A Mathematical Model for Tool Sharing between Workers by Exact Solution Approach

Ashish Yadav, Rupesh Nishad, Ramawatar Kulhary, and Sunil Agrawal

***Abstract*—Multi-manned assembly lines are generally used to produce large-sized volume products such as cars and trucks. This article addresses the multi-manned two sided assembly line balancing problem with the objectives sharing tool between workstations.**

This paper presents a mathematical model and a Lingo -16 solvers based exact algorithm for multi-manned two-sided assembly line system configuration with tool sharing between adjacent workstations for companies that need intelligent solutions to satisfy customized demands on time with existing resources. The results obtained indicate that tool shared between parallel stations of two or more parallel lines beneficial for assembly line to minimize workstations, idle time and reduce tool cost.

***Index Term*—Assembly line balancing, multi-manned assembly line balancing, tool sharing, lingo-16 solver.**

I. Introduction

Assembly lines balancing (ALB) have been used to produce large sized homogeneous products. The main purpose of assembly line balancing is to divide the total workload of assembly line into several workstations and to determine which task will be performed at each workstation by allocating every task only once throughout the line. Generally, the product moves from one workstation to its successive workstation by a transport system like conveyor belt [1], [2].

In the two-sided assembly lines, the operating direction of the assembly tasks will be carried out on the same product in parallel at both the left and right sides of the lines. Two sided assembly lines are typically used to deliver large volume big-sized standardized products, for example, cars, transports and truck. Due to the use of both sides of the lines, the tasks will have additional operating direction restrictions. The directions can be classified into three types: the left side (LS), the right side (RS) and either side (ES). [3, 4]

Multi-manned two-sided assembly line balancing problems (MTALBP) are a new type of assembly line balancing problems where there are the chances of assigning additional one operator to each workstation as per the product features. Assigning more than one operators on each workstation is the only difference between MTALBP and ALB problem. MALBP typically happen in industries with big size and large volume of products for example automotive industry where the size of the product is large to employ the multi-manned assembly line configuration.

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A MTALBP has substantial advantage over a simple assembly line balancing such as it increases compactness on each workstation and reduces idle time, reduces the length of the assembly line, Reduces the cost of tools and fixtures, the material handling, Reduces the amount of throughput time which increases production rate, worker movement, and setup time, possibility of completion of work increases when two or more operators work together on a single workstation [5], [6]. Fig. 1 shows the configuration of multi-manned two-sided assembly line.

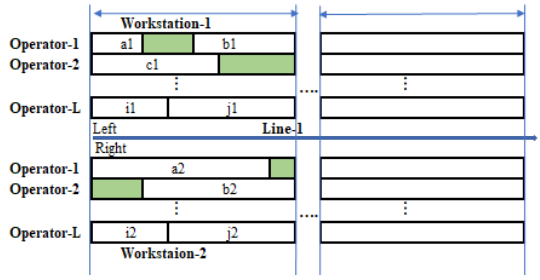

Fig. 1. Configuration of multi-manned two-sided assembly line.

In multi-manned two sided assembly line balancing problem more than one operator manufactured product model, those are situated in both left and right direction that can increase the efficiency of production and minimize the idle time of the complete assembly line system, is known as two-sided assembly line balancing (MTALBP). MTALBP offers several advantages over a two-sided assembly line: [7], [8]

1) It reduces the requirement of operators and space such that the cost of assembling the products can be lowered.
2) It can increase visibility and communication between operators.
3) Similar products of the same product can be produced on the lines.
4) It can increase the efficiency and reduce the idle time of the assembly lines.
5) It is capable to manage production with better utilization of operators on the lines.

II. Literature Review

Bartholdi [9] addressed an assembly line formation which contains two serial lines in parallel. In place of single stations, pairs of contrary stations on either side of the line work in parallel on the similar work piece. Furthermore, Kucukkoc and Zhang, 2015 [10] came up with the idea of sharing operators between adjacent workstations. In that model operator working on right side of Line I can execute tasks of left side of Line II with its allotted tasks. Then we came up with the idea of sharing tools between adjacent workstations. We developed a programming model with shared tools with operators. By sharing tools, we could

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reduce the cost of expansive tools by using a single tool in two or more workstations and we shared operators to reduce the total idle time and to increase the compactness of lines.

Dimitriadis [11] is first author to address assembly lines with multi-manned workstations that is addressed in this paper. He suggested a two-level heuristic based approach to solve MTALBP.

Fattahi *et al.* 2010 [12] introduced programming model for balancing single-line one-sided problem. But none of the previous papers proposed a mathematical model for balancing more than one two-sided line.

According to the literature review, none of the authors developed mathematical model for balancing problem of multi-manned two-sided assembly line with parallel workstations. Furthermore, we also made first attempts to show the tool sharing approach in MTALB problem.

This article mainly presents following contributions to the research field:

1) Developed Mathematical Model of MTALB problem with tool sharing approach to reduce cost of tool in assembly line.
2) The developed mathematical model is tested on a numerical problem and is solved using Lingo -16 solver to obtain the optimal solutions.

The remainder of this paper is prepared is as follow, in section third MTALB problem is explained. Few assumptions have been taken and then used notation is explained and the formulation of MTALB problem is presented with shared resources and parallel workstations. In section four, a numerical example to explain the proposed approach is solved. The results of MTALB proposed approach is mentioned in section five. This section shows reports and statistical analyses of MTALB. In final section authors mentioned conclusions of the results as well as future research directions.

III. Problem Statement

A. Main Characteristics

In MTALB problem, each line is positioned in parallel to its adjacent line, is represented by $(h = 1, \dots, H)$ and every model has its individual set of tasks $(i = 1, \dots, n_h)$. Generally these tasks are executed based on known precedence diagram between tasks which are defined because of certain technological and operational necessities. [13]

In MTALB problem products stop during the cycle time at each multi-manned workstation where there are numerous workers at the same time performing different operations on the same separate product.

In this multi-manned assembly line, product is assembled on two parallel lines and operators can work at the same time on parallel sides of the line. Also, the number of operators that can be allocated to each workstation is controlled by the maximum possible 'operator concentration (L)' which is determined through the system designer permitting to the workstation design, product size, tools availability. The number of station is also restricted by the maximum by feasible number (n). The main aim in a multi-manned assembly line formation is to decrease the line length of the simple assembly line whereas the total effectiveness of the line remains effective and optimal. In Fig. 1, numbers inside bars indicate task numbers (a1, b1, c1…) and lengths of the bars correspond to processing times of tasks. Also, the bars in green colour indicate idle time of that operator. Configuration of multi-manned two sided assembly line with parallel workstations is shown in Fig. 2. [14], [15].

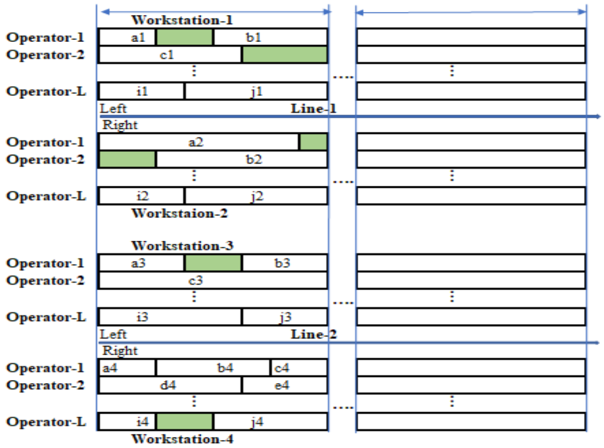

Fig. 2. Configuration of multi-manned two sided assembly line with parallel workstations.

B. Assumptions

Assumptions those are considered in the work are mentioned here: [16]-[18]

- Total number of product models will always be equivalent to the whole number of lines.
- The task times and precedence relationships of each product model are known and every product manufacturing model has its own precedence relationship diagram.
- Walking time of operator are not measured in process timing. (setup time)
- Workers perform tasks in parallel at both the sides of the line
- Some tasks may be required to be performed at one-side of the line, while others may be performed at either side of the line

C. Notations

Symbol	*Description*
h	Line index (h=1..) where H represents total number of lines
i	Task Index (i=1.. n_h) where n_h represents total number of tasks on line h
j	Side of line, $j=\begin{cases} 0 \text{ indicates left side} \\ 1 \text{ indicates right side} \end{cases}$
k	Station index (k=1,…,) where K represents total number of utilized stations
l	Operator index (l=1,…,L) where L represents maximum number on any workstation.
$jd0_{hi}$	Left side direction matrix (task i on line h)
$jd1_{hi}$	Right side direction matrix (task i on line h)
t_{hi}	Processing time of task i on line h
P_h	Set of precedence relationships in precedence diagram of line h
ZP	Set of pair of tasks that must be assigned to the same workstation
ZN	Set of pair of tasks that cannot be assigned to the same workstation
CT	Common cycle time of the workstations
μ_{hjk}	A large number

β_{hjk}	A large number
α	Weighing factor $\alpha > 1$

D. Decision Variables

Symbol	Description
P1	Workload on each sub-workstation
P2	Total number of utilized workstations,
$CWhjk$	Capacity of each workstation
$Xhijkl$	$\begin{cases} 1 & \text{if task i is assigned to station k on side j of line h by operator l} \\ 0 & \text{otherwise} \end{cases}$
TW$Shjk$ = W$Shjk$	$\begin{cases} 1 & \text{if station k is utilized on side j of line h} \\ 0 & \text{otherwise} \end{cases}$
$TSWhjkl$=$SWhjkl$	$\begin{cases} 1 & \text{if operator l work on side j of line h and station k} \\ 0 & \text{otherwise} \end{cases}$

E. Objective Function

$$\text{Min Z} = \alpha * \text{P2} - \text{P1} \tag{1}$$

$$P_1 = \sum_{h=1}^{1}\sum_{j=0}^{0}\sum_{k=1}^{K}\sum_{l=1}^{L}\left(\sum_{i=1}^{n_h} t_{hi} * X_{hijkl}\right)^2 \tag{2}$$

$$P_2 = \sum_{k=1}^{K} WS_{hjkl} \tag{3}$$

Here P_1 in equation (2) represents the total number of utilized workstations and P_2 represents total workload of the assembly line in equation (3). Similarly, α is a multiplication factor. This nonlinear objective function in equation (1) represents minimization of α time's total number of utilized workstations with maximization of workload so that the number of workstation and idle times can be minimized.

F. Constraints

$$\sum_{k=1}^{K}\sum_{l=1}^{L}(Jd0_{hi} * X_{hi0kl} + Jd1_{hi} * X_{hi1kl}) = 1 \tag{4}$$

$$\sum_{j=0}^{1}\sum_{k=1}^{K}\sum_{l=1}^{L} X_{hijkl} = 1 \quad \forall h = 1,\ldots,H; \quad \forall j \epsilon \{0,1\}; \ \forall i = 1 \ldots n_h \tag{5}$$

Constraints (4) and (5) ensure that all the tasks are assigned to the workstation and each task is assigned only once.

$$\sum_{i=1}^{n_h}\sum_{l=1}^{L} t_{hi} * X_{hijkl} - CT * TWS_{hjk} \leq 0 \tag{6}$$

$$\sum_{i=1}^{n_h} t_{hi} * X_{hijkl} - CT * TSW_{hjkl} \leq 0 \tag{7}$$

$$\sum_{j\epsilon\{0,1\}}\sum_{l=1}^{L}(t_{hi}^{s} + t_{hi}) * X_{hijk} \leq k * ct \tag{8}$$

Constraint (6) and (7) ensures that total workload can't exceed its capacity, means it can't exceed cycle time. Constraint (8) ensures that completion time of any task can't exceed that station time in which the task is assigned.

$$\sum_{i=1}^{n_h} X_{hijkl} - n_h * SW_{hjkl} \leq 0 \tag{9}$$

$$\sum_{i=1}^{n_h} X_{hijkl} - SW_{hjkl} \geq 0 \tag{10}$$

$$\sum_{l=1}^{L} SW_{hjkl} - n_h * WS_{hjk} \leq 0 \tag{11}$$

$$\sum_{l=1}^{L} SW_{hjkl} - CW_{hjk} \leq 0 \tag{12}$$

$$WS_{hj(k+1)} - WS_{hjk} \leq 0 \tag{13}$$

Constraints (9) to (13) ensure utilization of the particular workstation.

$$X_{hrjkl} - X_{hsjkl} = 0 \quad \forall (r,s) \epsilon ZP \tag{14}$$

$$X_{hrjkl} + X_{hsjkl} \leq 1 \quad \forall (r,s) \epsilon ZN; \quad \forall h = 1,\ldots,H; \quad \forall j \epsilon \{0,1\}; \quad \forall k = 1,\ldots,K \tag{15}$$

Some tasks may need to proceed in the same workstation for same specific reason that may originate from work environment or tool(s) requirement (Positive zoning constraint). Constraint (14) ensures that those tasks are assigned to same workstation.

Some tasks must be performed in different workstations due to safety rules or processing obligations (Negative zoning constraint). Constraint (15) ensures that those tasks are assigned to different workstations. ZN is the set of pair of tasks that must be assigned to the different workstations for line h.

$$t_{hr}^{s} + t_{hr} - t_{hs}^{s} \leq 0 \tag{16}$$

$$[t_{hs}^{s} - \{t_{hr}^{s} + t_{hr} + (k-1) * CT\}] + \mu * \left\{2 - \sum_{j\epsilon(0,1)}\sum_{l=1}^{L}(X_{hrjkl} + X_{hsjkl})\right\} \geq 0 \tag{17}$$

$$\sum_{j=0}^{1}\sum_{l=1}^{L} X_{hrjkl} - \sum_{j=0}^{1}\sum_{k1=k}^{K}\sum_{l=1}^{L} X_{hsj(k1)l} \leq 0 \quad \forall (r,s) \epsilon P_h; \ \forall h = 1,\ldots,H; \quad \forall j \epsilon \{0,1\}; \forall k = 1..K \tag{18}$$

Constraint (16) ensures that starting time of any task is equal to or greater than the completion time of immediate predecessor of that task in precedence diagram. Constraint (17) ensures that if tasks r and s are assigned to the same station on same line than starting time of task s is equal to or greater than the summation of completion time of task r and station time of summation of previous stations Constraint (18) ensures that task s always assigned after task r.

$$\sum_{l=1}^{L}(X_{ar1kl} - X_{bs0kl}) = 0 \tag{19}$$

$$\sum_{l=1}^{L}(X_{ar0kl} - X_{bs1kl}) \leq 1 \tag{20}$$

Constraints (19) and (20) show the tool sharing zone. It ensures that tasks r and s of adjacent lines (Right side of Line (h-1) with Left side of the Line (h)) are assigned to the same station in opposite direction.

IV. Solution Approch

The proposed algorithm was coded in Lingo-16 package and run on a 2.1 GHz Intel Core i3-2400 CPU 8 GB RAM computer for evaluating the performance of the algorithm by solving multi-manned two sided assembly line balancing test problems.

A. Numerical Problem

A numerical example is considered to provide an insight for modeling of MTALBP along with the utilization of parallel stations. There are two different products being assembled on two parallel assembly lines (Line I and Line II) each having the cycle time of 6-time units. Each product consists of 13 and 12 number of tasks respectively.

Table I indicates details of tasks, task processing times, task immediate predecessors and the preferred operation direction of the task.

TABLE I: DATA FOR ILLUSTRATIVE EXAMPLE

Line I					*Line II*		
Task No.	Task Side	Task Time	Task Immediate predecessor		Task Side	Task Time	Task Immediate predecessor
1	LS	2	-		LS	2	-
2	ES	4	1		RS	2	-
3	RS	3	-		LS	5	-
4	ES	3	2		ES	1	2
5	LS	6	1		RS	3	2
6	ES	4	1		ES	3	1
7	LS	5	4		LS	5	4
8	ES	4	4		ES	4	4,5
9	ES	3	8		LS	4	7
10	RS	2	3		ES	3	7,8
11	ES	2	10		ES	3	-
12	LS	2	6		LS	2	9
13	ES	4	11		-	-	-
Total Processing Time		**44**				**37**	

Theoretical minimum number of workstations can be calculated by the equation (21) mentioned below for line I and line II or both, if the lines are balanced separately as

$$Min\ K_h = [Total\ task\ time/Cycle\ time]^+ \quad (21)$$

Here $[X]^+$ indicates the lowest integer larger than or equals to X.

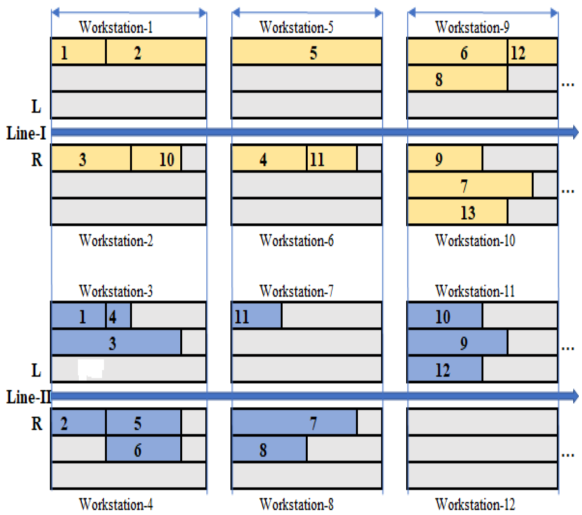

Fig. 3. A possible balancing solution using without sharing tool in MTALB.

According to equation if the considered cycle time is 6 and the lines are balanced individually then theoretical minimum number of workstations for both lines separately could be calculated as min $K_1 = [44/6]^+ = 8$ and min $K_2 = [37/6]^+ = 7$, respectively therefore, total minimum number of workstations would be $8 + 7 = 15$ but theoretical minimum number of workstations for both lines in together is min $K = [81/6]^+ = 14$, with the chance of allocating tasks into a more expanded position due to use of shared resources between adjacent workstations. but in the obtained result, it can be seen that only 11 workstations are utilized. So, the space for extra 4 workstations is saved.

Fig. 3 shows the use of multi-line stations for a pair of adjacent two-sided assembly lines positioned in parallel to one another. In this figure, numbers inside bars indicate task numbers and lengths of the bars relate to task processing time. Also, the bars in dark colour show idle times. Configuration of possible balancing solution using without sharing tool in MTALB problem with parallel workstations is shown in Fig. 3.

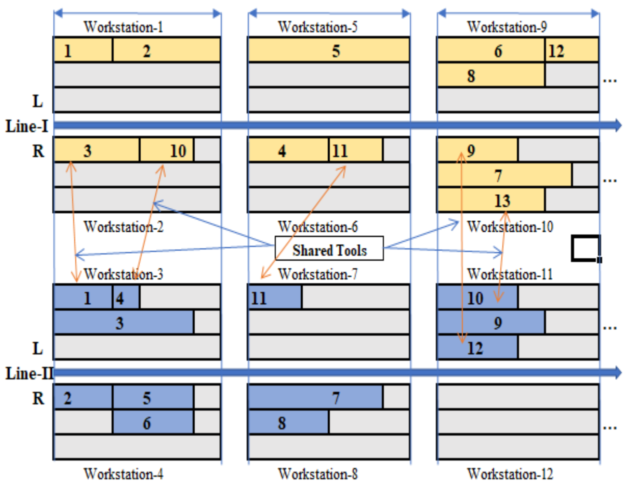

Fig. 4. A possible balancing solution using shared tool in MTALB.

Fig. 3 indicate that without sharing tool in multi-line stations total eleven workstations are required to execute total of twenty five tasks on both the lines. Task 1,2 are assign on the left side of line I and 3,10 are assign on the right side of line I. Similarly task 1,3,4 are assign on the left side of line II and 2,6,5 are assign on the right side of line II.

V. RESULTS AND DISCUSSION

In this section authors indicates that with sharing tool in multi-line stations total eleven workstations are required. Configuration of possible balancing solution with shared tool in MTALB problem with parallel workstations is shown in Fig. 4.

Table II indicate output data results after tool sharing approach. Here task 10 (Line I) tool shared with task 4(Line II). So, with the idea of balancing assembly line with common set of resources the expansive tools from tasks of right side of Line I are shared with left side of Line II or vice versa for saving the cost of purchasing extra tools. As shown in Table II, there are 5 sharable tools between the tasks of both the products.

TABLE II: OUTPUT DATA FOR TOOL SHARING

Sr. No.	Task no. (Line I)	Task no. (Line II)
1	3 ⟷	1
2	10 ⟷	4
3	11 ⟷	11
4	9 ⟷	12
5	13 ⟷	10

Results indicate that the communication between operators is increased and the required space for assembly line setup is decreased.

A total of 11 workstations are needed to perform total of 25 tasks on both the lines after sharing 6 tools. Tool used in Task-1 of Line II on workstation-3 is shared with Task-3 of Line I on workstation-2. Tool used in Task-4 of Line II on workstation-3 is shared with Task-10 of Line I on workstation-2. Tool used in Task-11 of Line II on workstation-7 is shared with Task-11 of Line I on workstation-6.

Tool used in Task-12 of Line II on workstation-11 is shared with Task-9 of Line I on workstation-10. Tool used in Task-10 of Line II on workstation-11 is shared with Task-13 of Line I on workstation-10.

It should be noted here that Task-1 of Line II workstation-3 cannot be performed with Task-3 of Line I on workstation-2 and Task-4 of Line II workstation-3 cannot be performed with Task-10 of Line I on workstation-2.

Similarly, Task-11 of Line II workstation-7 cannot be performed with Task-11 of Line I on workstation-6. Similarly, Task-10 of Line II workstation-11 cannot be performed with Task-9 of Line I on workstation-10 and Task-12 of Line II workstation-11 cannot be performed with Task-13 of Line I on workstation-10.

Table III is showing four criteria, i.e., theoretical minimum number of workstations of both lines LB theoretical independent minimum number of workstations on both lines IL, minimum number of utilized workstations UW,number of shared tools NT percentage of divergence between LB, UW, $DP(\%)$ is used for the results analysis UW ,is generally larger than the LB,and this condition take as a consideration into account for efficiency measure the established approach and comparatively analysis with the LB,The deviation between UW and LB,which is given by $DP(\%)$ is calculated by the equation (22) as mentioned below :

$$DP(\%) = \frac{UW - LB}{LB} \quad (22)$$

Obtained results are mentioned in Table III. ILB, LB, UW and $DP(\%)$ are obtained for data set of problems, Regarding the goal of minimizing the idle times it can be observed that the average of $DP(\%)$ which is 23.78 which indicates that the tool sharing approach is quite beneficial to reduce idle time and better use of tools. Table III indicate output data results after tool sharing approach.

TABLE III: OUTPUT DATA RESULTS BY MEANS OF TOTAL NUMBER OF REQUIRED WORKSTATIONS

S. N.	ILB (L1+L2)	LB	UW	NT	DP(%)
1	(8+7)	11	15	5	23.78

Table III indicates that theoretical minimum number of workstations of both lines LB is eleven. Minimum number of utilized workstations UW is fifteen and number of shared tools$NT$is five. The deviation between UW and LB,which is given by $DP(\%)$ is 23.78.

VI. CONCLUSION AND FUTURE SCOPE

In this paper, authors presented a numerical example of MTALB problem. The research gaps and the proposed mathematical model mentioned in literature and Problem Statement leads to carry out a study of MTALBP. According to the sequence of the task performed, precedence diagram is configured.

Lingo-16 solver is considered to solve the proposed approach, and numerical experiments, and demonstrate the efficiency of tool sharing approach. The experimental results shows that tool shared approach provide good solutions with minimized number of workstations as well as reduce cost of tool in workstations.

In future work, this mathematical model on two-sided assembly line balancing can be applied with meta-heuristic, such as simulated annealing algorithm, artificial bee colony algorithm, ant colony optimization algorithm and particle swarm optimization, grey wolf optimization to solve assembly line balancing problem. ALBP with multi-manned station can also be solved for different assembly line layout such as U line in future work. According to the industrial aspect, more realistic constraints such as position constraint and distance constraint can be beneficial for future work in ALBP with multi-manned station.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The research begun with Rupesh Nishad and Ramawatar Kulhary that managed to collect and analyze preliminary data based on the open data sources identified. Ashish Yadav collaborated in the analysis by adding new perspectives and complementing results. All the research was leaded by Sunil Agrawal, who guided the group through the process with a special focus on the relevance of multi-manned two sided assembly line to improve industrial productivity. All authors had approved the final version

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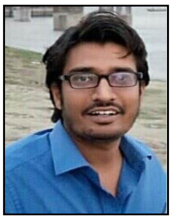

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