Workforce Allocation in Motorcycle Transmission Assembly Lines: A Case Study on Modeling, Analysis, and Improvement

Hang Ma, *Student Member, IEEE*, Hyo Kyung Lee, *Member, IEEE*, Zhongshun Shi, *Member, IEEE*, and Jingshan Li, *Fellow, IEEE*

***Abstract*—This letter presents a case study of workforce allocation in a gear assembly line at a motorcycle powertrain manufacturing plant. Through structural modeling of operators' work flow and part flow, assembly system models with different configurations are developed. Using iterative aggregation techniques, the performances of such systems are analyzed, and the associated workforce allocation strategies are investigated. By identifying and mitigating system bottlenecks, improvement recommendations are obtained. Such a study provides an effective method for operator assignment in assembly systems.**

***Index Terms*—Motorcycle manufacturing, workforce allocation, assembly system, Bernoulli model, workflow.**

I. Introduction

MOTORCYCLE manufacturing is an important element in manufacturing industry. In the US, motorcycle manufacturing has a combined annual revenue of about $5 billion among more than 70 manufacturing facilities [1]. The motorcycle manufacturing industry worldwide is also growing, with a 6% increase to 132 million units in 2018 [2], [3], and its revenue is expected to grow by about 4% per year through 2022 [1]. Like many other manufacturing industries, due to strong competitions, efficient production is a key enabler of success in motorcycle manufacturing.

Extensive research in manufacturing systems has been carried out for decades (see, for instance, monographs [4]–[8] and reviews [9]–[13]). Most of the studies focus on analysis of throughput, lead time, work-in-process (WIP), demand satisfaction, and various performance measures for serial lines, assembly systems, and other complex manufacturing systems in automotive, appliance, electronics, semiconductor, and food industry, etc.

Manuscript received January 30, 2020; accepted April 14, 2020. Date of publication April 22, 2020; date of current version May 14, 2020. This letter was recommended for publication by Associate Editor C.-B. Yan and Editor J. Yi upon evaluation of the reviewers' comments. *(Corresponding author: Jingshan Li.)*

Hang Ma and Zhongshun Shi are with the Department of Industrial and Systems Engineering, University of Tennessee, Knoxville, TN 37996 USA (e-mail: hma19@vols.utk.edu; tzshi@utk.edu).

Hyo Kyung Lee is with the Department of Industrial Engineering, University of Pittsburgh, Pittsburgh, PA 15261 USA (e-mail: hkl14@pitt.edu).

Jingshan Li is with the Department of Industrial and Systems Engineering, University of Wisconsin, Madison, WI 53706 USA (e-mail: jingshan.li@wisc.edu).

Digital Object Identifier 10.1109/LRA.2020.2989658

Among them, studies of motorcycle manufacturing, as a part of manufacturing systems research, have attracted research attentions from different angles, such as layout planning [14], workload balance [14], [15], manufacturing strategy [16], and operation optimization and comparison [17], [18]. Discrete-event simulation has been a prevailing tool in these studies. By introducing an analytical model of transmission case assembly systems, scheduling policies and productivity improvement strategies in multi-product motorcycle manufacturing are investigated in [19].

Manufacturing systems are composed of machines, products, and people. Workforce is an essential and critical part to ensure smooth and efficient manufacturing. In many manufacturing systems, both automatic machines and manual operations exist in the same production line, so that different work or operation efforts are needed. Moreover, workforce is typically cross-trained so that each operator can be responsible for multiple operations. In this case, how to allocate workforce to optimize production performance becomes an important issue.

Although there exist numerous studies on workforce allocation [20]–[23], most of them address the dedicated operations, i.e., each operator is only working on one operation. The scenarios where an operator sequentially operates multiple machines during a production cycle are less considered. To the best of our knowledge, there is no prior model analyzing workforce allocation in such production lines.

In this paper, a case study at a gear assembly line in a motorcycle powertrain manufacturing plant is introduced. As a leading motorcycle manufacturer in the world, multiple families of gears are assembled in the production line consisting of both manual and automatic machines. A limited number of operators are assigned to multiple work stations everyday based on production schedules, and typically, an operator needs to walk back and forth between stations as he/she is responsible for more than one operations. Thus, there is a need to develop an analytical approach to allocate workforce and evaluate the performance of such lines.

To analyze the system performance, the operators' work flow and part flow are considered simultaneously. The gear assembly process is transformed into a two component lines and one main line assembly system with Bernoulli machine reliability models. Using an aggregation-based iteration approach, the system

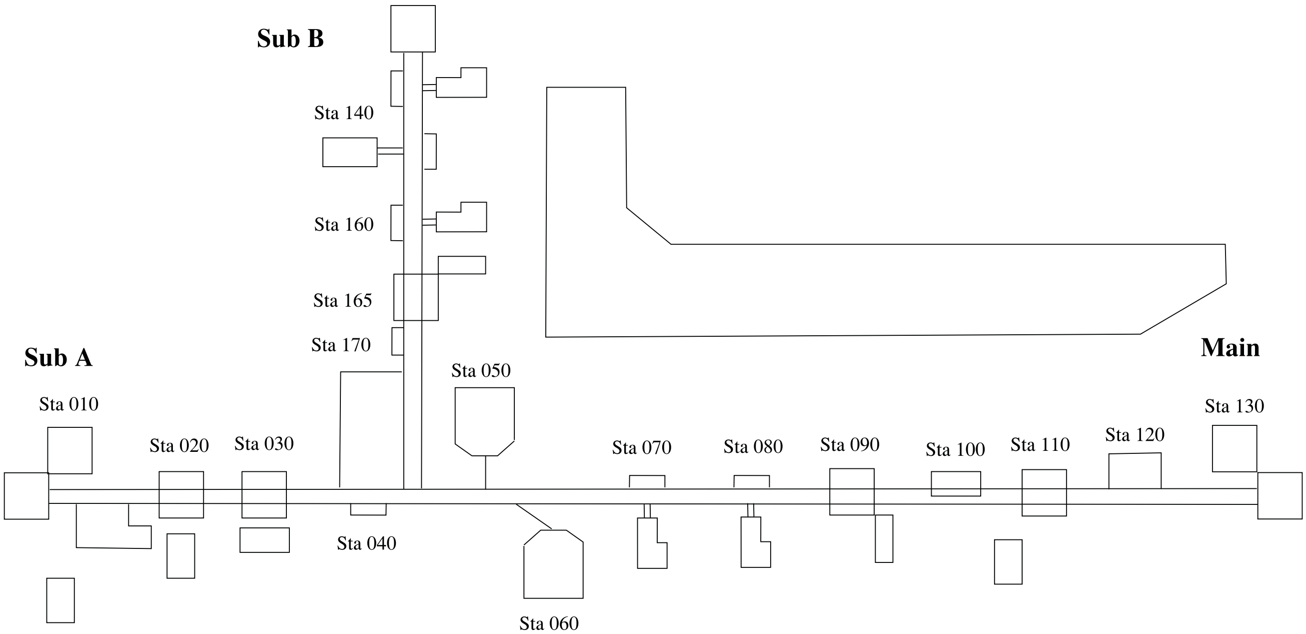

Fig. 1. System layout.

throughput is evaluated and bottleneck analysis is used to seek the largest improvement option. Comparisons between different workforce allocation policies are also carried out. These results can provide a guideline for operator assignment in the assembly system.

The main contribution of this paper lies in introducing a novel approach to integrate part flow and operator workflow and transform them into a Bernoulli assembly system model. Using such a model, we analyze system performance, investigate workforce allocation strategies, and develop improvement recommendations. This proposed approach will bridge the research gap to integrate workforce allocation, operator work flow, and part flow into a new structural model, which can initiate the development of a new methodology for assembly system research.

The remainder of the paper is structured as follows: Section II introduces the line layout and operator work flow. The assembly system model is then developed in Section III. The performance analysis method and results are presented in Section IV, and improvement recommendations are also provided. Finally, conclusions are summarized in Section V.

II. System Description

The gear assembly line at the motorcycle powertrain manufacturing plant has 15 manual stations and two fully automated machines (see Fig. 1 for system layout). Depending on the demand, different numbers of operators (six to eight) are scheduled to work in each shift on the line.

The system consists of two sub-assembly (or feeder) lines, Sub A and Sub B, and a main assembly line. The following operations will be carried out by the operators on the stations in Line Sub A:

- Station 10: The operator will load the main drive, main bearing, bushing and case to the press, and align them to the fixture on the machine.
- Station 20: Parts and case will be loaded to pinstamper and aligned to the fixture.
- Station 30: Washer/snap ring will be assembled, while the seals/shift lever will be loaded, and the sleeve will be pressed into the case.
- Station 40: Oil pan and gasket will be assembled and visually inspected. Then the oil pan will be positioned into the case and secured by the screws.

In Line Sub B, the following operations are conducted:

- Station 140: The operator will load input shaft and assembly parts to press, assemble the main shaft, pre-assemble the fourth gear sets, grown bearing, the third gear, black washer, and segments/lock ring.
- Station 160: The operator will assemble segments/lock ring, black bearing, and pre-assemble the second gear sets.
- Stations 165 and 170: The scissor gear clip will be removed, and brown borg, spacer, and the first gear will be assembled, and the bearing plate will be assembled to press. Note that the current gear products bypass Station 170 so that its cycle time can be ignored.

The main assembly line will perform the following operations:

- Stations 50 and 60: These two stations are the only automatic machines in the system. Two robots in the stations will transport and align the assembled parts, open/close doors, and open/dispose boxes.
- Stations 70, 80, and 90: The operator will assemble hub sprocket and nut, refill oil, and assemble gasket and case to gear pack, screws to lock plate, bushing over main shaft, and finally pin to tranny with nuts. The cycle time of Station

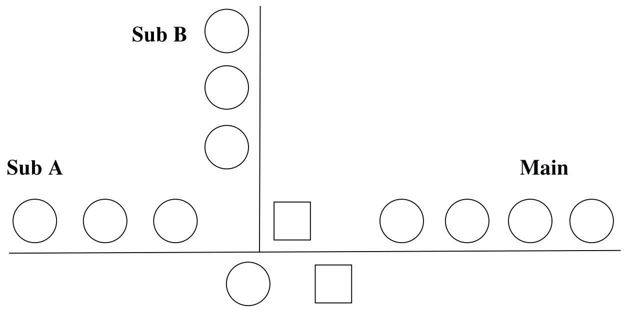

Fig. 2. Structural model.

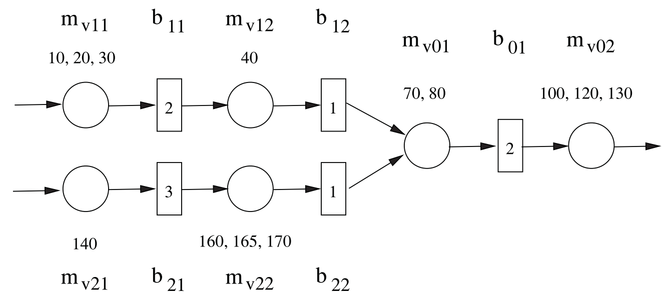

Fig. 3. Production line model with 6 operators.

90 can be ignored since it is bypassed by current products as well.

- Stations 100, 110, 120, and 130: The operator will continue the assembly operations in upstream assembly stations and release the pallets, bush press/bearing plate torque, and hoist the transmission to the buffer. At the end, the operator will finally finish the assembly process (completely knocked down – CKD). Similarly, Stations 110 and 120 are also bypassed, thus we again ignore their cycle times.

III. System Modeling

A. Structural Modeling

The purpose of structural modeling is to transfer the system layout into a simplified production line model with all the important features so that it can be used for analysis and improvement with high fidelity. Thus, first, we transform the layout into a part flow model shown in Fig. 2. Specifically, the cycle times of Stations 90, 110, 120, and 170 are ignored or combined with neighboring ones. Since the two robots for the automatic machines (Stations 50 and 60) are pretty reliable and their operations are faster, they will not block any continuous operations, and function like buffers. Thus, we model each as a one unit buffer.

B. Production Systems Models

Since the number of operators (either six, seven or eight) is much less than the number of stations, an operator is often responsible for multiple machines. To ensure a smooth production flow, all the operations should be appropriately scheduled so that the stations will not be frequently starved or blocked. For example, if an operator is responsible for two stations, he/she may set up the operation in the upstream station by loading the material, aligning the parts, and pressing the "start" button. Depending on the nature of the operation and the transfer scheme, in many cases, the operator does not need to monitor the complete processing cycle after setting up the operation (mainly loading, fixing, aligning, etc.), and is able to leave the station and walk to the downstream one to set up the operation there, where the previously finished part from upstream could be processed. Afterwards, the operator may walk back to the upstream station to unload the part and setup the operation for a new part. Thus, allocation of workforce to stations becomes critical, which will directly impact the system modeling and its performance. As one can see, the allocations are dependent on the number of operators, the operator work time and cycle time in each station, and the walking time between stations.

To develop a production system model, a typical way in most existing work (e.g., [4]–[8]) is to construct the model based on production flow only, i.e., following the sequence of part flow through every machine (e.g., stations in Fig. 2). However, such an approach is difficult to implement due to the complexity of operation dependence, since it needs to either assume the operators are always staying at the stations, which is not the case in the transmission assembly line under study, or require the information of operator's unavailability at each station to treat it as machine downtime, which is also difficult to obtain as we need to track the operator movement in every second. To solve this issue, we introduce a novel approach to integrate each operator's workflow and part flow into a virtual machine, which considers the complete working cycle of an operator as the virtual operation and calculates its corresponding cycle time. Detailed modeling techniques using such an approach are introduced below.

IV. Analysis and Improvement

A. Six Operators

1) Model Development: First, we consider the scenario of six operators. In such a workforce configuration, in Line Sub A, Operator 1 is responsible for Stations 10, 20 and 30, denoted as virtual machine m_{v11} in Fig. 3; while Operator 2 works on Station 40, i.e., virtual machine m_{v12}. In Line Sub B, Operator 3 is allocated to Station 140, represented by virtual machine m_{v21}, and Operator 4 takes care of Stations 160, 165, and 170, represented by virtual machine m_{v22}. The two sub-assembly lines are merged by the two robots (Stations 50 and 60, which function as two buffers) and the assembly operations are continued at the main line. Operator 5 will work on Stations 70 and 80, characterized by virtual machine m_{v01}; while Operator 6 will continue the assemblies in Stations 100, 120, and 130, illustrated as virtual machine m_{v02} in the figure. Through these steps, a six-machine assembly system model is obtained, as shown in Fig. 3.

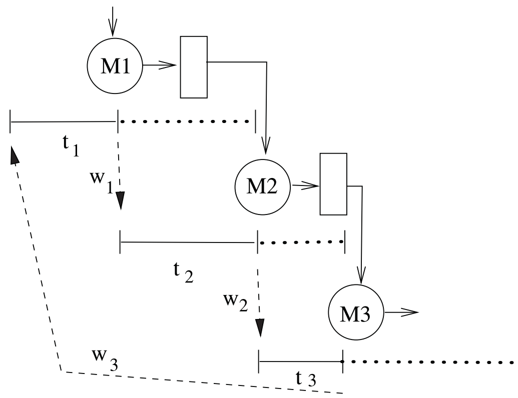

Fig. 4. Operator workflow.

To analyze this assembly system, identifying the parameters of the virtual machines and buffers is needed. The buffer capacity can be identified by counting the available space between the virtual machines. However, the cycle times are not easy to determine. As explained in Subsection III-B, the typical way to summing up all operational times of corresponding stations is not suitable for this gear assembly process, as one operator is responsible for multiple operations, and the operator walks back and forth in a cycle to load, unload, and adjust parts, and sometimes leaves the parts being processed by the machines only. To overcome this difficulty, both part flow and work flow of the operators need to be considered.

Specifically, a complete cycle of an operator's work on multiple machines is used to define the cycle time of a virtual machine. For instance, consider the following illustrative example in Fig. 4, where an operator works on machines M1, M2, and M3. The solid and dotted lines without arrows represent the operator work time and the machine's self-processing time, respectively, and the solid and dashed lines with arrows indicate the part flow and operator walking time, respectively. Then, the cycle time of the virtual machine includes the operator's working time on each machine (mainly setup time), t_k, as well as the walking time to those machines, $w_k, k = M1, M2, M3$. Thus,the virtual station cycle time τ_v is

$$\tau_v = \sum_k t_k + \sum_k w_k. \tag{1}$$

Using this approach, the cycle times of all virtual machines are calculated and summarized in Table I, where the cycle time of each station includes the time the operator walks to the station, and the time the operator spends on that station, and can be approximated by the self-processing time of the upstream station.

Using these cycle times, a Bernoulli machine reliability model is obtained by using the following transformation:

$$p_{vij} = \min\left\{\frac{\tau}{\tau_{vij}}, 1\right\}, \quad i = 0, 1, 2, \quad j = 1, 2, \tag{2}$$

where τ is the standard cycle time of the line. For the assembly system under study, $\tau = 57$ seconds. In addition, the capacity of buffer b_i is evaluated by the maximal space to hold the parts

TABLE I
CYCLE TIME: SIX OPERATORS

Station	10	20	30	40	140	160	165/170
Self-processing time (sec)	36	12	32	37	69	25	32
Operator	1			2	3	4	
Virtual machine cycle time (sec)	80			37	69	57	

(a) Sub lines

Station	70	80	100	120/130
Self-processing time (sec)	65	15	62	32
Operator	5		6	
Virtual machine cycle time (sec)	80		94	

(b) Main line

TABLE II
SYSTEM PARAMETERS: SIX-OPERATOR CASE

m_i	m_{v11}	m_{v12}	m_{v21}	m_{v22}	m_{v01}	m_{v02}
p_i	0.71	1	0.83	1	0.71	0.61
b_i	b_{11}	b_{12}	b_{21}	b_{22}	b_{01}	-
N_i	2	1	3	1	2	-

(but excluding the space to sustain continuous production of part flow), denoted as N_i. The parameters of the system are listed in Table II.

Remark 1: The Bernoulli machine reliability model has been used in many manufacturing systems studies, such as [19], [24]–[30], including an application in motorcycle transmission case production [19]. In such models, parameter p_i represents the probability to finish processing a part or the percentage of part being finished during a cycle. □

2) Performance Evaluation: Using these parameters, the production rate of the six-operator assembly system is evaluated by an iterative aggregation procedure. The idea of the procedure is explained in [8], where the assembly system is decomposed into an upper line (by considering buffer empty probability in b_{22} for virtual machine m_{v01}) and a lower line (by considering buffer empty probability in b_{12} for m_{v01}). Then the upper and lower lines are analyzed using a serial line aggregation procedure independently to evaluate the buffer empty probabilities in b_{12} and b_{22}, respectively. Updating these probabilities, the analysis is repeated anew until convergence. As proved in [8], the convergence of the iteration procedure is guaranteed and the system production rate can be obtained.

Procedure 1:

$$\begin{aligned}
p'_{v01}(s) &= p_{v01}(1 - st_{22}(s-1)),\\
st_{12}(s) &= \Psi(p_{v11}, p_{v12}, p'_{v01}(s), p_{v02}, N_{11}, N_{12}, N_{01}),\\
p''_{v01}(s) &= p_{v01}(1 - st_{12}(s)),\\
st_{22}(s) &= \Psi(p_{v21}, p_{v22}, p''_{v01}(s), p_{v02}, N_{21}, N_{22}, N_{01}),
\end{aligned} \tag{3}$$

with initial condition

$$st_{22}(0) = 0,$$

and s is iteration number,

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

where operator $\Psi(\cdot)$ represents the calculation of buffer empty probability, and p'_{v01} and p''_{v01} are the parameters of virtual machine m_{v01} when it is not starved by buffers b_{22} and b_{12}, respectively. The calculation is based on the serial line aggregation procedure introduced in [8], whose convergence is also proved. Specifically, in each iteration s, consider the upper line of machines m_{v11}, m_{v12}, $m'_{v01}(s)$, and m_{v02}, and buffers b_{11}, b_{12}, and b_{01}, serial line Procedure 2 is used:

Procedure 2:

$$\begin{aligned} p_k^b(n+1) &= p_k[1 - Q(p_{k+1}^b(n+1), p_k^f(n), N_k)], \\ & \quad k = v11, v12, v01', \\ p_k^f(n+1) &= p_k[1 - Q(p_{k-1}^f(n+1), p_k^b(n+1), N_{k-1})], \\ & \quad k = v12, v01', v02, \\ & \quad n = 0, 1, 2, \ldots, \end{aligned} \tag{4}$$

with initial conditions

$$p_k^f(0) = p_k, \quad k = v11, v12, v02,$$
$$p_{v01'}^f(0) = p_{v01'}(s),$$

and boundary conditions

$$p_{v11}^f(n) = p_{v11}, \quad p_{v02}^b(n) = p_{v02}, \quad n = 0, 1, 2, \ldots.$$

where,

$$Q(p_1, p_2, N_1) = \begin{cases} \frac{(1-p_1)(1-\phi)}{1-\frac{p_1}{p_2}\phi^{N_1}}, & \text{if } p_1 \neq p_2, \\ \frac{1-p}{N_1+1-p}, & \text{if } p_1 = p_2 = p, \end{cases} \tag{5}$$

$$\phi = \frac{p_1(1-p_2)}{p_2(1-p_1)}. \tag{6}$$

When Procedure 2 is convergent, we obtain

$$p_{v01'}^f = \lim_{n\to\infty} p_{v01'}^f(n), \tag{7}$$

$$st_{12}(s) = \Psi(\cdot) = 1 - \frac{p_{v01'}^f}{p_{v01'}(s)}. \tag{8}$$

A similar procedure can be applied to the lower line (machines m_{v21}, m_{v22}, $m''_{v01}(s)$, and m_{v02}, and buffers b_{21}, b_{22}, and b_{01}) as well to calculate $st_{22}(s)$ in iteration s of Procedure 1.

Finally, when Procedure 1 is convergent, we obtain

$$st_{i2} = \lim_{s\to\infty} st_{i2}(s), \quad i = 1, 2. \tag{9}$$

Then the system production rate can be calculated as:

$$PR = p_{v02}(1 - Q(p_{v_{01}}(1 - st_{12})(1 - st_{22}), p_{v02}, N_{01})). \tag{10}$$

This implies that the throughput per shift (7.5 hours) is

$$TP = PR \times \frac{7.5 \times 3600}{57}.$$

To validate the model, we compare the model output with historical data, and the results are shown in Table III. It can be seen that the difference is less than six parts per shift, which is about 2% discrepancy. Thus, the model is validated and can be used for further analysis.

TABLE III
MODEL VALIDATION: SIX-OPERATOR CASE

(parts/shift)	History	Model	Difference	Error
TP	250	255.93	5.93	2.38%

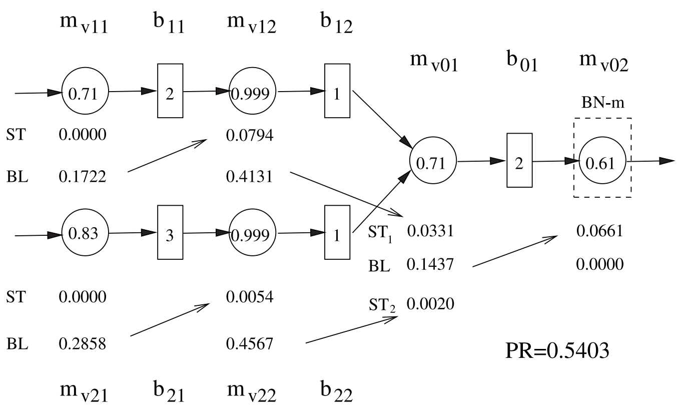

Fig. 5. Bottleneck in 6-operator production line model.

TABLE IV
MODEL VALIDATION: SIX-OPERATOR CASE

(parts/shift)	Original	New	Improvement	Error
TP	255.93	267.49	11.56	4.52%

3) Improvement Analysis: Bottleneck analysis is viewed as the most effective way to improve system performance. To identify a system bottleneck, let BL_i and ST_i be the probabilities of blockage and starvation of virtual machine m_i, respectively. Then an arrow assignment rule introduced in [8] can be utilized.

Arrow assignment rule: Assign arrows from upstream machine m_i to downstream m_{i+1} if $BL_i > ST_{i+1}$, otherwise, the arrow should be placed in the opposite direction. Then, the bottleneck machine (BN-m) is the one with no emanating arrows.

Specifically, as shown in Fig. 5, virtual machine m_{v02} only has an arrow pointing toward it without any other arrow pointing out, thus it is the system bottleneck. To mitigate this bottleneck, we first consider reallocating workforce by using other assignment options. However, almost no improvement can be obtained. Then, buffer adjustment is investigated. By increasing the capacity of buffer b_{01} in front of m_{v02} from 2 to 3, we can obtain close to 5% improvement in system throughput (see Table IV). Therefore, increasing buffer capacity can be a viable approach to improve system throughput when six operators are assigned.

B. Seven Operators

1) Model Development: For some gear types that have higher demands, sometimes seven operators are assigned to the stations. In this case, the allocation of Operators 1-4 in sub lines are still the same as those in six-operator model, i.e., for Line Sub A,

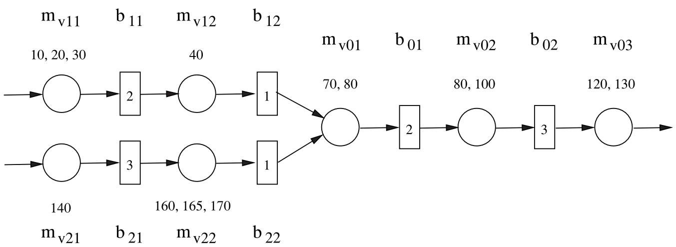

Fig. 6. Production line model with 7 operators.

TABLE V
MAIN LINE CYCLE TIME: SEVEN OPERATORS

Station	70	80	80	100	120/130
Time (sec)	65	7.5	7.5	62	32
Operator	5		6		7
Time (sec)	72.5		69.5		32

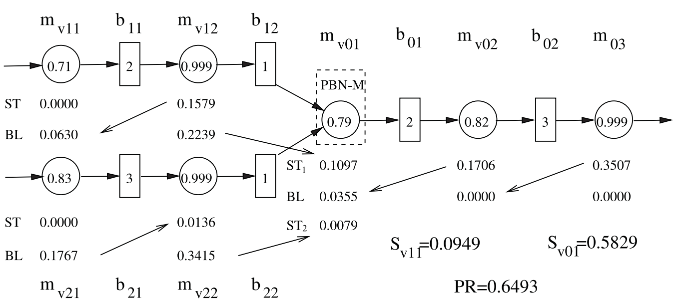

Fig. 7. Bottleneck in 7-operator production line model.

TABLE VI
SYSTEM PARAMETERS: SEVEN-OPERATOR CASE

m_i	m_{v11}	m_{v12}	m_{v21}	m_{v22}	m_{v01}	m_{v02}	m_{v03}
p_i	0.71	1	0.83	1	0.79	0.82	1
b_i	b_{11}	b_{12}	b_{21}	b_{22}	b_{01}	b_{02}	-
N_i	2	1	3	1	2	3	-

Operator 1 is still responsible for Stations 10, 20 and 30, and Operator 2 works on Station 40. For Line Sub B, Operator 3 takes care of Station 140, and Operator 4 works on Stations 160, 165, and 170. The difference comes from the main line, where Operator 5 is assigned to Station 70 and part of operations in Station 80 (such as loading and positioning), and Operator 6 continues the remaining work on Station 80 (such as screwing and pinning) and Station 100. Finally, Operator 7 is responsible for Stations 120 and 130. An illustration of such an allocation policy is given in Fig. 6, while the cycle times of main line stations are presented in Table V.

Similar to the six-operator case, by identifying the virtual machine parameters and buffer capacity, we obtain a seven-machine assembly system model, shown in Fig. 7 with parameters listed in Table VI. As one can see, Operators 5 and 6 split the work in Station 80 in the main line.

Note that this policy is also used as a baseline for comparison in the eight-operator model discussed in the next subsection.

TABLE VII
MODEL VALIDATION: SEVEN-OPERATOR CASE

(parts/shift)	History	Model	Difference	Error
TP	300	307.56	7.56	2.52%

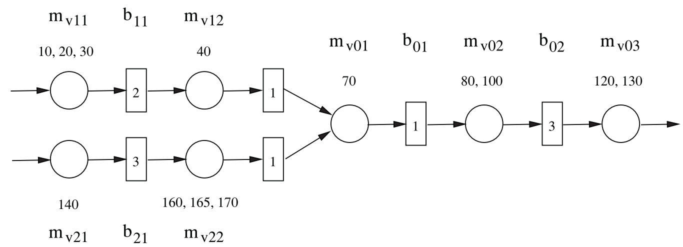

Fig. 8. Improvement in 7-operator production line model.

TABLE VIII
CONTINUOUS IMPROVEMENT: SEVEN-OPERATOR CASE

(parts/shift)	Original	Reallocation	$b_{12}\uparrow$	$b_{22}\uparrow$	Both $\uparrow$
TP	307.56	307.89	308.65	316.49	317.65
Improve	-	0.23	1.09	8.93	10.09
(%)	-	0.07%	0.35%	2.90%	3.28%

2) Performance Evaluation: Using the same iterative procedures, we can evaluate the system throughput, and validate the model by comparing with historical data. As shown in Table VII, only about 2% difference is observed. Thus the model is validated as well.

3) Improvement Analysis: As shown in Fig. 7, both virtual machines m_{v11} and m_{v01} are the bottlenecks, i.e., Operators 1 and 5, who are responsible for Stations 10, 20 and 30, and Stations 70 and 80, respectively, become the constraints. Note that for assembly machine m_{v01}, the starvations due to b_{12} and b_{22} are used to compare with blockages of m_{v12} and m_{v22}, respectively. In case of multiple bottlenecks, a severity index is defined as the absolute differences between blockages and starvations [8].

$$
\begin{aligned}
S_{v11} &= |ST_{12} - BL_{11}|, \\
S_{v01} &= |ST_{v02} - BL_{v01}| + |BL_{v12} - ST_{v01,1}| \\
&\quad + |BL_{v22} - STv01, 2|. \qquad (11)
\end{aligned}
$$

As one can see, $S_{v11} = 0.0949$ and $S_{v01} = 0.5829$. Thus, m_{v01} becomes the primary bottleneck machine. To mitigate this bottleneck, we first consider reallocating the operators' work. By removing station 80 from Operator 5, and make it solely belong to Operator 6, we obtain the following allocation model, shown in Fig. 8.

Studying such a configuration, we can find that the production rate is slightly increased from 0.6493 to 0.65. Since almost no improvement can be obtained, buffer increment is investigated. As m_{v01} is still the primary bottleneck (see Fig. 9), increasing the sub-assembly line buffers in front of m_{v01} is studied. As illustrated in Table VIII, increasing Line Sub A buffer does

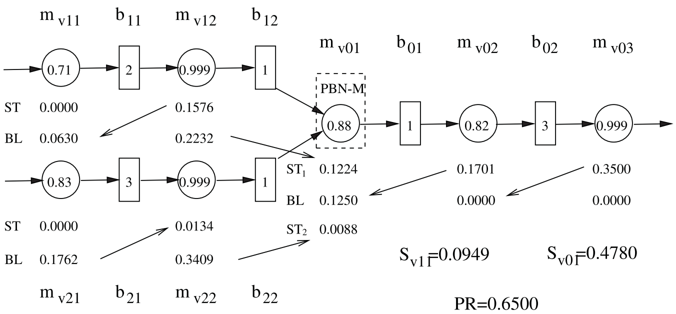

Fig. 9. Bottleneck in improved 7-operator production line model.

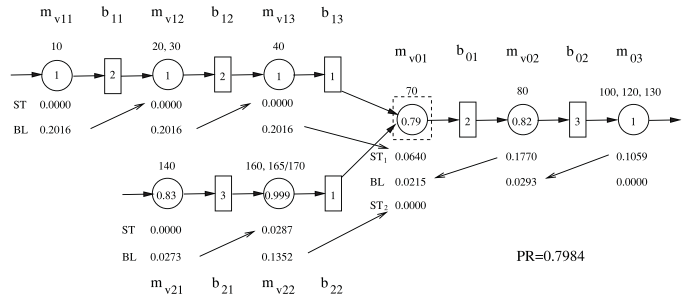

Fig. 11. Improvement in 8-operator production line model.

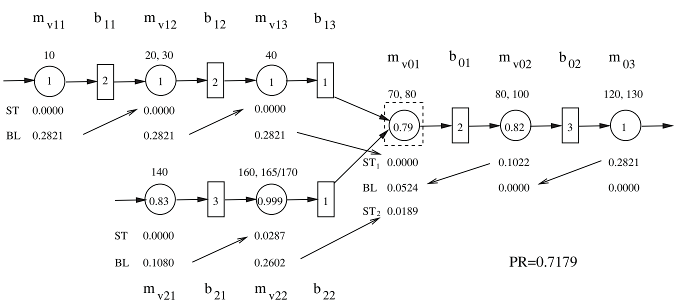

Fig. 10. Bottleneck in 8-operator production line model.

TABLE IX
CONTINUOUS IMPROVEMENT: EIGHT-OPERATOR CASE

(parts/shift)	Original	Reallocation
TP	340.44	378.57
Improve	-	38.13
(%)	-	11.2%

not lead to much improvement, while increasing Line Sub B buffer can result in a significant improvement. This can be explained by checking the blocking probabilities, where m_{v22} has more than 30% chance of blockage due to smaller buffer capacity. Of course, increasing both buffers will lead to the largest improvement.

C. Eight Operators

For some type of gears, additional treatment needs to be carried out at Station 10. Thus, eight operators may need to be assigned and a dedicated one is assigned to Station 10 (see Fig. 10).

Such a configuration results in a production rate of 0.7179. Operator 6 (Stations 70 and 80) becomes the constraint. To mitigate this bottleneck, we remove Station 80 from Operator 6, and assign it to Operator 7. To reduce the workload of Operator 7, we shift Station 100 to Operator 8. Using such a reallocation (see Fig. 11), the production rate is increased to 0.7984, i.e., the throughput is increased from 340 to almost 379 parts per shift, which is more than 11% improvement (see Table IX).

V. CONCLUSION

This letter introduces an application study of modeling, analysis and improvement of a gear assembly system in a motorcycle powertrain plant. By considering both part flow and operators' workflow, assembly system models for six- seven-, and eight-operator cases are developed, validated with high accuracy, and then used for improvement analysis. Through bottleneck identification and mitigation, improvement suggestions have been recommended to the plant management with a positive feedback. Therefore, such a work provides an effective method to study workforce allocation problem and a viable tool for production engineers and managers to improve system performance.

Note that this approach is not only useful for the gear assembly line in the motorcycle powertrain plant, but also applicable to many manufacturing facilities where a limited workforce operates multiple machines so that the work flow and part flow are deviated, such as U-shape lines and parallel lines, which incur a flexible workforce allocation, and in metal, plastic, and machine tools manufacturing lines with semi-automated stations.

The future work can be directed to extending the method to consider both machine failures and operator unavailability, as well as different work flow structures. Exponential, geometric or general machine reliability models can be studied. Moreover, generalizing the approach of workforce allocation to a wide variety of manufacturing systems is needed. By integrating with simulation approaches, systems with more complex structures and control logic can be analyzed. In addition to manufacturing systems, such approaches can also be applied to service and other engineering systems where staff allocation is of importance to integrate work flow (or, documentation flow, job assignment) and process or entity flow (e.g., patient flow, information flow). Furthermore, developing effective data-driven learning methods for performance evaluation and sensitivity analysis in such systems can be another venue.

ACKNOWLEDGMENT

The authors would like to thank A. Burton, S. Deshpande and J. Makola of the University of Wisconsin-Madison and the plant engineers and managers for their support and help in this study.

REFERENCES

[1] Motorcycle Manufacturing Industry Profile, 2019. [Online]. Available: http://www.firstresearch.com/Industry-Research/Motorcycle-Manufacturing.htm

[2] The Freedonia Group, "World motorcycles," 2016. [Online]. Available: https://www.freedoniagroup.com/industry-study/world-motorcycles-3454.htm

[3] C. Morris, "Motorcycle trends in the United States," *BTS Special Report*, 2009. [Online]. Available: https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/special_reports_and_issue_briefs/special_report/2009_05_14/html/entire.html

[4] N. Viswanadham and Y. Narahari, *Performance Modeling of Automated Manufacturing Systems*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1992.

[5] J. A. Buzacott and J. G. Shanthikumar, *Stochastic Models of Manufacturing Systems*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1993.

[6] H. T. Papadopoulos, J. Browne, and C. Heavey, *Queueing Theory in Manufacturing Systems Analysis and Design*. London, U.K.: Chapman & Hall, 1993.

[7] S. B. Gershwin, *Manufacturing Systems Engineering*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1994.

[8] J. Li and S. M. Meerkov, *Production Systems Engineering*. New York, NY, USA: Springer, 2009.

[9] Y. Dallery and S. B. Gershwin, "Manufacturing flow line systems: A review of models and analytical results," *Queueing Syst.*, vol. 12, no. 1-2, pp. 3–94, 1992.

[10] H. T. Papadopoulos and C. Heavey, "Queueing theory in manufacturing systems analysis and design: A classification of models for production and transfer lines," *Eur. J. Oper. Res.*, vol. 92, no. 1, pp. 1–27, 1996.

[11] M. K. Govil and M. C. Fu, "Queueing theory in manufacturing: A survey," *J. Manuf. Syst.*, vol. 18, no. 3, pp. 214–240, 1999.

[12] J. Li, D. E. Blumenfeld, N. Huang and J. M. Alden, "Throughput analysis of production systems: Recent advances and future topics," *Int. J. Prod. Res.*, vol. 47, no. 14, pp. 3823–3851, 2009.

[13] C. T. Papadopoulos, J. Li, and M. E. O'Kelly, "A classification and review of timed Markov models of manufacturing systems," *Comput. Ind. Eng.*, vol. 128, no. 2, pp. 219–244, 2019.

[14] K. Zhou, R. Zhang, Y. Wang, and B. Wang, "Study on workshop layout of a motorcycle company based on systematic layout planning (SLP)," in *Proc. Int. Conf. Image Process. Pattern Recognit. Ind. Eng.*, 2010, pp. 78203R–78203R.

[15] X. Zhang, D. Zhao, X. Xie and T. Yu, "Simulation and analysis of a motorcycle engine production cell," *Key Eng. Mater.*, vol. 467, pp. 1511–1515, 2011.

[16] J. Miltenburg, "Setting manufacturing strategy for a factory-within-a-factory," *Int. J. Prod. Econ.*, vol. 113, no. 1, pp. 307–323, 2008.

[17] P. Cortes, L. Onieva, and J. Guadix, "Optimising and simulating the assembly line balancing problem in a motorcycle manufacturing company: A case study," *Int. J. Prod. Rese.*, vol. 48, no. 12, pp. 3637–3656, 2010.

[18] U. Sutee and P. K. D. V. Yarlagadda, "Simulation-based comparison of pull-push systems in motorcycle assembly line," *Appl. Mech. Mater.*, vol. 241, pp. 1507–1513, 2013.

[19] K. Park and J. Li, "Improving productivity of a multi-product machining line at a motorcycle manufacturing plant," *Int. J. Prod. Res.*, vol. 57, no. 2, pp. 470–487, 2019.

[20] V. I. Cesani and H. J. Steudel, "A study of labor assignment flexibility in cellular manufacturing systems," *Comput. Ind. Eng.*, vol. 48, no. 3, pp. 571–591, 2005.

[21] M. J. Brusco, "An exact algorithm for a workforce allocation problem with application to an analysis of cross-training policies," *IIE Trans.*, vol. 40, no. 5, pp. 495–508, 2008.

[22] R. Langer, J. Li, S. Biller, Q. Chang, N. Huang, and G. Xiao, "Simulation study of a bottleneck-based dispatching policy for a maintenance workforce," *Int. J. Prod. Res.*, vol. 48, no. 6, pp. 1745–1763, 2009.

[23] M. Saadat, M. C. Tan, M. Owliya, and G. Jules, "Challenges and trends in the allocation of the workforce in manufacturing shop floors," *Int. J. Prod. Res.*, vol. 51, no. 4, pp. 1024–1036, 2013.

[24] S.-Y. Chiang, C.-T. Kuo, J.-T. Lim, and S.M. Meerkov, "Improvability of assembly systems II: Improvability indiators and case study," *Math. Problems Eng.*, vol. 6, no. 4, pp. 359–393, 2000.

[25] C.-T. Kuo, J.-T. Lim, and S. M. Meerkov, "Bottlenecks in serial production lines: A system-theoretic approach," *Math. Problems Eng.*, vol. 2, pp. 233–276, 1996.

[26] J. Li and S. M. Meerkov, "Customer demand satisfaction in production systems: A due-time performance approach," *IEEE Trans. Robot. Autom.*, vol. 17, no. 4, pp. 472–482, Aug. 2001.

[27] C. Wang and J. Li, "Approximate analysis of re-entrant lines with Bernoulli reliability models," *IEEE Trans. Autom. Eng.*, vol. 7, no. 3, pp. 708–715, Jul. 2010.

[28] J. Arinez, S. Biller, S. M. Meerkov and L. Zhang, "Quality/quantity improvement in an automotive paint shop: A case study," *IEEE Trans. Autom. Sci. Eng.*, vol. 7, no. 3, pp. 755–761, Oct. 2010.

[29] C. Zhao and J. Li, "Analysis and improvement of multi-product assembly systems: An application study at a furniture manufacturing plant," *Int. J. Prod. Res.*, vol. 52, no. 21, pp. 6399–6413, 2014.

[30] C. Zhao, N. Kang, J. Li and J. Horst, "Production control in partially flexible production-inventory systems: Theory and application," *IEEE Trans. Autom. Control*, vol. 63, no. 2, pp. 477–491, 2018.