Appendix A: Mathematical programming model for capacity planning problem under demand certainty

1. Indices

   c = customer (c = 1, 2,…, C).
   i = product type (i = 1, 2,…, I).
   l = production line (l = 1, 2,…, L).
   s = production stage (s = 1, 2,…, S).
   j = resource configuration (j = 1, 2,…, J).
   m = material type (m = 1, 2,…, M).
   k = machine type (k = 1, 2,…, K).
   n = tool type (n = 1, 2,…, N).
   t = time period (t = 1, 2,…, T).

2. Parameters

   de_{ict} = the demand quantity of customer c for product i in time t.
   pr_{ict} = sales price of customer c for product i in time t.
   kl_{lsk} = initial amount of machine k in line l at stage s.
   ku_{ls} = maximum number of machines in line l at stage s.
   ks_{ijsk} = required work hours of machine k used at stage s for manufacturing a unit of product i with resource configuration j.
   ka_{sk} = available work hours of machine k at stage s.
   $kb_{ll's}$ = machine migration capability from line l to l' at stage s.
   nl_{lsn} = initial amount of tool n in line l at stage s.
   nu_{ls} = maximum number of tools in line l at stage s.
   ns_{ijsn} = required work hours of tool n used at stage s for manufacturing a unit of product i with resource configuration j.
   na_{sn} = available work hours of tool n at stage s.
   $nb_{ll's}$ = tool migration capability from line l to l' at stage s.
   mq_{smt} = total available quantity of material m at stage s in time t.
   ms_{ijsm} = consumption ratio of material m for manufacturing a unit of product i at stage s with resource configuration j.
   tf_{ijs} = production capability of product i at stage s with resource configuration j.
   $tb_{lsl'(s+1)}$ = transportation capability from line l at stage s to line l' at stage $s+1$.
   vc_{iljs} = production cost for manufacturing a unit of product i in line l at stage s with resource configuration j.
   kc_s = machine migration cost at stage s.
   nc_s = tool migration cost at stage s.

3. Decision variables

   KQ_{lskt} = the number of machine k for line l at stage s in time t.
   $KM_{ll'skt}$ = the migration number of machine k from line l to line l' at stage s in time t.
   NQ_{lsnt} = the number of tool n for line l at stage s in time t.
   $NM_{ll'snt}$ = the migration number of tool n from line l to line l' at stage s in time t.
   XQ_{iljst} = production amounts of product i with resource configuration j for line l at stage s in time t.
   $RQ_{iljsl'j'(s+1)t}$ = transportation amounts of product i from line l with resource configuration j at stage s to line l' with resource configuration j' at stage ($s+1$) in time t.
   SQ_{ict} = sales amounts of product i for customer c in time t.
   SL_c = service level for customer c.

4. Objective Function

$$\begin{aligned} &\textit{Maximize} \\ &\sum_{i}\sum_{c}\sum_{t}(pr_{ict}\times SQ_{ict})-\sum_{i}\sum_{l}\sum_{j}\sum_{s}\sum_{t}(vc_{iljs}\times XQ_{iljst}) \\ &-\sum_{l}\sum_{l'}\sum_{s}\sum_{k}\sum_{t}(kc_s\times KM_{ll'skt})-\sum_{l}\sum_{l'}\sum_{s}\sum_{n}\sum_{t}(nc_s\times NM_{ll'snt}) \end{aligned} \tag{1}$$

   It aims to obtain the optimal capacity planning decision to seek the maximization of net profit.

5. Constraints

- Machine migration balance constraints

$$KQ_{lsk0} = kl_{lsk} \quad \forall l,s,k\,. \tag{2}$$

$$KQ_{lskt} = KQ_{lsk(t-1)} - \sum_{l'} KM_{ll'skt} + \sum_{l'} KM_{l'lskt} \quad \forall l,s,k,t\,. \tag{3}$$

$$KQ_{lskt} \le ku_{ls} \quad \forall l,s,k,t\,. \tag{4}$$

$$KM_{ll'skt} \le M \times kb_{ll's} \quad \forall l,l',s,k,t\,. \tag{5}$$

- Tool migration balance constraints

$$NQ_{lsn0} = nl_{lsn} \quad \forall l,s,n\,. \tag{6}$$

$$NQ_{lsnt} = NQ_{lsn(t-1)} - \sum_{l'} NM_{ll'snt} + \sum_{l'} NM_{l'lsnt} \quad \forall l,s,n,t\,. \tag{7}$$

$$NQ_{lsnt} \le nu_{ls} \quad \forall l,s,n,t\,. \tag{8}$$

$$NM_{ll'snt} \le M \times nb_{ll's} \quad \forall l,l',s,n,t\,. \tag{9}$$

- Production and transportation balance constraints

$$XQ_{iljst} = \sum_{l'}\sum_{j'} RQ_{iljsl'j'(s+1)t} \quad \forall i,l,j,s=1,\ldots S-1,t\,. \tag{10}$$

$$\sum_{l'}\sum_{j'} RQ_{il'j'(s-1)ljst} = XQ_{iljst} \quad \forall i,l,j,s=2,\ldots S,t\,. \tag{11}$$

- Capacity constraints

$$\sum_{i}\sum_{j} (XQ_{iljst} \times ks_{ijsk}) \le KQ_{lskt} \times ka_{sk} \quad \forall l,s,k,t\,. \tag{12}$$

$$\sum_{i}\sum_{j} (XQ_{iljst} \times ns_{ijsn}) \le NQ_{lsnt} \times na_{sn} \quad \forall l,s,n,t\,. \tag{13}$$

- Material constraint

$$\sum_{i}\sum_{l}\sum_{j} (XQ_{iljst} \times ms_{ijsm}) \le mq_{smt} \quad \forall s,m,t\,. \tag{14}$$

- Production capability constraint

$$XQ_{iljst} \le M \times tf_{ijs} \quad \forall i,l,j,s,t\,. \tag{15}$$

- Transportation capability constraint

$$RQ_{iljsl'j'(s+1)t} \le M \times tb_{lsl'(s+1)} \quad \forall i,l,j,s,l',j',t\,. \tag{16}$$

- Demand fulfillment constraints

$$\sum_{l}\sum_{j} XQ_{iljst} = SQ_{ict} \quad \forall i,s=S,c,t\,. \tag{17}$$

$$SQ_{ict} \le de_{ict} \quad \forall i,c,t\,. \tag{18}$$

- Service level

$$SL_c = \left\lfloor \frac{\sum_{i} SQ_{ict}}{\sum_{i} de_{ict}} \right\rfloor \quad \forall c,t\,. \tag{19}$$

- Domain restriction for decision variables

$$KQ_{lskt}, KM_{ll'skt}, NQ_{lsnt}, NM_{ll'snt} \in \text{integer} \qquad \forall l,s,k,n,t\,. \tag{20}$$

$$XQ_{iljst}, RQ_{iljsl'j'(s+1)t}, SQ_{ict}, SL_c \ge 0 \quad \forall i,l,l',j,j',s,t,c\,. \tag{21}$$

Appendix B: Input information

Table B.1~Table B.22 show the related information for the large-scale semiconductor packaging and testing factory case required in this paper.

Table B.1 Index information

Customer		c1	c2	c3					
Product		i1	i2	i3	i4	i5	i6	i7	i8
Line		ℓ1	ℓ2						
Stage		DB	WB	MD					
Scenario		r1	r2	r3					
Material		m1	m2	m3	m4				
Machine		k1	k2	k3					
Tool		n1	n2	n3	n4				
Period		1	2	3	4				
Configuration	DB	j1	j2	j3					
	WB	j1	j2	j3					
	MD	j1	j2	j3	j4	j5	j6	j7	

Table B.2 Resource configuration

DB(s1)	$j_1=k_1$	$j_2=k_2$	$j_3=k_3$				
WB(s2)	$j_1=k_1$	$j_2=k_2$	$j_3=k_3$				
MD(s3)	$j_1=k_1+n_1+m_4$	$j_2=k_1+n_2+m_1$	$j_3=k_1+n_3+m_2$	$j_4=k_2+n_3+m_4$	$j_5=k_2+n_4+m_4$	$j_6=k_3+n_1+m_4$	$j_7=k_3+n_4+m_2$

1. Demand-related parameters

Table B.3 shows customer demands for all products under each scenario. This case covers four time periods. Table B.4 shows sales prices of products. Table B.5 shows the occurring probability of all scenarios.

Table B.3 Customer demands for all products under each scenario

Scenario	Customer	Product	Period (month) 1	2	3	4
r1	c1	i1	45,955	80,375	22,548	37,665
		i2	137,865	40,187	72,153	0
		i3	137,865	40,187	0	75,331
	c2	i4	91,910	60,281	54,115	0
		i5	22,977	120,562	45,096	15,066

		i6	110,292	58,606	4,509	41,432
	c3	i7	53,614	24,112	54,115	33,899
		i8	225,946	21,768	0	11,299
		i1	48,000	96,000	30,000	60,000
	c1	i2	144,000	48,000	96,000	0
		i3	144,000	48,000	0	120,000
		i4	96,000	72,000	72,000	0
r2	c2	i5	24,000	144,000	60,000	24,000
		i6	115,200	70,000	6,000	66,000
	c3	i7	56,000	28,800	72,000	54,000
		i8	236,000	26,000	0	18,000
		i1	50,044	111,624	37,451	82334
	c1	i2	150,134	55,812	119,846	0
		i3	150,134	55,812	0	164668
		i4	100,089	83,718	89,884	0
r3	c2	i5	25,022	167,437	74,903	32933
		i6	120,107	81,393	7,490	90567
	c3	i7	58,385	33,487	89,884	74100
		i8	246,053	30,231	0	24700

Table B.4 Sales prices of products

Products	i1	i2	i3	i4	i5	i6	i7	i8
Sales prices	20	30	20	25	100	50	60	70

Table B.5 Occurring probability of all scenarios

Scenarios	Probability
r1	1/3
r2	1/3
r3	1/3

2. Machine-related parameters

There is an initial machine allocation in each line at each stage, as shown in Table B.6; Table B.7 indicates that there is the upper limit of machine allocation in each line at each stage; Required work hours of machines for manufacturing a unit of product is presented in Table B.8; Production capacity of each machine (machine hour) at each production stage is shown in Table B.9. Machine migration capability between different lines at each stage is shown in Table B.10, which is a binary parameter. Below, 1 means that they can be moved between lines; 0 means that they cannot be moved.

Table B.6 Initial machine allocation in each line at each stage

Lines	Production stages	Types of machine		
		k1	k2	k3
ℓ1	DB	10	15	0
	WB	5	6	0
	MD	10	10	0
ℓ2	DB	0	5	6
	WB	0	10	9
	MD	0	8	6

Table B.7 Upper limit of machine allocation in each line at each stage

Production line	Production stage		
	DB	WB	MD
ℓ1	17	7	11
ℓ2	8	12	10

Table B.8 Work hours of machines for producing a unit of product at all stages under all kinds of configurations

Product	Resource configuration	Production stage (s)	Type of machine	ks_{ijsk}	Product	Resource configuration	Production stage (s)	Type of machine	ks_{ijsk}
i1	j1	DB	k1	10	i5	j1	MD	k1	20
i1	j1	WB	k1	30	i5	j3	DB	k3	12
i1	j1	MD	k1	10	i5	j3	WB	k3	30
i1	j2	DB	k2	8	i5	j7	MD	k3	10
i1	j2	MD	k1	5	i6	j2	WB	k2	25
i2	j1	WB	k1	35	i6	j3	DB	k3	7
i2	j2	DB	k2	11	i6	j3	WB	k3	20

i2	j2	WB	k2	25	i6	j4	MD	k2	25
i2	j2	MD	k1	15	i6	j7	MD	k3	15
i2	j3	DB	k3	7	i7	j2	DB	k2	12
i2	j3	MD	k1	10	i7	j3	WB	k3	35
i3	j1	DB	k1	12	i7	j6	MD	k3	33
i3	j1	MD	k1	12	i8	j1	DB	k1	15
i3	j2	WB	k2	40	i8	j1	WB	k1	40
i4	j2	DB	k2	9	i8	j2	WB	k2	30
i4	j3	WB	k3	20	i8	j3	DB	k3	10
i4	j3	MD	k1	10	i8	j3	MD	k3	40
i5	j1	DB	k1	15	i8	j5	MD	k2	25
i5	j1	WB	k1	40					

Table B.9 Production capacity of each machine (machine hour) at each production stage

Production stage	Type of machine		
	k1	k2	k3
DB	4,320,000	2,160,000	4,320,000
WB	8,640,000	6,912,000	7,776,000
MD	2,592,000	3,888,000	2,592,000

Table B.10 Machine migration capability between different lines at each stage

Lines	Move to line	Production stages		
		DB	WB	MD
ℓ1	ℓ2	0	1	1
ℓ2	ℓ1	0	1	1

3. Tool-related parameters

The MD stage has an initial tool allocation in each line, as shown in Table B.11; Table B.12 indicates that there is the upper limit of tool allocation in each line; Required work hours of tools for manufacturing a unit of product under all kinds of configurations is presented in Table B.13. Production capacity of each tool (tool hour) is shown in

Table B.14. Tool migration capability between different lines is shown in Table B.15, which is a binary parameter. Below, 1 means that they can be moved between lines; 0 means that they cannot be moved.

Table B.11 Initial tool allocation in each line at MD stage

Lines	Production stage	Type of tool			
		n1	n2	n3	n4
ℓ1	MD	0	30	0	30
ℓ2	MD	30	0	20	0

Table B.12 Upper limit of tool allocation in each line at MD stage

Lines	Upper limit of tool allocation
ℓ1	70
ℓ2	80

Table B.13 Work hours of tools for producing a unit of product at MD stage under all kinds of configurations

Product (i)	Resource configuration (j)	Production stages (s)	Type of tool (n)	ns_{ijsn}
i1	j1	MD	n1	10
i1	j2	MD	n2	5
i2	j2	MD	n2	15
i2	j3	MD	n3	10
i3	j1	MD	n1	12
i4	j3	MD	n3	10
i5	j1	MD	n1	20
i5	j7	MD	n4	10
i6	j4	MD	n3	25
i6	j7	MD	n4	15
i7	j6	MD	n1	20
i8	j3	MD	n3	40
i8	j5	MD	n4	25

Table B.14 Production capacity of each tool (tool hour) at MD stage

	Type of tool

Production stage	n1	n2	n3	n4
MD	12,960,000	12,960,000	8,640,000	12,960,000

Table B.15 Tool migration capability between different lines at MD stage

Lines	Move to line	Production stages
		MD
ℓ1	ℓ2	1
ℓ2	ℓ1	1

4. Material related parameters

Table B.16 shows the material available amount at all production stages. Table B.17 indicates material consumption ratio for manufacturing a unit of product at production stages under resource configurations.

Table B.16 Material available amount at MD stage

Production stage	Category of material	Period (month)			
		1	2	3	4
MD	m1	7,000,000	6,000,000	7,000,000	6,000,000
	m2	1,000,000	8,000,000	1,000,000	8,000,000
	m3	6,000,000	100,000	6,000,000	100,000
	m4	7,000,000	4,000,000	7,000,000	4,000,000

Table B.17 Material consumption ratio for manufacturing a unit of product

Product (i)	Resource configuration (j)	Production stage (s)	Category of material (m)	ms_{ijsm}
i1	j1	MD	m4	1
i1	j2	MD	m1	1
i2	j2	MD	m1	1
i2	j3	MD	m2	1
i3	j1	MD	m4	1
i4	j3	MD	m2	1
i5	j7	MD	m2	1
i6	j4	MD	m3	1
i6	j7	MD	m2	1

i7	j6	MD	m3	1
i8	j3	MD	m2	1
i8	j5	MD	m4	1

5. Production capability related parameters

Production capability for each product at production stages with resource configurations is shown in Table B.18.

Table B.18 Production capability for each product at production stages with resource configurations

Product	Resource configuration	Production stage			Product	Resource configuration	Production stage		
		DB	WB	MD			DB	WB	MD
	j1	1	1	1		j1	1	1	1
	j2	1	0	1		j2	0	0	0
	j3	0	0	0		j3	1	1	0
i1	j4			0	i5	j4			0
	j5			0		j5			0
	j6			0		j6			0
	j7			0		j7			1
	j1	0	1	0		j1	0	0	0
	j2	1	1	1		j2	0	1	0
	j3	1	0	1		j3	1	1	0
i2	j4			0	i6	j4			1
	j5			0		j5			0
	j6			0		j6			0
	j7			0		j7			1
	j1	1	0	1		j1	0	0	0
i3	j2	0	1	0	i7	j2	1	0	0
	j3	0	0	0		j3	0	1	0

	j4			0		j4			0
	j5			0		j5			0
	j6			0		j6			1
	j7			0		j7			0
	j1	0	0	0		j1	1	1	0
	j2	1	0	0		j2	0	1	0
	j3	0	1	1		j3	1	0	1
i4	j4			0	i8	j4			0
	j5			0		j5			1
	j6			0		j6			0
	j7			0		j7			0

6. Transportation-related parameters

Transportation capability between production stages is shown in Table B.19, which is a binary parameter. Below, 1 means transportation operation is available; 0 means transportation operation is unavailable.

Table B.19 Transportation capability between production stages

		Post-production stage			
		Line ℓ1		Line ℓ2	
Line	Pre-production stage	WB'	MD'	WB'	MD'
ℓ1	DB	1	0	0	0
	WB	0	1	0	0
ℓ2	DB	0	0	1	0
	WB	0	0	0	1

7. Costs-related parameters

Variable cost for manufacturing a unit of product in lines at production stages with resource configurations is shown in Table B.20. Migration cost for moving machines and tools between lines at each production stage is presented in Table B.21 and Table B.22.

Table B.20 Variable cost for manufacturing a unit of product in lines at production stages with resource configurations

Product (i)	Line (ℓ)	Resource configuration (j)	Production stage (s)	vc_{iljs}	Product (i)	Line (ℓ)	Resource configuration (j)	Production stage (s)	vc_{iljs}

i1	ℓ1	j1	MD	3	i5	ℓ1	j7	MD	6
i1	ℓ1	j2	MD	2	i5	ℓ2	j1	MD	8
i1	ℓ2	j1	MD	4	i5	ℓ2	j7	MD	6
i1	ℓ2	j2	MD	2	i6	ℓ1	j4	MD	10
i2	ℓ1	j2	MD	5	i6	ℓ1	j7	MD	8
i2	ℓ1	j3	MD	4	i6	ℓ2	j4	MD	9
i2	ℓ2	j2	MD	7	i6	ℓ2	j7	MD	9
i2	ℓ2	j3	MD	4	i7	ℓ2	j6	MD	9
i3	ℓ1	j1	MD	6	i8	ℓ1	j3	MD	12
i3	ℓ2	j1	MD	6	i8	ℓ1	j5	MD	11
i4	ℓ1	j3	MD	5	i8	ℓ2	j3	MD	12
i4	ℓ2	j3	MD	4	i8	ℓ2	j5	MD	13
i5	ℓ1	j1	MD	8					

Table B.21 Machine migration costs at each production stages

Stages	Machine migration costs
DB	1,000
WB	500
MD	3,000

Table B.22 Tool migration costs at MD production stage

Stages	Tool migration costs
MD	1,000