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Quantitative approach for Theory of Constraints in Manufacturing

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Abstract

In this paper, a systematic and quantitative view is presented for the application of the theory of constraints in manufacturing. This is done employing the operational research technique of mathematical programming. The potential of the theory of constraints in manufacturing is demonstrated. By applying the TOC philosophy based on this information, managers will be able to take the right actions that will improve the profitability of their companies. The model is proposed to be used with the TOC philosophy in order to improve the financial performance of a company.

Keywords: Theory of Constraints, bottlenecks, Capacity-constrained resources (CCR), Throughput

1. Introduction

The Constraints resource manufacturing organizing encounter very often the situation of surplus demand that its capacity to manufacture, which is because of the company policy to grasp all the market demand in order to prevent other major competitors from penetrating the market and at the same time maintains the company reputation for on time delivery. Manufacturing has undergone a number of changes in the last few years, in view of the economic environment in which companies are operating and of the introduction of advanced manufacturing technology. The model so prepared relates capacity constrained resources, material cost, direct labour cost, availability of capital, selling price, demand.

2. Theory of constraints

Theory of constraints is management policy developed by E.M. Goldratt. It maintains a focus on system constraints. Assumes the firm goal is to make money. Theory of constraints concept of measurement system was conceived on three simple performance measures, namely Throughput, inventory and operating expenses. Five steps of Theory of constraints are

2.1 Identify the system constraints.

2.2 Decide how to exploit system constraints.

2.3 Subordinate everything else to the above decision.

2.4 Elevate the system constraints.

2.5 Go back to step 1, do not allow inertia to be the constraint.

The Theory of Constraints, hereafter abbreviated as TOC, is a production and operations management strategy centered on the concept of capacity-constrained resources (CCR), more commonly called bottlenecks. TOC starts from the assumption of the existence of one or more CCR in any system. This assumption tends to lose its validity in systems with balanced loads. The performance may be profit, production volume, or any other suitable criterion. A simple example of a CCR is the slowest operation in a continuous simple flow line of production of discrete parts. The implementation of TOC in practice is achieved in a sequence of logical steps;

1. CCR Identification
2. CCR Management
3. Performance Improvement

3. CCR Identification

A CCR is defined as a resource which prevents the system from achieving a higher level of performance. It is then necessary to define precisely a metric for performance. In TOC, as it is applied in manufacturing environments, performance is considered to be profit which is defined as

PROFIT = THROUGPUT – OPERATING EXPENSES,

In turn, Throughput is defined as the sale prices of finished products, and Operating Expenses are defined as the costs of raw materials employed in obtaining these finished products.

Assuming that a manufacturing facility such as a workshop can make a number of several finished products, each with its unit sale price, unit raw material costs, and market demand, then maximum profit is obtained by making the most profitable mix of finished products subject to multi-resource capacities available. A CCR is defined as the resource which has the highest ratio of utilization to availability. Now we develop a linear programming (LP) model for CCR identification in manufacturing systems by introducing necessary notation.

i – index denoting part; i = 1,…,I
j – index denoting resource; j = 1,…,J
$\mathbf{A_{ij}}$ – unit i processing time of part i in resource j
$\mathbf{B_i}$ – unit profit of part i
$\mathbf{C_j}$ – capacity of resource j in planning horizon
$\mathbf{D_i}$ – market demand for part i in planning horizon
$\mathbf{R_i}$ – amount produced of part i in planning horizon
$\mathbf{S_j}$ – idle time of resource j in planning horizon

The LP model for CCR identification may be set down as:

$$\text{Maximise} \quad \sum_{i=1}^{I} Bi \times Ri \qquad (1)$$

The objective function (1) represents the total profit obtained over the planning horizon.

Subject to

$$\sum_{i=1}^{I} \mathbf{A_{ij} + S_j = C_j} \qquad \mathbf{j = 1 \ldots J} \qquad \mathbf{(2)}$$

The constraints **(2)** ensure the capacity limit for each resource j.

$$\mathbf{Ri \le Di} \qquad \mathbf{i = 1 \ldots I} \qquad \mathbf{(3)}$$

The constraints **(3)** ensure that production of each part does not exceed demand.

$$Ri \ge 0 \qquad i = 1 \ldots I \qquad \mathbf{(4)}$$

$$Sj \ge 0 \qquad j = 1 \ldots J \qquad (5)$$

Finally, the constraints (4) and (5) guarantee the no negativity of the decision variables R_i and S_j of the LP model, whose input parameters consist of the set A_{ij}, B_i, and C_i. The resource with the highest ratio of utilization to availability, C_j, is the same as the resource with the minimum idle time, S_j. Consequently, any resource with $S_j = 0$ is a CCR. It can be seen that the LP model seeks to identify the optimum part mix and the CCR (s) in the manufacturing system. The LP model provides the master production schedule which maximizes Throughput.

$$\sum_{i=1}^{I} \mathbf{A_{ij}} \times \mathbf{Ri} \qquad \textbf{(6)}$$

4.CCR Management

Once identified, a CCR must be used effectively in such a way so as to obtain the desired performance of the manufacturing system. This is known as CCR management, which is implemented by a scheduling technique referred to as drum-buffer-rope (DBR). DBR reduces this complexity by focusing attention on CCRs as opposed to all resources. In order to achieve the highest performance possible, CCRs must be scheduled with a view to avoiding unnecessary idle time which implies lost throughput.

1. Each task/activity happens only once.
2. Precedence among tasks/activities is specified explicitly than through the nature and amounts of material movement between tasks/activities. These two limitations are removed by employing the state task network (STN) representation.

5. STN – DBR Scheduling

Before developing the model, we introduce necessary notation

i = index denoting task; i=1,…,I	$\mathbf{C_s}$ = maximum storage capacity dedicated to state *S*
j = index denoting production unit; j=1,…J	$\mathbf{I_j}$ = Set of tasks which can be performed by production unit *j*
t = index denoting time; *t*=1,…*H*	V_{ij}^{max} = maximum capacity of production unit *j* when used for performing task *i*
s = index denoting material state; s=1,…S	V_{ij}^{min} = minimum capacity of production unit *j* when used for performing task *i*
$\mathbf{S_i}$ = set of states which has task *i* as input	$\mathbf{W_{ijt}}$ = binary decision variable = 1 if production unit *j* starts processing task *j* at the start of period *t ;* = 0 otherwise
$\bar{S}_i$ = set of states which has task *i* as output	$\mathbf{B_{ijt}}$ = amount of material which starts undergoing task *i* in production unit *j* at the start of period *t*
$\boldsymbol{\rho_{is}}$ = proportion of input of task *i* from state $S \in S_i$	$\mathbf{S_{st}}$ = amount of material stored in state *S* at the start of period *t*
$\bar{\rho}_{is}$ = Proportion of output of task *i* to state $S \in S_i$	**M** = sufficiently large number
$\mathbf{P_{is}}$ = processing time for output of task *i* to	$\mathbf{F_{sjt}}$ = amount of material of state *s* being held in production during the tome interval *t*
$\mathbf{P_i}$ = completion time of task *i*,	**B** = index denoting buffer unit
$\mathbf{K_i}$ = set of production units capable of performing task	**C** = index denoting CCR unit
$\underline{\mathbf{T}}$ = set of tasks which has input from state *S*	$\mathbf{F_s}$ = set of states whose members are finished products
$\bar{T}_s$ = set of tasks which has output to state *S*	$\mathbf{R_{st}}$ = quantity of finished products in state S scheduled for delivery at time t

The STN model for DBR scheduling may then be set down as:

Minimise

$$\sum_{i \in H} \quad \sum_{S \in Fs} (Sst - Rst, 0), \qquad (7)$$

$$\sum_{i \in Ij} Wijt \ \leq 1 \qquad j \neq c, \ \ \forall t \qquad (8)$$

$$\sum_{i\epsilon Ij} Wijt = 1 \quad j = c. \quad \forall t \tag{9}$$

$$\sum_{t\epsilon Ij} \sum W\, p\rho - 1 \leq M(1 - Wijt) \leq 1 \quad \forall j, \forall t, \forall i, \epsilon\, Ij, \tag{10}$$

$$W_{ijt}\, V_{ij}^{min} \leq B_{ijt} \leq W_{ijt}\, V_{ij}^{max} \quad \forall j, \forall t, \forall i, \epsilon\, Ki, \tag{11}$$

$$0 \leq Sst \leq Cs \quad \forall s, \forall t, \tag{12}$$

$$S_{st} = S_{s,\, i\text{-}1} + \sum_{i\epsilon Ts} ris \sum_{j\epsilon ki,\, j\neq c} Bi, j, t - pis - \sum_{i\epsilon Ts} ris \sum_{j\epsilon ki,\, j\neq c} Bi, j, t \tag{13}$$

$$\sum_{j\epsilon b} Fsjt = Ss, t-1 + \sum_{j\epsilon b} Fs, j, t-1 + \sum_{i\epsilon Ts} ris \sum_{j\epsilon ki} Bi, j, t - pis - \sum_{i\epsilon Ts} ris \sum_{j\epsilon ki} Bijt \quad \forall s, \forall \tag{14}$$

$$W_{ijt}\, \epsilon \{0,1\} \quad \forall i, \forall j, \forall t \tag{15}$$

$$B_{ijt} \geq 0 \quad \forall i, \forall j, \forall t \tag{16}$$

$$S_{st} \geq 0 \quad \forall i, \forall j, \forall t \tag{17}$$

In the objective function (7), we seek to minimize the maximum difference between delivered quantities and stored finished products.

The constraints (8) ensure that at any given time, a production unit which is not a CCR can only start at most one task. For a CCR, the constraints (9) guarantee that it is never idle, since by definition a CCR is the resource that sets an upper limit to manufacturing system performance. The constraints (10) serve to ensure that tasks are performed non-preemptively. The constraints (11) ensure that the quantity of material undergoing a task in a production unit is bounded by the minimum and maximum capacities of that unit. The constraints (12) guarantee that the quantity of material stored in a state does not exceed the maximum storage capacity for that state. The constraints (13) and (14) constitute material balances for production units and buffers, respectively. The binarity and non-negativity of the appropriate decision variables are ensured by the constraints (15)-(17).

In the STN model, we have assumed that the only unit possessing an input buffer is a CCR. Neither setup non maintenance tasks are taken into consideration. At the same time, we note that all the aforementioned aspects can be easily incorporated into a more general STN model. We purposely restricted our scope so as to focus on the attainment of scheduled deliveries of finished products.

6. Performance Improvement

The identification and management of CCRs serve to achieve maximum performance for given capacity and demand levels. In order to go beyond this level of performance, measures have to be taken and the corresponding investments have to be made to increase capacity and/or demand.

6.1- Throughput (TH) defined as the rate at which the manufacturing system generates revenue.
6.2- Inventory (IN) defined as the investment made to generate revenue.
6.3- Operating expense (OE) defined the cost of transforming inventory into throughput.

In the context of TOC, system performance is improved by increasing inventory in order to increase throughput and/or decrease operating expense. It is clear that the performance measurements of TOC are very different from traditional management accounting approaches.

Apart from external constraints, such as market demand, internal CCRs by definition limit the performance of manufacturing system. Consequently, CCRs must be the focus of all improvement efforts. For a CCR machine, its capacity may be increased by such measures as setup reduction, breakdown reduction, and processing speed enhancement. All such measures naturally involve investments.

7. Case Study

A manufacturing organization considered in this article is based nearby the capital of India. Due to sudden increase in export order from African countries, management had to decide on action plan. As demand was uncertain to sustain management was not interested in strategic investment for resource acquisition. After considering the entire related factor, management was not interested on providing overtime also. Management was interested on outsourcing. Thus, the present study was conducted to guide the management about outsourcing.

Company manufactures five different types of particular product (consumer durable) coded A, B, C, D and E. The weekly market demands and selling prices were also shown all top of **Figure1**. All the calculations were done on Indian currency (Rs). Raw material passes through differ internal resources as shown in Figure 1, Raw materials to manufacture product A were A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11and A12 as shown in **Figure1**. Similarly for product B. raw materials were B I, B2, B3, B4, B5, BG, B7, B8, B9, Bl0, B11 and B12, for C, raw materials were Cl, C2, C3, C4, *C5*, C6, C 7, C8, *C8*, C9, Cl0, C11, and *C12* and for D, raw materials were Dl, D2, D3, D4,.D5, D6, D7, D8, D9, D l0, D 11 and D12. Again for E, raw materials were El, E2, E3, E4, E5, EG, E7, E8, E9, El0, Ell and E 12. Cost of various raw materials for product A, B, C, D and E were given in (**Table B**). Material passes through total twelve types of work centre(WC). Work centre for certain operation were double for Example, WC1 to meet the demand. In case of final assembly there were three work centre (WC 8). Dark lines indicates flow path shown in **Figure1** of particular component route that component passes through work centre 10, 6 and assembled at work centre 8. Another component passes through Work Centre1,2,3,4,5,6,7, and assembled at Work Centre 8. Third one passes through work centre 9, 12 and assembled at Work Centre 8. To manufacture these products, materials passes through various work centre. Times consumed by these materials at various work centre are given at (Cycle time and capacity utilisation) **(Table A)**. Column two represents the processing time of components at various Work Centre to manufacture A, to manufacture A raw material A1 at WC1 required 0.23 min. Then A1 and A2 combined at WC2 required 0.25 min likewise column 3 ,4 ,5,6, represents time taken by various work centre to process B,C,D,E.

Company runs for six days in a week with single shift. Overhead expenses per week for organization were Rs 4104000. Set up time for all the stations on an average taken was 12 min /setup. On any particular day maximum no. of set up required was one. Set up time and no of set ups per day was assumed so after analysis of last six months data. Weekly capacity for work center (WC) was calculated as follows, there were two number of WC1. For daily 8 hrs run total weekly time was $(48\times2\times6) = 5760$ min. calculation of weekly setting time was 12 min per set up, one WC required one set up, a two nos of WC1 that is $12\times2\times6=144$ min .Weekly capacity (total weekly time- time lost due to sets up) is equal to 55760-144=5616 min.

From **(Table A)**, we clear that 9WC and 10 WC are constrained Resource. The WC5, 6, 7 utilized work center least. To over come the problems, suggestions given to management was to run all three. Total capacity increased was 180×3 that is 540. Only one work centre 10 was run for five days, so capacity increased in work center 10 was $(30\times5=150\text{min})$. Overhead expenses remained the same.As seen in Table A, for product cost calculation and raw material price to manufacture A (A1, A2,A3,A4, ...A12) was Rs.498.2 Product A consumes 2.77 min as seen in Table B. Cost of 2.77 min was (2.77×62.87) =Rs.174.15 Profit per working min for all the products was calculated. As per standard accounting higher profit/working min was the indication of manufacturing priorities.

Thus sequences of priorities were A, B, E, C, and D. As seen in **(Table C)**, one unit of A consumes 0.55 min of constrained resource. After producing all "A" (8200) still some constraint resource time available on hand. Total product throughput calculation for B was = (9089 $\times$ 275.2) + (1411 $\times$ 80) which was equal to Rs.2614173. Similarly throughput for other products was calculated. Net profit as per standard accounting was Rs.1330433 which can be seen in (**Table C)**. In TOC analysis **(Table D)** throughput/constraint resource min was found out, which is different from standard accounting,. It considers all resources equality. Throughput per manufactured unit of product A was equal to 800- 498.2=301.8 Throughput per contracted unit of A was equal to 800-700 = 100. Total product Throughput calculation for A was equal to 6943 $\times$ 301.8 + (1257$\times$100) which was equal to Rs. 2221097. Similarly throughput for other products was calculated.

Net Profit in that case increased from standard accounting system by Rs. (1352197-1330433) = Rs.21764, that is increased by 1.63%

Products throughput and net profit was calculated as described in earlier two cases.

In LP analysis based on TOC model, net profit increased by (1399630-1330433) = Rs.62421 from standard accounting, that is 5.2% and Rs. 47433 or 3.51% from TOC model.

This problem can be solved by the LP objective function also as follows

Zmax = (700-498.2) A + (680- 484.8) B+ (640 - 471.8) C + (640 - 462.2) D + (625 - 446.35) E,

Subject to the following constraints

Technological Constraints

$0.23A+0.22B+0.2C+02D+0.21E \leq 5616$

$0.25A+0.23B+0.22C+0.22D+0.2E \leq 5616$

…… ……. ………

$0.1A+0.1B+0.1C+0.1D+0.1E \leq 2808$

Market constraints

A=8200, B=10500, C=1550, D=1350, E= 2400 and A, B, C, D, E = 0

The resulting optimum product mix is same as given in **(Table E)**, that is to manufacture 2572, 10500, 1550, 1350, 2400 of A,B,C,D,E respectively.

8. Results

The details of comparisons of three models are given in **(Table F)**. The LP model based on TOC suggested manufacturing 2572 numbers A, 10500 of B, 1550, of C 1350, of D and 2400 of E and to outsource 5628 of A only is shown in **(Table F)**. Similarly to manufacture and to outsource quantity suggested by TOC and SAC models can be depicted in Table F. After going through this an analysis by a cross-functional team, management decided to implement this model under sudden increase in order.

9. Conclusions and Suggestions

For unbalanced manufacturing systems, TOC constitutes a useful strategy for maximising and improving system performance. We have shown that the operational research technique of mathematical programming provides a systematic basis for the implementation of TOC in practice. A substantial scope exists for developing mathematical models of TOC in automated manufacturing systems and their validation in industrial practice.

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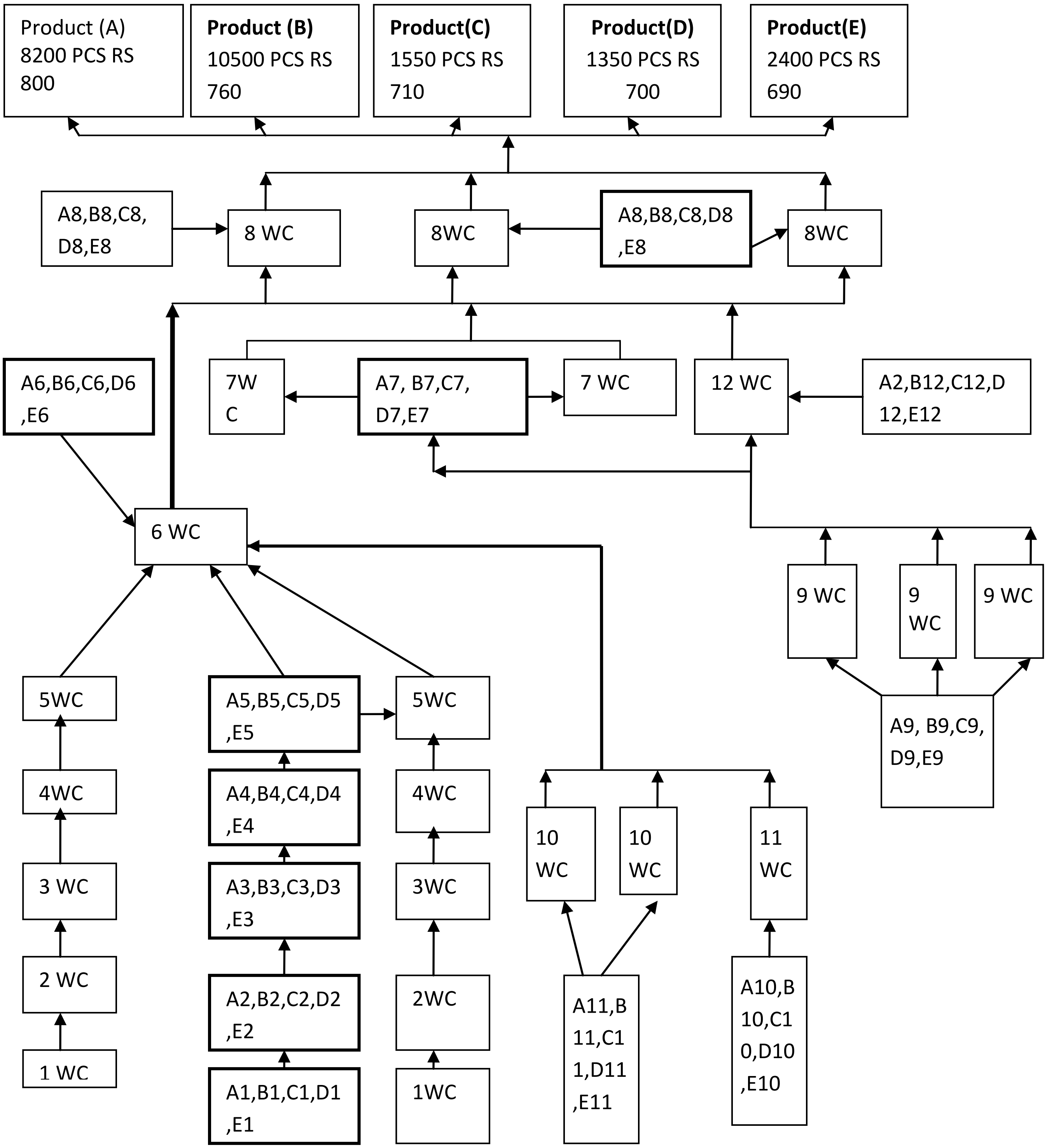

Figure 1 Systematic Representation of process details

WORK CENTRE	Time/piece at various work centres, min					Weekly load on work centre	Weekly capacity of work centre	Utilisation of work centre percentage	Capacity after adjustment	Utilsation after adjustment percentage
	A	B	C	D	E					
WC1	0.23	0.22	0.20	0.20	0.21	5280	5616	94.01	5616	
WC2	0.25	0.23	0.22	0.22	0.20	5583	5616	99.41	5616	
WC3	0.23	0.23	0.23	0.23	0.23	5520	5616	98.29	5616	
WC4	0.23	0.23	0.23	0.23	0.23	5520	5616	98.29	5616	
WC5	0.21	0.21	0.21	0.21	0.21	5040	5616	89.74	5616	
WC6	0.08	0.08	0.08	0.08	0.08	1930	2808	68.37	2808	
WC7	0.21	0.21	0.21	0.21	0.21	5040	5616	89.74	5616	
WC8	0.32	0.32	0.32	0.32	0.32	7680	8424	91.17	8424	
WC9	0.55	0.49	0.44	0.44	0.47	12059	8424	143.15	8964	134.53
WC10	0.25	0.24	0.23	0.23	0.22	5765	5616	102.65	5766	100
WC11	0.11	0.11	0.11	0.11	0.11	2040	2808	94.01	2808	
WC12	0.10	0.10	0.10	0.10	0.10	2400	2808	85.47	2808	
TOTAL	**2.77**	**2.67**	**2.58**	**2.58**	**2.59**				**65274**	

(Table A) Cycle time and capacity Utilisation

WC	Product A		Product B		Product C		Product D		Product E	
	Component	Cost/Unit	Component	Cost/Unit	Component	Cost/Unit	Component	Cost/Unit	Component	Cost/Unit
WC1	A1	34.00	B1	32.00	C1	31.50	D1	31.00	E1	31.60
WC2	A2	3.20	B2	2.80	C2	2.80	D2	2.50	E2	2.80
WC3	A3	2.55	B3	2.35	C3	2.35	D3	1.95	E3	1.95
WC4	A4	1.75	B4	2.25	C4	2.25	D4	1.85	E4	1.85
WC5	A5	2.20	B5	2.20	C5	2.20	D5	2.20	E5	1.80
WC6	A6	1.50	B6	1.50	C6	1.40	D6	1.40	E6	1.20
WC7	A7	9.10	B7	8.90	C7	8.90	D7	8.50	E7	7.80
WC8	A8	383.90	B8	376	C8	366.10	D8	361.60	E8	344.60
WC9	A9	21.90	B9	19.90	C9	16.90	D9	15.90	E9	15.40
WC10	A10	29.50	B10	28.50	C10	29.50	D10	27.60	E10	30.25
WC11	A11	7.50	B11	7.30	C11	6.80	D11	6.60	E11	6.00
WC12	A12	1.10	B12	1.10	C12	1.10	D12	1.10	E12	1.10
TOTAL		**498.2**		**484.8**		**471.8**		**462.2**		**446.4**

(Table B) (Raw material cost for product)

Details	Product				
	A	B	C	D	E
Total working minutes per products	2.77	2.67	2.58	2.58	2.59
Product cost (time cost + raw material)	67235	65266	634	624.4	609.18
Product market price	800	760	710	700	690
Product profile(price - cost)	127.65	107.34	76	75.6	80.82
Profit per working minute	46.08	40.20	29.46	29.30	31.20
Market demand	8200	10500	1550	1350	2400
Units to manufacture	8200	9089	0	0	0
Throughput per manufactured unit	301.8	275.2	238.2	237.8	243.65
Units contracted outside	0	1411	155	135	240
Throughput per contract unit	100	80	70	60	65
Total product throughput	2474760	2614173	108500	81000	156000
Overall throughput(I)			**5434433**		
Operating expenses(OE)			**4104000**		
Net profit (T - OE)			**1330433**		

(Table C)Standard Accounting Analysis

Details	Product				
	A	B	C	D	E
Product market price per unit	800	700	710	700	600
Raw material cost per unit	498.2	484.8	471.8	462.2	446.35
Throughput/ manufactured unit	301.8	275.2	238.2	237.8	243.65
Constraint resource(9 WC)/unit, min	0.55	0.49	0.44	0.44	0.47
Through put/ constraints resource unit	548.7	561.6	541.4	540.5	518.4
Market demand	8200	10500	1550	1350	2400
Unit to manufacture	6943	10500	0	0	0
Throughput/manufactured unit	301.8	275.2	238.2	237.8	243.65
Units contracted outside	1257	0	1550	1350	2400
Throughput per contract unit	100	80	70	60	65
Total product throughput	2221097	2889600	108500	81000	156000
Overall throughput(I)	5456197				
Operating expenses(OE)	4104000				
Net profit (T - OE)	1352197				

Table (D) TOC Analysis

DETAILS	Product				
	A	B	C	D	E
Contractor price	700	680	640	640	625
Raw material cost/unit	498.20	484.80	471.80	462.20	446.35
Contractor profit	201.80	195.20	168.20	177.80	178.65
Constraint resource(9 WC) /unit, min	0.55	0.49	0.44	0.44	0.47
Contractor profit/constraint resource minutes	366.90	398.40	382.30	404.10	380.1
Market demand	8200	10500	1550	1350	2400
Unit to manufacture	2572	10500	1550	1350	2400
Throughput/manufactured unit	301.80	275.20	238.20	237.80	243.65
Units contracted outside	5628	0	0	0	0
Throughput per contract unit	100	80	70	60	65
Total product throughput	1339030	2889600	369240	321030	584760
Overall throughput(I)			5503630		
Operating expenses(OE)			4104000		
Net profit (T - OE)			1399630		

Table (E) LP Based TOC

		L.P MODEL	TOC	SAC
Manufacture	A	2572	6943	8200
	B	10500	10500	9089
	C	1550	0	0
	D	1350	0	0
	E	2400	0	0
Outsource	A	5628	1257	0
	B	0	0	1411
	C	0	1550	1550
	D	0	1350	1350
	E	0	2400	2400
Net profit		1399630	1352197	1330433

(Table F)Comparison between LP, TOC and SAC