Reconfiguring Mixed-Model Assembly Line by Considering Feeding Lines: Using a Pareto Optimal Solution

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ABSTRACT

A mixed-model assembly line is a type of assembly line where various products with common basic features are assembled. Accordingly, this study aims to investigate and analyze the requirements and challenges of reconfiguring mixed-model assembly lines in the presence of sub-lines. In this paper, an optimization problem related to sequencing in a mixed-model assembly line is examined. Reconfigurable systems are designed around families of similar products. A mixed-model assembly line requires reconfiguration after assembling each batch of products within a family. The main objective of this research is to optimize the sequencing process in mixed-model assembly lines, which presents unique challenges due to the high variety of products and the need for rapid changes in the lines. To address these challenges, products have been categorized into different families based on commonality and complexity indices. This categorization is aimed at reducing the time and costs associated with reconfiguring the lines after assembling each product family. This optimization problem is solved by using Pareto-optimal solutions, which represent the optimal sequence of products within each family.

Keywords: **Mixed-model assembly line, reconfiguration, feeding lines, family, delivery deviation, pareto optimal**

1. INTRODUCTION

A mixed-model assembly line is a special type of assembly line where different models of similar products are intermingled for assembly on a single line. This is a production method that can meet the market demand for products with minimal changes and by keeping the work in progress low. For this reason, this type of production line is increasingly accepted in the industry to align with the trend of customer demand diversification. Mixed-model assembly lines can quickly respond to forecasted changes in product demand without holding large inventories. Designing such a line involves solving traditional assembly line design problems (including balancing the line, determining cycle times, and the number and sequencing of stations), in addition to sequencing the products on the assembly line.

The need for reconfiguration in such lines arises because each product model may require different operations, tools, or settings. As production shifts from one model to another, the assembly line must quickly adjust to efficiently produce the new product without stoppages. This reconfiguration includes adjustments to machinery, changes in the assembly sequence, and sometimes adjustments in the workforce. Doing this effectively is crucial; otherwise, the production line may face issues like decreased productivity, increased waste, or even production stoppages. Proper and timely reconfiguration improves efficiency and increases production flexibility. The presence of sub-lines aids reconfiguration in the production system, as these lines can operate independently from the main line and improve the preparation of various components.

In modern manufacturing, the need for flexibility and efficiency is more critical than ever. Dynamic and changing markets compel manufacturers to produce diverse products at the same time with limited resources. One of the main strategies for meeting this need is the use of mixed-model assembly lines, allowing manufacturers to produce several different models of a product simultaneously on one production line.

However, implementing this strategy requires the constant reconfiguration of the production line to adapt to changes in different product models.
Reconfiguring correctly and in a timely manner enhances production efficiency and flexibility. Additionally, the presence of sub-lines dedicated to assembling specific parts of products increases the complexity and challenges of reconfiguration. Although these sub-lines contribute to optimizing production processes and increasing productivity, coordinating them with the main line requires precise planning and effective management.

2. LITERATURE REVIEW

Considering the importance of reconfiguring assembly lines, particularly mixed-model assembly lines, Hou and colleagues conducted a comprehensive review of research in the field of assembly system design, planning, and operations in response to product variety[1]. They analyzed and summarized various representation and production methods, evaluating approaches for assembly representation, production sequencing, and assembly line balancing. Additionally, Kuziak and colleagues[2] assessed the operational complexities and the crucial role of human operators in assembly systems, given the high diversity of products. Kuziak and colleagues also proposed three applicable rules for designing products for agile assembly from an operational perspective. These rules aim to support product design to meet agile manufacturing requirements, and examples are provided to demonstrate the potential of these design rules. Juhani et al. [3] presented a semi-automated modular approach combining flexible automation and human skills as the best solution for reconfiguration and agility. The proposed solution allows for adjusting volume by adding new modules or automating manual tasks step by step. To maintain flexibility, they introduced the concept of an intelligent pallet, meaning the use of escort memory, transporting a product along with other hardware that facilitates paperless production, which even supports a large size of a product. This approach shows how to create flexible capability and capacity in final assembly systems.
J.K.L. [4], in their paper, used motion genes to solve reconfiguration problems of flexible assembly line systems to cope with ever-changing production requirements. The main issues of reconfiguring such systems are described, and an approach to using motion genes to overcome them is proposed. The study shows that conveyor components can be encoded and evolved through linear and angular transfer movements. Additionally, genetic mating can be used to produce alternative conveyor system layouts that meet specific production requirements, with the best selected based on the concept of "survival of the fittest." Liang and colleagues [5] also proposed an integrated approach to product module selection and assembly line design/reconfiguration problems. They recommended using general-purpose quality loss functions to quantify incomparable and potentially conflicting performance criteria involved in the integrated problem. Brian and colleagues [6] introduced a set of methods for the co-evolution of product families and assembly systems over product generations. They also introduced criteria to evaluate the effectiveness of co-evolution designs, which have the potential to reduce product development costs and time by identifying changes in the assembly system as early as possible.
Moradi and colleagues [7] introduced an approach to search for a locally optimal Pareto frontier of a mixed-model sequencing problem in a Just-In-Time (JIT) environment, where simultaneous minimization of setups and production rate variations is desired. These two objectives are inversely related. Another feature of the problem examined in this article is its combinatorial nature, which makes traditional optimization techniques impractical for large problems. Tracht and colleagues [8] presented two planning methods that facilitate decision-making in two stages: the design stage and the reconfiguration stage of modular assembly lines. The procedures list distinct decision-making stages in a structured and logical order, providing guidance to designers and planners. In this way, the design and reconfiguration processes are accelerated, and the level of specialized knowledge required is reduced. Gulay and colleagues [9] introduced a new two-stage framework for managing capacity in modular and manual assembly systems. At the higher level, the production planning problem is solved to determine batch sizes and the corresponding number of operators. At the lower level, the detailed production schedule is specified, including operator tasks and the start time of production batches.
Fattahi et al. [10] proposed a method for determining product sequencing in a mixed-model assembly line, taking into account Just-In-Time (JIT) production systems. Additionally, the supply of certain required components from sub-lines was considered. There is another study which developes a two-step framework for optimizing customer relationships and order sequencing in mixed model assembly lines by clustering customers based on priority and using a multi-objective tabu search algorithm to maximize high-priority

customer satisfaction and profits, while integrating periodic maintenance to improve sequencing efficiency[11]. Kumar [12] examined a three-objective optimization problem related to sequencing in multi-model reconfigurable assembly systems. These systems are also designed around families of products similar to more general reconfigurable manufacturing systems. A multi-model assembly line requires reconfiguration after assembling each batch of products from this family. Moreover, transitioning the assembly line from one type of product to another involves varying degrees of complexity and reconfiguration costs. The paper proposed two new indices for commonality and reconfiguration complexity of assembly lines. There is a study on the multi-objective process plan generation problem in reconfigurable manufacturing systems by proposing and comparing three optimization approaches—an iterative multi-objective integer linear program, archived multi-objective simulated annealing, and the non-dominated sorting genetic algorithm—while incorporating a novel optimization criterion to minimize maximum machine exploitation time for high-quality production[13].

3. RECONFIGURABLE ASSEMBLY SYSTEMS

A reconfigurable assembly system can be considered an application of reconfiguration philosophy, specifically aimed at general production and assembly processes. These systems share certain characteristics such as product family-based design, modular assembly equipment, and reconfigurable control. This type of assembly system is designed around a product family. All types of products within this family can be assembled by reconfiguring hardware and software components. The shift from assembling one type of product to another always involves varying degrees of difficulty or ease. In practice, such a changeover often requires reprogramming or using modular controllers for various material handling devices, conveyors, robots, fastening processes, and replacing reconfigurable fixtures, pallets, etc. The greater the number of shared components between two products, the simpler the reconfiguration process becomes. In theory, each workstation in the assembly line should be capable of achieving the same number of configurations as the number of product variants within the family[12].

4. MATHEMATICAL MODEL AND PROBLEM DEFINITION

Considering the previously mentioned characteristics of reconfigurable assembly lines, in this section, the mathematical model for the mixed-model assembly line, as developed by Fattahi and colleagues[10], will be reviewed. This model is aimed at categorizing product families and reconfiguring them to reduce the costs associated with deviations from delivery schedules. In this model, sub-lines are also taken into account. The problem is initially modeled using mixed-integer nonlinear programming, and then, by linearizing the nonlinear expressions, the model is transformed into mixed-integer linear programming.

4.1 Definitions and Assumptions of the Problem

The assumptions considered for this model are as follows:

- Demand for each product within the family is fixed and certain for a specified time period (e.g., one week or two weeks).
- The demand quantity for each model is known at the start of operations.
- The main assembly line and sub-lines are balanced.
- All stations (in both main and sub-lines) are of the closed type.
- The main assembly line consists of SSS workstations.

4.2 Indices

i	Product sequence index	i=1,2,…,n
j	Workstation index	j=1,2,…,s
r	Component index	r=1,2,…,Co
m	Product model index	m=1,2,…,M

f	Product family index	f=1,…,p

4.3Parameters

M	Number of models
d_m	Demand for model m
S	Number of stations
Q	Total number of final products
Co	Number of required components from feeding lines for assembling all products
Cx_{rm}	Number of component needed to assemble one unit of product model m
Nc_r	Total number of components needed for the assembly of all final products
Y_{ir}	Cumulative number of components required to assemble products up to sequence i
t_{mj}	Time required to perform operations on product m at station j
t'_j	Time required to perform operations at station j
T_c	Total cycle time
W1	Weight of the first objective function
W2	Weight of the second objective function
N_m	Required components for product m
Dc	Cost of component delivery deviation from feeding lines(dollars/min)
C_{mq}	Number common components between products m and q
R_{mq}	Complexity index between product m and q
S_{mq}	Commonality index between product m and q
Rc_{mq}	Reconfiguration cost from product m to q

4.4 Decision Variables

F_{fm}	A binary variable equal to 1 if product m belongs to family f, and otherwise 0
x_{im}	A binary variable equal to 1 if the product in sequence i is of model m, and 0 otherwise
Cd_i	Deviation in the delivery time of all required parts for sequence i
z^1_{imq}	Auxiliary variable
z^2_{hmf}	Auxiliary variable

4.5 Mathematical Model

$$minZ = W1\sum_{i=1}^{n} Cd_i * DC + W2\sum_{i=1}^{n}\sum_{j=1}^{Co}\sum_{m=1}^{M}\sum_{q=1}^{M} Rc_{mq} * t_{qj} * x_{im} * x_{(i+1)q} \qquad (1)$$

$$Cd_i = \sum_{r=1}^{C}\sqrt{\left(\frac{iNC_r}{Q} - \sum_{r=1}^{c} y_{ir}\right)^2} \qquad i=1,\dots,n;\ f=1,\dots,p \qquad (2)$$

$$y_{ir} = \sum_{h=1}^{i}\sum_{m=1}^{M} Cx_{rm} * x_{hm} * \sum_{f=1}^{p} F_{fm} \qquad i=1,\dots,n;\ r=1,\dots,Co \qquad (3)$$

$$\sum_{m=1}^{M} x_{im} = 1 \qquad i=1,\dots,n \qquad (4)$$

$$\sum_{m=1}^{M} F_{fm} = 1 \qquad f=1,\dots,p \qquad (5)$$

$$\sum_{i=1}^{n} x_{im} = dm \qquad m=1,\dots,M \qquad (6)$$

$$max t'_j \le T_c \le \sum_{j=1}^{S} t'_j \qquad (7)$$

$$Rc_{mq} = \sum_{m=1}^{M} \sum_{q=1}^{M} \frac{R_{mq}}{S_{mq}} \qquad (8)$$

In mixed model assembly lines, where products are assembled based on demand, the difference between the number of assembled products and the demand is of great importance. Therefore, reconfiguring assembly lines is aimed at reducing costs, including the costs associated with deviation in delivery. In objective function (1), the costs related to reconfiguration and deviation from delivery are calculated in a sequence, and these two costs are weighted by values w1 and w2 such that w1 + w2 = 1. Constraint (2) shows the deviation of the required parts for each product from the expected amount. Constraint (3) represents the number of parts needed to assemble the products of each family in a sequence and ensures that the demand for each product is met in one cycle. Constraint (4) states that each product can only appear in one sequence. Constraint (5) indicates that each product belongs to only one family. Constraint (6) displays the demand for each product model. Constraint (7) ensures that the operation time performed at all stations will not exceed the specified cycle time. Constraint (8), using indices of commonality and complexity between the products of each family, calculates the reconfiguration cost from one family to another.
The commonality index (9), focusing on shared parts between products, and the complexity index (10), focusing on the assembly time of products, lead to a reduction in reconfiguration costs.

$$S_{mq} = \frac{C_{mq}}{min(N_m . N_q)} \qquad \forall Cmq \neq 0;\ m \neq q;\ 0 \le S_{mq} \le 1 \qquad (9)$$

$$R_{mq} = \frac{\sum_{c=1}^{N_q} t_{cq} - \sum_{c=1}^{c_{mq}} t_{cm}}{\sum_{c=1}^{N_q} t_{cq}} \qquad m \neq q;\ 0 \le R_{mq} \le 1 \qquad (10)$$

Due to the nonlinear nature of the model, efforts have been made to linearize certain nonlinear constraints so that the software can potentially find the optimal solution in less time.
In the objective function (1), the term "$x_{im} * x_{(i+1)q}$" causes nonlinearity, which is linearized as follows:

$$x_{im} * x_{(i+1)q} = z^1_{imq} \qquad (11)$$

$$x_{im} \ge z^1_{imq} \qquad (12)$$

$$x_{(i+1)q} \ge z^1_{imq} \qquad (13)$$

$$1 - x_{im} + x_{(i+1)q} \ge z^1_{imq} \qquad (14)$$

In constraint (3), the term "$x_{hm} * F_{fm}$" causes nonlinearity, which is linearized as follows:

$$x_{hm} * F_{fm} = z^2_{hmf} \qquad (15)$$

$$x_{hm} \ge z^2_{hmf} \qquad (16)$$

$$F_{fm} \ge z^2_{hmf} \qquad (17)$$

$$1 - x_{hm} + F_{fm} \ge z^2_{hmf} \qquad (18)$$

5. COMPUTATIONAL RESULTS ANALYSIS

A hypothetical assembly system similar to a typical car manufacturing plant is considered to demonstrate the proposed model. Eight different types of products (families) are produced by assembling ten different parts. These components include sub-assemblies purchased from suppliers or assembled separately, as well as individual parts. Table1 shows the common parts between each product pair and the number of parts needed to assemble each product.

Table 1. *Product-component incidence matrix*

	Components										
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Products	P_1		1		1		1	1	1		1
	P_2	1	1	1		1	1		1	1	
	P_3	1		1	1	1		1	1	1	
	P_4		1	1	1	1				1	1
	P_5	1		1		1	1	1	1		1
	P_6		1		1	1	1		1	1	1
	p_v	1	1		1	1		1	1	1	
	P_8	1			1			1	1	1	1

For the assembly line configuration, we consider that each product belongs to one family. A product with the highest priority has the shortest delivery time, and vice versa. Using Pareto-optimal solutions, an optimal sequence is determined based on delivery requirements as follows:
P5 → P7 → P8 → P4 → P6 → P2 → P1 → P3

Table2 indicates the optimal Pareto solutions for the assembly sequencing, obtained after several runs. It is noteworthy that all six solutions found are equally good, and the final choice is left to the decision-maker based on the priority of objectives or any other constraints. Using the shared parts between each pair of products, we calculate the commonality and complexity indices for the following sequences, and then compute the costs related to the first objective function (deviation from delivery) and the second (reconfiguration).

Table 2. *pareto optimal sequences*

sequence	Pareto optimal	Objective function1	Objective function2
1	P7 → P5 → P6 → P4 → P8 → P1 → P3 → P2	16960	33.264
2	P5 → P8 → P7 → P4 → P6 → P1 → P2 → P3	6760	30.870
3	P4 → P7 → P8 → P5 → P6 → P3 → P2 → P1	17604	35.154
4	P8 → P5 → P7 → P4 → P1 → P2 → P6 → P3	15012	34.429
5	P5 → P7 → P8 → P4 → P6 → P2 → P1 → P3	44220	38.461
6	P6 → P7 → P5 → P2 → P8 → P4 → P1 → P3	20451	53.770

The figure below shows a comparison of costs before and after reconfiguration:

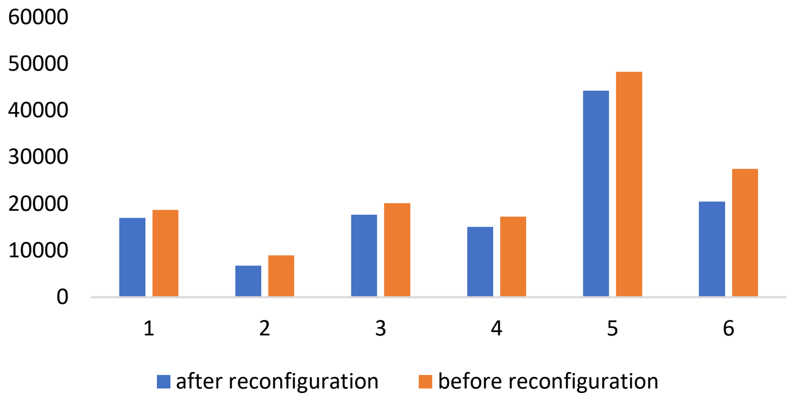

Fig. 1. *comparing costs before and after reconfiguration*

6. CONCLUSION

In this paper, a model was proposed to reduce assembly costs through the reconfiguration of mixed-model assembly lines. This model was developed using the GAMS software. All experiments were conducted on a computer with 8 GB of RAM and an Intel Core i5-8250U processor. During the formulation of the problem, new indices such as commonality and reconfiguration complexity were introduced to reflect the modular characteristics of the system. This model attempts to reduce the costs of retooling by grouping similar products. The results showed that categorizing products based on commonality and complexity indices had a direct impact on reducing the time and costs of reconfiguring assembly lines.

Using this approach led to more efficient management of the assembly process and increased overall system productivity. The mathematical model was first formulated using mixed-integer nonlinear programming and then linearized into mixed-integer linear programming.

To determine the optimal assembly sequence, a Pareto-optimal solution was used to weigh and calculate the costs of the obtained sequences. The objective functions—related to deviation costs and reconfiguration costs—were calculated using this solution, resulting in reduced product assembly costs after reconfiguration.

Finally, the findings of this research can serve as a practical solution for improving the efficiency of production lines in various industries. The present study also lays the foundation for future research on optimizing reconfiguration and managing assembly lines in complex production environments.

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