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ORIGINAL RESEARCH

# Assembly line performance and modeling

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**Abstract** Automobile sector forms the backbone of manufacturing sector. Vehicle assembly line is important section in automobile plant where repetitive tasks are performed one after another at different workstations. In this thesis, a methodology is proposed to reduce cycle time and time loss due to important factors like equipment failure, shortage of inventory, absenteeism, set-up, material handling, rejection and fatigue to improve output within given cost constraints. Various relationships between these factors, corresponding cost and output are established by scientific approach. This methodology is validated in three different vehicle assembly plants. Proposed methodology may help practitioners to optimize the assembly line using lean techniques.

**Keywords** Simulation · Optimization · Lean · Mathematical modeling · Line balancing · Output · Utilization · Efficiency · Cost constraint · Downtime

## Introduction

Attaining manufacturing excellence to gain leadership and competitive advantage has become necessity of hour over last few years. Some of the challenges in automobile industry are demands of customers, price sensitivity, environmental and safety concerns, automation, etc. Vehicle assembly line is vast, complex and involves many components received from vendors and other departments. Higher cycle time, lengthy changeover time, unnecessary buffers, bottlenecks, inadequate resource utilization are common issues. Thus, objective is to analyze and resolve all these issues scientifically without increasing manufacturing cost. For improving assembly line performance, different approaches are used by researchers which includes use of lean techniques, classical mathematical models, process simulation using commercial software's, meta-heuristic approach, cost based approach, integrated approach, etc. Few researchers work is presented here in brief.

Gokcen and Erel (1998) demonstrated basic assembly line balancing model to minimize number of stations. Bergen et al. (2001) have focused on constraint-based vehicle assembly line sequencing. Model was tested with three different algorithms and two constraints. Distribution constraint allows the assembly line worker to ensure that at least a certain amount of every order is produced prior to any unexpected line shutdowns while 'Change-over' constraints prohibit undesirable transitions. Authors demonstrated improvements averaging 11.6% using Branch and Bound algorithm.

Ali and Seifoddini (2006) addressed effect of factors like machine breakdown, labor dynamics, material arrival and unpredictable customer orders. Authors have simulated response to stochastic variations. Sandanayake et al. (2008) identified the impact of set-up time, number of workstations and inspection on process time by regression modeling. It is also noted that few researchers have used statistical tools. Torenli (2009) improved the output by identifying bottlenecks and wastes. New layout was suggested.

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Major efforts are seen to develop faster algorithms and to compare their results. Chica et al. (2011) have used various search algorithms like Simulated Annealing, Genetic algorithm etc. for minimizing number of workstations. Author demonstrated that Genetic Algorithm-II is better than others. Kuo and Yang (2011) verified the results of FlexSim software with Particle Swarm Optimization to reduce waiting time. Kanda et al. (2013) used Maynard Operation Sequence Technique (MOST) for improving the productivity at Maruti Suzuki. Falck and Rosenqvist (2014) have explained cost of rejection exhaustively while Hakami et al. (2014) presented various mathematical models for different assembly line parameters.

Jadhav et al. (2015) have presented a roadmap for Lean implementation in Indian automotive component industry. Authors have proposed Interpretive Structural Model for sustainable Lean implementation. Chramcov et al. (2015)proposed mathematical model for robotic automated line to minimize assembly time. Authors have included heuristic algorithms in their simulation model for control determining of the assembly line.

Lee et al. (2016) have considered effect of monotony on workers performance to improve the productivity. Authors have demonstrated five step design framework towards gamification approach for bolt tightening work. Dao et al. (2017) have put forward modern virtual computer-integrated manufacturing system. Authors have proposed Genetic algorithm to find optimised solution which is verified by a numerical example. Kia et al. (2017) studied a dynamic flexible flow line problem with sequence-dependent set-up times to minimize mean flow time and mean tardiness. Authors have used genetic programming as well as discrete-event simulation model to examine the performances of scheduling rules.

Due to many factors and complexity of vehicle assembly line, mathematical modeling is tedious. Methodologies developed demands redesigning of line which attracts re-investment. Many researchers have studied the influence of individual factor like skill, breakdown, layout, priority and buffer on output. However, no work is reported to achieve cost constrained pragmatic solution for integrated effect of set-up, equipment failure, skill level of workers, absenteeism, material shortage, rejection, fatigue, material handling, etc. on output. Also, effect of interaction between these factors on output is not reported.

Based on data, literature review and discussion with domain experts, objective of the present research is **to propose methodology to "Optimize vehicle assembly line performance using simulation based approach" within imposed cost constraints**.

In the present research, detailed analysis of various vehicle assembly lines is conducted at three different plants; wherein data collection and analysis are carried out.

## Description of vehicle assembly line at various plants

A typical vehicle assembly line consists of many workstations, where the components are assembled sequentially in a fixed pattern repeatedly and continuously as shown in Fig. 1.

There is a fixed precedence between these stations. Workers move with the moving conveyor to complete the task of that stage and reposition themselves to their initial position to work on the subsequent vehicle which might have arrived at the upstream stage. There are three main assembly lines viz. Trim, Chassis and Finish. Progress of each vehicle can be tracked by means of its Vehicle Identification Number and a small radio frequency transponder attached to the chassis. Figure 2 shows the layout of the assembly line at plant A which is commissioned on 2nd October 1965.

Trim lines 1 and 2 consist of 33 stations numbered from 41 to 73. While work is being carried out at Trim line, simultaneously chassis is loaded on chassis line consisting of workstations numbered from 1 to 17. Finish line starts from station 18 till 40. As the chassis passes along the conveyor,

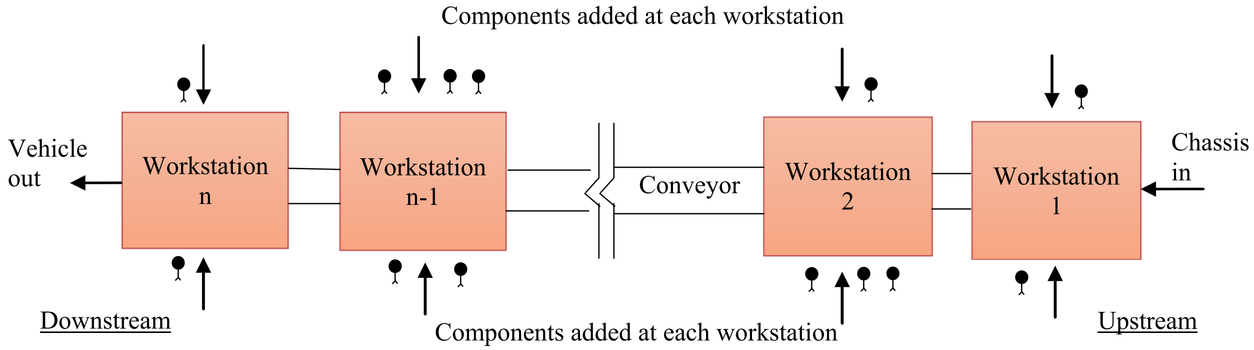


**Fig. 1** Typical assembly line

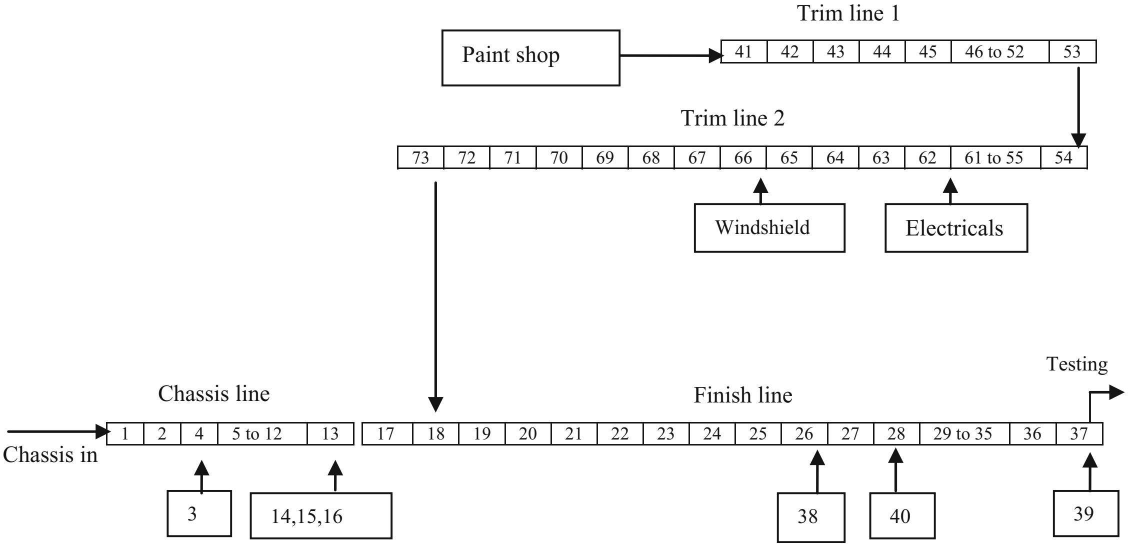


**Fig. 2** Layout of assembly shop at plant A (Courtesy—M & M)

the body from the Trim line is placed onto the chassis at workstation 18. Parallel workstations viz. 3,14,15,16,38,39,40, Windshield and Electricals are called as Feeder stations. Similarly assembly lines of two more plants were studied. Plant B is commissioned on 31st March 2009, manufacturing different models of car while Plant C is commissioned on 31st March 2001 and manufactures different models of commercial vehicles. Lines were studied in terms of layout, automation level, inventory, cycle time, resources, material handling, ergonomics, etc.

## Selection of factors and data collection

Output of assembly lines is affected by many factors. Major factors affecting the output and which are considered in this thesis are; (1) time lost due to equipment failure ($T_{bd}$), 2) time lost due to shortage of material ($T_{inv}$), (3) time lost due to absenteeism ($T_{ab}$), (4) time lost due to setup ($T_{setup}$), (5) Time lost due to rejection ($T_{rej}$), (6) time lost due to material handling ($T_{mh}$) and (7) time lost due to fatigue ($T_f$). Independent factors are taken as $T_{bd}$, $T_{inv}$ and $T_{ab}$ as they control $T_{setup}$, $T_{mh}$, $T_{rej}$ and $T_f$. It is required to minimize this time loss to improve the output. As the output is governed by the slowest station (bottleneck station), it is necessary to identify bottleneck station.

To identify bottleneck station, MOST is used at all stations. MOST divides the task into smallest activities. Table 1 gives summary of MOST study. At workstation 1, operator 6 takes maximum time, i.e., 87.17 s, which is termed as process time of workstation 1. So product moves out of workstation 1 at every 87.17 s to workstation 2. MOST data of all station is not presented here due to space constraints. In Table 1, **W.S. no.** and **Op** indicates workstation number and operator, respectively. Numbers inside the cell (except first column) represents task timing in seconds.

As per Goldratt (1992), cycle time is defined as the time taken by the slowest station which will govern the output of the assembly line. Here, workstation 28 is the bottleneck station having process time of 92.34 s. This process time is reduced by lean techniques so that bottleneck shifts to workstation 34 having process time of 91.85 s. Bottleneck keeps shifting till further reduction in time is not possible at a particular station. To optimize the bottleneck station, data have to be studied to investigate the losses reducing the output.

**Table 1** MOST Study at all workstations

| W.S. no. | Process time | Op 1 | Op 2 | Op 3 | Op 4 | Op 5 | Op 6 | Op 7 | Op 8 | Op 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 87.17 | 83.2 | 72.6 | 68.3 | 86.3 | 82.1 | 87.2 | 57.9 | | |
| 2 | 88.15 | 81.4 | 78.3 | 88.2 | 80.9 | 79.4 | | | | |
| 18 | 91.25 | 91 | 89.9 | 90.8 | 90.2 | 90.2 | 91.3 | 82.2 | | |
| 21 | 91.38 | 90.6 | 87.6 | 88.5 | 87.6 | 88.4 | 81.9 | 91.4 | 68.6 | 88.6 |
| 28 | 92.34 | 86.5 | 92.3 | 75.5 | 86.5 | 63.2 | | | | |
| 34 | 91.85 | 91.9 | 84.1 | 88.5 | | | | | | |
| 36 | 91.49 | 82.2 | 91.5 | | | | | | | |

Data for 50 days were collected through Integrated Production Management System (IPMS) and is given in Table 2. $C_{\mathrm{bd}}$ and $C_{\mathrm{inv}}$ are the cost of failure and cost of inventory, respectively in Rs. lacs. $C_{\mathrm{ab}}$ is the cost of absenteeism in Rs. Cost values are based on cost of spare parts, equipment, labor, etc. Downtime is in min. Due to space constraints only 10-day data are presented here.

## Development of mathematical formulation

Literature review clearly reveals that models for time loss and cost in vehicle assembly line are not attempted in detail. In this thesis these models are developed successfully by regression technique (Hair et al. 2015) up to third degree polynomial. To tradeoff between accuracy and complexity of various higher degree models, linear models are selected for all seven dependent variables in this study.

### Establishing relationship for time loss

Step by step evolutions of various models developed during the process are put forward for $T_{\mathrm{setup}}$. The philosophy remains same for other dependent factors. As described earlier $T_{\mathrm{setup}}$ depends on $T_{\mathrm{bd}}$, $T_{\mathrm{inv}}$ and $T_{\mathrm{ab}}$. Using data from the Table 2, relations between $T_{\mathrm{setup}}$ and independent factors are developed by regression modeling. Interaction effect of independent variables was checked from accuracy point of view up to third degree polynomial.

1. Linear relationship without interaction effect ($R$ sq—90.6%)

$$T_{\mathrm{setup}} = -5.13 + 0.247(T_{\mathrm{bd}}) + 0.265(T_{\mathrm{inv}}) + 0.268(T_{\mathrm{ab}}) \tag{1}$$

2. Quadratic relationship without interaction effect ($R$ sq—91.5%)

$$\begin{aligned} T_{\mathrm{setup}} = {} & 3.34 + 0.157(T_{\mathrm{bd}}) - 0.144(T_{\mathrm{inv}}) \\ & - 0.040(T_{\mathrm{ab}}) + 0.00183(T_{\mathrm{bd}})^2 + 0.0102(T_{\mathrm{inv}})^2 \\ & + 0.00655(T_{\mathrm{ab}})^2 \end{aligned} \tag{2}$$

3. Cubic relationship with interaction effect ($R$ sq—93.7%)

$$\begin{aligned} T_{\mathrm{setup}} = {} & -9.6 + 0.29(T_{\mathrm{bd}}) - 0.65(T_{\mathrm{inv}}) + 1.68(T_{\mathrm{ab}}) \\ & + 0.107(T_{\mathrm{bd}})(T_{\mathrm{inv}}) - 0.0878(T_{\mathrm{bd}})T \\ & - 0.0420(T_{\mathrm{inv}})(T_{\mathrm{ab}}) - 0.00316(T_{\mathrm{bd}})(T_{\mathrm{inv}})(T_{\mathrm{ab}}) \\ & - 0.00109(T_{\mathrm{bd}})(T_{\mathrm{inv}})^2 + 0.00261(T_{\mathrm{inv}})(T_{\mathrm{ab}})^2 \\ & + 0.00310(T_{\mathrm{ab}})(T_{\mathrm{bd}})^2 - 0.000957(T_{\mathrm{bd}})^3 \\ & + 0.000543(T_{\mathrm{inv}})^3 - 0.000747(T_{\mathrm{ab}})^3 \end{aligned} \tag{3}$$

The small change in accuracy of $R$-sq value of higher order models may not affect major number of change in vehicles produced. To trade off between accuracy and complexity of various higher degree models, linear model is selected in the present study for remaining dependent variables which are listed below.

$$T_{\mathrm{mh}} = -0.0079 + 0.00382(T_{\mathrm{bd}}) + 0.00359(T_{\mathrm{inv}}) + 0.00278(T_{\mathrm{ab}}) \tag{4}$$

$$T_{\mathrm{rej}} = -12.6 + 0.447(T_{\mathrm{bd}}) + 0.512(T_{\mathrm{inv}}) + 0.372(T_{\mathrm{ab}}) \tag{5}$$

$$T_{\mathrm{f}} = 0.759 + 0.00200(T_{\mathrm{bd}}) + 0.00251(T_{\mathrm{inv}}) + 0.00249(T_{\mathrm{ab}}) \tag{6}$$

Any plant is time based and cost based. Literature review reveals that models for $C_{\mathrm{bd}}$, $C_{\mathrm{inv}}$, $C_{\mathrm{ab}}$ in vehicle assembly line are not established. This has been demonstrated ahead.

**Table 2** Downtime and cost data at plant A

| Day | $T_{\mathrm{bd}}$ | $T_{\mathrm{inv}}$ | $T_{\mathrm{ab}}$ | $T_{\mathrm{setup}}$ | $T_{\mathrm{mh}}$ | $T_{\mathrm{rej}}$ | $T_{\mathrm{f}}$ | $C_{\mathrm{bd}}$ | $C_{\mathrm{inv}}$ | $C_{\mathrm{ab}}$ | Line output |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 19.87 | 15.42 | 34.84 | 13.19 | 0.22 | 17.03 | 0.92 | 4.02 | 7.96 | 5700.13 | 237 |
| 2 | 25.66 | 16.57 | 20.66 | 11.15 | 0.20 | 15.24 | 0.90 | 3.95 | 8.01 | 5704.25 | 232 |
| 3 | 20.04 | 20.26 | 24.57 | 11.79 | 0.21 | 16.50 | 0.92 | 4.06 | 7.95 | 5705.29 | 236 |
| 4 | 23.27 | 23.27 | 23.66 | 13.07 | 0.23 | 17.37 | 0.91 | 3.91 | 8.15 | 5735.18 | 232 |
| 5 | 28.27 | 25.55 | 28.99 | 16.90 | 0.27 | 24.71 | 0.95 | 3.96 | 8.14 | 5745.29 | 231 |
| 6 | 31.24 | 24.27 | 31.07 | 16.90 | 0.29 | 25.18 | 0.97 | 3.94 | 8.02 | 5705.12 | 227 |
| 7 | 17.99 | 16.55 | 17.96 | 8.22 | 0.16 | 11.03 | 0.88 | 4.08 | 7.95 | 5704.22 | 236 |
| 8 | 19.27 | 15.27 | 19.53 | 8.81 | 0.17 | 11.32 | 0.89 | 4.4 | 8.20 | 5755.32 | 236 |
| 9 | 24.66 | 19.57 | 22.57 | 11.23 | 0.23 | 15.91 | 0.91 | 4.35 | 8.23 | 5722.51 | 234 |
| 10 | 21.27 | 26.66 | 28.96 | 15.80 | 0.25 | 21.07 | 0.95 | 4.29 | 8.21 | 5750.78 | 234 |

These data are further analyzed for mathematical formulation

## Establishing relationship for cost

If the time lost due to failure is to be reduced, then funds have to be invested in spare parts and machinery. Additional cost is also involved in deploying more people, training of the people, etc. So the cost associated with failure ($C_{bd}$) will increase to minimize this time. Jung et al. (2007) have presented replacement models but relationship between $T_{bd}$ and $C_{bd}$ is not demonstrated. Analysis is done for cubic, quadratic and linear relationship from the data given in Table 2. The distribution plot for all the relationships is shown in Fig. 3.

The models developed are as below.

$$\text{Linear } (R-\text{sq} \;= 95.8\%)\; C_{bd} = 6.696 - 0.1356(T_{bd}) \tag{7}$$

$$\text{Quadratic } (R-\text{sq} \;= 97.5\%)\; C_{bd} = 9.762 - 0.3908(T_{bd}) + 0.005153)^2 \tag{8}$$

$$\text{Cubic } (\mathrm{R-sq} = 97.6\%)\; \mathrm{C_{bd}} = 15.51 - 1.111(\mathrm{T_{bd}}) + 0.03471(\mathrm{T_{bd}})^2 - 0.000398(\mathrm{T_{bd}})^3 \tag{9}$$

As the value of $R$-sq obtained for linear relationship is more than 95%, it was selected for the present study due to simplicity of model. Similarly linear models for Inventory and absenteeism were developed and are given below.

$$\text{Linear } (R-\text{sq} \;= 95.1\%)\; C_{inv} = 12.45 - 0.3093(T_{inv}) \tag{10}$$

$$\text{Linear } (R-\text{sq} \;= 96.1\%)\; C_{ab} = 6019 - 13.35(T_{ab}) \tag{11}$$

Further, all these developed relationships need to be verified before defining objective function.

## Validation of various dependent functions for time losses

Dependent functions are estimated using three independent variables from the relationships developed. These are checked with plant actual values to find the deviation as shown in Table 3.

It can be seen very clearly that relationships developed, gives result in close agreement within ± 7%. Similarly cost models were verified. Thus, developed relationships

**Fig. 3** $C_{bd}$ v/s $T_{bd}$

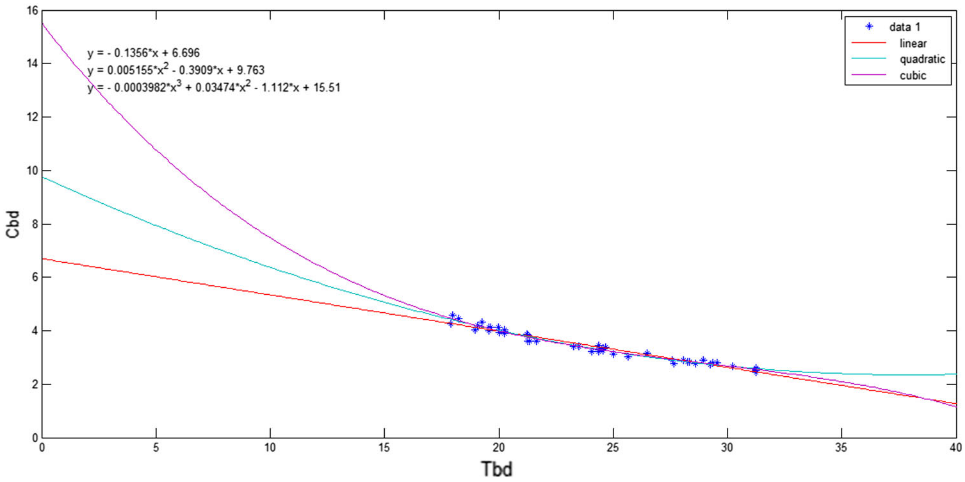


**Table 3** Deviation of dependent variables

| Day | $T_{bd}$ | $T_{inv}$ | $T_{ab}$ | $(T_{setup})_A$ | $(T_{mh})_A$ | $(T_{rej})_A$ | $(T_f)_A$ | $T_{setup}$ | % Dev | $T_{mh}$ | % Dev | $T_{rej}$ | % Dev | $T_f$ | % Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 19.87 | 15.42 | 34.84 | 13.19 | 0.22 | 17.03 | 0.92 | 13.20 | −0.09 | 0.22 | −0.33 | 17.14 | −0.63 | 0.92 | −0.78 |
| 2 | 25.66 | 16.57 | 20.66 | 11.15 | 0.20 | 15.24 | 0.90 | 11.13 | 0.15 | 0.21 | −1.03 | 15.03 | 1.35 | 0.90 | −0.93 |
| 3 | 20.04 | 20.26 | 24.57 | 11.79 | 0.21 | 16.50 | 0.92 | 11.77 | 0.15 | 0.21 | −0.24 | 15.87 | 3.82 | 0.91 | 0.43 |
| 4 | 23.27 | 23.27 | 23.66 | 13.07 | 0.23 | 17.37 | 0.91 | 13.12 | −0.38 | 0.23 | −1.59 | 18.51 | −6.55 | 0.92 | −1.04 |
| 5 | 28.27 | 25.55 | 28.99 | 16.90 | 0.27 | 24.71 | 0.95 | 16.39 | 3.04 | 0.27 | −0.14 | 23.90 | 3.30 | 0.95 | −0.19 |
| 6 | 31.24 | 24.27 | 31.07 | 16.90 | 0.29 | 25.18 | 0.97 | 17.34 | −2.59 | 0.28 | 1.52 | 25.34 | −0.64 | 0.96 | 0.75 |
| 7 | 17.99 | 16.55 | 17.96 | 8.22 | 0.16 | 11.03 | 0.88 | 8.51 | −3.55 | 0.17 | −3.74 | 10.59 | 3.97 | 0.88 | −0.69 |
| 8 | 19.27 | 15.27 | 19.53 | 8.81 | 0.17 | 11.32 | 0.89 | 8.91 | −1.08 | 0.17 | −2.81 | 11.09 | 2.03 | 0.88 | 1.09 |
| 9 | 24.66 | 19.57 | 22.57 | 11.23 | 0.23 | 15.91 | 0.91 | 12.19 | −8.53 | 0.22 | 2.98 | 16.83 | −5.80 | 0.91 | −0.03 |
| 10 | 21.27 | 26.66 | 28.96 | 15.80 | 0.25 | 21.07 | 0.95 | 14.95 | 5.42 | 0.25 | 0.19 | 21.33 | −1.21 | 0.94 | 1.00 |

are validated. As developed relationships are validated, these models may be used for developing or proposing optimal solution. Similarly cost models were validated.

## Proposed methodology for optimal solution

As per Hakami et al. (2014), time ($T$) required to produce the product is given by,

$$T = \frac{\text{Total working time}}{\text{Demand}}$$

According to Goldratt (1992), $T$ is known as Time Allowed to Complete the Task (TACT) as it varies as per demand. Cycle time (Tc) is the time taken by slowest processing station which governs the output of the line. Hence, the above equation needs to be modified. So output $N$ can be written as, $N = \frac{T_{\mathrm{wt}}}{\mathrm{Tc}}$. Where, $T_{\mathrm{wt}}$ is actual working time.

Rejected products cannot be considered in output. As per literature review, time lost due to fatigue ($T_{\mathrm{f}}$) and time lost due to rejection ($T_{\mathrm{rej}}$) is ignored in vehicle assembly line. In the present study, both $T_{\mathrm{rej}}$ and $T_{\mathrm{f}}$ are considered. So, the objective function can be written as,

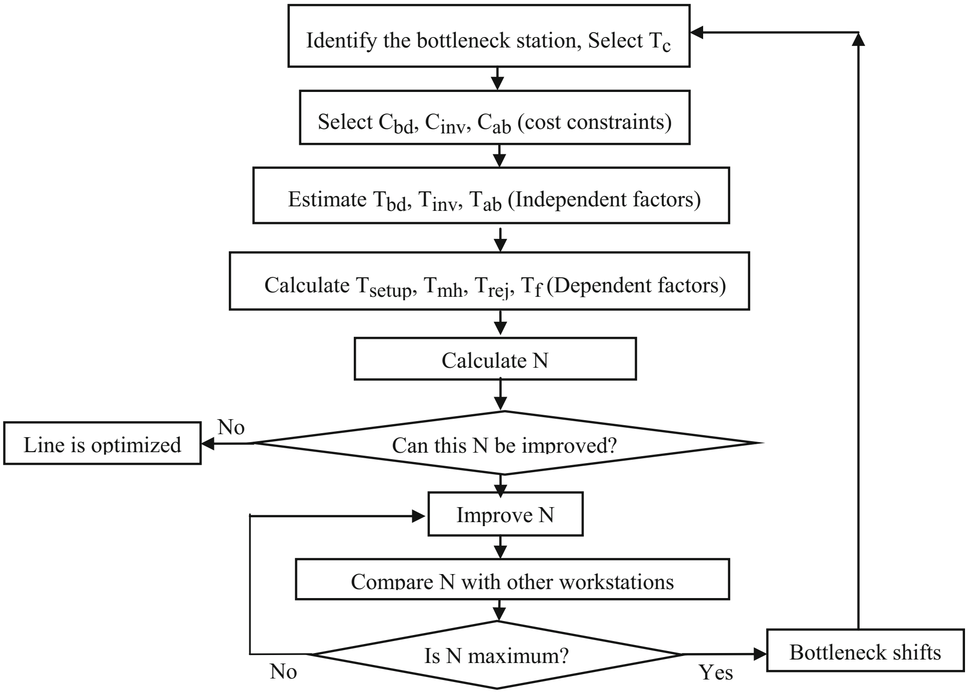
Maximize output ($N$),

$$N = \left[\frac{T_{\mathrm{wt}} - \left(\boldsymbol{T}_{\mathbf{bd}} + \boldsymbol{T}_{\mathbf{inv}} + \boldsymbol{T}_{\mathbf{ab}} + T_{\mathrm{setup}} + T_{\mathrm{mh}} + T_{\mathrm{rej}} + T_{\mathrm{f}}\right)}{\boldsymbol{T}_{\mathbf{c}}}\right] \tag{12}$$

A methodology for optimal solution is proposed based on objective function and is given in Fig. 4.

From Table 1, bottleneck station and corresponding cycle time can be identified. $C_{\mathrm{bd}}$, $C_{\mathrm{inv}}$ and $C_{\mathrm{ab}}$ are selected from the Table 2. As per proposed methodology, next step is to estimate independent factors using Eqs. 7, 10 and 11. The dependent factors are to be estimated as per the Eqs. 1, 4, 5 and 6. In the next step, output N is estimated using Eq. 12. In the subsequent stage, whether the output can be further improved or not is checked. If No, the output is already optimal hence line is optimized. If Yes, lean techniques are used to improve output by reducing cycle time and time loss. This improved output is to be compared with output of other workstations. If improved output is not maximum, then output of this particular workstation still needs to be improved. Optimal solution in any vehicle assembly line can be obtained through the iterative process, wherein for a particular bottleneck station the maximum number of vehicles produced can be identified and further it can be checked whether bottleneck station can be shifted by releasing the resource constraint within the given cost constraints. This process will be repeated till the optimal solution is obtained. This proposed methodology is initially validated by using the data collected at plant A. The said methodology can also be checked whether it can be applied for other plants.

**Fig. 4** Flow chart for the optimization model



## Results and discussion

The present research focuses on optimization of assembly line performance using simulation based approach. The optimization model is evolved by using data from plant A with three independent and seven dependent factors. Initially proposed model is validated for a particular plant operation which is presented ahead.

### Validation of model at plant 'A'

From Table 1, bottleneck station can be identified as workstation 28, i.e., tyre fitment. First five critical workstations in this plant are 28, 34, 36, 21 and 18 having process times as 92.34, 91.85, 91.49, 91.38 and 91.25 s, respectively. Process time of workstation 28 is reduced to 90 s by maintaining inventory of rims, investing in spares and new tools, etc. Workstation 34 (Diesel and Battery fitment) now becomes a bottleneck station having process time as 91.85 s. Maintenance of hoist, availability of parts and provision of high speed dispensing pump could reduce the process time to 88 s. In these circumstances, bottleneck is at workstation 36, i.e., Bonnet fitment. Thus, bottleneck keeps shifting to other workstations after improvements.

Process time of all these workstations after improvement is 90, 88, 89, 88 and 89 s. Thus, workstation 28 becomes bottleneck station again. To reduce this time further, it is proposed to use six spindle nut runner and also to automate tyre loading process. This will need additional investment and approval. As of now process reached to saturation level, additional investment may not prove to be competitive in the market because as investment increases, cost of the product also increases. There can be tradeoff between the number of vehicles produced and additional investment cost. Therefore, present state can be considered as an optimal solution for the said plant.

To explain the implementation of proposed methodology for finding the optimal solution, calculations for only two cases viz. initial bottleneck station 28 (process time as 92.34 s) and second again the same bottleneck station 28 after the improvement (process time as 90 s) is shown. The cost data are retrieved from Table 2. Estimated values of time loss and output N using Eqs. 7, 10, 11, 1, 4, 5, 6 and 12, respectively, are given in Table 4. $T_l$ is total time loss.

These estimated values indicates that time loss occurs due to failure of tyre balancing machine, shortage of tyres, people not reporting in time, adjustments as per wheel base, defective parts, increase in handling time due to tripping of motor, fatigue loss due to improper tools, etc. It can be seen from Table 4 that absenteeism has major impact followed by equipment breakdown and shortage of inventory. This initial stage of iterative process in the proposed methodology has predicted 246 numbers of vehicles and can be compared with actual number of vehicles produced in the same plant under the same cost constraints which is 237 and can be seen from Table 2. The percentage error seen is 3.8%, i.e., mainly due to cumulative error in the multistage approach of mathematical formulation.

Next step as per proposed methodology is to check whether output can be improved or not. From the objective function it is clear that N can be increased by reducing the time loss and cycle time. If the output $N$ can not be improved then it can be deduced that line is optimized.

Second case of output calculation is again based on the bottleneck station as workstation 28 with improved process time as 90 s. Revised data of downtime, cost values and number of vehicles produced were collected. From these data, maximum number of vehicles produced in plant is observed as 264. Corresponding to this, new values of cost constraints after improvement in plant A are given in Table 4 below. Under these revised cost constraints for improvement of productivity, estimated time loss and output $N$ are given in Table 5.

It is clear that due to various improvement activities, time loss is reduced remarkably by 24% while cycle time is reduced by 2.5%. This final stage of iterative process gives 265 number of vehicles produced. It can be seen that line output is increased from 237 to 264 which is 11% more. It can be also seen that the proposed methodology produces result in close agreement with the actual number of vehicles produced on the same assembly line at plant A.

**Table 4** Estimation of time loss and output N before improvement

| $C_{bd}$ | $C_{inv}$ | $C_{ab}$ | $T_{bd}$ | $T_{inv}$ | $T_{ab}$ | $T_{setup}$ | $T_{mh}$ | $T_{rej}$ | $T_f$ | $T_l$ | $N$ | Line output |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.02 | 7.96 | 5700 | 19.735 | 14.517 | 23.895 | 9.995 | 0.186 | 12.543 | 0.894 | 81.765 | 246 | 237 |

**Table 5** Estimation of time loss and output N after improvement

| $C_{bd}$ | $C_{inv}$ | $C_{ab}$ | $T_{bd}$ | $T_{inv}$ | $T_{ab}$ | $T_{setup}$ | $T_{mh}$ | $T_{rej}$ | $T_f$ | $T_l$ | $N$ | Line output |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.12 | 8.15 | 5840 | 18.997 | 13.902 | 13.408 | 6.840 | 0.152 | 7.998 | 0.865 | 62.162 | 265 | 264 |

**Table 6** Estimation of time loss and output N

| Plant | $C_{\mathrm{bd}}$ | $C_{\mathrm{inv}}$ | $C_{\mathrm{ab}}$ | $T_{\mathrm{bd}}$ | $T_{\mathrm{inv}}$ | $T_{\mathrm{ab}}$ | $T_{\mathrm{setup}}$ | $T_{\mathrm{mh}}$ | $T_{\mathrm{rej}}$ | $T_{\mathrm{f}}$ | $T_{\mathrm{l}}$ | $N$ | Average production/shift |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B | 5.6 | 10.2 | 5800 | 8.01 | 7.11 | 16.4 | 3.13 | 0.09 | 0.72 | 0.8 | 36.30 | 221 | 207 |
| C | 5.7 | 9.89 | 5790 | 7.35 | 8.28 | 17.2 | 3.47 | 0.10 | 1.3 | 0.8 | 38.49 | 281 | 267 |

## Testing of proposed model at plant B and C

In these plants, equipments are new and average age of staff is 40 years. In plant B, as models being cars, work content is more and cycle time is 115 s. Type of assembly is Monocoque, i.e., a small chassis is provided for engine–gear box. Chassis line and finish line are of U type. Six main lines and five feeder lines are available. Number of workstations are 100 as against 73 in plant A. Automation level is higher than plant A with wooden flooring throughout, which reduces fatigue. In plant C, models are same as plant A. Number of workstations are 41 having more number of feeder stations. Automation level is more than plant A and cycle time at bottleneck station is 90 s.

Under these circumstances, same methodology was tested to check the feasibility of utility of proposed methodology. Downtime and number of vehicles produced per day are acquired for 50 days through IPMS. However, cost values were not known. Hence for these plants, management suggested values of cost constraints are used as given in Table 6. Same procedure is followed as mentioned in "Establishing relationship for time loss" section to calculate output $N$. Results are as given in Table 6.

It can be seen from Table 6 that the values of simulation output $N$ and average production per shift are closer but cannot be compared, as both are not based on the same cost constraints.

## Concluding remarks

To improve output of vehicle assembly line; cycle time and time loss due to major factors like equipment failure, shortage of inventory, absenteeism, setup, rejection, material handling and fatigue has to be reduced. Therefore, in this study, detailed asymptotic analysis of vehicle assembly line at different plants A, B and C is done. MOST is used for identifying bottleneck station. Based on data, inter-relationships for dependent functions were formulated by regression modeling using three independent variables. To tradeoff between accuracy and complexity of various higher degree models, linear models are selected in the present study. Estimated values of dependent factors were in agreement within ±7% of actual plant values. Relationship between various factors and output was formulated to develop an objective function.

Subsequently, a methodology is proposed to find optimal solution. The proposed methodology helps in predicting the number of vehicles produced under certain constraints. The comparison of predicted number of vehicles and actual vehicles produced in the same plant are in close agreement within 4% of error. Once the initial iteration for number of vehicles produced is predicted, further possible improvements within the imposed cost constraints, in terms of reduction in time loss and cycle time can be carried out until process reached saturation level, which gives optimal production. In the process, reduction in time loss is 24%. Cycle time is reduced from 92.34 to 90 s (2.5%). This leads to an increase in actual output from initial number of vehicles from 237 to 264 at plant A over a period, which is 11% more in output.

Proposed methodology is effective in practice and numerically less intensive. It is tested satisfactorily at three plants having different setup and conditions. Simulation results predicted by proposed methodology and actual plant values are in good agreement. Hence it can be said that major contribution of the present research is, proposed methodology for simulating optimal number of vehicles produced in a given cost constraints for vehicle assembly line. Practitioners may use this methodology to reduce cycle time and time loss by tradeoff between budgeted cost and ROI, to optimize the performance of assembly line using simulation approach.

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