Proceedings of the ASME 2013 International Manufacturing Science and Engineering Conference
MSEC2013
June 10-14, 2013, Madison, Wisconsin, USA

MSEC2013-1155

MODELING, ANALYSIS, AND IMPROVEMENT OF DOOR PRODUCTION LINE AT AN AUTOMOTIVE BODY SHOP

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ABSTRACT

In this paper, we introduce a case study of modeling, analysis, and continuous improvement of a door production line at an automotive body shop using production systems engineering methods. Analytical models have been developed, and recursive procedures have been derived to evaluate line production rate. An arrow-based bottleneck analysis method is introduced to identify the bottlenecks, whose improvement can lead to the largest improvement in system performance. Such methods provide a quantitative tool for plant engineers and managers to operate and improve door production line to achieve high productivity, and are also applicable to other large volume manufacturing systems.

Keywords: Production systems engineering, door line, body shop, production rate, bottleneck.

1 INTRODUCTION

Door production line is an important element in vehicle manufacturing. Efficient production of doors is essential for high productivity in the automotive body shop. Therefore, developing an analytical method to evaluate the performance of door line and improve its productivity has significant importance.

Performance analysis and continuous improvement of manufacturing systems have attracted substantial research efforts during the last 50 years. Both simulation analysis and analytical investigation have been carried out extensively. Although simulations can provide a detailed and graphical presentation of system dynamics, it suffers from long model development time and long simulation time. It is also difficult to discover some system theoretic properties. Analytical methods, on the other hand, can provide a quick analysis of system behavior, and enable us to investigate the nature of the system. Many analytical methods have been developed to analyze line performance (see, for example, monographs [1]- [4], and reviews [5]- [7]). Production Systems Engineering (PSE), as an emerging engineering branch, provides a rigorous engineering theory to uncover the fundamental principles governing production system operations and use them for design, analysis and continuous improvement.

In this paper, we introduce a case study of modeling, analysis, and improvement of a door production line at an automotive body shop using PSE methods. Structural modeling is introduced to simplify the complicated system layout to an assembly system without losing the fidelity. Next, an iterative procedure is presented to approximate the production rate of the system. The method is validated by comparing with the actual throughput observed on the factory floor. It is shown that the model has achieved a high accuracy. Then, using the validated model, bottleneck analysis is introduced to identify the machines that impede line production rate in the strongest manner. By mitigating the bottleneck machines, the system productivity can be improved significantly.

The remainder of the paper is structured as follows: Section 2 describes the system layout. Structural modeling is intro-

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duced in Section 3. Section 4 outlines the performance evaluation method and validates the model. The continuous improvement study is presented in Section 5. Finally, conclusions are provided in Section 6.

2 SYSTEM DESCRIPTION

The door production line in this study consists of 31 robots and 3 manual loading positions to carry out welding, hemming, transferring, and punching operations, etc. Each robot is programmed to handle a single or multiple operations. The layout of the door line is shown in Figure 1.

There are three sections in the door production line: inner section, marriage 1 section, and marriage 2 section. In the inner section, the inner panels of a door are loaded and welded. Then it will be welded with outer panels (i.e., "married") and hemmed in marriage 1 section. Finally, marriage 2 section finishes punching operation and hangs the door onto the conveyor. Below the detailed operations are explained.

In the inner section, the inner door components are loaded manually by an operator to station S1, and robots R1 and R2 alternatively pick up and transfer them to station S2. Two robots, R3 and R4, carry out the spot welding operations at S2. Then, robot R5 will handle the welded part from S2 to spot welding and marriage station S4. Similarly, the other inner parts are loaded by another operator at station S3 and then transferred to S4 by robots R11 and R12 alternatively. At S4, robots R7 and R8 will spot weld the two inner parts together. Then the finished part will be loaded by robot R6 to the rack, which is represented as an idle station S6. Robots R9 and R10 will then pick it up from the rack alternatively and load to PED (pressure equipment directive) welding station S7.

In next section, marriage 1, both inner and outer parts are assembled together. The outer parts are loaded by an operator at outer loading station S10, and two robots R15 and R16 transfer them alternatively to a sealing station S11. Robots R17 and R18 glue the parts together and then transfer them to robot R14. At the same time, robots R9 and R10 will transfer the parts finishing PED welding to robot R14 as well. Then R14 handles both parts to station S12, representing the inner-outer marriage activity. The assembled parts will then be loaded by robots R19 and R20 alternatively to an outer hemming station S13. Four robots R201, R21, R22, and R23 work on the hemming operation. Then the same robots, R19 and R20, will load the finished one to idle station S14.

Robot 24 handles the door from station S14 to another idle station S15. Then, robot R26 will pick up it and send to the inner hemming station S16. Robots R202, R25, R27, and R28 will carry out the hemming operation. After the inner parts being hemmed, robot R29 will load and transfer them to punching station S17. Robot R30 load them to hang on station S18 and then transfer them to the conveyor, where the finished doors will be sent to the main line of the body shop. These comprise the marriage 2 section.

3 SYSTEM MODELING

After layout investigation, structural modeling is needed to develop a simplified model which is tractable for analysis without losing the fidelity. Such a simplification procedure is introduced below.

3.1 Structural Modeling

In this study, simplification procedure is carried out step by step based on the observations in the production line.

1. The manual loading stations S1, S3, and S10 are viewed as virtual machines whose over cycle time is treated as machine downtime.
2. The following pairs of robots are working dependently at the corresponding stations: (R1, R2), (R9, R10), (R11, R12), and (R15, R16). In other words, if one robot has a fault, another one stops functioning. Thus, they can be treated as aggregated robots in the simplification process.
3. All the robots (except R24 and R30) can be aggregated to the corresponding stations based on their functionality, as shown in Figure 1 with color shaded boxes.

After such simplification, we obtain a new model of the door line, shown in Figure 2, where the circles represent the machines (or stations). The dash circles indicate that these are the transferring robots.

Such a model can be further simplified by considering the following facts:

1. Station S2 transfers small parts, such as buckets and window bins, into station S4 for inner door marriage. The operation of S2 is faster than that of S4. These two stations can be viewed as one assembly station (referred to as S2/S4) for inner doors.
2. The two idle stations S14 and S15 are connected through a transfer robot R24. In productions, S14, S15 and R21 work dependently, and the failures of S14 and S15 are mostly due to R24. Therefore, these two stations and the transfer robots are grouped to form an aggregated station S14/S15.
3. Since "block after service" regime is applied in the door line, the door part can stay on the robots or stations if it is blocked by the downstreams. To convert it into a "block before service" model, which will be used in performance analysis, a buffer of capacity one will be added between any two consecutive stations. Note that additional buffer capacity is added before S16 since doors can be held on S14, S15 and R21.
4. According to the data collected, the door line is seldom blocked by the body shop if a large number of carriers are

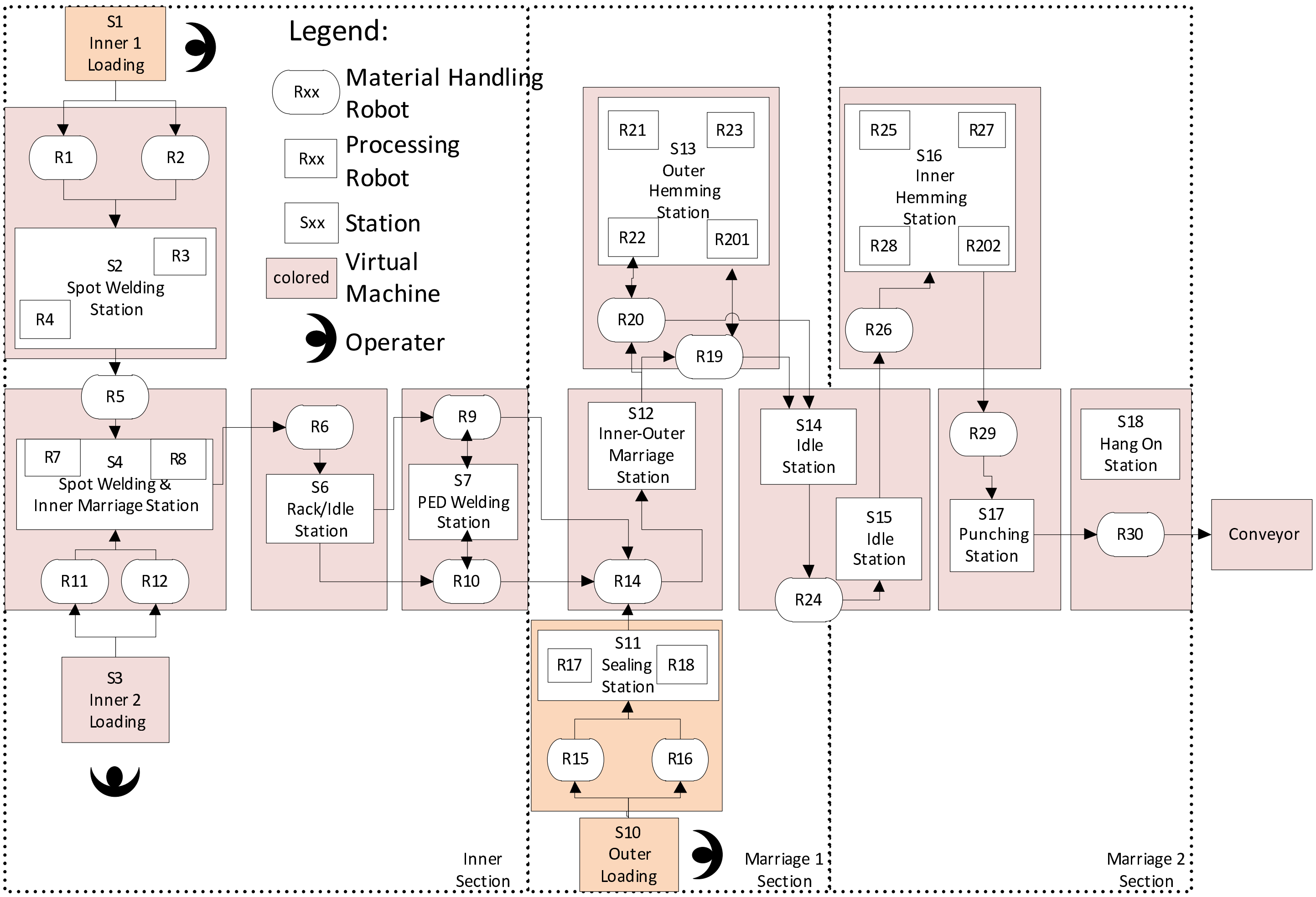

FIGURE 1. DOOR LINE LAYOUT

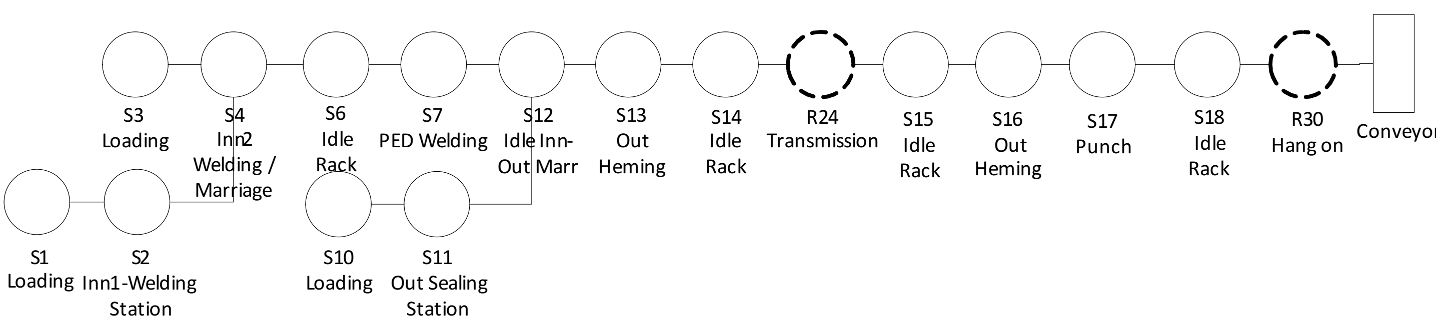

FIGURE 2. SIMPLIFIED DOOR LINE MODEL

kept on the conveyor system. Thus, the conveyor can be treated as an infinite buffer. In other words, station S18 will be aggregated with robot R30 and is never blocked.

After such simplifications, the final model is shown in Figure 3, where the rectangles are the buffers (where the numbers inside are the buffer capacity). Such a model will be used in throughput analysis and continuous improvement in subsequent sections.

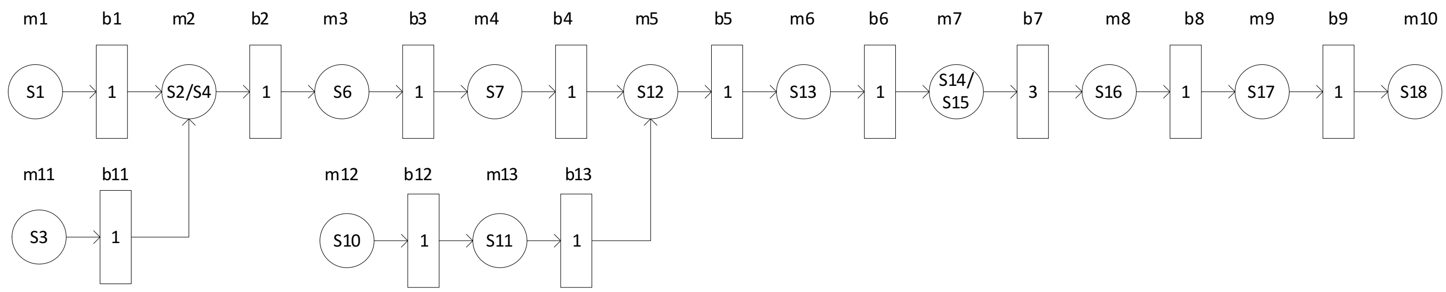

FIGURE 3. DOOR LINE MODEL FOR ANALYSIS AND IMPROVEMENT

3.2 Parameter Identification

In this study, one month of production data is collected through the factory information system. Using the collected data, the average uptime ($T_{up,i}$) and downtime ($T_{down,i}$) of each machine are calculated as follows:

$$T_{up,i} = \frac{\sum_{j=1}^{n_i} t_{up,i}^j}{n_i},$$
$$T_{down,i} = \frac{\sum_{j=1}^{n_i} t_{down,i}^j}{n_i}, \quad i = 1, \ldots, 13,$$

where n_i is the number of breakdowns for machine m_i during the collection period, and $t_{up,i}^j$, $t_{down,i}^j$ are the duration of j-th up- and downtime of machine m_i, respectively. Then, the failure and repair rates (λ_i and μ_i, respectively), as well as the machine efficiency (e_i) can be obtained (see Table 1).

$$\lambda_i = \frac{1}{T_{up,i}},$$
$$\mu_i = \frac{1}{T_{down,i}},$$
$$e_i = \frac{T_{up,i}}{T_{up,i} + T_{down,i}} = \frac{\mu_i}{\lambda_i + \mu_i}, \quad i = 1, \ldots, 13.$$

The buffer capacity N_i is also shown in Table 1.

Note that due to confidentiality, the data has been modified and is for illustration purpose only. However, the basic property of the data does not change.

TABLE 1. MACHINE AND BUFFER PARAMETERS

m_i	Station #	$T_{up,i}$ (min)	$T_{down,i}$ (min)	e_i	N_i
1	1	155.917	2.733	0.983	1
2	2/4	74.883	3.2	0.961	1
3	6	17.567	1.683	0.913	1
4	7	268.067	4.042	0.98	1
5	12	492.3	3.883	0.992	1
6	13	836.583	27.15	0.969	1
7	14/15	628.742	4.242	0.991	3
8	16	249.05	1.7	0.993	1
9	17	479.05	17.133	0.965	1
10	18	789.783	14.383	0.982	
11	3	690.583	15.933	0.977	1
12	10	224.233	4.4	0.981	1
13	11	81.783	6.55	0.926	1

4 PERFORMANCE ANALYSIS AND MODEL VALIDATION

4.1 Performance Evaluation

Due to the complexity of the system, exact analysis is not available. Thus, we seek an approximate solution. The idea of the approximation is based on overlapping decomposition [8], where a serial line aggregation approach is used as a building block. Specifically, the assembly system described in Figure 3 is decomposed into three serial lines with multiple overlapped machines:

$$\text{Line 1: } m_1, m_2, \ldots, m_{10},$$
$$\text{Line 2: } m_{11}, m_2, m_3, \ldots, m_{10},$$
$$\text{Line 3: } m_{12}, m_{13}, m_5, m_6, \ldots, m_{10}.$$

First, we consider line 1. The overlapped assembly machines m_2 and m_5 in the line will be modified to m_2' and m_5', respectively, to accommodate the effects from lines 2 and 3, respectively. Let $st_{i,j}$ denote the probability that the upstream buffer (in front of machine m_i, $i = 2, 5$) in line j, $j = 1, 2, 3$, is empty. Then the starvation time due to such emptiness can be viewed as m_i's downtime so that its repair rate will be decreased. Therefore, the downtime of m'_2 and m'_5 can be defined as:

$$T'_{down,2} = T_{down,2}/(1-\Pr\{\text{upstream buffer in line 2 is empty}\}),$$
$$T'_{down,5} = T_{down,5}/(1-\Pr\{\text{upstream buffer in line 2 is empty}\}).$$

In addition, the uptime of m'_2 and m'_5 will be modified so that m_i's isolated efficiency will be decreased by the same factor. Then, we have

$$\begin{aligned}
\mu'_2 &= \mu_2(1-st_{2,2}),\\
\lambda'_2 &= \lambda_2+\mu_2-\mu'_2,\\
\mu'_5 &= \mu_5(1-st_{5,3}),\\
\lambda'_5 &= \lambda_5+\mu_5-\mu'_5.
\end{aligned}$$

Thus, a serial line with two modified machines will be obtained, m_1, m'_2, m_3, m_4, m'_5, m_6, ..., m_{10}. Using the serial line analysis method ([4]), the upstream buffer empty probabilities at machine m_2 and m_5 can be calculated.

$$\begin{aligned}
st_{2,1} = \Psi_2(&\lambda_1,\mu_1,\lambda'_2,\mu'_2,\lambda_3,\mu_3,\lambda_4,\mu_4,\lambda'_5,\mu'_5,\lambda_6,\mu_6,\ldots,\\
&\lambda_{10},\mu_{10},N_1,\ldots,N_9),\\
st_{5,1} = \Psi_5(&\lambda_1,\mu_1,\lambda'_2,\mu'_2,\lambda_3,\mu_3,\lambda_4,\mu_4,\lambda'_5,\mu'_5,\lambda_6,\mu_6,\ldots,\\
&\lambda_{10},\mu_{10},N_1,\ldots,N_9),
\end{aligned}$$

where operator $\Psi_i(\cdot)$, $i=2,5$, is introduced to calculate the probability of upstream buffer empty for machine m_i.

Next, using probability $st_{2,1}$ we just obtained, consider line 2, where the overlapped assembly machine m_2 will be modified to m''_2 by taking into account of $st_{2,1}$. Thus,

$$T''_{down,2} = T_{down,2}/(1-\Pr\{\text{upstream buffer in line 1 is empty}\}).$$

In other words, we have

$$\begin{aligned}
\mu''_2 &= \mu_2(1-st_{2,1}),\\
\lambda''_2 &= \lambda_2+\mu_2-\mu''_2.
\end{aligned}$$

Again, the serial line analysis approach is applied to calculate buffer empty probability $st_{2,2}$.

$$\begin{aligned}
st_{2,2} = \Psi_2(&\lambda_{11},\mu_{11},\lambda''_2,\mu''_2,\lambda_3,\mu_3,\lambda_4,\mu_4,\lambda'_5,\mu'_5,\lambda_6,\mu_6,\ldots,\\
&\lambda_{10},\mu_{10},N_{11},N_2,\ldots,N_9).
\end{aligned}$$

Finally, we consider line 3, and assembly machine m_5 is modified to m''_5 as follows:

$$\begin{aligned}
\mu''_5 &= \mu_5(1-st_{5,1}),\\
\lambda''_5 &= \lambda_5+\mu_5-\mu''_5.
\end{aligned}$$

Then probability of buffer being empty, $st_{5,3}$, can be calculated as

$$\begin{aligned}
st_{5,3} = \Psi_3(&\lambda_{12},\mu_{12},\lambda_{13},\mu_{13},\lambda''_5,\mu''_5,\lambda_6,\mu_6,\ldots,\\
&\lambda_{10},\mu_{10},N_{12},N_{13},N_5,\ldots,N_9).
\end{aligned}$$

Since the probabilities $st_{2,2}$ and $st_{5,3}$ are unknown, we introduce iterations. In the first iteration, assume $st_{2,2}$ and $st_{5,3}$ are known (e.g., equal to 0.5), we calculate $st_{2,1}$ and $st_{5,1}$ and then obtain the new values for $st_{2,2}$ and $st_{5,3}$. In the second iteration, these probabilities are replaced into line 1 again to generate $st_{2,1}$ and $st_{5,1}$, and then update $st_{2,2}$ and $st_{5,3}$. The process is repeated anew until it is convergent.

Mathematically, such a process can be described as follows:

Procedure 1.

$$\begin{aligned}
\mu'_2(s) &= \mu_2(1-st_{2,2}(s-1)),\\
\lambda'_2(s) &= \lambda_2+\mu_2-\mu'_2(s),\\
\mu'_5(s) &= \mu_5(1-st_{5,3}(s-1)),\\
\lambda'_5(s) &= \lambda_5+\mu_5-\mu'_5(s),\\
st_{2,1}(s) &= \Psi_2(\lambda_1,\mu_1,\lambda'_2(s),\mu'_2(s),\lambda_3,\mu_3,\lambda_4,\mu_4,\lambda'_5(s),\mu'_5(s),\\
&\qquad \lambda_6,\mu_6,\ldots,\lambda_{10},\mu_{10},N_1,\ldots,N_9),\\
st_{5,1}(s) &= \Psi_5(\lambda_1,\mu_1,\lambda'_2(s),\mu'_2(s),\lambda_3,\mu_3,\lambda_4,\mu_4,\lambda'_5(s),\mu'_5(s),\\
&\qquad \lambda_6,\mu_6,\ldots,\lambda_{10},\mu_{10},N_1,\ldots,N_9),\\
\mu''_2(s) &= \mu_2(1-st_{2,1}(s)),\\
\lambda''_2(s) &= \lambda_2+\mu_2-\mu''_2(s),\\
st_{2,2}(s) &= \Psi_2(\lambda_{11},\mu_{11},\lambda''_2(s),\mu''_2(s),\lambda_3,\mu_3,\lambda_4,\mu_4,\lambda'_5(s),\mu'_5(s),\\
&\qquad \lambda_6,\mu_6,\ldots,\lambda_{10},\mu_{10},N_{11},N_2,\ldots,N_9),\\
\mu''_5(s) &= \mu_5(1-st_{5,1}(s)),\\
\lambda''_5(s) &= \lambda_5+\mu_5-\mu''_5(s),\\
st_{5,3}(s) &= \Psi_3(\lambda_{12},\mu_{12},\lambda_{13},\mu_{13},\lambda''_5(s),\mu''_5(s),\lambda_6,\mu_6,\ldots,\\
&\qquad \lambda_{10},\mu_{10},N_{12},N_{13},N_5,\ldots,N_9),
\end{aligned}$$

with initial conditions

$$st_{2,2}(0) = st_{5,3}(0) = 0.5,$$

and s is iteration number,

$$s = 1,2,\ldots.$$

The operator $\Psi_i(\cdot)$ is obtained through the serial line aggregation method introduced in [4]. Consider a serial line of M machines with uptime and downtime parameters p_i and r_i, respectively, and $M-1$ buffers with capacity K_i between each consecutive machine pairs, we have:

$$\Psi_i = 1 - \frac{\frac{r_i^f}{p_i^f + r_i^f}}{\frac{r_i}{p_i + r_i}},$$

where p_i^f and r_i^f are the limits of series defined in the following procedure:

Procedure 2.

$$\begin{aligned}
r^b(n+1) &= r_i - r_i Q(r_{i+1}^b(n+1), p_{i+1}^b(n+1), r_i^f(n), p_i^f(n), K_i),\\
p_i^b(n+1) &= p_i + r_i - r_i^b(n+1), \quad i = 1, \cdots, M-1,\\
r_i^f(n+1) &= r_i - r_i Q(r_{i+1}^b(n+1), p_{i+1}^b(n+1), r_i^f(s), p_i^f(s), K_i),\\
p_i^f(n+1) &= p_i + r_i - r_i^b(n+1), \quad i = 1, \cdots, M-1,
\end{aligned}$$

with initial conditions:

$$p_i^f(0) = p_i, \quad r_i^f(0) = r_i, \quad i = 2, \cdots, M-1,$$

with boundary conditions:

$$\begin{gathered}
p_1^f(n) = p_1, \quad r_1^f(n) = r_1,\\
p_M^b(n) = p_M, \quad r_M^b(n) = r_M,\\
n = 0, 1, \ldots,
\end{gathered}$$

where n is the iteration number, and

$$Q(p_1, r_1, p_2, r_2, K) = \begin{cases} \frac{(1-e_1)(1-\phi)}{1-\phi e^{-\beta N}}, & \text{if } \frac{p_1}{r_1} \neq \frac{p_2}{r_2},\\[2ex] \frac{p_1(p_1+p_2)(r_1+r_2)/(p_1+r_1)}{(p_1+p_2)(r_1+r_2)+p_2 r_1(p_1+p_2+r_1+r_2)K}, & \text{if } \frac{p_1}{r_1} = \frac{p_2}{r_2}, \end{cases} \tag{1}$$

$$\phi = \frac{e_1(1-e_2)}{e_2(1-e_1)}. \tag{2}$$

The convergence of Procedure 2 has been proved in [4], i.e.,

$$\begin{gathered}
p_i^f = \lim_{n\to\infty} p_i^f(n), \quad r_i^f = \lim_{n\to\infty} r_i^f(n),\\
p_i^b = \lim_{n\to\infty} p_i^b(n), \quad r_i^b = \lim_{n\to\infty} r_i^b(n),\\
i = 1, 2, \ldots, M.
\end{gathered}$$

For the assembly system under study, it can be shown that Procedure 1 is convergent and it leads to an estimate of system production rate.

Theorem 1. *Procedure 1 is convergent, i.e.,*

$$\begin{gathered}
\lim_{s\to\infty} \mu_i'(s) = \mu_i', \quad \lim_{s\to\infty} \lambda_i'(s) = \lambda_i',\\
\lim_{s\to\infty} \mu_i''(s) = \mu_i'', \quad \lim_{s\to\infty} \lambda_i''(s) = \lambda_i'',\\
i = 2, 5,
\end{gathered}$$

and the system production rate is defined by

$$\begin{aligned}
PR = \frac{\mu_{10}}{\lambda_{10}+\mu_{10}}(1 - \Psi_{10}(&\lambda_1, \mu_1, \lambda_2', \mu_2', \lambda_3, \mu_3, \lambda_4, \mu_4, \lambda_5', \mu_5',\\
&\lambda_6, \mu_6, \ldots, \lambda_{10}, \mu_{10}, N_1, \ldots, N_9)).
\end{aligned}$$

The proof of this theorem is similar to the proof of convergence of the assembly system described in [4], therefore, omitted in this paper.

4.2 Model Validation

Using the method introduced above and the data shown in Table 1, we calculate line production rate as 0.768. Comparing with the actual production rate of 0.761, the difference is only 0.92%. Therefore, the model is validated and can be used for subsequent analysis.

5 CONTINUOUS IMPROVEMENT

5.1 Bottleneck Analysis

Bottleneck analysis has been shown as the most effective way to improve production system performance ([4]). To improve the production rate of the door line, we need to identify the machine that impedes the line performance in the strongest manner. In other words, improvement on the bottleneck machine will lead to the largest improvement in system production rate comparing with improving all other machines. Here we define bottleneck machine (BN-m) as:

Definition 1. *Machine m_i is the bottleneck machine if*

$$\frac{\partial PR}{\partial T_{down,i}} > \frac{\partial PR}{\partial T_{down,j}}, \quad \forall j \neq i.$$

Such bottlenecks can be discovered using the bottleneck identification method introduced in [4]. Specifically, we use an arrow assignment rule based on probabilities of blockage and starvation of each machine. The arrows are assigned from the upstream machine to the downstream if $BL_i > ST_{i+1}$, otherwise,

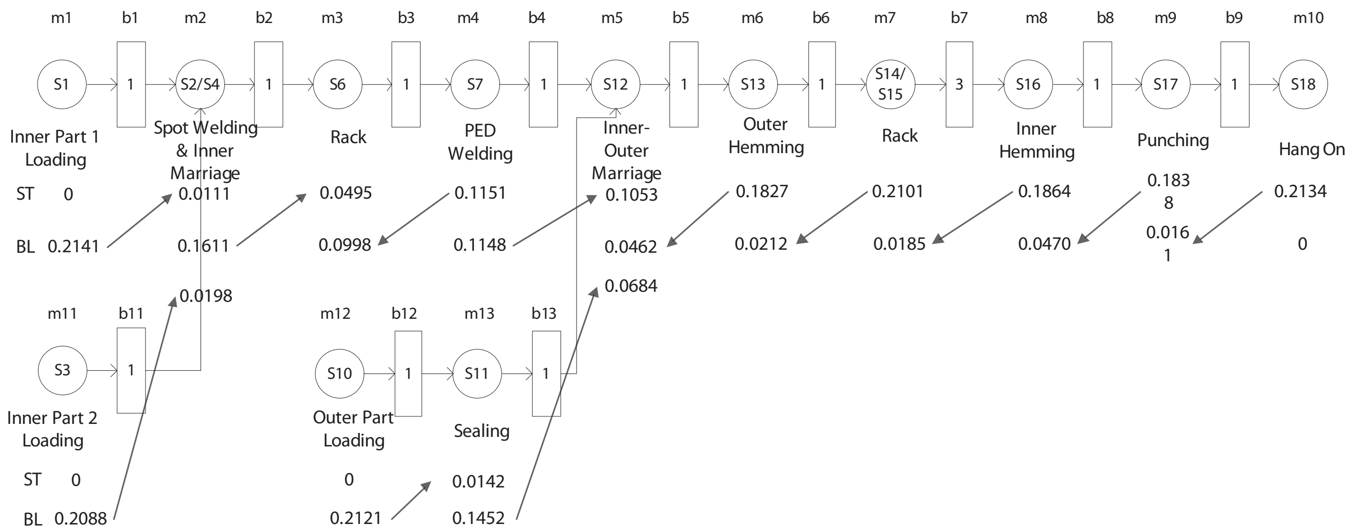

FIGURE 4. BOTTLENECK IDENTIFICATION OF DOOR LINE

the arrow should be in opposite direction. Then, the bottleneck machine is the one with no emanating arrows. In case of the assembly machine m_2 (or m_5), the starvations due to b_1 and b_{11} (respectively, b_4 and b_{13}) are used to compare with blockages of m_1 and m_{11} (respectively, m_4 and m_{13}), respectively. An illustration of such identification is shown in Figure 4. As one can see, both machines m_3 and m_5 have no emanating arrows, thus, they are the bottleneck machines. Such results are matching with floor observations. It has been found that machine m_3 has breakdown data due to part falling on the station, and machine m_5 typically become the source of severe blockage and starvation in adjacent machines.

5.2 Improvement Analysis

To improve the performance of door line, what-if analysis has been carried out to mitigate the impact of bottlenecks. Specifically, the average downtimes of bottleneck machines m_3 and m_5 have been reduced and the buffer capacity in front of them are increased. The results are shown in Figures 5-8.

As one can see from these figures, the improvement of line production rate due to downtime reduction of m_3 is much larger than that due to m_5. Therefore, machine m_3 should be the primary bottleneck to be focused on. In addition, increasing buffer b_4 capacity in front of m_5 has a more significant impact on line production rate than increasing b_2.

In summary, by considering the feasibility constraints in the plant, the following continuous improvement procedure has been proposed to plant management:

1. Decrease the downtime of station S6 (i.e., m_3) by 30%. This results in 2.46% improvement. Then, the bottleneck will be shifted to station S12 (i.e., m_5).
2. In addition, decrease the downtime of the inner-outer marriage station S12 (i.e., m_5) by 30%. This leads to 2.90% improvement. The bottleneck machine is still S12.
3. Further improvement can be achieved by increasing the buffer b_4 capacity to 3 before the inner-outer marriage station. This will result in 8.20% improvement, a substantial increase in line production rate.

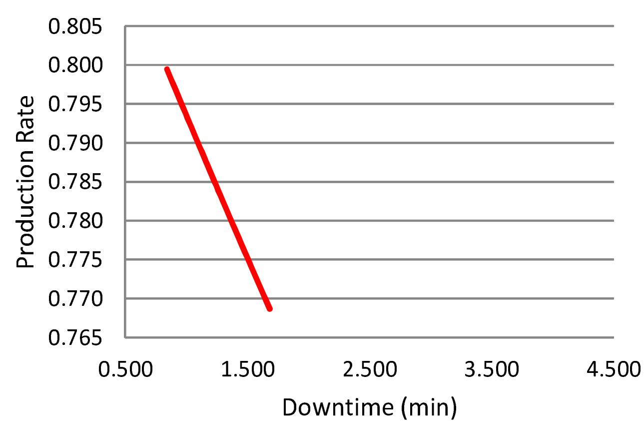

FIGURE 5. IMPROVEMENT BY DECREASING m_3's AVERAGE DOWNTIME

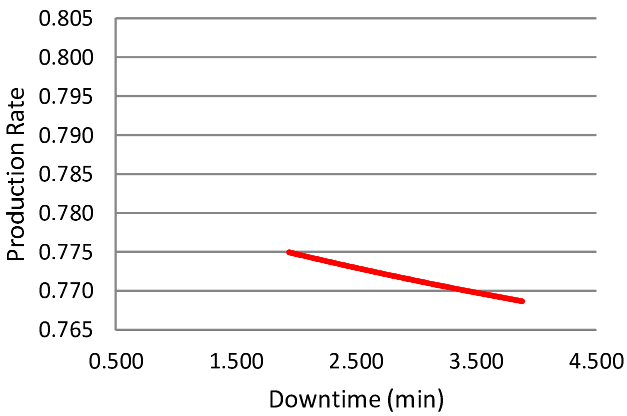

FIGURE 6. IMPROVEMENT BY DECREASING m_5's AVERAGE DOWNTIME

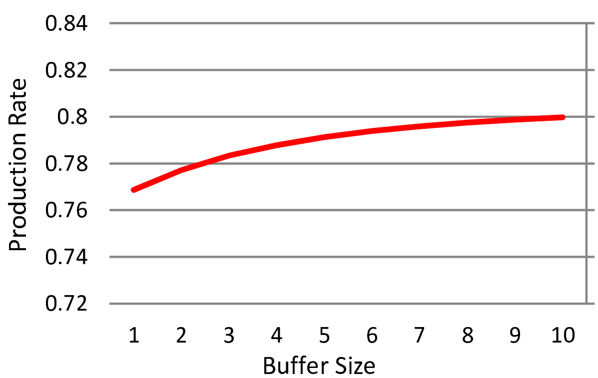

FIGURE 7. IMPROVEMENT BY INCREASING b_2's CAPACITY IN FRONT OF m_3

6 CONCLUSIONS

This paper introduces a case study of door production line in an automotive body shop. Through structural modeling of the line, an assembly system model has been developed and an iterative procedure to evaluate line production rate has been introduced. Using the data collected on the factory floor, the model has been validated with high accuracy. A bottleneck identification and mitigation method has been adopted to identify the bottleneck machine and what-if analysis has been carried out to predict the improvement results. This model provides a quantitative tool for plant engineers and managers to operate production system with high efficiency.

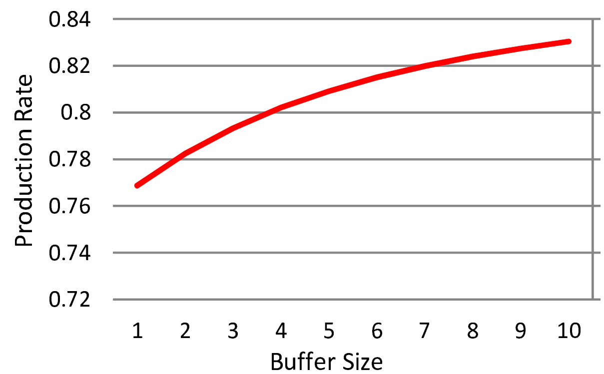

FIGURE 8. IMPROVEMENT BY INCREASING b_4's CAPACITY IN FRONT OF m_5

ACKNOWLEDGEMENT

This work is supported in part by NSF grant CMMI 1063656. The authors thank to the help of S. Hughes and S. Tate of Chrysler Belvidere Plant.

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