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Reconfigurable Mixed Model Assembly Line Design in a Dynamic Production Environment

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Abstract - **A mixed model assembly line is generally designed to produce a certain production mixed and volume that is assumed to be steady for a long period. As a result, the line performance tends to decline by some fluctuations in production demand. In a dynamic production environment, an assembly line configuration and product sequence may need to be revised every time the demand changes to keep the line efficient. However, frequent or radical reconfiguration of the line could be costly; the change of the line configuration and product sequence should be optimized. This paper presents a model of a reconfigurable mixed model assembly line design in a dynamic production environment. The model is formulated in a non linear integer programming formulation that minimizes total cost of assembly line reconfiguration for a multiple-period. Numerical example of the model shows the application of the model and yields a reconfigurable mixed model assembly line.**

Keywords - **Reconfigurable line design, mixed model assembly line, products sequence**

I. INTRODUCTION

A product family is developed to offer diversified products to meet the preferences of consumers, and maintain the production economy of scale [1]. Optimization should consider the link between product family and its manufacturing processes [2], [3]. A product family is assembled in the mixed model assembly line [4]. The mixed model assembly line should be designed to operate efficiently in producing different product variety and volume to cope with diverse customer needs.

Production facilities shall be designed to adapt changes in volume and product mix variations of families that must be met. Dynamic production environment considerations in the layout and production system, has been widely investigated in the study of cellular manufacturing and machining processes to account for material handling costs [5], [6], [7]. Some researchers are focusing more on logical activity of Reconfigurable Manufacturing System (RMS). Some aspects are examined in RMS logical activities, including scheduling and operational aspects [8], [9], [10], and strategic aspects of flexibility and convenience for the reconfigured [11], [12]. Design models and product family grouping was also developed for the determination of the module in designing RMS [13], [14], [15]. A few studies focus on subassembly clustering approach on modular product family and to produce an efficient and reconfigurable line [16], [17], [18], [19], [20].

In a mixed model assembly line design, two important variables should be optimized are line configuration and products sequence. In a dynamic production environment, those variables may need to be revised every time the production requirement changes to keep the line efficient. However, frequent or radical reconfiguration of the line could be costly. Companies may prefer not to reconfigure their lines and operate inefficiently. Yet, the inefficient assembly line can cause significantly operational cost. The decision to keep or to change the whole or part of the line configuration is an important problem that has to be solved when the line is designed. Therefore, a reconfigurable assembly line is needed to save the cost of reconfiguration while maintain the line efficient. This paper aims to develop a model of a mixed model assembly line design that is reconfigurable to deal with demand fluctuation.

II. MODEL OF RECONFIGURABLE MIXED MODEL ASSEMBLY LINE DESIGN

Proposed model of reconfigurable mixed model assembly line design is characterized by some conditions, as follows:

1. The line is unpaced mixed model assembly line
2. The assembly line is planned for some periods of t, where $t = 1, 2, \ldots, T$. A time period can be one or several months, semesters, or years.
3. Variety and volume of variant products to be assembled can differ for every period. Variety and volume is represented in minimal part set (MPS) and the number of MPS.
4. Variety and volume of variant products in every period are known at design stage and deterministic.

The model is developed based on the following principles:

1. Demand of any period must be met
2. Trade off is done between reconfiguration cost and operational costs for the entire period of the planning horizon:
   a. Line configuration changes are made to a minimum
   b. Line capacity is determined as close as possible to the production requirement

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3. Decision variables are: assembly operations allocations, mixed production sequence and time between MPS, for every period.

The line reconfiguration (relayout) is measured by:

1. Change in the number of workstations. This change is represented by installment or stop off cost of a workstation.
2. Change in operation allocation in workstation. A setup is needed to prepare workstation due to operation allocation change. This change is expressed by setup cost of addition or reduction of the operation on workstation.

Efficiency (operational performance) is measured by:

1. The total of workstations. Every workstation needs a cost in order to operate. This cost called operational cost.
2. Idle time. Idle time is undesirable in context of line efficiency and expressed as idle time cost.
3. Waiting time. Waiting time for work in process product is counted as waiting time cost.

The constraints of the model are described as follows:

1. The line capacity has to be sufficient to produce products mix and volume on every period.
2. Every assembly operation is a non-preemptive operation; therefore every operation is allocated only on one station.
3. The operations allocation on workstation has to be valid according to precedence diagram.
4. The total of the workstations on a period has to be equal to the total of the workstations on previous period plus the amount of installed workstations reduced by the amount of stopped off workstations.
5. The operations on a workstation have to be the same with the operations on that workstation on previous period plus allocated operations minus removed operations.

Notations used in the design of dynamic models are as follows:

Indexes:

- b Index of product type, b=1, ..., V
- i Index of product sequence in MPS, i = 1, 2, ...P
- j Index of operation, j= 1, 2,…, N
- k Index of workstation, k= 1, 2,…, M
- t Index of periods, t = 1, 2, ..., τ

Parameters:

- δ Idle time cost of workstation
- λ Waiting cost of product
- β Operational cost of workstation
- α Cost of installing workstation
- ϕ Cost of work station stopped off
- η Setup cost of adding operation
- φ Setup cost of removing operation
- C_t Cycle time
- D_t Total MPS for the entire demand, D=Q/P, in period t
- G_j Set of operations that precede operation j
- H_{bt} Quantity of product type b in MPS, in period t
- M Upper limit of number of workstations
- N Number of assembly operations
- P_t Number of products in MPS, in period t
- Q_t Total quantity of production, in period t
- q_i Demand quantity of product i
- V Number of product type in family
- w_{bj} Assembly time of operation of product i
- ζ_k = 1 if work station k is used in period 0, 0 if otherwise
- τ Number of period
- χ_{jk} = 1 if operation j is allocated in station k in period 0, 0 if otherwise

Variables:

- TOR Total reconfiguration cost
- a_{ikt} Total assembly time of product i at station k in period t
- f_{ikt} Idle time on station k before it processes the i^{st} product in period t
- d_{kt}^{dum} Total assembly time of the 1[st] product in the next MPS at station k in period t
- f_{kt}^{dum} Idle time on station k before it processes the 1[st] product in the next MPS in period t
- d_t The bisggest station time, d=max{a_k} in perioda t
- π_{ibt} = 1 if product i is type b, 0 if otherwise, in period t
- f_{ikt} Idle time in work station k before product i come, in period t
- r_{jkt} = 1 if operation j is removed from work station k between periods (t-1,t), 0 if otherwise
- s_t Number of installed work stations between periods (t-1,t)
- u_t Number of stopped off work stations between periods (t-1,t)
- x_{jkt} = 1 if operation j is allocated to work station k in period t, 0 if otherwise
- y_{kt} = 1 if station k is used in period t, 0 if otherwise
- z_{jkt} = 1 if operation j is added to work station k between periods (t-1,t), 0 if otherwise
- γ_{ikt} Waiting time of product i before it is processed in work station k, in period t

The mathematical model is described as follows:

Objective function: Minimize total cost of reconfiguration

$$Min.TOR = \sum_{t=1}^{\tau}(\alpha s_t + \varphi u_t) + \sum_{t=1}^{\tau}\sum_{k=1}^{M}\beta y_{kt} + \sum_{t=1}^{\tau}\sum_{j=1}^{N}\sum_{k=1}^{M}(\eta z_{jkt} + \varphi r_{jkt}) + \sum_{t=1}^{\tau}\sum_{k=1}^{M}\sum_{i=2}^{P_t}\left(\left(f_{ikt} + f_{kt}^{dum}\right)D_t + f_{1kt}\right)\delta + \sum_{t=1}^{\tau}\sum_{k=1}^{M}\sum_{i=2}^{P_t}\gamma_{ikt}D_t\lambda \quad (1)$$

Subject to:

$$\sum_{k=1}^{M} x_{jkt} = 1 \quad , j=1,2,...N, t=1,2, .. \tau \quad (2)$$

$$\sum_{k=1}^{M} k.x_{hkt} \le \sum_{k=1}^{M} k.x_{jkt}, \quad j=1,2,...N, t=1,2, .. \tau, h \in G_j \quad (3)$$

$$\sum_{b=1}^{V}\pi_{ibt}=1 \quad , i=1,2,\ldots P_t \text{ dan } t=1,2,\ldots\tau \qquad (4)$$

$$\sum_{i=1}^{P_t}\pi_{ibt}=H_{bt} \quad , b=1,2,\ldots V,\ t=1,2,\ldots\tau \qquad (5)$$

$$\sum_{b=1}^{V}\sum_{j=1}^{N}w_{bj}x_{jkt}\pi_{ibt}-a_{ikt}=0, \quad i=1,2,\ldots,P_t,\ t=1,2,\ldots\tau,\ k=1,2,\ldots M \qquad (6)$$

$$a_{kt}^{dum}=a_{1kt},\ k=1,2,\ldots M,\ t=1,2,\ldots\tau \qquad (7)$$

$$\left(f_{1kt}+\left(\sum_{i=1}^{P_t}(a_{ikt}+f_{ikt})-f_{1kt}+f_{kt}^{dum}\right)D_t\right)\Big/Q_t\le C_t, \quad k=1,2,\ldots M,\ t=1,2,\ldots\tau \qquad (8)$$

$$f_{i1t}=0, \quad i=1,2,\ldots,P_t,\ t=1,2,\ldots\tau \qquad (9)$$

$$\sum_{s=1}^{k-1}a_{1st}-f_{1kt}=0, \quad k=2,\ldots M,\ t=1,2,\ldots\tau \qquad (10)$$

$$\sum_{r=1}^{i}\left(a_{r(k-1)t}+f_{r(k-1)t}\right)-\sum_{r=1}^{i-1}\left(a_{rkt}+f_{rkt}\right)+\gamma_{ikt}=f_{ikt}$$
$$k=2,\ldots M,\ t=1,2,\ldots\tau,\ r=1,2,\ldots,i,\ i=2,\ldots,P_t \qquad (11)$$

$$a_{(k-1)t}^{dum}+f_{(k-1)t}^{dum}+\sum_{i=1}^{P_t}\left(a_{i(k-1)t}+f_{i(k-1)t}\right)-\sum_{i=1}^{P_t}\left(a_{ikt}+f_{ikt}\right)\le f_{kt}^{dum}$$
$$k=2,\ldots M,\ t=1,2,\ldots\tau,\ i=2,\ldots,P_t \qquad (12)$$

$$\sum_{j=1}^{N}x_{jkt}-Ny_{kt}\le 0, \quad k=1,2,\ldots M,\ t=1,2,\ldots\tau \qquad (13)$$

$$y_{st}-y_{s+1,t}\ge 0, \quad s=1,2,\ldots(k-1),\ k=2,\ldots M,\ t=1,2,\ldots\tau \qquad (14)$$

$$\chi_{jk}+z_{jk1}-r_{jk1}=x_{jk1}, \quad j=1,2,\ldots N,\ k=1,2,\ldots M \qquad (15)$$

$$x_{jkt-1}+z_{jkt}-r_{jkt}=x_{jkt}, \quad j=1,2,\ldots N,\ k=1,2,\ldots M,\ t=2,\ldots\tau \qquad (16)$$

$$\sum_{k=1}^{M}\zeta_k+s_1-u_1=\sum_{k=1}^{M}y_{k1}, \qquad (17)$$

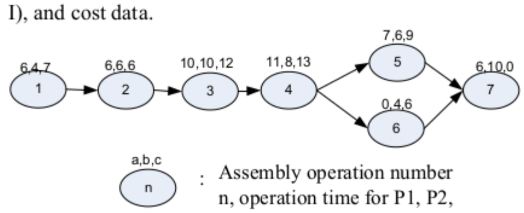
$$\sum_{k=1}^{M}y_{kt-1}+s_t-u_t=\sum_{k=1}^{M}y_{kt}, \quad t=2,\ldots\tau \qquad (18)$$

$$x_{jkt},y_{kt},\chi_{jk},\zeta_k,z_{jkt},r_{jkt},\pi_{ibt}\in\{0,1\} \quad j=1,2,\ldots N,\ k=1,2,\ldots M,\ t=1,2,\ldots\tau \qquad (19)$$

Constraints. Task constraint (2) ensures that each assembly operation is assigned to exactly one work station. Precedence constraint (3) ensures that no assembly operation is assigned early on work station than its predecessor operations. Product sequence constraints: (4) ensures that every product is assigned to exactly one position in the sequence, and (5) ensures that the number of product in sequence is equal to the number of that product in MPS. Station time constraints (6) and (7) ensure that station time of a product is equal to the total operations time allocated in a station. Cycle time constraint (8) ensures that total actual production time divided by total demand does not exceed defined cycle time. Idle and waiting time constraints (9), (10), (11), and (12) ensure that idle and waiting time happen because of the process time differentiation between product and between stations. Workstation constraint (13) ensures that only station with at least one operation is used, and (14) ensures that the station index is sequential. Constraints of operation reallocation (15) and (16) ensure that the operations on a workstation have to be the same with the operations of the workstation on previous period plus allocated operations minus removed operations. Constraints of exchanged work stations (17) and (18) ensure that total workstations on a period has to be equal to the total workstations on previous period plus the amount of installed workstations reduced by the amount of stopped off workstations.

III. NUMERICAL EXAMPLE

Numerical examples (hypotetic data) of product family A, consist of: product family the combined precedence diagram (Fig. 1), initial configuration (Fig. 2), product type and demand for the next two periods (Table I), and cost data.



: Assembly operation number n, operation time for P1, P2, and P3 are a, b, c, respectively

Fig. 1 Combined precedence product family A

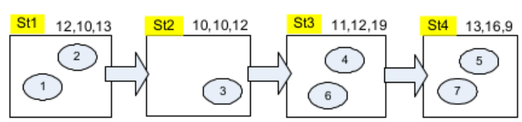


Fig. 2 Initial configuration

TABLE I
DEMAND OF PRODUCT FAMILY A

i	Product	Demand	
		t=1	t=2
1	P_1	50	80
2	P_2	50	0
3	P_3	25	80
Total		125	160

Cost data is defined as follows:
Operasional cost of work station : 100 unit cost/unit time
Idle cost of work station : 0,05 unit cost/unit time
Waiting cost of product : 0,05 unit cost/unit time
Setup cost of installing work station: 100 unit cost/setup
Cost of work station stopped off : 25 unit cost/setup
Setup cost of adding operation : 2 unit cost/operation

Setup cost of removing operation : 1 unit cost/operation

First period demand, resulting in cycle time by 32 units of time and MPS (Q1 = 50,50,25) are P1 = 2,2,1, with the greatest common divisor of Q1 is D1 = 25. Second period demand, resulting in cycle time by 25 units of time and MPS (Q2 = 80,0,80) is P2 = 1,0,1, with the greatest common divisor of Q2 is D2 = 80.

Dynamic assembly designed for periods 1 and 2 can be seen in Fig. 3, the objective function value of 907.85 units of cost. Configuration changes from the initial configuration to line configuration in period 1, namely the reduction of two work stations and the reallocation of the five assembly operations. Configuration changes also occur from the configuration in the period 1 to period 2, namely the installation of a stations and reallocation of two assembly operations.

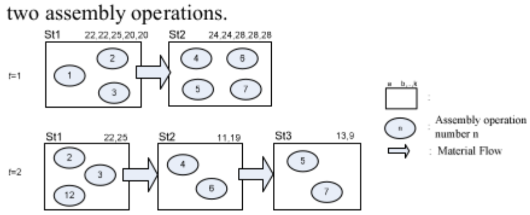


Fig. 3 Reconfigurable assembly line of product family A

The optimum sequence order of the product (π_n) generated for period 1 is $\pi_1 = P_1$, $\pi_2 = P_1$, $\pi_3 = P_3$, $\pi_4 = P_2$, and $\pi_5 = P_2$, while for the period 2 is $\pi_1 = P_2$, $\pi_2 = P_1$. Gantt chart illustrating the assembly process of product family A can be seen in Fig. 4.

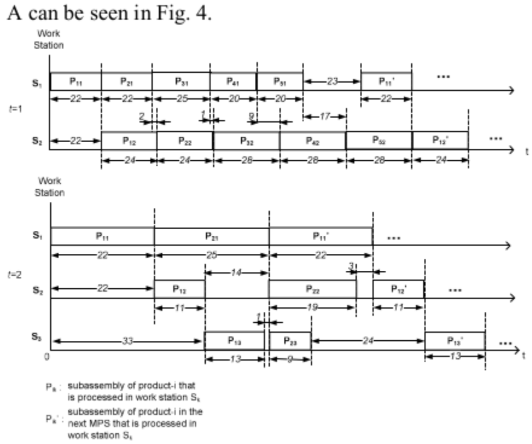


Fig. 4. Gantt chart of product family A assembly processes

V. CONCLUSION

1. Consideration of the dynamics demand in the proposed model of a mixed model assembly line design, produced the reconfigurable line that is more efficient than models built on the line design of static demand.
2. Contributions of the proposed model are as follows:
   a. Accomplishing a trade off beetween reconfiguration cost (change of station number and job allocation to reconfigure the line) and operational cost (idle and waiting time).
   b. Considering changes in both volume and variations in demand for some period ahead.
   c. A new mathematical formulation to optimize assembly line balancing and products sequencing simultaneously in a dynamic production environment.
3. For further research, model of reconfigurable assembly line design could consider the structure of product family and variation development to optimize the total benefit of commonality, variety and configurability [18,19]. Moreover, consideration of stochastic product demand could result in more accurate line reconfiguration decisions as well as optimal product sequences.

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