21)	3.000000	0.000000
22)	3.000000	0.000000
23)	0.000000	0.000000
24)	2.000000	0.000000
25)	1.800000	0.000000
26)	0.800000	0.000000
27)	0.000000	0.000000
28)	0.000000	0.000000
29)	0.200000	0.000000
30)	0.000000	0.000000
31)	2.500000	0.000000
32)	0.000000	0.000000
33)	0.000000	0.000000

APPENDIX B

TABLE B-1**REAL DATA FOR TESTING THE APPLICATION OF THE MODEL**

OPERATION i	AVG YLD	CUM YLD	% EFFN	% SAM	SPACE FACTOR	Operator available	Tooling available
PRE-TRIM	100%	75.24%	95%	100%	1.0	< 35	< 15
PRE-CLEAN	100%	75.24%	95%	100%	1.0	< 30	< 10
LOAD HEAD	100%	75.24%	95%	100%	1.0	< 30	< 10
GIMBAL BOND	100%	75.24%	95%	100%	1.0	< 30	< 10
FLEX BOND	100%	75.24%	95%	100%	1.0	< 30	< 10
LEAD BOND	100%	75.24%	95%	100%	1.0	< 30	< 10
CAOT LEAD	100%	75.24%	95%	100%	1.0	< 30	< 10
TACK TAIL	100%	75.24%	95%	100%	1.0	< 30	< 10
OVEN					6.0		
UNLOAD JIT TOOL	100%	75.24%	95%	100%	1.0	< 35	< 20
LOAD IAT ARM	100%	75.24%	95%	100%	1.0	< 30	< 10
PUSH FLEX & SPOT CLAEN	100%	75.24%	95%	40%	1.0	< 30	< 10
HEAD SET	100%	75.24%	95%	100%	1.0	< 30	< 10
AUTOGRAM	100%	75.24%	95%	100%	1.5	< 18	< 5
SAAM	100%	75.24%	95%	100%	1.5	< 17	< 7
CUT FLEX	100%	75.24%	95%	100%	1.0	< 30	< 10
MRE & REMOVE PRE SHUT	100%	99.00%	90%	100%	1.5	< 18	< 5
FLEX SHUNTING	100%	99.00%	90%	100%	1.0	< 30	< 10
UNLOAD IAT ARM & FOLD FLAPPER	100%	99.00%	90%	100%	1.0	< 45	< 15

TABLE B-2

PROGRAM LISTING FOR TESTING THE APPLICATION OF THE MODEL

MODEL

```

max d18 !obj. func. max dn
st
!1. d(i+1)<=di    i=1,...,n-1

d18-d17<0
d17-d16<0
d16-d15<0
d15-d14<0
d14-d13<0
d13-d12<0
d12-d11<0
d11-d10<0
d10-d9<0
d9-d8<0
d8-d7<0
d7-d6<0
d6-d5<0
d5-d4<0
d4-d3<0
d3-d2<0
d2-d1<0

!2. case3 operator working with tooling
d1-9937m1<0
d2-6605m2<0
d3-5104m3<0
d4-3768m4<0
d5-3482m5<0
d6-3542m6<0
d7-5584m7<0
d8-5479m8<0
d9-5734m9<0
d10-5584m10<0
d11-6004m11<0
d12-10958m12<0
d13-5576m13<0
d14-2867m14<0
d15-13059m15<0
d16-5538m16<0
d17-10349m17<0
d18-6537m18<0

m1-x1=0
m2-x2=0
m3-x3=0
m4-x4=0
m5-x5=0
m6-x6=0
m7-x7=0
m8-x8=0
m9-x9=0
m10-x10=0
m11-x11=0
m12-x12=0
m13-x13=0
m14-x14=0
m15-x15=0
m16-x16=0
m17-x17=0
m18-x18=0

!3.space si >= si(operator) multiply Xi

```

```

s1-X1>0
s2-X2>0
s3-X3>0
s4-X4>0
s5-X5>0
s6-X6>0
s7-X7>0
s8-X8>0
s9-X9>0
s10-X10>0
s11-X11>0
s12-X12>0
s13-1.5X13>0
s14-1.5X14>0
s15-X15>0
s16-1.5X16>0
s17-X17>0
s18-X18>0

```

```
s1+s2+s3+s4+s5+s6+s7+s8+s9+s10+s11+s12+s13+s14+s15+s16+s17+s18<48
```

```
!bound on operator(xi)
```

```

x1<35
x2<30
x3<30
x4<30
x5<30
x6<30
x7<30
x8<30
x9<35
x10<30
x11<30
x12<30
x13<18
x14<17
x15<30
x16<18
x17<30
x18<45

```

```
x1+x2+x3+x4+x5+x6+x7+x8+x9+x10+x11+x12+x13+x14+x15+x16+x17+x18<37
```

```
! bounded on machine(mi)
```

```

m1<15
m2<10
m3<10
m4<10
m5<10
m6<10
m7<10
m8<10
m9<20
m10<10
m11<10
m12<10
m13<5
m14<7
m15<10
m16<5
m17<10
m18<15

```

```
END
```

```
!INTEGER PROGRAMMING
```

```

GIN D1
GIN D2
GIN D3
GIN D4
GIN D5
GIN D6
GIN D7
GIN D8
GIN D9
GIN D10

```

GIN D11
GIN D12
GIN D13
GIN D14
GIN D15
GIN D16
GIN D17
GIN D18

GIN X1
GIN X2
GIN X3
GIN X4
GIN X5
GIN X6
GIN X7
GIN X8
GIN X9
GIN X10
GIN X11
GIN X12
GIN X13
GIN X14
GIN X15
GIN X16
GIN X17
GIN X18

GIN M1
GIN M2
GIN M3
GIN M4
GIN M5
GIN M6
GIN M7
GIN M8
GIN M9
GIN M10
GIN M11
GIN M12
GIN M13
GIN M14
GIN M15
GIN M16
GIN M17
GIN M18

REPORT SOLUTION

LP OPTIMUM FOUND AT STEP 59
OBJECTIVE VALUE = 11243.9854

SET	M12 TO <=	1 AT	1.	BND=	0.1096E+05	TWIN=	0.1094E+05	75
SET	D4 TO <=	11475 AT	2.	BND=	0.1096E+05	TWIN=	0.1096E+05	78
SET	X2 TO >=	2 AT	3.	BND=	0.1096E+05	TWIN=	6605.	80
SET	X18 TO >=	2 AT	4.	BND=	0.1096E+05	TWIN=	6537.	82
SET	X15 TO >=	1 AT	5.	BND=	0.1096E+05	TWIN=	0.0000E+00	85
SET	M11 TO >=	2 AT	6.	BND=	0.1094E+05	TWIN=	6004.	88
SET	M12 TO >=	1 AT	7.	BND=	0.1094E+05	TWIN=	0.0000E+00	100
SET	M1 TO <=	1 AT	8.	BND=	9937.	TWIN=	0.1058E+05	104
SET	X14 TO >=	4 AT	9.	BND=	9937.	TWIN=	8601.	110
SET	M9 TO >=	2 AT	10.	BND=	9937.	TWIN=	5734.	112
SET	X4 TO <=	4 AT	11.	BND=	9937.	TWIN=	9660.	124
SET	X7 TO <=	3 AT	12.	BND=	9937.	TWIN=	9746.	131
SET	X4 TO >=	3 AT	13.	BND=	9937.	TWIN=	7536.	139
SET	M10 TO <=	3 AT	14.	BND=	9937.	TWIN=	9500.	152
SET	M13 TO <=	3 AT	15.	BND=	9937.	TWIN=	9501.	165
SET	X8 TO <=	3 AT	16.	BND=	9937.	TWIN=	9519.	178
SET	M9 TO <=	3 AT	17.	BND=	9937.	TWIN=	9660.	182
SET	X7 TO >=	2 AT	18.	BND=	9937.	TWIN=	5584.	191
SET	X16 TO >=	2 AT	19.	BND=	9937.	TWIN=	5538.	197
SET	M10 TO >=	2 AT	20.	BND=	9937.	TWIN=	5584.	207

SET	M13 TO >=	3 AT	21.	BND=	9605.	TWIN=	9937.	209
SET	M1 TO <=	0 AT	22.	BND=	0.0000E+00	TWIN=	9573.	221
NEW INTEGER SOLUTION OF 0.000000000E+00 AT BRANCH 22 PIVOT 221								
BOUND ON OPTIMUM: 10958.00								
FLIP	M1 TO >=	1 AT	22	WITH BND=	9573.1787			
SET	M8 TO >=	2 AT	23.	BND=	9280.	TWIN=	5479.	229
SET	M3 TO >=	2 AT	24.	BND=	9007.	TWIN=	5104.	231
SET	M6 TO <=	2 AT	25.	BND=	7084.	TWIN=	7816.	241
SET	X17 TO <=	1 AT	26.	BND=	7084.	TWIN=	7023.	246
SET	X17 TO >=	1 AT	27.	BND=	7084.	TWIN=	0.0000E+00	249
SET	X2 TO <=	2 AT	28.	BND=	7084.	TWIN=	7023.	251
SET	X14 TO <=	4 AT	29.	BND=	7084.	TWIN=	7023.	254
SET	M8 TO <=	2 AT	30.	BND=	7084.	TWIN=	7023.	258
SET	M11 TO <=	2 AT	31.	BND=	7084.	TWIN=	7023.	261
SET	X4 TO <=	3 AT	32.	BND=	7084.	TWIN=	7023.	264
SET	X7 TO <=	2 AT	33.	BND=	7084.	TWIN=	7023.	267
SET	X16 TO <=	2 AT	34.	BND=	7084.	TWIN=	7023.	270
SET	M10 TO <=	2 AT	35.	BND=	7084.	TWIN=	7023.	273
SET	X5 TO >=	3 AT	36.	BND=	7084.	TWIN=	6964.	278
NEW INTEGER SOLUTION OF 7084.00000 AT BRANCH 36 PIVOT 278								
BOUND ON OPTIMUM: 10958.00								
DELETE	X5 AT LEVEL	36						
DELETE	M10 AT LEVEL	35						
DELETE	X16 AT LEVEL	34						
DELETE	X7 AT LEVEL	33						
DELETE	X4 AT LEVEL	32						
DELETE	M11 AT LEVEL	31						
DELETE	M8 AT LEVEL	30						
DELETE	X14 AT LEVEL	29						
DELETE	X2 AT LEVEL	28						
DELETE	X17 AT LEVEL	27						
DELETE	X17 AT LEVEL	26						
FLIP	M6 TO >=	3 AT	25	WITH BND=	7816.1851			
SET	X2 TO <=	2 AT	26.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	X4 TO <=	3 AT	27.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	X7 TO <=	2 AT	28.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	X14 TO <=	4 AT	29.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	X15 TO <=	1 AT	30.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	X16 TO <=	2 AT	31.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	X18 TO <=	2 AT	32.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	M3 TO <=	2 AT	33.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	M6 TO <=	3 AT	34.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	M8 TO <=	2 AT	35.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	M9 TO <=	2 AT	36.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	M10 TO <=	2 AT	37.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	M11 TO <=	2 AT	38.	BND=	7816.	TWIN=-0.1000E+31	282	
SET	M5 TO <=	2 AT	39.	BND=	6964.	TWIN= 0.0000E+00	288	
DELETE	M5 AT LEVEL	39						
DELETE	M11 AT LEVEL	38						
DELETE	M10 AT LEVEL	37						
DELETE	M9 AT LEVEL	36						
DELETE	M8 AT LEVEL	35						
DELETE	M6 AT LEVEL	34						
DELETE	M3 AT LEVEL	33						
DELETE	X18 AT LEVEL	32						
DELETE	X16 AT LEVEL	31						
DELETE	X15 AT LEVEL	30						
DELETE	X14 AT LEVEL	29						
DELETE	X7 AT LEVEL	28						
DELETE	X4 AT LEVEL	27						
DELETE	X2 AT LEVEL	26						
DELETE	M6 AT LEVEL	25						
DELETE	M3 AT LEVEL	24						
DELETE	M8 AT LEVEL	23						
DELETE	M1 AT LEVEL	22						
FLIP	M13 TO <=	2 AT	21	WITH BND=	9937.0000			
SET	M1 TO >=	1 AT	22.	BND=	9937.	TWIN=-0.1000E+31	296	
SET	M13 TO >=	2 AT	23.	BND=	9937.	TWIN= 5576.	300	
SET	X17 TO <=	1 AT	24.	BND=	9937.	TWIN= 9494.	305	
SET	X17 TO >=	1 AT	25.	BND=	9937.	TWIN= 0.0000E+00	308	
SET	X2 TO <=	2 AT	26.	BND=	9937.	TWIN= 9494.	310	
SET	X14 TO <=	4 AT	27.	BND=	9937.	TWIN= 9494.	312	
SET	M11 TO <=	2 AT	28.	BND=	9937.	TWIN= 9494.	314	

SET	X3 TO <=	2 AT	29.	BND=	9937.	TWIN=	9308.	323
SET	M9 TO >=	3 AT	30.	BND=	9494.	TWIN=	9937.	325
SET	M8 TO >=	2 AT	31.	BND=	9145.	TWIN=	5479.	333
SET	M3 TO >=	2 AT	32.	BND=	8779.	TWIN=	5104.	343
SET	X4 TO <=	3 AT	33.	BND=	8779.	TWIN=-0.1000E+31		343
SET	X7 TO <=	2 AT	34.	BND=	8779.	TWIN=-0.1000E+31		343
SET	X15 TO <=	1 AT	35.	BND=	8779.	TWIN=-0.1000E+31		343
SET	X16 TO <=	2 AT	36.	BND=	8779.	TWIN=-0.1000E+31		343
SET	X18 TO <=	2 AT	37.	BND=	8779.	TWIN=-0.1000E+31		343
SET	M3 TO <=	2 AT	38.	BND=	8779.	TWIN=-0.1000E+31		343
SET	M8 TO <=	2 AT	39.	BND=	8779.	TWIN=-0.1000E+31		343
SET	M10 TO <=	2 AT	40.	BND=	8779.	TWIN=-0.1000E+31		343
SET	M6 TO <=	2 AT	41.	BND=	7084.	TWIN=	6964.	347
DELETE	M6 AT LEVEL		41					
DELETE	M10 AT LEVEL		40					
DELETE	M8 AT LEVEL		39					
DELETE	M3 AT LEVEL		38					
DELETE	X18 AT LEVEL		37					
DELETE	X16 AT LEVEL		36					
DELETE	X15 AT LEVEL		35					
DELETE	X7 AT LEVEL		34					
DELETE	X4 AT LEVEL		33					
DELETE	M3 AT LEVEL		32					
DELETE	M8 AT LEVEL		31					
FLIP	M9 TO <=	2 AT	30	WITH BND=	9937.0000			
SET	X5 TO <=	3 AT	31.	BND=	9937.	TWIN=	9080.	383
SET	X4 TO <=	3 AT	32.	BND=	9937.	TWIN=	9494.	385
SET	X6 TO <=	3 AT	33.	BND=	9937.	TWIN=	9014.	414
SET	X17 TO <=	2 AT	34.	BND=	9937.	TWIN=	9494.	417
SET	X7 TO <=	2 AT	35.	BND=	9937.	TWIN=	9494.	419
SET	M10 TO <=	2 AT	36.	BND=	9937.	TWIN=	9494.	422
SET	M8 TO <=	2 AT	37.	BND=	9937.	TWIN=	9145.	443
SET	M8 TO >=	2 AT	38.	BND=	9937.	TWIN=	5479.	445
SET	M6 TO >=	3 AT	39.	BND=	9937.	TWIN=	7084.	447
SET	X5 TO >=	3 AT	40.	BND=	9937.	TWIN=	6964.	449
SET	X3 TO >=	2 AT	41.	BND=	9937.	TWIN=	5104.	451

NEW INTEGER SOLUTION OF 9937.00000 AT BRANCH 59 PIVOT 451
 BOUND ON OPTIMUM: 10958.00

DELETE	X3 AT LEVEL		41					
DELETE	X5 AT LEVEL		40					
DELETE	M6 AT LEVEL		39					
DELETE	M8 AT LEVEL		38					
DELETE	M8 AT LEVEL		37					
DELETE	M10 AT LEVEL		36					
DELETE	X7 AT LEVEL		35					
DELETE	X16 AT LEVEL		34					
DELETE	X6 AT LEVEL		33					
DELETE	X4 AT LEVEL		32					
DELETE	X5 AT LEVEL		31					
DELETE	M9 AT LEVEL		30					
DELETE	X3 AT LEVEL		29					
DELETE	M11 AT LEVEL		28					
DELETE	X14 AT LEVEL		27					
DELETE	X2 AT LEVEL		26					
DELETE	X17 AT LEVEL		25					
DELETE	X17 AT LEVEL		24					
DELETE	M13 AT LEVEL		23					
DELETE	M1 AT LEVEL		22					
DELETE	M13 AT LEVEL		21					
DELETE	M10 AT LEVEL		20					
DELETE	X16 AT LEVEL		19					
DELETE	X7 AT LEVEL		18					
DELETE	M9 AT LEVEL		17					
DELETE	X8 AT LEVEL		16					
DELETE	M13 AT LEVEL		15					
DELETE	M10 AT LEVEL		14					
DELETE	X4 AT LEVEL		13					
DELETE	X7 AT LEVEL		12					
DELETE	X4 AT LEVEL		11					
DELETE	M9 AT LEVEL		10					
DELETE	X14 AT LEVEL		9					
FLIP	M1 TO >=	2 AT	8	WITH BND=	10583.049			
SET	M9 TO >=	2 AT	9.	BND=	0.1052E+05	TWIN=	5734.	478
SET	M10 TO >=	2 AT	10.	BND=	0.1047E+05	TWIN=	5584.	483

SET	M7 TO >=	2 AT	11.	BND=	0.1040E+05	TWIN=	5584.	496
SET	X2 TO <=	2 AT	12.	BND=	0.1040E+05	TWIN=-0.1000E+31		496
SET	X15 TO <=	1 AT	13.	BND=	0.1040E+05	TWIN=-0.1000E+31		496
SET	X18 TO <=	2 AT	14.	BND=	0.1040E+05	TWIN=-0.1000E+31		496
SET	M1 TO <=	2 AT	15.	BND=	0.1040E+05	TWIN=-0.1000E+31		496
SET	M7 TO <=	2 AT	16.	BND=	0.1040E+05	TWIN=-0.1000E+31		496
SET	M9 TO <=	2 AT	17.	BND=	0.1040E+05	TWIN=-0.1000E+31		496
SET	M10 TO <=	2 AT	18.	BND=	0.1040E+05	TWIN=-0.1000E+31		496
SET	M11 TO <=	2 AT	19.	BND=	0.1040E+05	TWIN=-0.1000E+31		496
SET	M13 TO >=	2 AT	20.	BND=	0.1033E+05	TWIN=	5576.	501
SET	M13 TO <=	2 AT	21.	BND=	0.1033E+05	TWIN=-0.1000E+31		501
SET	M8 TO >=	2 AT	22.	BND=	0.1026E+05	TWIN=	5479.	506
SET	M8 TO <=	2 AT	23.	BND=	0.1026E+05	TWIN=-0.1000E+31		506
SET	M3 TO <=	2 AT	24.	BND=	0.1021E+05	TWIN=	9583.	521
SET	M3 TO >=	2 AT	25.	BND=	0.1021E+05	TWIN=-0.1000E+31		521
SET	X14 TO >=	4 AT	26.	BND=	9891.	TWIN=	8601.	524
DELETE	X14 AT LEVEL		26					
DELETE	M3 AT LEVEL		25					
DELETE	M3 AT LEVEL		24					
DELETE	M8 AT LEVEL		23					
DELETE	M8 AT LEVEL		22					
DELETE	M13 AT LEVEL		21					
DELETE	M13 AT LEVEL		20					
DELETE	M11 AT LEVEL		19					
DELETE	M10 AT LEVEL		18					
DELETE	M9 AT LEVEL		17					
DELETE	M7 AT LEVEL		16					
DELETE	M1 AT LEVEL		15					
DELETE	X18 AT LEVEL		14					
DELETE	X15 AT LEVEL		13					
DELETE	X2 AT LEVEL		12					
DELETE	M7 AT LEVEL		11					
DELETE	M10 AT LEVEL		10					
DELETE	M9 AT LEVEL		9					
DELETE	M1 AT LEVEL		8					
DELETE	M12 AT LEVEL		7					
DELETE	M11 AT LEVEL		6					
DELETE	X15 AT LEVEL		5					
DELETE	X18 AT LEVEL		4					
DELETE	X2 AT LEVEL		3					
FLIP	D4 TO >=	11476 AT	2	WITH BND=	10958.000			
SET	M12 TO >=	1 AT	3.	BND=	0.1096E+05	TWIN=-0.1000E+31		539
SET	M10 TO <=	2 AT	4.	BND=	0.1096E+05	TWIN=	0.1076E+05	547
SET	X18 TO >=	2 AT	5.	BND=	0.1096E+05	TWIN=	6537.	553
SET	M2 TO >=	2 AT	6.	BND=	0.1095E+05	TWIN=-0.1000E+31		556
SET	M1 TO >=	2 AT	7.	BND=	0.1059E+05	TWIN=-0.1000E+31		562
SET	M11 TO >=	2 AT	8.	BND=	0.1048E+05	TWIN=	6004.	567
SET	M9 TO >=	2 AT	9.	BND=	0.1039E+05	TWIN=	5734.	585
SET	X18 TO <=	2 AT	10.	BND=	0.1039E+05	TWIN=-0.1000E+31		585
SET	M1 TO <=	2 AT	11.	BND=	0.1039E+05	TWIN=-0.1000E+31		585
SET	M2 TO <=	2 AT	12.	BND=	0.1039E+05	TWIN=-0.1000E+31		585
SET	M9 TO <=	2 AT	13.	BND=	0.1039E+05	TWIN=-0.1000E+31		585
SET	M11 TO <=	2 AT	14.	BND=	0.1039E+05	TWIN=-0.1000E+31		585
SET	M7 TO >=	2 AT	15.	BND=	0.1032E+05	TWIN=	5584.	589
SET	M7 TO <=	2 AT	16.	BND=	0.1032E+05	TWIN=-0.1000E+31		589
SET	M10 TO >=	2 AT	17.	BND=	0.1022E+05	TWIN=	5584.	600
SET	M13 TO >=	2 AT	18.	BND=	0.1011E+05	TWIN=	5576.	604
SET	M13 TO <=	2 AT	19.	BND=	0.1011E+05	TWIN=-0.1000E+31		604
SET	M8 TO >=	2 AT	20.	BND=	9988.	TWIN=	5479.	616
SET	M8 TO <=	2 AT	21.	BND=	9988.	TWIN=-0.1000E+31		616
SET	M3 TO >=	3 AT	22.	BND=	9397.	TWIN=-0.1000E+31		622
DELETE	M3 AT LEVEL		22					
DELETE	M8 AT LEVEL		21					
DELETE	M8 AT LEVEL		20					
DELETE	M13 AT LEVEL		19					
DELETE	M13 AT LEVEL		18					
DELETE	M10 AT LEVEL		17					
DELETE	M7 AT LEVEL		16					
DELETE	M7 AT LEVEL		15					
DELETE	M11 AT LEVEL		14					
DELETE	M9 AT LEVEL		13					
DELETE	M2 AT LEVEL		12					
DELETE	M1 AT LEVEL		11					
DELETE	X18 AT LEVEL		10					
DELETE	M9 AT LEVEL		9					

DELETE	M11 AT LEVEL	8				
DELETE	M1 AT LEVEL	7				
DELETE	M2 AT LEVEL	6				
DELETE	X18 AT LEVEL	5				
FLIP	M10 TO >=	3 AT	4 WITH BND=	10755.981		
SET	M1 TO >=	2 AT	5, BND=	0.1039E+05	TWIN=-0.1000E+31	645
SET	M2 TO >=	2 AT	6, BND=	0.1028E+05	TWIN=-0.1000E+31	646
SET	M1 TO <=	2 AT	7, BND=	0.1028E+05	TWIN=-0.1000E+31	646
SET	M2 TO <=	2 AT	8, BND=	0.1028E+05	TWIN=-0.1000E+31	646
SET	M10 TO <=	3 AT	9, BND=	0.1028E+05	TWIN=-0.1000E+31	646
SET	M11 TO >=	2 AT	10, BND=	0.1014E+05	TWIN= 6004.	653
SET	X4 TO >=	4 AT	13, BND=	0.1014E+05	TWIN=-0.1000E+31	653
SET	M3 TO >=	3 AT	13, BND=	0.1014E+05	TWIN=-0.1000E+31	653
SET	M4 TO >=	4 AT	13, BND=	0.1014E+05	TWIN=-0.1000E+31	653
SET	D4 TO <=	11476 AT	14, BND=	9344.	TWIN=-0.1000E+31	674
SET	M3 TO <=	3 AT	15, BND=	9344.	TWIN=-0.1000E+31	674
SET	M4 TO <=	4 AT	16, BND=	9344.	TWIN=-0.1000E+31	674
SET	M11 TO <=	2 AT	17, BND=	9344.	TWIN=-0.1000E+31	674
SET	M9 TO >=	2 AT	18, BND=	9156.	TWIN= 5734.	684
DELETE	M9 AT LEVEL	18				
DELETE	M11 AT LEVEL	17				
DELETE	M4 AT LEVEL	16				
DELETE	M3 AT LEVEL	15				
DELETE	D4 AT LEVEL	14				
DELETE	M4 AT LEVEL	13				
DELETE	M3 AT LEVEL	12				
DELETE	X4 AT LEVEL	11				
DELETE	M11 AT LEVEL	10				
DELETE	M10 AT LEVEL	9				
DELETE	M2 AT LEVEL	8				
DELETE	M1 AT LEVEL	7				
DELETE	M2 AT LEVEL	6				
DELETE	M1 AT LEVEL	5				
DELETE	M10 AT LEVEL	4				
DELETE	M12 AT LEVEL	3				
DELETE	D4 AT LEVEL	2				
FLIP	M12 TO >=	2 AT	1 WITH BND=	10939.583		
SET	M1 TO >=	2 AT	2, BND=	0.1065E+05	TWIN= 9937.	708
SET	M2 TO >=	2 AT	3, BND=	0.1052E+05	TWIN= 6605.	713
SET	M11 TO >=	2 AT	4, BND=	0.1043E+05	TWIN= 6004.	717
SET	M9 TO >=	2 AT	5, BND=	0.1036E+05	TWIN= 5734.	723
SET	M7 TO >=	2 AT	6, BND=	0.1030E+05	TWIN= 5584.	727
SET	M1 TO <=	2 AT	7, BND=	0.1030E+05	TWIN=-0.1000E+31	727
SET	M2 TO <=	2 AT	8, BND=	0.1030E+05	TWIN=-0.1000E+31	727
SET	M7 TO <=	2 AT	9, BND=	0.1030E+05	TWIN=-0.1000E+31	727
SET	M9 TO <=	2 AT	10, BND=	0.1030E+05	TWIN=-0.1000E+31	727
SET	M11 TO <=	2 AT	11, BND=	0.1030E+05	TWIN=-0.1000E+31	727
SET	M12 TO <=	2 AT	12, BND=	0.1030E+05	TWIN=-0.1000E+31	727
SET	M10 TO >=	2 AT	13, BND=	0.1023E+05	TWIN= 5584.	732
SET	M10 TO <=	2 AT	14, BND=	0.1023E+05	TWIN=-0.1000E+31	732
SET	M13 TO >=	2 AT	15, BND=	0.1015E+05	TWIN= 5576.	736
SET	M13 TO <=	2 AT	16, BND=	0.1015E+05	TWIN=-0.1000E+31	736
SET	M8 TO >=	2 AT	17, BND=	0.1007E+05	TWIN= 5479.	751
SET	M8 TO <=	2 AT	18, BND=	0.1007E+05	TWIN=-0.1000E+31	751
SET	M3 TO >=	2 AT	19, BND=	0.1006E+05	TWIN= 5104.	753
SET	M3 TO <=	2 AT	20, BND=	0.1006E+05	TWIN=-0.1000E+31	753
SET	M4 TO >=	3 AT	21, BND=	9824.	TWIN= 7536.	755
DELETE	M4 AT LEVEL	21				
DELETE	M3 AT LEVEL	20				
DELETE	M3 AT LEVEL	19				
DELETE	M8 AT LEVEL	18				
DELETE	M8 AT LEVEL	17				
DELETE	M13 AT LEVEL	16				
DELETE	M13 AT LEVEL	15				
DELETE	M10 AT LEVEL	14				
DELETE	M10 AT LEVEL	13				
DELETE	M12 AT LEVEL	12				
DELETE	M11 AT LEVEL	11				
DELETE	M9 AT LEVEL	10				
DELETE	M7 AT LEVEL	9				
DELETE	M2 AT LEVEL	8				
DELETE	M1 AT LEVEL	7				
DELETE	M7 AT LEVEL	6				
DELETE	M9 AT LEVEL	5				
DELETE	M11 AT LEVEL	4				

DELETE M2 AT LEVEL 3
 DELETE M1 AT LEVEL 2
 DELETE M12 AT LEVEL 1
 ENUMERATION COMPLETE. BRANCHES= 91 PIVOTS= 755

LAST INTEGER SOLUTION IS THE BEST FOUND
 RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 9937.000

VARIABLE	VALUE	REDUCED COST
D1	9937.000000	0.000000
D2	9937.000000	0.000000
D3	9937.000000	0.000000
D4	9937.000000	0.000000
D5	9937.000000	0.000000
D6	9937.000000	0.000000
D7	9937.000000	0.000000
D8	9937.000000	0.000000
D9	9937.000000	0.000000
D10	9937.000000	0.000000
D11	9937.000000	0.000000
D12	9937.000000	0.000000
D13	9937.000000	0.000000
D14	9937.000000	0.000000
D15	9937.000000	0.000000
D16	9937.000000	0.000000
D17	9937.000000	0.000000
D18	9937.000000	-1.000000
X1	1.000000	0.000000
X2	2.000000	0.000000
X3	2.000000	0.000000
X4	3.000000	0.000000
X5	3.000000	0.000000
X6	3.000000	0.000000
X7	2.000000	0.000000
X8	2.000000	0.000000
X9	2.000000	0.000000
X10	2.000000	0.000000
X11	2.000000	0.000000
X12	1.000000	0.000000
X13	2.000000	0.000000
X14	4.000000	0.000000
X15	1.000000	0.000000
X16	2.000000	0.000000
X17	1.000000	0.000000
X18	2.000000	0.000000
M1	1.000000	0.000000
M2	2.000000	0.000000
M3	2.000000	0.000000
M4	3.000000	0.000000
M5	3.000000	0.000000
M6	3.000000	0.000000
M7	2.000000	0.000000
M8	2.000000	0.000000
M9	2.000000	0.000000
M10	2.000000	0.000000
M11	2.000000	0.000000
M12	1.000000	0.000000
M13	2.000000	0.000000
M14	4.000000	0.000000
M15	1.000000	0.000000
M16	2.000000	0.000000
M17	1.000000	0.000000
M18	2.000000	0.000000
S1	1.000000	0.000000
S2	2.000000	0.000000
S3	2.000000	0.000000
S4	3.000000	0.000000
S5	3.000000	0.000000
S6	3.000000	0.000000
S7	2.000000	0.000000
S8	2.000000	0.000000

S9	2.000000	0.000000
S10	2.000000	0.000000
S11	2.000000	0.000000
S12	1.000000	0.000000
S13	3.000000	0.000000
S14	6.000000	0.000000
S15	1.000000	0.000000
S16	3.000000	0.000000
S17	1.000000	0.000000
S18	2.000000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	0.000000
3)	0.000000	0.000000
4)	0.000000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	0.000000	0.000000
11)	0.000000	0.000000
12)	0.000000	0.000000
13)	0.000000	0.000000
14)	0.000000	0.000000
15)	0.000000	0.000000
16)	0.000000	0.000000
17)	0.000000	0.000000
18)	0.000000	0.000000
19)	0.000000	0.000000
20)	3273.000000	0.000000
21)	271.000000	0.000000
22)	1367.000000	0.000000
23)	509.000000	0.000000
24)	689.000000	0.000000
25)	1231.000000	0.000000
26)	1021.000000	0.000000
27)	1531.000000	0.000000
28)	1231.000000	0.000000
29)	2071.000000	0.000000
30)	1021.000000	0.000000
31)	1215.000000	0.000000
32)	1531.000000	0.000000
33)	3122.000000	0.000000
34)	1139.000000	0.000000
35)	412.000000	0.000000
36)	3137.000000	0.000000
37)	0.000000	0.000000
38)	0.000000	0.000000
39)	0.000000	0.000000
40)	0.000000	0.000000
41)	0.000000	0.000000
42)	0.000000	0.000000
43)	0.000000	0.000000
44)	0.000000	0.000000
45)	0.000000	0.000000
46)	0.000000	0.000000
47)	0.000000	0.000000
48)	0.000000	0.000000
49)	0.000000	0.000000
50)	0.000000	0.000000
51)	0.000000	0.000000
52)	0.000000	0.000000
53)	0.000000	0.000000
54)	0.000000	0.000000
55)	0.000000	0.000000
56)	0.000000	0.000000
57)	0.000000	0.000000
58)	7.000000	0.000000
59)	0.000000	0.000000
60)	0.000000	0.000000
61)	0.000000	0.000000
62)	0.000000	0.000000
63)	0.000000	0.000000

64)	0.000000	0.000000
65)	0.000000	0.000000
66)	0.000000	0.000000
67)	0.000000	0.000000
68)	0.000000	0.000000
69)	0.000000	0.000000
70)	0.000000	0.000000
71)	0.000000	0.000000
72)	0.000000	0.000000
73)	0.000000	0.000000
74)	34.000000	0.000000
75)	28.000000	0.000000
76)	28.000000	0.000000
77)	27.000000	0.000000
78)	27.000000	0.000000
79)	27.000000	0.000000
80)	28.000000	0.000000
81)	28.000000	0.000000
82)	33.000000	0.000000
83)	28.000000	0.000000
84)	28.000000	0.000000
85)	29.000000	0.000000
86)	16.000000	0.000000
87)	13.000000	0.000000
88)	29.000000	0.000000
89)	16.000000	0.000000
90)	29.000000	0.000000
91)	43.000000	0.000000
92)	0.000000	0.000000
93)	14.000000	0.000000
94)	8.000000	0.000000
95)	8.000000	0.000000
96)	7.000000	0.000000
97)	7.000000	0.000000
98)	7.000000	0.000000
99)	8.000000	0.000000
100)	8.000000	0.000000
101)	18.000000	0.000000
102)	8.000000	0.000000
103)	8.000000	0.000000
104)	9.000000	0.000000
105)	3.000000	0.000000
106)	3.000000	0.000000
107)	9.000000	0.000000
108)	3.000000	0.000000
109)	9.000000	0.000000
110)	13.000000	0.000000

NO. ITERATIONS= 766
 BRANCHES= 91 DETERM.= 1.000E 0

TABLE B-3

PROGRAM LISTING FOR TESTING THE APPLICATION OF THE MODEL WHEN REMOVE THE CONSTRAINT OF TOTAL NUMBERS OF OPERATOR

MODEL

```

max d18 !obj. func. max dn
st
|1. d(i+1)<=di    i=1,...,n-1

d18-d17<0
d17-d16<0
d16-d15<0
d15-d14<0
d14-d13<0
d13-d12<0
d12-d11<0
d11-d10<0
d10-d9<0
d9-d8<0
d8-d7<0
d7-d6<0
d6-d5<0
d5-d4<0
d4-d3<0
d3-d2<0
d2-d1<0

|2. case3 operator working with tooling
d1-9937m1<0
d2-6605m2<0
d3-5104m3<0
d4-3768m4<0
d5-3482m5<0
d6-3542m6<0
d7-5584m7<0
d8-5479m8<0
d9-5734m9<0
d10-5584m10<0
d11-6004m11<0
d12-10958m12<0
d13-5576m13<0
d14-2867m14<0
d15-13059m15<0
d16-5538m16<0
d17-10349m17<0
d18-6537m18<0

m1-x1=0
m2-x2=0
m3-x3=0
m4-x4=0
m5-x5=0
m6-x6=0
m7-x7=0
m8-x8=0
m9-x9=0
m10-x10=0
m11-x11=0
m12-x12=0
m13-x13=0
m14-x14=0
m15-x15=0
m16-x16=0
m17-x17=0
m18-x18=0

```

```
!3.space si >= si(operator) multiply Xi
```

```
s1-X1>0
s2-X2>0
s3-X3>0
s4-X4>0
s5-X5>0
s6-X6>0
s7-X7>0
s8-X8>0
s9-X9>0
s10-X10>0
s11-X11>0
s12-X12>0
s13-1.5X13>0
s14-1.5X14>0
s15-X15>0
s16-1.5X16>0
s17-X17>0
s18-X18>0
```

```
s1+s2+s3+s4+s5+s6+s7+s8+s9+s10+s11+s12+s13+s14+s15+s16+s17+s18<48
```

```
!bound on operator(xi)
```

```
x1<35
x2<30
x3<30
x4<30
x5<30
x6<30
x7<30
x8<30
x9<35
x10<30
x11<30
x12<30
x13<18
x14<17
x15<30
x16<18
x17<30
x18<45
```

```
! bounded on machine(mi)
```

```
m1<15
m2<10
m3<10
m4<10
m5<10
m6<10
m7<10
m8<10
m9<20
m10<10
m11<10
m12<10
m13<5
m14<7
m15<10
m16<5
m17<10
m18<15
END
```

```
!INTEGER PROGRAMMING
```

```
GIN D1
GIN D2
GIN D3
GIN D4
GIN D5
GIN D6
GIN D7
GIN D8
GIN D9
GIN D10
GIN D11
```


GIN D12
GIN D13
GIN D14
GIN D15
GIN D16
GIN D17
GIN D18

GIN X1
GIN X2
GIN X3
GIN X4
GIN X5
GIN X6
GIN X7
GIN X8
GIN X9
GIN X10
GIN X11
GIN X12
GIN X13
GIN X14
GIN X15
GIN X16
GIN X17
GIN X18

GIN M1
GIN M2
GIN M3
GIN M4
GIN M5
GIN M6
GIN M7
GIN M8
GIN M9
GIN M10
GIN M11
GIN M12
GIN M13
GIN M14
GIN M15
GIN M16
GIN M17
GIN M18

REPORT SOLUTION

LAST INTEGER SOLUTION IS THE BEST FOUND
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 11077.00

VARIABLE	VALUE	REDUCED COST
D1	19874.000000	0.000000
D2	13209.000000	0.000000
D3	13209.000000	0.000000
D4	11303.000000	0.000000
D5	11303.000000	0.000000
D6	11303.000000	0.000000
D7	11168.000000	0.000000
D8	11152.000000	0.000000
D9	11152.000000	0.000000
D10	11152.000000	0.000000
D11	11152.000000	0.000000
D12	11152.000000	0.000000
D13	11152.000000	0.000000
D14	11152.000000	0.000000
D15	11152.000000	0.000000
D16	11077.000000	0.000000
D17	11077.000000	0.000000

D18	11077.000000	-1.000000
X1	2.000000	0.000000
X2	2.000000	0.000000
X3	3.000000	0.000000
X4	3.000000	0.000000
X5	4.000000	0.000000
X6	4.000000	0.000000
X7	2.000000	0.000000
X8	3.000000	0.000000
X9	2.000000	0.000000
X10	2.000000	0.000000
X11	2.000000	0.000000
X12	2.000000	0.000000
X13	2.000000	0.000000
X14	4.000000	0.000000
X15	1.000000	0.000000
X16	2.000000	0.000000
X17	2.000000	0.000000
X18	2.000000	0.000000
M1	2.000000	0.000000
M2	2.000000	0.000000
M3	3.000000	0.000000
M4	3.000000	0.000000
M5	4.000000	0.000000
M6	4.000000	0.000000
M7	2.000000	0.000000
M8	3.000000	0.000000
M9	2.000000	0.000000
M10	2.000000	0.000000
M11	2.000000	0.000000
M12	2.000000	0.000000
M13	2.000000	0.000000
M14	4.000000	0.000000
M15	1.000000	0.000000
M16	2.000000	0.000000
M17	2.000000	0.000000
M18	2.000000	0.000000
S1	2.000000	0.000000
S2	2.000000	0.000000
S3	3.000000	0.000000
S4	3.000000	0.000000
S5	4.000000	0.000000
S6	4.000000	0.000000
S7	2.000000	0.000000
S8	3.000000	0.000000
S9	2.000000	0.000000
S10	2.000000	0.000000
S11	2.000000	0.000000
S12	2.000000	0.000000
S13	3.000000	0.000000
S14	6.000000	0.000000
S15	1.000000	0.000000
S16	3.000000	0.000000
S17	2.000000	0.000000
S18	2.000000	0.000000



BIOGRAPHY

Napit Schunhsri was born on the April, 6,1977 in Bangkok. She obtained her B.Eng. on Chulalongkorn University (Industrial Engineering) in 1997. She then pursues a further study in a Master Degree course at the Regional Centre for Manufacturing Systems Engineering, Faculty of Engineering, Chulalongkorn University.