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Capacity Evaluation Strategies under Dynamic Linear Pricing

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Abstract. Traditionally, a fixed unit price is applied in examining capacity planning. However, using a fixed price to predict capacity requirements may not be appropriate for practical problems. The unit price will be varied due to the difference between quantity supplied and demanded, the market competition, and the consumer's behavior. Also, different unit prices will affect the quantity demanded since increasing the unit price will decrease the quantity demanded. In this research, we examine the capacity requirements in multiple periods with Walrasian price adjustment constraints. A mathematical model is presented and the results indicate that industries might increase the unit price to reduce machine and inventory costs.

1. Introduction

In designing a manufacturing system, capacity planning is always discussed. The capacity is defined as the number of units that the plant can produce in a given time. Since capacity policy plays a key role in determining the firm's competitive position in the market place, a capacity strategy must take into account a variety of factors [19]. For example, capacity should be designed to satisfy demand, adapt a new technology process, and strengthen a company's competitiveness. Therefore, capacity expansion is always an important decision for a company to be more competitive in the market.

To determine whether capacity should be extended, capacity decisions must be made in a dynamic environment such as demand fluctuation. Also, a fixed unit price is usually applied in modeling capacity planning problems. However, using a fixed price to predict capacity requirements may not be appropriate for practical problems. The unit price will be varied due to the difference between quantity supplied and demanded, the market competition, and the consumer's behavior. Furthermore, different unit prices will affect the quantity demanded since increasing the unit price will decrease the quantity demanded.

This paper examines the effect of price adjustment on capacity expansion problems using Walrasian price adjustment constraints. A mathematical model is proposed and solved to maximize total profit and understand capacity decisions when the unit price is varied. Total profit is obtained by subtracting the inventory, machine, and production cost from total revenue. Section 2 of this paper provides a literature review on capacity planning and Walrasian price adjustment. Section 3 presents a mathematical model. Section 4 demonstrates experimental results while Section 5 discusses the conclusions and future directions of research.

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2. Literature Review

Lots of research has been dedicated in the areas of capacity planning and price adjustment. Important literature for these two topics are presented and discussed.

Capacity planning is usually considered as a long term planning problem. Many papers determine capacity expansions by when and where to add more facilities [17]. Johnson and Montgomery [12] provide formulations for different planning problems using linear programming, dynamic programming and other approaches. However, some papers [4-5, 23] analyze capacity decisions for single period models using a queueing network. Bretthauer and Cote [6] use a queueing network for examining a multiple-period model. They provide the size and time for the capacity expansion and demonstrate the impact of these capacity changes.

Since capacity planning determines the resources required for the manufacturing system, its effectiveness depends upon other planning strategies such as facility layout, process planning and production planning. Wysk et. al. [26] propose an integrated model for process selection and capacity planning. Egbelu [9] provides a mathematical model with the integration of machine requirement and flow planning. Askin and Mitwasi [3] integrate facility layout, process selection, and capacity planning into a mathematical model. Schaller et. al. [21] provide an approach to integrate the cell design and production planning.

For an extensive review on capacity planning, capacity decisions are evaluated in various directions. However, a fixed unit price is applied in these models that do not consider the supply effect in changing the price. One important area of discussing the supply effect is the joint pricing and lot sizing problem (JPLP). For an overview of this research, we refer to [1, 8, 10-11, 13-15, 24]. These papers investigate JPLP with a calculus-based iterative method, geometric programming, retailing situations with and without quantity discounts, and manufacturing settings with unlimited capacity.

Lee and Kim [16] investigate the relationship of joint pricing, lot sizing, and capacity expansion. They provide the optimal capacity decisions for a single product model. However, they assume a monopolistic price setting where a firm has complete control over demand by price. Thus, the demand becomes a decreasing power function of its selling price and constant over a planning horizon.

In this research, we introduce a different approach by adapting Walrasian price adjustment into a capacity planning model. This price adjustment hypothesis was first explored by Walras and was formulated mathematically by Samuelson. It demonstrates a hypothesis that the domestic price rises when quantity demanded exceeds quantity supplied. Furthermore, this hypothesis can be presented using the following formulation,

$$\frac{dp}{dt} = g\left[D(p) - S(p)\right] \tag{1}$$

Where D(p) denotes the quantity demanded, S(p) represents the quantity supplied, p denotes the product price, and t is the time factor. Also, the first order condition of g should be greater than zero ( ). Therefore, demonstrates the increasing or decreasing of the price. Moreover, the price rises if quantity demanded exceeds quantity supplied and the price lowers if quantity supplied exceeds quantity demanded. Therefore, if there is a shortage when quantity demanded exceeds quantity supplied in the commodity market, the sellers will find it to their advantage to raise the price. On the other hand, if there is a surplus when quantity supplied exceeds quantity demanded in the commodity market, the sellers will lower the price for their benefits. For an overview on Walrasian price adjustment, we refer to [22, 25].

3. Model Formulation

In this section, we present a mixed-integer model for designing capacity planning with dynamic price. Since capacity planning is a long-term planning strategy, the planning horizon is at least five years and each period resembles a year. Also, we have assumed that the salvage value of each machine is zero and each machine depreciated using the straight-line method. Since the straight-line method is used, the annual depreciation amount for machines is a constant value that will only affect the final value of objective function. Therefore, we didn't include a term to represent the salvage value of each machine in the model. The following notation is used throughout this paper.

Indexes

i: product index (i = 1,…,I);
j: process index (j = 1,…,J);
t: period (year) index (t = 1,…,T).
r: period (year) index (r = 1,…,T).

Parameters

F_{it}: forecasting demand for product i at period t;
MFG_{ij}: manufacturing cost for product i in process j; $Hold_{it}$: holding cost for product i at period t;
π_{it} : price adjustment factor for product i at period t, where $0 < \pi_{it} < \infty$;
C_j: unit cost for purchasing machine j;
A_j: available hours for machine j;
H_{ij}: hours required for product i at machine j;
S: demand elasticity factor, where $0 < S < 1$ represents the demand elasticity for the necessary product like sugar or salt and $1 < S < \infty$ represents the demand elasticity for the non-necessary product.

Decision variables

D_{it}: quantity demanded for product i at period t; P_{it}: price for product i at period t;
Q_{it}: production quantity for product i at period t; M_{jt}: number of machines j required at period t;
I_{it}: inventory quantity for product i at period t.
Z_{jt}: maximum number of machines j purchased among periods 1 to t;

The objective of this model is to maximize the profit while considering production quantity and capacity planning under dynamic price. The formulation is presented as follows.

Max

$$\sum_{i=1}^{I}\sum_{t=1}^{T}P_{it}\left(Q_{it}+I_{i,t-1}-I_{it}\right)-\sum_{j=1}^{J}\sum_{t=1}^{T}C_j\left(M_{jt}-Z_{j,t-1}\right)^{+}-\sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{j=1}^{J}MFG_{ij}Q_{it}-\sum_{i=1}^{I}\sum_{t=1}^{T}Hold_{it}I_{it} \tag{2}$$

Subject to

$$\left(D_{i,t-1}-Q_{i,t-1}\right)\pi_{i,t-1}=P_{it}-P_{i,t-1} \qquad i=1,...,I;t=1,...,T. \tag{3}$$

$$D_{it}=F_{it}-SP_{it} \qquad i=1,...,I;t=1,...,T. \tag{4}$$

$$\sum_{i=1}^{I}H_{ij}Q_{it}\le M_{jt}A_j \qquad j=1,...,J;t=1,...,T. \tag{5}$$

$$I_{it}=Q_{it}+I_{i,t-1}-D_{it} \qquad i=1,...,I;t=1,...,T. \tag{6}$$

$$Z_{j,t-1}=\underset{1\le r\le t-1}{MAX}\left(M_{j,r}\right) \qquad j=1,...,J;t=1,...,T. \tag{7}$$

$D_{it}, Q_{it}, I_{it}, M_{jt}$ nonnegative integer, $P_{it} \geq 0$.

The objective function sums revenue, machine cost, production cost, and inventory cost for all products over the planning horizon. The constraint set (3) is the Walrasian price adjustment constraints. The price adjustment factor, π_{it}, represents the effectiveness of the difference between quantity demanded and production on the price. The value of π_{it} is achieved using empirical data analysis (Rotemberg [20] and Carlton [7]) and is between 0 and ∞. Moreover, a small price adjustment value means that the difference between quantity demanded and production will have low effect on price. These constraints indicate that the difference between quantity demanded and production will change the price. For example, if quantity demanded exceeds the quantity produced, price will increase due to the supply shortage of the market. On the other hand, if the quantity produced exceeds quantity demanded, price will decrease due to the supply surplus of the market.

The constraint set (4) adapts economics theory to adjust the quantity demanded from forecasting using the demand elasticity factor. The value of the demand elasticity factor depends on the product characteristics and is between 0 and ∞. For example, the value of the demand elasticity for the necessary product like sugar or salt is between 0 and 1. Since these products are required in life, their price will not have significant effect on quantity demanded. For non-necessary products like cars, computers or television sets, the value of the demand elasticity is between 1 and ∞. The reason is that reducing price will attract more consumers in purchasing these products. Therefore, the value of demand elasticity for a non-necessary product should be greater than 1 so that adjusting price will show significant changes on quantity demanded. Furthermore, these constraints show that increasing the price will decrease the quantity demanded.

The constraint set (5) is the capacity constraint. These constraints ensure that the required capacity to produce products will be satisfied by the available capacity. The constraint set (6) provides the inventory levels for all of the products over the planning horizon. The constraint set (7) determines the maximum number of machines j purchased among period 1 to t.

4. Numerical Example

Some examples are used to test the effectiveness of using Walrasian price adjustment constraints on the capacity planning model. These examples are adapted from Abdelmola et al. [2] and Mosier [18]. Table 1 summarizes the required machining time and cost while table 2 demonstrates the quantity demanded of six periods for all product.

To test the effectiveness of this model and provide insights in analyzing capacity planning, two factors, the demand elasticity and price adjustment, are identified. The factors and their levels are shown in Table 3. To simplify the model, we assume the same market characteristic for all products in all the periods. Therefore, all products will use the same demand elasticity value at each level. Also, the same price adjustment value is applied to all products at each level. This model is implemented in Lingo 6.0 and a Pentium 4, 1.7 GHz with 256 RAM is used to run all the experiments.

Table 1. Average machining requirements (minutes/part)

Part type	Sales Price ($)	Machine									
		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
P1	14	10	0	0	0	0	0	0	0	16	0
P2	14	0	0	12	14	0	0	0	15	0	0
P3	11	0	0	0	0	12	18	0	0	0	0
P4	10	20	0	0	0	0	0	0	0	0	0
P5	10	0	0	0	0	0	0	15	0	18	0
P6	14	12	0	0	0	0	0	16	0	13	0
P7	12	0	0	21	0	0	0	14	12	17	0
P8	13	0	0	0	0	0	14	0	0	0	15
P9	13	0	11	16	12	0	0	0	14	0	0
P10	11	0	12	18	10	0	0	0	0	0	0
Annual cost of machine (in hundreds)		100	200	250	200	150	130	170	150	300	120
Available machining time (minutes in hundreds)		80	102	109	92	88	96	85	80	100	90

Table 2. Annual demand for multiple periods

Annual Demand (in hundreds)										
Period/ product	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	29.9	29.1	23.9	21	20.3	28.1	24.8	26	23.7	25.50
2	38.4	31.3	23.66	26.41	5.56	33.51	28.11	29.36	21.28	25.53
3	36.86	42.53	18.4	14.43	30.88	23.02	35.55	28.62	27.23	22.41
4	34.52	33.97	22.57	12.38	12.94	33.22	18.56	31.14	24.36	26.06
5	41.11	17.89	25.36	14.47	27.69	23.37	23.37	21.39	13.71	26.69
6	26.35	21.11	19.3	22.53	22.11	19.24	40.72	33.52	20.75	28.9

Table 3. Factors and levels

Factors	Levels
π_{it}	1, 10, 100
S	0.1, 10

We use factors and levels shown in Table 3 to test these examples. Also, the same assumptions, same demand elasticity value and price adjustment value for all products, are also applied to these examples. Tables 4 and 5 show the results for 0.1 demand elasticity instance and the results of price for each product with different price adjustment values, respectively. Column 1 presents the levels for the price adjustment factor, it. Note that the result for the model with fixed unit price is achieved when it is set to 0. Column 2 shows the total profit while column 4 reports capacity decisions for six periods. Capacity decisions are in terms of the number of machines required for demand satisfaction. Column 5 presents the inventory level for each period.

Table 4. Capacity results for demand elasticity equals to 0.1

π_{it}	Total Profit (in millions)	Period	Capacity decisions (number of machine needed)										Inventory level (holding cost = $2)
			M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	
0.1	56	1	1	0	0	0	0	0	0	0	0	0	0
		2	1	0	0	0	0	1	0	0	0	0	0
		3	1	0	2	2	0	1	0	0	0	0	0
		4	2	1	2	2	1	1	2	2	2	1	0
		5	2	1	2	2	1	1	2	2	2	1	0
		6	2	1	2	2	1	1	2	2	2	1	0
		Period	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	
1	387	1	0	0	0	0	0	0	0	0	0	0	0
		2	1	0	2	1	1	1	0	2	2	1	0
		3	1	1	2	1	1	1	1	2	2	1	0
		4	1	1	2	1	1	1	1	2	2	1	0
		5	1	1	2	1	1	1	1	2	2	1	0
		6	1	1	2	1	1	1	1	2	2	1	0
		Period	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	
10	555	1	1	1	1	1	1	1	1	1	1	1	0
		2	1	1	1	1	1	1	1	1	1	1	0
		3	1	1	1	1	1	1	1	1	1	1	427
		4	1	1	1	1	1	1	1	1	1	1	334
		5	1	1	1	1	1	1	1	1	1	1	622
		6	1	1	1	1	1	1	1	1	1	1	0
		Period	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	
100	516	1	0	1	0	1	0	0	0	0	0	0	0
		2	1	1	1	1	1	1	1	1	1	1	166
		3	1	1	1	1	1	1	1	1	1	1	328
		4	1	1	1	1	1	1	1	1	1	1	362
		5	1	1	1	1	1	1	1	1	1	1	442
		6	1	1	1	1	1	1	1	1	1	1	0

The results show that different price adjustment values will not have significant effect on capacity decisions but will have dramatic effect on the price. This phenomenon is resulted from small demand in this example. Since demand are small, purchasing more machines to satisfy extra demand will not increase the total profit. To satisfy extra demand and increase the total profit, a firm can change the price of certain products to a proper level so that demand can be altered to meet the capacity restriction without purchasing more machines. Table 4 demonstrates this analysis. Furthermore, the dramatic changes in the price are because of 0.1 demand elasticity which resembles the necessary product like sugar or salt. Since these products are required in life, their price will not have significant effect on quantity demanded. Therefore, significant price changes are identified in Table 5 and the level of significance increases when the price adjustment value changes from 0.1 to 100. Moreover, the level of significance for price change will be reduced when demand elasticity is 10. Tables 6 and 7 demonstrate this phenomenon.

Table 5. Price results for demand elasticity equals to 0.1

π_{it}	**Period**	Price for product in each period									
		1	2	3	4	5	6	7	8	9	10
0.1	**1**	60	60	60	60	60	60	60	60	60	60
	2	358.4	350	298.4	269.4	262.4	340.4	307.4	319.4	296.4	314.4
	3	738.8	659.9	532	530.8	315.4	672.1	585.4	609.8	506.2	566.6
	4	1100	1078.6	710.7	530.8	621	895.6	935.1	889.9	773.5	785
	5	1100	1078.6	710.7	530.8	621	895.6	935.1	889.9	773.5	785
	6	1100	1078.6	710.7	530.8	621	895.6	935.1	889.9	773.5	785
	Period	1	2	3	4	5	6	7	8	9	10
1	**1**	60	60	60	60	60	60	60	60	60	60
	2	3044	2964	2444	2154	2084	2864	2534	2654	2424	2604
	3	6580	5798	4566	4580	2431	5929	5091	5324	4310	4897
	4	6580	5798	4566	4580	5276	5929	5091	5498	4310	5667
	5	6580	5798	4566	4580	5276	5929	28.6	5498	4310	5667
	6	6580	5798	4566	4580	5276	5929	0	5498	4310	5667
	Period	1	2	3	4	5	6	7	8	9	10
10	**1**	60	60	60	60	60	60	60	60	60	60
	2	20609	20214	9798	6677	60	17664	60	14574	60	14240
	3	20609	20214	9798	6677	60	17664	60	14574	60	14240
	4	20609	20214	9798	6677	60	14715	60	13840	60	13247
	5	17269	21029	9798	6677	60	14715	60	13840	60	14903
	6	17269	28809	9798	7530	60	14710	60	10832	60	14903
	Period	1	2	3	4	5	6	7	8	9	10
100	**1**	60	60	60	60	60	60	60	60	60	60
	2	25286	19362	18472	15023	4021	23020	18560	20393	19425	0
	3	25286	32173	11396	7021	19410	23020	18560	18910	26394	0
	4	16918	24503	15408	0	12940	23020	18560	23373	23169	0
	5	28815	11672	16665	11601	6470	17493	18559	11431	11724	0
	6	16193	17053	16665	0	0	15644	34754	19628	0	0

The reason for this phenomenon is because of 10 demand elasticity which resembles non-necessary products like cars or computers. For these non-necessary products, increasing or lowering price will have significant changes on quantity demanded which limit the adjusting differences among prices.

Table 6. Capacity results for demand elasticity equals to 10

π_{it}	Total Profit (in millions)	Period	Capacity decisions (number of machine needed)										Inventory level (holding cost = $2)
			M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	
0.1	**5.2**	**1**	1	1	1	1	1	1	1	1	1	1	0
		2	1	1	1	1	1	1	1	1	1	1	324
		3	1	1	1	1	1	1	1	1	1	1	0
		4	1	1	1	1	1	1	1	1	1	1	216
		5	1	1	1	1	1	1	1	1	1	1	0
		6	1	1	1	1	1	1	1	1	1	1	0
		Period	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	
1	**5**	**1**	1	0	1	1	1	1	1	1	1	1	0
		2	1	1	1	1	1	1	1	1	1	1	12
		3	1	1	1	1	1	1	1	1	1	1	0
		4	1	1	1	1	1	1	1	1	1	1	0
		5	1	1	1	1	1	1	1	1	1	1	0
		6	1	1	1	1	1	1	1	1	1	1	0
		Period	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	
10	**3.1**	**1**	1	1	1	1	1	1	1	1	2	1	0
		2	1	1	1	1	1	1	1	1	2	1	2
		3	1	1	1	1	1	1	1	1	2	1	2
		4	1	1	1	1	1	1	1	1	2	1	10
		5	1	1	1	1	1	1	1	1	2	1	31
		6	1	1	1	1	1	1	1	1	2	1	0
		Period	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	
100	**6.3**	**1**	1	1	1	1	1	1	1	1	1	1	0
		2	1	1	1	1	1	1	1	1	1	1	5
		3	1	1	1	1	1	1	1	1	1	1	0
		4	1	1	1	1	1	1	1	1	1	1	1
		5	1	1	1	1	1	1	1	1	1	1	1
		6	1	1	1	1	1	1	1	1	1	1	0

Table 7. Price results for demand elasticity equals to 10

π_{it}	Period	Price for product in each period									
		1	2	3	4	5	6	7	8	9	10
0.1	**1**	60	60	60	60	60	60	60	60	60	60
	2	203.5	212.9	128.4	123.9	55.6	182.9	208.7	155.4	167.3	166
	3	203.5	212.9	128.4	89	55.6	168.7	206	155.4	162.5	155.4
	4	203.5	187.8	128.4	89	123.7	168.7	130.1	155.4	159.8	155.4
	5	203.5	115.4	128.4	89	123.7	147	59	155.4	91.1	155.4
	6	145.5	115.4	114.2	89	123.7	115.7	58.7	155.4	6.6	155.4
	Period	1	2	3	4	5	6	7	8	9	10
1	**1**	60	60	60	60	60	60	60	60	60	60
	2	225.5	194.3	159.5	155.3	38.8	202.2	60	162.4	60	188.1
	3	225.5	294.6	123.7	94.2	207.1	190.3	60	162.4	60	169.2
	4	184	231.1	148.6	94.2	103	190.3	60	180.2	60	193.4
	5	248.4	108.9	148.6	94.2	198.4	190.3	60	143.8	60	193.4
	6	159.6	139.93	140.3	120.2	136.6	58.8	58.8	204	58.8	193.4
	Period	1	2	3	4	5	6	7	8	9	10
10	**1**	60	60	60	60	60	60	60	60	60	60
	2	227.6	185.5	236.6	157.5	54.1	334.6	281.1	293.1	212.2	255.3
	3	227	299.7	183	108.6	198.6	229.1	274.4	184.7	272.3	223.4
	4	214.4	224	225.7	123.6	128.2	229.1	184.2	184.7	243.6	260.5
	5	247	177.7	184.9	144.7	177.5	184.3	233	159.1	135.3	268.7
	6	263	211.1	193	140.2	221.1	161.4	302.7	207.6	207.5	287.8
	Period	1	2	3	4	5	6	7	8	9	10
100	**1**	60	60	60	60	60	60	60	60	60	60
	2	205.6	174	134.2	141	40.7	186.6	170.1	159.3	134.6	150.9
	3	209.4	253.2	108	81.2	188.1	151.7	246.7	155.7	186.4	144.5
	4	186.2	187	128.8	70.9	77.7	185.1	122.3	168.1	158.4	162.7
	5	227	107	151.2	81.33	160.5	144	154.8	119.5	95.6	156.9
	6	145.3	131.7	112.5	121.6	131	123.1	255.2	182	142.4	179.5

5. Conclusions and Future Research

We formulated and investigated capacity planning with Walrasian price adjustment constraints. Examples are examined with different levels of price adjustment and demand elasticity to test the effectiveness of using Walrasian price adjustment constraints. The results from different levels of price adjustment are compared to fixed price results. We find that inventories are required at some levels of price adjustment and the capacity decisions will be varied due to different levels of price adjustment and demand elasticity. Our findings indicate that industries can achieve better capacity decisions and price after determining the level of price adjustment and demand elasticity that should be defined based on the product and market characteristics. Also, a better profit might be achieved using price adjustment. Although our results demonstrate the usefulness of Walrasian price adjustment, further work can be done in this area. For example, we use the same price adjustment value and demand elasticity for all products. However, different values of these two factors should be applied to different products to achieve a more realistic result. Also, this research can be extended with manufacture or subcontract decisions and capacity leasing, purchasing or selling decisions.

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