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Production, Capacity and Workforce Planning: A Mathematical Model Approach

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Abstract: In the era of globalization, integrated planning for production, workforce, and capacity is the key factor for attaining success in any industry. This paper provides a mathematical model to determine the best possible combination of required capacity, workforce, and lot size for a multi-product, multi-stage, and multi-model production system. The model provides a blueprint of a detailed workforce distribution plan to optimize the available capacity and determine the ideal lot size based on the ways (i.e. tray/trolley) of handling material to control the space required for setup and floor area. This model uses linear programming to reduce the manufacturing cost. A real-world numerical illustration proves the competency of this model, which - for an industry - serves as a practical guide to achieve the best combination of capacity, workforce, and lot size.

Keywords: Mathematical model, linear programming, one-piece flow, capacity planning, workforce planning.

1 Introduction

Since the beginning of the 21st century, many industries has only on the means to reduce the production cost. Later, instead of using a dedicated line, manufacturing industries used the concept of multi-product in multi-model production line to enhance other resources and the equipment level. The main objective of the multi-model line is to reduce both production and setup cost. In a multi-model production line, different products (i.e. A, B, C, etc.) pass through various process cells/stages/machines (i.e. main and sub-assembly) that have a mix of dedicated and shared resource facility (Figure 1). A majority of computational and practical concepts of production and capacity-planning factors are independent [1]. However, in real-world production planning, factors of workforce flexibility and machine flexibility impact capacity and utilization. Similarly, capacity-planning factor for forecast demand, overtime, and under time is significantly influenced by the production-planning elements of production cost, inventory-holding cost, back-order cost, lead time, and delivery time. Integrated planning to reduce cost has not been adopted in many real-world approaches. Thus for many manufacturers, integrating strategies of production and other related operations appear to be a prerequisite for ensuring performance excellence.

The research scope of integration is still vast as many researchers have proposed different concepts for production capacity planning and workforce planning models separately for the objective function of minimizing the overall production cost in the Production Planning Control (PPC) framework. Most of the production capacity planning and workforce planning models are deterministic and use either Linear Programming (LP), Integer Programming (IP), or Mixed Integer LP (MILP) [2–12]. Optimization approaches based on pure simulation or simulation-based experimental designs propose and consider the uncertainties associated with production capacity planning in the PPC framework [13–16]. Capacity and workforce planning problems considered are dynamic in nature [17, 18] and heuristics [19].

Multi-criterion Production Capacity and Workforce Planning (PCWFP) models with objectives of cycle time minimization, the number of setup/setup time minimization, profit maximization, overtime minimization, and maximizing resource utilization, along with cost minimization have been also resolved [20, 21]. Very few authors suggested that handling the capacity problems is oversimplified using the non-traditional

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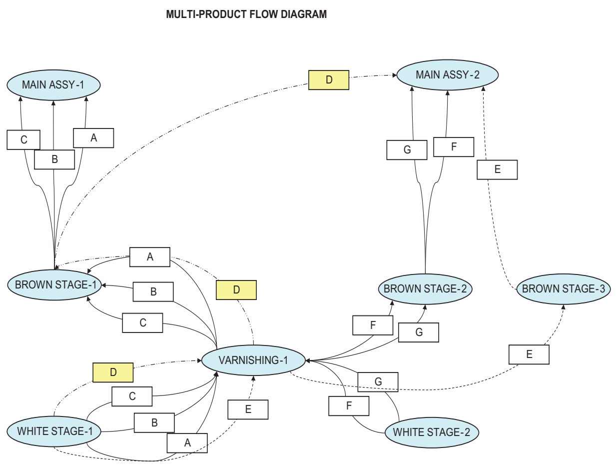

Fig. 1: Multi-Product, Multi-Stage, and Multi-Model with Shared Resource Facility

search techniques such as genetic algorithm, Simulated Annealing (SA), tabu search, swarm intelligence, and pattern search [22]. These methods mostly use CPLEX, LINGO, LINDO, MATLAB (i.e. MATrix LABoratory), C/C++ programming language. The main purpose of search techniques is the multi-directional search to find the global optimum.

In this paper, we develop a PCWFP model to distribute the optimal workforce for performing a set of tasks with the main objective function of the manufacturing cost minimization in an automobile manufacturing industry with multi-period, multi-stage, and multi-product system. Many worthwhile thoughts have been developed on lean production. The remaining paper is organized as follows. Section 2 provides a detailed literature review on the model development and techniques based on capacity-workforce planning optimization. Section 3 deals with the problem description and assumptions made for the model development. The mathematical model and details of constraints are provided in Section 4. Section 5 describes practical implementation of the model and managerial insights in detail.

2 Literature Review

The workforce planning is one of the most complex managerial tasks in the PPC network when calculating the capacity and aggregate planning. It becomes more complex when capacity is the most sensitive factor to the product mix and process sequence, and new bottleneck tools would enter the system as the demand changes due to uncertainties. Hopp et al. [23] clearly explained the relationship between strategic PPC tasks of the forecast, capacity plan, and workforce plan, which formed the basis of the aggregate plan to achieve the determined production. In real-world problem, there is a gap in the calculation of workforce planning factors of workforce assignment and workforce utilization with overtime and hiring/firing being the crucial elements in the performance of a manufacturing system. Therefore, the workforce planning is a productive pathway to continue further study. Many research articles have been published on the PCWFP; with various capacity and demand fluctuations [2, 4, 6, 11, 16, 19, 24–33]. Mathematical model and programming techniques have been used extensively for solving capacity-planning problems compared to static-, simulation-, and queuing-based analysis [26].

Few studies have solved capacity-workforce-type problem with the advanced mathematical tools such as goal programming, dynamic programming, non-LP, and various search techniques. Leung et al. [21] address the aggregate production planning problem with diverse functioning constraints, including workforce level, production capacity, factory locations, machine utilization, storage space, and other resource limitations, which are solved by a pre-emptive goal. Chen [8] mainly focused on the product mix problem and order selection based on the optimal set of work/customer to maximize the operational profit over a planning horizon with mixed IP (MIP) using CPLEX solver. Lot-sizing and sequencing of multiple products on capacity-constrained resources is the significant decision in the capacitated-lot-sizing problem [34] formulated by the MILP. Ryu [35] proposes an integrated planning framework for production capacity and supply chain capacity formulated by the MILP. Mula et al. [36] proposed a fuzzy mathematical programming model for the capacity and material requirement planning problem. Lee et al. [37] considered the decomposition approach for solving the capacity problem in the flexible assembly system. Kim and Uzsoy [19] represented models for capacity planning problem that clearly distinguish the relationship between capability levels and functional performance criteria such as work in progress and throughput. The problem is solved using two constructive heuristic and extent of the Lagrangian heuristic to resolve the multi-stage problem. Hsu and Le [38] studied mixed integer non-linear programming model based on the SA for the capacity optimization problem to enhance the supply chain network in a high-tech manufacturing industry. Mokhtari et al. [31] produced an integrated model between production capacity planning and operational scheduling, and then a two-phase genetic algorithm approach for solving the crashing and sequencing functions.

Most of the above-mentioned paper deals with planning approaches used over the years, which are relevant to the proposed production capacity workforce and still have one or more following limitations:

–Most of the suggested mathematical models consider single-stage/assembly with single-product, multi-stage/assembly with single-product, or single-stage/assembly with multi-product, but rarely discussed multi-stage/assembly with multi-product and multi-period system. In addition, solving real-life problems involves using various production-associated variables (i.e. production capacity, product flow, volume, lot size, machine capacity, processing time, setup time, and line stoppage and maintenance downtime).

–However, many research models provide application potential, but research implementation in real-life problems is still lacking. Incorporation of production capacity, workforce, and its level of utilization and then lot-size determination based on the material handling size are rare decision variables for cost minimization.

We have developed the mathematical model for PCWFP for multi-model production line in various process types of an industry. Note that comparing the competence of different optimization technique is not in the scope of this paper.

3 Problem description and assumptions

Our aim is to develop a mathematical model that completely integrates production in regular time, contingency production of the overtime/holiday working (i.e. lay-off/hiring workforce), inventory, back-order, and setup cost of multi-product, multi-period stages of a real-world manufacturing situation. Thus, the optimization models that consider the objectives such as the change in capacity level maximize the shared resource utilization, but other than total cost minimization these models rarely solve detailed setup cost based on lot-size optimization. Such models are also oversimplified (i.e. not comprehensive to study multi-period, multi-stage, and multi-product system). Therefore there has been the need to develop a flexible mathematical model dealing with production capacity-workforce planning problems for fluctuated demand scenarios. Most real-world problems are non-linear to solve [39] and linear relationship between all variables does not always supply the best results; but too much of non-linear relationships makes the problem very difficult to solve.

To solve the model, first we define the indices, input variables (i.e. parameter), and decision variables, then provide the detailed problem formulation in Section 4.

Indices

i: Index for time periods ($i = 1,\ldots,I$)
c: Index for manufacturing cells ($c = 1,\ldots,C$)
m: Index for stations/machines ($m = 1,\ldots,M$)
v: Index for product varieties ($v = 1,\ldots,V$)
x: Index for production channel (x = 1, 2, and 3)
If $x = 1 \Rightarrow$ Normal production channel (i.e. consider 1st and 2nd shift)
If $x = 2 \Rightarrow$ Contingency-overtime production channel (i.e. consider 3rd shift)
If $x = 3 \Rightarrow$ Contingency-lay-off production channel (i.e. Holiday shifts)
n: Index for number of material handling ($n = 1,\ldots,N$)

Input variables

FD_{iv}: Forecast demand
$C_{c,max}$: Maximum available capacity of all three shifts in cell c (i.e. $C_{iv} + C'_{iv}$)
C_{iv}: Available (i.e. working day) capacity in all shifts during the period i for product v
C'_{iv}: Additional (i.e. holiday) capacity in all shifts during the period i for product v
C_i: Capacity during the period i

For production cost

T: Total working hours/day (i.e. total number of shifts per day $\times$ working hours per shift)
h: Total working time per shift
S: Total number of shifts
$TOCt_{cv}$: Total operator cycle time
BNt_{cv}: Bottleneck time
WD_i: Number of working days
HD_i: Number of holidays
γ_c: Overall Equipment Efficiency (i.e. OEE)
ρ_c: Number of additional facilities (i.e. parallel)
∂_i: Absenteeism and other delays
OP_{cv}: Average productivity per man per shift
$W_{icv,min}$: Minimum number of workforce
$W_{icv,max}$: Maximum number of workforce (i.e. including holidays)
W_i: Required workforce based on demand
$W_{i\partial}$ Required workforce based on demand with delay
CP_{cvx}: Production cost per unit channel $\times$ for product v in cell c

For setup cost

α_c: Material handling (i.e. container) size in cell c
Pt_{cv}: Processing time in cell c for product v
St_{cv}: Average setup time in cell c for product v
$Lt_{(n,\alpha c)}$: Current n number of material handling operation time in cell c
$Ltrd_{cv}$: Operation time ratio in cell c
CS_v: Average setup cost/unit time of cells for product v

For inventory cost

PU_{icv}: Customer priority and uptime decision factor during the period i in cell c for product v (i.e. $PU_{icv} \leq 1$)
H_i: Inventory carrying cost of semi-finished product per unit in period i
CI_{iv}: Inventory carrying cost of finished product per unit in period i for product v
NP_v: Number of partitions for each product v
NV_p: Number of products in each partition p
CP_{cv}: Production cost per unit for product v in cell c

For back-order cost

CB_{iv}: Average penalty cost per unit of unfulfilled demand in period i for product v

Decision variables:

For production cost

W_{ic1}: Total workforce for normal production during the period i in cell c

W_{ic2}: Total workforce for contingency overtime production during the period i in cell c

WF_{ic}: Total workforce for contingency lay-off production during the period i in cell c (i.e. lay-off/hiring workforce)

P_{icvx}: Total units produced through channel x during the period i in cell c for product v

For setup cost

N_{cv}: Total quantity of materials handling in cell c for product v

β_{cv}: Lot-size in cell c for product v

SN_{icv}: Number of setup during the period i in cell c for product v

For inventory cost

Bt_{cv}: Batch processing time in cell c for product v

PR_{cv}: Production rate in cell c for product v

APR_{icv}: Average production rate in cell c for product v

Wt_{icv}: Waiting time during the period i in cell c for product v

I_{icv}: Total finished product inventory during the period i in cell c for product v (i.e. $c = 1$ always)

PA_{iv}: Number finished unit dispatched to customer dispatch center (CDC) during the period i for product v

For back-order cost

B_{iv}: Total unfulfilled demand in period i for product v

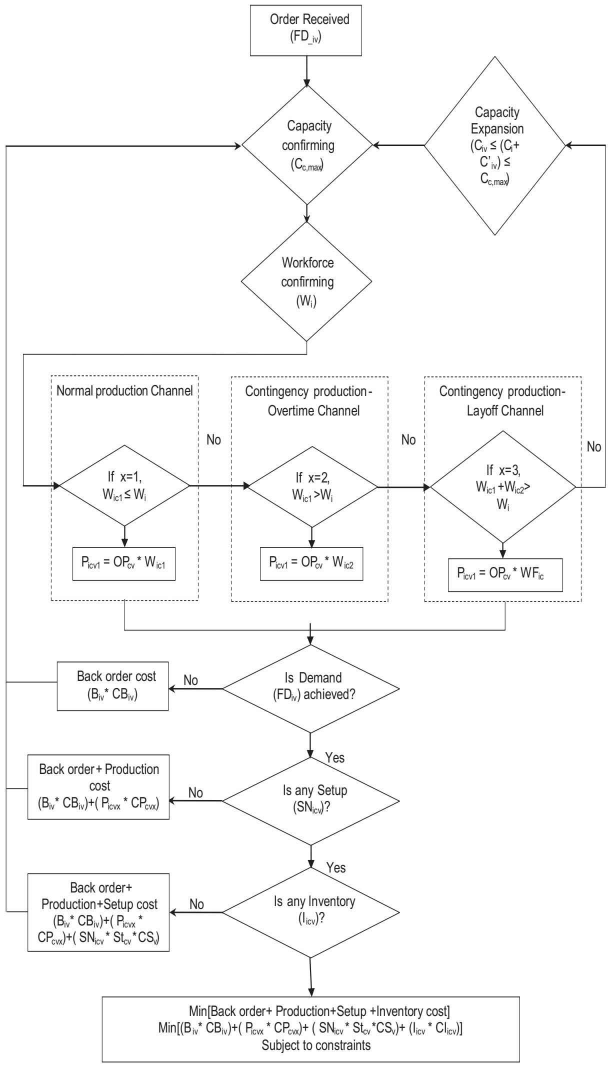

Fig. 2: The Decision Framework Flow of the PCWFP Model

4 Problem formulation

The main objective of our mathematical model is to find the best possible capacity required and lot-sizes at each production stage by minimizing the Total Manufacturing Cost (TMC). TMC includes production, setup, inventory-holding (including main and sub-assembly), and back-order cost. The motive of the objective function is to balance the production rates at successive production stages of multi-product through a concurrent adjustment of the capacity, workforce, and lot-size, and considering the trade-off between the capacity cost and savings in setup, inventory and back-order costs. We've used two following main novel approaches: (1) Distributing the workforce regarding normal, overtime, and lay-off production channels based on available capacity and required demand and (2) Reducing the production and setup cost by determining lot-size based on the floor space and the number of material handled. Figure 2 shows the decision framework flow of the PCWFP model. On a receipt of an order, the available capacity and the workforce level within available resource facility are checked to know when the required workforce level (W_i) is less than or equal to usual production workforce ($W_i \leq W_{ic1}$), and whether the usual production channel is activated. However, when the required workforce level (W_i) is greater than the normal production workforce (i.e. $W_i > W_{ic1}$), the contingency overtime production channel would be activated along with the ordinary channel ($W_{ic1} + W_{ic2}$). When the need to satisfy the upcoming high/uncertain demand from more than two channels of workforce levels ($W_i > (W_{ic1} + W_{ic2})$) arises, the contingency lay-off production channel would be activated along with the other two channels $(W_{ic1}+W_{ic2}+WF_{ic})$. The details of the objective function and constraints are provided in the following subsections.

4.1 The objective function

The objective function of total cost minimization is provided in Equation (1);
Total Cost (Z) Minimization = {[Production Cost of (Normal channel + Contingency-overtime channel + Contingency-lay-off channel)]^{a} + [Setup cost]^{b} + [Inventory-Holding Cost (Main assembly^{c1} + Sub-assembly^{c2})] + [Back-order Cost]d}

$$Min_Z = \left\{ \begin{aligned} &\left(\left[\sum_{x=1}^{3}\sum_{c=1}^{C}\sum_{v=1}^{V}\sum_{i=1}^{I} P_{icvx}\times CP_{cvx}\right]\right)^{a} \\ &+\left(\left[\sum_{v=1}^{V}\sum_{c=1}^{C}\sum_{i=1}^{I} SN_{icv}\times St_{cv}\times CS_{cv}\right]\right)^{b} \\ &+\left(\left[\sum_{v=1}^{V}\sum_{c=2}^{C-1}\sum_{i=1}^{I} SN_{icv}\times Wt_{icv}\times\beta_{cv}\times CP_{cv}\times H_i\right]^{c_1}\right. \\ &\left.+\left[\sum_{v=1}^{V}\sum_{c=1}\sum_{i=1}^{I} I_{icv}\times CI_{icv}\right]^{c_2}\right) \\ &+\left(\left[\sum_{v=1}^{V}\sum_{c=1}\sum_{i=1}^{I} B_{iv}\times CB_{iv}\right]\right)^{d} \end{aligned} \right\} \tag{1}$$

where
a = production cost of (normal channel + contingency-overtime channel + contingency-lay-off channel)
b = setup cost
c_1 = inventory-holding cost (main assembly)
c_2 = inventory-holding cost (sub-assembly)
d = Back-order Cost

The required product quantities produced during normal, overtime, and lay-off production are calculated using equations (2)-(4), respectively. Equation (2) calculates the number of normal production workforce, equation (3) calculates the number of overtime workforce in case of upcoming high demand/irregular order/priority changes, setting off the overtime channel. Equation (4) calculates the lay-off workforce whenever any delay such as machine breakdown, material delay, capacity shortage due to uncertain demand occurs in the process flow, activating the lay-off channel.

$$\text{If } x=1 \text{ (normal channel) } P_{icv1} = OP_{cv}\times W_{ic1}\forall\, i,c, \text{ and } v \tag{2}$$

$$\text{If } x=2 \text{ (contingency-overtime channel)}$$
$$P_{icv2} = OP_{cv}\times W_{ic2}\forall\, i,c, \text{ and } v \tag{3}$$

$$\text{If } x=3 \text{ (contingency-lay-off channel)}$$
$$P_{icv3} = OP_{cv}\times WF_{ic}\forall\, i,c, \text{ and } v \tag{4}$$

Workforce planning: The maximum level of workforce design in three shifts, including of working on a holiday, required demand workforce, and additional delay during all the demand periods is calculated using equations (5)-(8), respectively, based on efficient workforce scheduling [40].

$$W_{icv,min} = [(TOCt_{cv}/BNt_{cv})\times WD_i\times S\times\gamma_c\times\rho_c] \\ \forall\, i,c, \text{ and } v \tag{5}$$

$$W_{icv,max} = [(TOCt_{cv}/BNt_{cv})\times(WD_i+HD_i) \\ \times S\times\gamma_c\times\rho_c]\ \forall\, i,c, \text{ and } v \tag{6}$$

$$W_i = FD_{iv}/OP_{cv}\forall\, i,c, \text{ and } v \tag{7}$$

$$W_{\partial i} = (W_i+\partial_i\times W_i)\forall\, i,c, \text{ and } v \tag{8}$$

The novel approach from equations (5) to (11) is a detailed workforce distribution plan based on the maximum available capacity and the expected demand. In general, demand increase results in immediate increases in the number of workforce to achieve the essential result; but after a certain level/point, even increasing the number of workforces does not achieve the desired output, and that level/point is called Workforce Break Even Point (WBEP). Figure 3 provides a detailed understanding of the WBEP. The chart represents increasing the number of workforce to reach the maximum level of cell/machines capacity of 1859 parts/day with 11 workforce/day; if the deployed workforce is more than the design workforce (i.e. 11 workforces/day), the output level (1859 parts/day) will be the same, that point is WBEP. Based on this strategy, a detailed workforce distribution plan is calculated from equations (9) to (11). Equation (9) calculates the normal production workforce and Equation (10) calculates the overtime production workforce from the total number of available shifts per day (i.e. decision-making process). Equation (11) relates to selecting contingency lay-off production workforce when the capacity and another shortfall occur as evident from equation (11), which shows that lay-off workforce is permitted only when the normal workforce is absent or when workforce requirement is more than the maximum workforce for each cell and other reasons for delays. Nowadays industries, more particularly the automobile manufacturing industry, maintain a contingent workforce based on the hiring/firing/lay-off concept instead of permanent workforce [41] when the demand is uncertain. Workforce distribution is one of the challenging processes in a shared workforce and in an uncertain workforce environment [42,43].

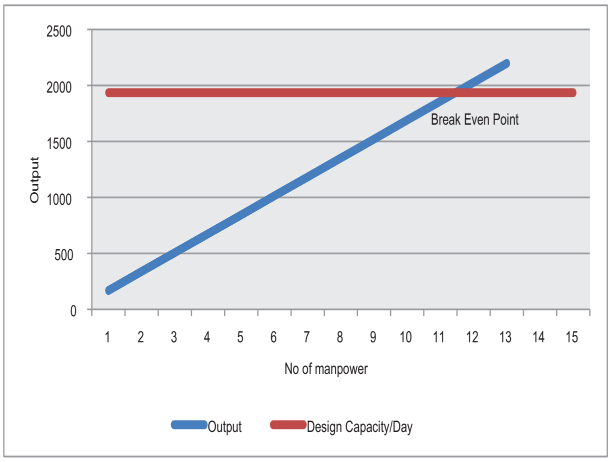

Fig. 3: Workforce Break Even Point (WBEP)

For selecting normal production workforce:
If
$Max([2/3\times W_{icv,min}],[2/3\times(W_i+\partial_i\times W_i)])$
$\leq(W_i+\partial_i\times W_i)$
Select
$W_{ic1}=Min([2/3\times W_{icv,min}],[2/3\times(W_i+\partial_i\times W_i)])$
Else If
$Max([2/3\times W_{icv,min}],[2/3\times(W_i+\partial_i\times W_i)])$
$\leq 2/3\times(W_i+\partial_i\times W_i)$
Select
$W_{ic1}=Max([2/3\times W_{icv,min}],[2/3\times(W_i+\partial_i\times W_i)])$
Else

$$W_{ic1}=(W_i+\partial_i\times W_i)])\forall\ i,c,\text{ and } v \tag{9}$$

For selecting contingency overtime production workforce

$$W_{ic2}=Min([1/3\times W_{icv,min}],[(W_i+\partial_i\times W_i)-W_{ic1}])\quad\forall\ i,c,\text{ and } v \tag{10}$$

For selecting contingency lay-off production workforce

$$WF_{ic}\leq min(WC_iWB_i)\forall\ i,c,\text{ and } v \tag{11}$$

where

$$WC_i=HD_i\times((W_i+\partial_i\times W_i)/WD_i)$$
$$WB_i=(W_i+\partial_i\times W_i)-WC_{ic1}-WC_{ic2}$$

An illustrative example is presented for better understanding the workforce distribution (equations 9-11), decision variables, and condition. Here the primary underlying assumption is that 2/3 of shifts/day considered normal production, 1/3 of shifts/day is considered overtime production, and lay-off work is found on an available holiday time. Select the normal production workforce (W_{ic1}) value; if the maximum of 2/3 design workforce or 2/3 required demand workforce is less than or equal to the required workforce. Select value W_{ic1} if it is equal to minimum of 2/3 design workforce or 2/3 required demand workforce. Else, maximum of 2/3 design workforce or 2/3 required demand workforce should be less than or equal to the 2/3 required demand workforce. Select the value W_{ic1} if it is equal to maximum of 2/3 design workforce or 2/3 required demand workforce, otherwise select the required demand workforce. The main objective is to select a workforce limit, within the available capacity and not beyond the WBEP. Similarly, we decide the level of the contingent overtime production workforce (W_{ic2}) and contingent lay-off production workforce (WF_{ic}) from the available capacity and not beyond the WBEP.

Setup and lot-size: The need for setup time and setup reduction becomes increasingly important in production lines with an extensive product variant [44]. The benefit of controlling the setup time process is not only the increased production capacity without buying the new facility, but other significant positive impacts on quality, scrap and rework, inventory along with the system flexibility and responsiveness to the customer.

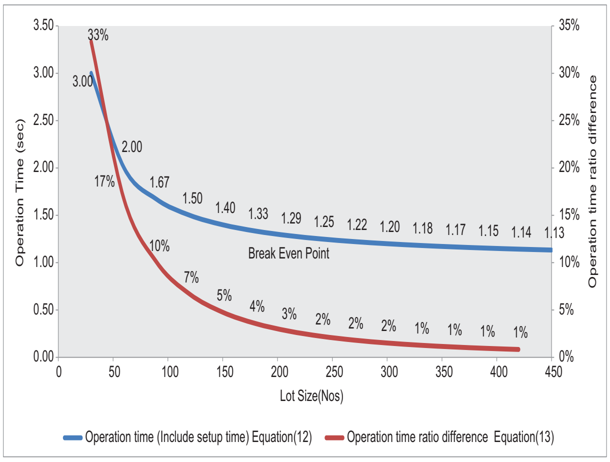

Fig. 4: Lot-Size (B_{cv}) Yield Variability Based on Operation Time ($Lt_{(n,\alpha c)}$)

Equations (12)-(16) employ a novel approach for estimating the number of setup from the lot-size. Lot-sizes are derived from equation (15); when we increase the lot-size, the operation time ratio differences are significantly reduced (i.e. production-operation time). After attaining the optimal value (i.e. breakeven point) even increasing the lot-size has no/small impact on production-operation time [45]. From Figure 4 it can be observed that after 1.33 sec there is no greater impact on operation time. Thus, the optimal value of lot-size is 200. Based on this strategy, the number of material-handling containers has been calculated by applying equation (14), the operation time ratio selection depends on production supervisor.

$$Lt_{(n,\alpha_c)} = Pt_{cv} + (St_{cv}/(n \times \alpha_c)) \forall\, i,c, \text{ and } v \tag{12}$$

$$Ltrd_{cv} = (Lt_{(n,\alpha_c)} - Lt_{(n+1,\alpha_c)})/Lt_{(n,\alpha_c)} \forall\, i,c, \text{ and } v \tag{13}$$

$$N_{cv} = \begin{cases} (n+1)_{cv} & \text{if } Ltrd_{cv} \geq 4\% \\ n_{cv} & \text{otherwise} \end{cases} \forall\, i,c, \text{ and } v \tag{14}$$

$$\beta_{cv} = N_{cv} \times \alpha_c \forall\, i,c, \text{ and } v \tag{15}$$

$$SN_{icv} = \sum_{v=1}^{V} \sum_{c=1}^{C} \sum_{i=1}^{I} FD_{iv}/\beta_{cv} \forall\, i,c, \text{ and } v \tag{16}$$

Adjustment of the workforce plan and output rate maximization based on bottleneck/non-bottleneck process plan is conceived while controlling and estimating the capacity planning [46]. Here the capacity planning of available capacity is computed from the bottleneck of each cell using equation (17). Additional capacity includes working on holiday and the maximum available capacity calculated, respectively, from equations (18) and (19).

$$C_{iv} = min\{([WD_i \times T \times \rho_c]/BNt_{cv})_{cells}\} \forall\, i,c, \text{ and } v \tag{17}$$

$$C'_{iv} = min\{([HD_i \times T \times \rho_c]/BNt_{cv})_{cells}\} \forall\, i,c, \text{ and } v \tag{18}$$

$$C_{c,max} = min\{([WD_i + HD_i) \times T \times \rho_c]/BNt_{cv})_{cells}\} \forall\, i,c, \text{ and } v \tag{19}$$

Inventory and unmet demand: Equations (20)-(25) are used for calculating the inventory and unmet demand for main and sub-assembly in each production stage during all the periods. Equation (20) calculates the processing time for a batch size. The production rate is inversely proportional to the processing time (21). In equation (22), average production rate and uptime decision factor mainly depend on the customer priority and product variety, respectively. Equation (23) is applied for estimating the mean waiting time [47] for the production rate, the quantity of lot-size, and waiting time mainly used for semi-finished product/sub-assembly inventory value calculation. This type of problem is rarely solved and is especially meant for cellular-type manufacturing industry. Equation (24) deals with the total CDC capacity, while equation (25) is used for calculating the finished units dispatched to CDC based on available/customer-defined CDC capacity. In equation (26), the inventory units equal the divergence between the initial stock, a total number of finished goods (i.e. main assembly), and the total number of goods sent to CDC from the main assembly during each period. Here we assume that the initial inventory equals the available capacity (C_{iv}). Equation (27) calculates the unmet demand (i.e. back-order) found by subtracting the initial back-order, total number of goods transported from the main assembly to CDC, and forecast demand.

$$Bt_{cv} = \beta_{cv} \times TOCt_{cv} \forall\, i,c, \text{ and } v \tag{20}$$

$$PR_{cv} = 1/Bt_{cv} \forall\, i,c, \text{ and } v \tag{21}$$

$$APR_{icv} = PR_{cv} \times PU_{icv} \forall\, i,c, \text{ and } v \tag{22}$$

$$\sum_{v=1}^{V} \sum_{c=2}^{C-1} \sum_{i=1}^{I} Wt_{icv} = \frac{APR_{icv}}{APR_{i(c+1)v} \times (APR_{i(c+1)v} - APR_{icv})} \forall\, i,c, \text{ and } v \tag{23}$$

$$CDC\_inv = NP_v \times NV_p \forall\, i,c, \text{ and } v \tag{24}$$

$$PA_{iv} = CDC\_inv \times WD_i \forall\, i,c, \text{ and } v \tag{25}$$

$$\sum_{v=1}^{V} \sum_{c=1} \sum_{i=1}^{I} I_{icv} = [I_{i-1v} + [P_{iv1} + P_{iv2} + P_{iv3}] - [\sum_{v=1}^{V} \sum_{i=1}^{I} PA_{iv} \times WD_i]] \forall\, i,c, \text{ and } v \tag{26}$$

$$\sum_{v=1}^{V} \sum_{c=1} \sum_{i=1}^{I} B_{iv} = [B_{i-1v} + FD_{iv} - (\sum_{v=1}^{V} \sum_{i=1}^{I} PA_{iv} \times WD_i)] \forall\, i,c, \text{ and } v \tag{27}$$

4.2 The constraints

In the real-world scenario, production capacity-workforce planning problems face several constraints related to production or recourses shortfall (e.g. cost, labour, production capacity, and floor constraint), so this section presents the formulations for some real-world constraints.

Linear equality/inequality constraints: Equation (28) provides means to control the deployed normal, contingency overtime, and lay-off production workforce level that should be within the maximum design working day workforce level. The number of materials handled is controlled by the factory floor space constraint. It depends on the required demand and management decision on the lot-size determination as expressed in equation (29). The setup process optimization constraints are added for controlling the setup time and lot-size (equation 30). Each lot-size operation time is greater than the setup time of each lot-size for reducing/eliminating the machine idle time arising out of large setup time. This constraint is optimal when setup time is more than normal hours [48]. Equations (31) and (32) are used for determining inventory control (i.e. production quantity should be less than the forecast demand) and waiting time between the cells, respectively.

$$W_{ic1}+W_{ic2}+WF_{ic}\leq W_{icv,min}\forall\ i,c,\ \text{and}\ v \tag{28}$$

$$N_{icv}\leq 7\forall\ i,c,\ \text{and}\ v \tag{29}$$

$$\beta_{icv}*TOCt_{cv}>St_{icv}\forall\ i,c,\ \text{and}\ v \tag{30}$$

$$\sum_{v=1}^{V}\sum_{c=1}^{C}\sum_{i=1}^{I}SN_{icv}\times\beta_{icv}\leq FD_{icv}\forall\ i,c,\ \text{and}\ v \tag{31}$$

$$\sum_{v=1}^{V}\sum_{c=1}^{C}\sum_{i=1}^{I}Wt_{icv}\leq\sum_{v=1}^{V}\sum_{i=1}^{I}Wt_{iv}\forall\ i,c,\ \text{and}\ v \tag{32}$$

Bound constraints and non-negative constraints: These constraints are used for obtaining faster and more reliable solutions. Equations (33)-(36) are bound constraints used for restricting the decision variables. For example, equation (33) is used for controlling the normal, overtime, and lay-off workforce within the minimum and maximum level of design workforce.

$$W_{icv,min}\leq W_{ic1}+W_{ic2}+WF_{ic}\leq W_{icv,max}\forall\ i,c,\ \text{and}\ v \tag{33}$$

$$0\leq SN_{icv}\leq FD_{icv}/\beta_{icv}\forall\ i,c,\ \text{and}\ v \tag{34}$$

$$Wt_{icv,min}\leq Wt_{iv}\leq Wt_{icv,max}\forall\ i,c,\ \text{and}\ v \tag{35}$$

$$W_{ic1},W_{ic2},WF_{ic},SN_{icv}\geq 0\forall\ i,c,\ \text{and}\ v \tag{36}$$

5 Practical implementation and managerial insights

The previous section indicated the importance of the integrated PCWFP model, problem formulation, and constraints. In this section, the problem is solved by the LP methodology and coded in the MATLAB. The result focuses on minimizing the overall manufacturing cost. Therefore, the proposed PCWFP model provides a balance between normal production and contingency production. Inventory and back-order level consider both the assembly and sub-assembly of the production line. The lot-size depends on the number of setup and the number of material handling size (i.e. space constraint). A great deal of workforce level is required for all manufacturing stages. One of the main approaches is representing the bound constraints for capacity expansion processes when the demand is more than available capacity. The most significant performance of the recommended model is to evaluate and minimize the yield variability of lot-size (Figure 4), batch size, processing time, setup time, line stoppage time, and maintenance downtime in order to maximize the organization operations, leading to minimization in the manufacturing price.

Real-world data have been collected on auto-electrical parts manufacturing industry, accommodating multi-model, multi-product, and multi-stage Cellular Manufacturing System (CMS) with JIT (i.e. Just In Time) environment under volatile market conditions. The proposed mathematical model aims to bring down the manufacturing cost and helps the decision maker of the company in efficient allotment of workforce in various sub-assembly levels for several customer requirements considering available facilities. The model concurrently generates the production capacity-workforce plan to oversee the resources available at all the levels and effectively controls the lot-size.

5.1 Input Variables

The demand pattern for all the product varieties, the number of planned production days for 12 periods (months), input variables (i.e. parameter), and average setup cost/unit time are shown in Tables 1-4, respectively. It should be noted that the value of zero for any input variable means that the concerned process is not suitable for a particular variety of product. For example, Table 3 shows that variety 1does not pass through processes 4 and 19.

Table 1: Demand Pattern

Period, i	Product Variety, v													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	19712	7414	6336	22572	6952	4994	7414	12166	1540	1892	6094	7106	154	418
2	20608	7751	6624	23598	7268	5221	7751	12719	1610	1978	6371	7429	161	437
3	23296	8762	7488	26676	8216	5902	8762	14378	1820	2236	7202	8398	182	494
4	22400	8425	7200	25650	7900	5675	8425	13825	1750	2150	6925	8075	175	475
5	21504	8088	6912	24624	7584	5448	8088	13272	1680	2064	6648	7752	168	456
6	22598	8500	7264	25876	7970	5725	8500	13947	1766	2169	6986	8147	177	480
7	16800	6319	5400	19238	5925	4257	6319	10369	1313	1613	5194	6057	132	357
8	17472	6572	5616	20007	6162	4427	6572	10784	1365	1677	5402	6299	137	371
9	21728	8173	6984	24881	7663	5505	8173	13411	1698	2086	6718	7833	170	461
10	16948	6375	5448	19407	5978	4295	6375	10461	1325	1627	5240	6111	133	360
11	19990	7519	6426	22891	7050	5065	7519	12338	1562	1919	6180	7207	157	424
12	20268	7623	6515	23209	7148	5135	7623	12509	1584	1946	6266	7307	159	430

Table 2: Number of Planned Production Days

Planning Period, i	1	2	3	4	5	6	7	8	9	10	11	12
WD_i	22	23	26	25	26	24	25	26	25	24	24	25
HD_i	8	8	4	6	5	6	6	4	6	7	4	6

Table 3: Input Variables (i.e. parameter) to the Model

Cell, c	Product variety, $v = 1$									
	OP_{cv}	γ_c	ρ_c	$TOCt_{cv}$	BNt_{cv}	St_{cv}	α_c	CP_cv1	CP_cv2	CP_cv3
1	35	0.75	1.88	12.29	1.12	20	36	138.2	161.7	183.8
2	373	0.70	0.75	1.15	0.45	90	120	13.0	15.2	17.3
3	919	0.70	0.56	0.47	0.40	22	120	5.3	6.2	7.0
4	0	0	0	0	0	0	0	0.0	0.0	0.0
5	1470	0.70	0.38	0.29	0.25	15	120	3.3	3.9	4.4
6	1050	0.70	0.75	0.41	0.35	30	120	4.6	5.4	6.1
7	290	0.70	0.40	1.48	0.33	23	120	16.7	19.5	22.2
8	2205	0.70	0.38	0.20	0.17	32	120	2.2	2.6	2.9
9	551	0.70	0.94	0.78	0.67	15	48	8.8	10.3	11.7
10	401	0.70	1.00	1.07	0.92	25	48	12.1	14.1	16.0
11	298	0.70	0.94	1.44	1.23	20	48	16.2	19.0	21.6
12	848	0.70	0.94	0.51	0.43	20	48	5.7	6.7	7.6
13	67	0.70	1.13	6.42	0.72	15	48	72.2	84.5	96.0
14	490	0.70	1.29	0.88	0.87	10	48	9.9	11.6	13.1
15	538	0.70	0.75	0.80	0.68	10	48	9.0	10.5	12.0
16	441	0.70	1.32	0.98	0.83	30	48	11.0	12.8	14.6
17	2005	0.80	0.38	0.21	0.35	15	120	2.4	2.8	3.2
18	1696	0.80	0.38	0.25	0.22	15	120	2.9	3.3	3.8
19	0	0	0	0	0	0	0	0.0	0.0	0.0
20	171	0.80	0.94	2.51	0.85	13	40	28.3	33.1	37.6
21	1161	0.80	0.38	0.37	0.32	15	40	4.2	4.9	5.5
22	0	0	0	0	0	0	0	0.0	0.0	0.0
23	52	0.80	1.13	8.27	1.18	35	40	93.0	108.9	123.7

5.2 Computational results and discussion

The problem using MATLAB-R2013a is iterated using Intel(R) Core (TM) i3-5005U CPU 2.00 GHz, 4GB RAM computer. The detailed production-workforce distributed plan (i.e. W_{ic1}, W_{ic2}, and WF_{ic}) and the number of setup based on lot-size (i.e. SN_{cv}) for the best output solution generated using LP for the 14th cell are shown in Tables

Table 4: Average Setup Cost/Unit Time/Variety

Product Variety, v	1	2	3	4	5	6	7	8	9	10	11	12	13	14
CS_v	11.3	9.8	17.6	13.5	28.5	10.4	11.7	18.2	35.7	16.7	22.5	15.2	31.8	15.0

Table 5: Normal Production - Workforce Distributed Plan (W_{ic1})

Period, i	Product Variety, v for cell $c = 14$													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	27.62	0	10.26	46.99	10.82	0	11.01	17.05	2.4	3.06	0	0	0	0
2	28.88	0	10.73	49.12	11.32	0	11.51	17.82	2.51	3.2	10.96	13.9	0.3	0.75
3	32.65	0	12.13	55.53	12.79	0	13.01	20.15	2.83	3.62	12.38	15.71	0.34	0.85
4	31.39	0	11.66	53.39	12.3	0	12.51	19.37	2.72	3.48	11.91	15.11	0.32	0.81
5	44.76	0	11.19	51.26	11.81	0	13.01	18.6	2.62	3.34	12.38	14.5	0.31	0.85
6	31.67	0	11.76	36.26	12.41	0	12.01	18.66	2.63	3.51	11.43	15.24	0.31	0.78
7	34.97	0	8.75	40.05	13.7	0	10.23	14.53	2.04	2.61	9.72	11.33	0.25	0.67
8	36.37	0	9.10	41.65	14.25	0	10.64	15.11	2.13	2.72	10.11	11.79	0.26	0.69
9	45.23	0	11.31	51.79	11.93	0	12.51	18.79	2.64	3.38	11.91	14.66	0.32	0.81
10	35.28	0	8.82	40.4	9.31	0	10.32	14.66	2.06	2.63	9.80	11.43	0.25	0.67
11	41.61	0	10.41	47.65	10.98	0	12.01	17.29	2.43	3.11	11.43	13.48	0.29	0.78
12	42.19	0	10.55	48.31	11.13	0	12.35	17.53	2.47	3.15	11.72	13.67	0.30	0.8

Table 6: Contingency Overtime Production - Workforce Distributed Plan (W_{ic2})

Period, i	Product Variety, v for cell $c = 14$													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	13.41	0	4.98	0	5.25	0	5.5	8.28	1.16	1.49	0	0	0	0
2	14.02	0	5.21	0	5.49	0	5.75	8.65	1.22	1.56	5.48	6.75	0.15	0.37
3	15.85	0	5.89	0	6.21	0	6.5	9.78	1.38	1.76	6.19	7.63	0.17	0.42
4	15.24	0	5.66	0	5.97	0	6.25	9.4	1.32	1.69	5.95	7.33	0.16	0.41
5	0	0	5.43	0	5.73	0	6.45	9.03	1.27	1.62	6.09	7.04	0.15	0.42
6	15.37	0	5.71	17.6	6.02	0	6	9.33	1.32	1.71	5.72	7.4	0.16	0.39
7	0	0	4.25	0	0	0	4.97	7.05	0.99	1.27	4.72	5.5	0.12	0.32
8	0	0	4.42	0	0	0	5.17	7.34	1.03	1.32	4.91	5.72	0.12	0.34
9	0	0	5.49	0	5.79	0	6.25	9.12	1.28	1.64	5.95	7.11	0.15	0.41
10	0	0	4.28	0	4.52	0	5.01	7.12	1	1.28	4.76	5.55	0.12	0.33
11	0	0	5.05	0	5.33	0	6	8.39	1.18	1.51	5.72	6.55	0.14	0.39
12	0	0	5.12	0	5.4	0	5.99	8.51	1.2	1.53	5.69	6.64	0.14	0.39

5-7, respectively. Similarly, we've got the final decision variables for all the cells (i.e. 23 cells), from that values we've derived the main function of TMC. Here the normal, overtime and lay-off workforce distribution plan are derived from the WBEP, such that workforce breakeven point is considered as maximum limit of the workforce allocation.

The PCWFP model tends to prefer the normal production workforce (W_{ic1}) and then contingency overtime production (W_{ic1}) when the required workforce (W_i) is more than both channels ($W_{ic1} + W_{ic1}$), and when only the contingency lay-off production channel is activated (i.e. Tables 5-7). Due to this, the laying-off workers reduce expenses. The number of setup is (i.e. Table 8) also controlled based on the required demand, according to the available floor space and material handling size (equations 12-16). Table 9 shows the level of the main assembly (i.e. finished product) inventory and unmet demand (i.e. back-order) across all the periods. The level of unmet demand is zero in the 7th and 8th period. Even in the other period the unmet demand is very less. Therefore, the penalty cost and the loss are reduced to the maximum extent due to the unmet demand.

As mentioned, a problem has 12 periods, 14 product varieties, and 23 sub-assembly cells, thus each decision factor handles the $12 \times 14 \times 23$ variables for every iteration. The integrity constraints of the mathematical model are mentioned in subsection 4.2; constraints are relaxed and the problem makes some of the assumptions referred in Section 3 to find the globally optimal solution.

Table 7: Contingency Lay-off Production - Workforce Distributed Plan (WF_{ic})

Period, i	Product Variety, v for cell $c = 14$													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	0	0	0	0	0	1.33	0	0	0	0	0	0	0
2	0	0	0	0	0	0	1.39	0	0	0	1.27	0	0	0.09
3	0	0	0	0	0	0	1.57	0	0	0	1.44	0	0	0.1
4	0	0	0	0	0	0	1.51	0	0	0	1.38	0	0	0.1
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	2.44	1.04	0.14	0	2.27	0	0.02	0.16
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0.9	0	0	0	0.81	0	0	0.06
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0.08	0	0	0	0.03	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8: Number of Setup Based on Lot-Size (i.e. SN_{cv})

Period, i	Product Variety, v for cell $c = 14$													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	58.67	0	18.86	67.18	20.69	0	22.07	36.21	4.58	5.63	0	0	0	0
2	61.33	0	19.71	70.23	21.63	0	23.07	37.85	4.79	5.89	18.96	22.11	0.48	1.3
3	69.33	0	22.29	79.39	24.45	0	26.08	42.79	5.42	6.65	21.43	24.99	0.54	1.47
4	66.67	0	21.43	76.34	23.51	0	25.07	41.15	5.21	6.4	20.61	24.03	0.52	1.41
5	64	0	20.57	73.29	22.57	0	24.07	39.5	5	6.14	19.79	23.07	0.5	1.36
6	67.26	0	21.62	77.01	23.72	0	25.3	41.51	5.26	6.46	20.79	24.25	0.53	1.43
7	50	0	16.07	57.26	17.63	0	18.81	30.86	3.91	4.8	15.46	18.03	0.39	1.06
8	52	0	16.71	59.54	18.34	0	19.56	32.1	4.06	4.99	16.08	18.75	0.41	1.1
9	64.67	0	20.79	74.05	22.81	0	24.32	39.91	5.05	6.21	19.99	23.31	0.51	1.37
10	50.44	0	16.21	57.76	17.79	0	18.97	31.13	3.94	4.84	15.6	18.19	0.4	1.07
11	59.49	0	19.13	68.13	20.98	0	22.38	36.72	4.65	5.71	18.39	21.45	0.47	1.26
12	60.32	0	19.39	69.07	21.27	0	22.69	37.23	4.71	5.79	18.65	21.75	0.47	1.28

Table 9: Total Inventory, Unmet Demand for Main Assembly from the LP Solutions

Period, i	1	2	3	4	5	6	7	8	9	10	11	12
I_i	14268	32927	30646	25362	34582	33766	18482	35493	34582	32241	35636	35617
B_i	2226	2328	2631	2530	1679	3011	0	0	2173	8	1625	1397

The problem has non-integer decision variables by default. The problem is also converged to a global optimum solution of TMC for all the cells, INR1592965258.6833. After adding the bound constraints, the TMC reduced from an initial solution and the final optimal solution is INR1570726175.2189, detailed manufacturing cost breakup for all the cells is shown in Table 10. Having added the bound constraints and one of the primary notifications of the solution, when the required capacity is beyond the design capacity (i.e. capacity expansion), the setup constraint (equation 31) gives the near-optimal global solution comparable to workforce constraint (equation 28); since the setup and setup cost control the other cost factors of inventory and waiting for time variables [49].

6 Conclusion and future research

LP-based PCWFP distribution model has evolved and considered three different types of production costs (regular, overtime, and lay-off production cost) along with inventory-holding cost, unmet demand cost, and detailed setup cost. This statement is true when the temporary workforce is used instead of the permanent workforce, especially in the automobile manufacturing sector. The PCWFP model is a better way of handling all constraints, especially the setup and inventory constraints, to find the global optimal solution. The mathematical model is the most appropriate tool to solve the capacity planning-type problem. In addition WFBP is one of the best practical strategies for controlling the workforce

Table 10: Total Manufacturing Cost (TMC) - Cellwise From the LP Solutions

Cell	Manufacturing Cost (No bound constraints)	Manufacturing Cost (With bound constraints)	Remarks
1	307177980.0012	307177980.0012	No change
2	91529307.9333	80409766.2011	The required capacity beyond the design capacity
3	49788327.7843	49788327.7843	No change
4	74086680.7309	74086680.7309	No change
5	37295760.0927	37295760.0927	No change
6	8900220.8589	8900220.8589	No change
7	9961272.0959	9961272.0959	No change
8	6123388.3232	6123388.3232	No change
9	17036626.7647	17036626.7647	No change
10	3363123.8120	3363123.8120	No change
11	28156168.4969	17036626.7647	The required capacity beyond the design capacity
12	68229566.4577	68229566.4577	No change
13	130063719.9663	130063719.9663	No change
14	22549253.7934	22549253.7934	No change
15	87221325.1559	87221325.1559	No change
16	38568003.2724	38568003.2724	No change
17	75111956.5212	75111956.5212	No change
18	5426322.7832	5426322.7832	No change
19	295154081.7937	295154081.7937	No change
20	91779256.6446	91779256.6446	No change
21	8346477.3271	8346477.3271	No change
22	10388080.5918	10388080.5918	No change
23	121556472.5355	121556472.5355	No change
Cost(I,B)	5151884.9465	5151884.9465	No change
TMC	1592965258.6833	1570726175.2189	Up to 1.40% Total manufacturing cost reduced

distribution in a practical manner. Future studies may extend the proposed model by altering or adding to the following points. Some of the input variables (γ_c, ρ_c, and α_c) should be considered deterministic and known factors so that the model extension may be stochastic in nature [50]. Unfortunately, the significant key decision variables such as W_{ic1}, W_{ic2}, WF_{ic}, and SN_{cv} assume decimal values, rounding off those variables leads to an infeasible solution and requires total recalculation of the variables. Thus currently, we have restricted the integer value for the significant key decision variables. Compared to linear value, a mixed integer value may provide the ideal solution for the PCWFP model. Further extension of this research to develop a meta-heuristic solution approach to solve the model with the focus on solving large-scale problems is under progress by an author. Here we have considered only linear relations as constraints, but most of the problems seen in practice are non-linear in nature [39]. The non-linear relationship must be added (i.e. inventory and setup cost constraints) among the constraints, maybe it would play a role for a strong PCWFP model.

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References

[1] M. Akhtar Hasin, N. Thuy, M.A Shareef, Implications of selected production planning functions: impact analysis through simulation, Production Planning & Control, Vol. 11, No. 7, pp. 641-647 (2000).

[2] P.K Johri, A linear programming approach to capacity estimation of automated production line with finite buffers, International Journal of Production Research, Vol. 25, No. 6, pp. 851-867 (1987).

[3] J.F Bard, K. Srinivasan, D. Tirupati, An optimization approach to capacity expansion in semiconductor manufacturing facilities, International Journal of Production Research, Vol. 37, No. 15, pp. 3359-3382 (1999).

[4] J.R Birge, Option methods for incorporating risk into linear capacity planning models,Manufacturing and Service Operations Management, Vol. 2, No. 1, pp. 19-31 (2000).

[5] B. Catay, S.S Erenguc, A.J Vakharia, Tool capacity planning in semiconductor manufacturing, Computers & Operations Research, Vol. 30, No. 9, pp. 1349-1366 (2003).

[6] S.J Hood, S. Bermon, F. Barahona, Capacity planning under demand uncertainty for semiconductor manufacturing, IEEE Transactions on Semiconductor Manufacturing, Vol. 16, No. 2, pp. 273-280 (2003).
[7] K. Huang, S. Ahmed, The Value of Multistage Stochastic Programming in Capacity Planning Under Uncertainty, Operations Research, Vol. 57, No. 4, pp. 893-904 (2009).
[8] C-S. Chen, S. Mestry, P. Damodaran, C. Wang, The capacity planning problem in make-to-order enterprises, Mathematical and Computer Modelling, Vol. 50, No. 9-10, pp. 1461-1473 (2009).
[9] I. Mahdavi, A. Aalaei, M.M Paydar, M. Solimanpur, Designing a mathematical model for dynamic cellular manufacturing systems considering production planning and worker assignment, Computers and Mathematics with Applications, Vol. 60, No. 4, pp. 1014-1025 (2010).
[10] T. Wu, L. Shi, Mathematical models for capacitated multi-level production planning problems with linked lot-sizes, International Journal of Production Research, Vol. 49, No. 20, pp. 6227-6247 (2011).
[11] J-H Ho, C-C Fang, Production capacity planning for multiple products under uncertain demand conditions, International Journal of Production Economics, Vol. 141, No. 2, pp. 593-604 (2013).
[12] T. Sillekens, A. Koberstein, L. Suhl, Aggregate production planning in the automotive industry with special consideration of workforce flexibility, International Journal of Production Research, Vol. 49, No. 17, pp. 5055-5078 (2011).
[13] P.K Johri, Engineering a Circuit Board Assembly Line for a Desired Capacity and Flow time,Journal of Manufacturing Systems, Vol. 10, No. 6, pp. 492-500 (1991).
[14] A.S Marucheck, M.K Mcclelland, Planning Capacity Utilization in an Assemble-to-Order Environment, International Journal of Operations and Production Management, Vol. 12, No. 9, pp. 18-38 (1992).
[15] W. Abdul-Kader, A. Gharbi, Capacity estimation of a multi-product unreliable production line, International Journal of Production Research, Vol. 40, No. 18, pp. 4815-4834 (2002).
[16] A.M Uribe, J.K Cochran, D.L Shunk, Two-stage simulation optimization for agile manufacturing capacity planning, International Journal of Industrial Engineering: Theory, Applications and Practice, Vol. 15, No. 4, pp. 360-372 (2003).
[17] E.G Anderson, D.J. Morrice, G. Lundeen, The physics of capacity and backlog management in service and custom manufacturing supply chains, System Dynamics Review, Vol. 21, No. 3, pp. 217-247 (2005).
[18] H.A Stephan, T. Gschwind, S.S Minner, Manufacturing capacity planning and the value of multi-stage stochastic programming under Markovian demand, Flexible Services and Manufacturing Journal, Vol. 22, No. 3-4, pp. 143-162 (2010).
[19] S. Kim, R. Uzsoy, Heuristics for capacity planning problems with congestion, Computers and Operations Research, Vol. 36, No. 6, pp. 1924-1934 (2009).
[20] W. Abdul-Kader, O. Ganjavi, F. Baki, A nonlinear model for optimizing the performance of a multi-product production line, International Transaction in Operational Research, Vol. 18, No. 5, pp. 561-577 (2011).
[21] S.C.H Leung, S.W.C Shirley, Goal programming model for aggregate production planning with resource utilization constraint, Computers and Industrial Engineering, Vol. 56, No. 3, pp. 1053-1064 (2009).
[22] S.A Mansouri, A Multi-Objective Genetic Algorithm for mixed-model sequencing on JIT assembly lines, European Journal of Operational Research, Vol. 167, No. 3, pp. 696-716 (2005).
[23] W.J Hopp, M.L Spearman, Factory Physics, Waveland press, Illinois, (2008).
[24] H-P Wiendhal, J-W Breithaupt, Automatic production control applying control theory, International Journal of Production Economics, Vol. 63, No. 1, pp. 33-46 (2000).
[25] J. Van Mieghem, Capacity management investment and hedging: review and recent developments, Manufacturing Service Operation Management, Vol. 5, No. 4, pp. 269-302 (2003).
[26] N. Geng, Z. Jiang, A review on strategic capacity planning for the semiconductor manufacturing industry, International Journal of Production Research, Vol. 47, No. 13, pp. 3639-3655 (2009).
[27] O. Ceryan, Y. Koren, Manufacturing capacity planning strategies, CIRP Annals-Manufacturing Technology, Vol. 58, No. 1, pp. 403-406 (2009).
[28] A. Tenhiala, Contingency theory of capacity planning: The link between process types and planning methods, Journal of Operations Management, Vol. 29, No. 1-2, pp. 65-77 (2011).
[29] A.P Rastogi, J.W.Flower, W. M Carlyle, O.M Azar, M. Arnold, B. Burak, Supply network capacity planning for semiconductor manufacturing with uncertain demand and correlation in demand considerations, International Journal of Production Economics, Vol. 134, No. 2, pp. 322-332 (2011).
[30] L. Yang, C.T Ng, T.C.E Cheng, Optimal production strategy under demand fluctuations: Technology versus capacity, European Journal of Operational Research, Vol. 214, pp. 393-402 (2011).
[31] H. Mokhtari, I.N.K Abadi, S.Z Zegordi, Production capacity planning and scheduling in a no-wait environment with controllable processing times, Expert Systems with Applications, Vol. 38, No. 10, pp. 12630-12642 (2011).
[32] L. Yang, C.T Ng, Flexible capacity strategy with multiple market periods under demand uncertainty and investment constraint, European Journal of Operational Research, Vol. 236, No. 2, pp. 511-521 (2014).
[33] M.C Carme, M.M Marta, B. Ernest, C. Albert, A review of mathematical programming models for strategic capacity planning in manufacturing, International Journal of Production Economics, Vol. 153, pp. 66-85 (2014).
[34] S. Mohan, M. Gopalakrishnan, R. Marthe, A. Rajan, A note on modelling the capacitated lot-sizing problem with set-up carryover and set-up splitting, International Journal of Production Research, Vol. 50, No. 19, pp. 5538-5543 (2012).
[35] J-H Ryu, Developing an integrated capacity planning framework for production processes and demand-supply chains, Korean Journal of Chemical Engineering, Vol. 30, No. 1, pp. 27-32 (2013).
[36] J. Mula, R. Poler, J.P Garcia-Sabater, Capacity and material requirement planning modelling by comparing deterministic and fuzzy models, International Journal of Production Research, Vol. 46, No. 20, pp. 5589-5606 (2008).
[37] H.F Lee, M.M Srinivasan, C.A Yano, A framework for capacity planning and machine configuration in flexible assembly systems, International Journal of Flexible

Manufacturing Systems, Vol. 18, No. 4, pp. 239-268 (2006).

[38] C-I Hsu, H-C Le, An integrated plant capacity and production planning model for high-tech manufacturing firms with economies of scale, International Journal of Production Economics, Vol. 118, No. 2, pp. 486-500 (2009).

[39] F.S Hillier, G.J Lieberman, Operations Research Concepts and Cases, Tata McGraw-Hill, New Delhi, 2005.

[40] B.S Banu, C. Ozguven, Y. Kariper, Shift scheduling with break windows, ideal break periods, and ideal waiting times, Flexible Services and Manufacturing Journal, Vol. 29, No. 2, pp. 203-222 (2017).

[41] E.J Pinker, R.C Larson, Optimizing the use of contingent labour when demand is uncertain, European Journal of Operational Research, Vol. 144, No. 1, pp. 39-55 (2003).

[42] M.F Paca, O. Alp, T. Tan, Integrated workforce capacity and inventory management under labour supply uncertainty, International Journal of Production Research, Vol. 47, No. 15, pp. 4281-4304 (2009).

[43] K.H Han, G. Lee, S.H Choi, Manufacturing cycle time reduction for batch production in a shared worker environment, International Journal of Production Research, Vol. 51, No. 1, pp. 1-8, (2013).

[44] M.A Almomani, M. Aladeemy, A. Abdelhadi, A. Mumani, A proposed approach for set-up time reduction through integrating conventional SMED method with multiple criteria decision-making techniques,Computers and Industrial Engineering, Vol. 66, No. 2, pp. 461-469, (2013).

[45] A.P Dillion, S. Shingo, A Revolution in Manufacturing: The SMED System. CRC Press, Florida, (1985).

[46] H. Lodding, A manufacturing control model, International Journal of Production Research, Vol. 50, No. 22, pp. 6311-6328 (2012).

[47] A. Gunasekaran, S.K Goyal, T. Martikainen, P. Yli-Olli, Production capacity planning and control in multi-stage manufacturing,Journal of the Operational Research Society, Vol. 49, No. 6, pp. 625-634 (1998).

[48] J.R.T Alex, M. Farzad, Analysis of multi-cell production systems considering cell size and worker flexibility, International Journal of Production Research, Vol. 41, No. 6, pp. 1181-1197 (2008).

[49] A. Allahvardi, H.M Soroush, The significance of reducing set-up times/set-up costs, European Journal of Operational Research, Vol. 187, pp. 978-984 (2008).

[50] C-F. Chen, P-C. Chu, L. Zhao, Overall resource effectiveness (ore) indices for total resource management and case studies, International Journal of Industrial Engineering: Theory, Applications and Practice, Vol. 22, No. 5, pp. 618-630, (2015).

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