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An optimization model for material supply scheduling at mixed-model assembly lines

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Abstract

This study is motivated by a real case study and addresses the material supply problem at assembly lines. The aim of the study is to optimally schedule the delivery of raw material at assembly lines while using the minimum number of vehicles. To cope with the problem an original mixed integer linear programming model has been proposed based on the assumptions and constraints observed in the case study. The validity of the model has been examined by solving several real cases and analysing different scenarios. The results of the study show the efficiency and effectiveness of the model.

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Keywords: Optimization; Material supply; Mixed integer linear programming; Assembly line.

1. Introduction

In today's competitive market, an important challenge for most industries is to produce a variety of products while keeping their costs as low as possible. In this regard, most manufacturers tend to use mixed-model assembly lines, which enable them to produce a wide variety of products, at large quantities, without expending much effort in term of human resources and equipment. Relevant examples can be found in the automobile industry, where customers can customize their order by choosing from a wide range of options (e.g., sunroof, leather trim) resulting in a very large number of car models [1]. Practical applications may also be found in many other industries such as consumer electronics, furniture and clothing.

Despite the advantages of mixed-model assembly lines, part supply at these high-variant assembly lines is still a major concern for manufacturing companies [2]. According to the literature (e.g. [3]), continuous supply is the most commonly used material feeding principle in assembly lines, where components are sorted by part number and all part numbers are present at the assembly stations at all times regardless of the assembly object. However, in high-variant mixed-model assembly lines where the large amount of a range of products need different part numbers, it may not be easy to find enough space at operation stations to store/present all part numbers in a way they are easily accessible to assembly workers. Under such circumstance, presenting parts in small packages that results in a space-efficient part presentation could be an applicable solution to the space limitation problem at assembly lines. Undoubtedly, presenting small packages at assembly stations will increase the visit frequency to stations, which from the practical standpoint imposes the need to have a higher number of transportation vehicles and an efficient scheduling system/tool. To overcome this challenge, many manufacturers establish some preparation areas close to the assembly line which is often called 'supermarket' [4].

Using a supermarket allows manufacturers to take advantage of a small lot-wise delivery scheme, which offer some benefits such as an increase in the production flexibility, reduction of lineside inventory and space required at operation

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stations, better control and visibility, and higher ergonomic level.

Although using the supermarket has several advantages, the higher delivery frequency at assembly stations will turn the supplying process into a critical task, and any shortage in delivering the right amounts of the right parts on the right time will result in an assembly line stoppage. Under such circumstances, optimally scheduling the material delivery becomes of significant importance. This means, in order to have a reliable Just-In-Time (JIT) material supply, it is crucial to find the best amount of each part number to be delivered to each assembly station/line on a set of delivery vehicles with a known loading capacity and under certain constraints and objectives while using the least number of vehicles.

Given the above explanations, this study aims to tackle the assembly line material supplying problem by proposing an exact optimization model with aim of minimizing the number of required material delivery vehicles, when a continuous supply principle is applied.

The reminder of the paper is structured as follows. Section 2 presents a brief review of the previous studies in the area of material supply at assembly lines. The problem description is presented in Section 3. Section 4 presents an original mathematical optimization model to cope with the material supply problem. Numerical experiments and results are presented in Section 5, while Section 6 contains the conclusions and recommendations for the future research.

2. Literature review

Among the several decision problems related to material supply (e.g., storage, sorting, line side presentation, and delivery), material delivery to line has recently gained a considerable attention by both researchers and industrial practitioners [5]. This significant interest in material delivery optimization can be regarded as a consequence of applying lean concept and JIT paradigm, which require a precise delivery schedule to avoid line stoppage and excessive cost of transportation. According to the literature (e.g. [5-7]), the most commonly used transport vehicles for material delivery at assembly lines are forklift, tow train, and Autonomous Guided Vehicles (AGVs).

Kozan [8] extended the traditional vehicle routing problem and proposed genetic algorithms to find the best assignment of delivery jobs to a set of forklifts as well as the sequence of deliveries for each forklift in a truck plant. The results of this study showed promising level of reduction in the delivery times. Boysen and Bock [9] proposed a dynamic programming and a simulated annealing algorithm to optimize the delivery plan of containers to assembly line by forklifts. The optimization criteria considered was minimizing the inventory level at the assembly stations.

Fathi et al. [10] addressed the part feeding problem at assembly lines via tow train with the aim of minimizing the number of delivery tours and inventory level at stations. These authors proposed a mathematical model and a modified particle swarm optimization algorithm to solve the tow train loading problem and tow train scheduling, simultaneously. Rao et al. [11] developed an optimization model and a hybrid genetic algorithm and simulated annealing approach to cope with the part supply problem at assembly lines. The aim of their study was to find the optimum schedule for the part delivery to stations through a single vehicle (tow train). The objective function considered for both the optimization model and the hybrid algorithm was minimizing the total inventory holding and travelling costs. Emde and Boysen [12] suggested a dynamic programming approach to optimally route and schedule tow trains for material delivery at assembly lines. In this study, the routing problem was simplified to a partition problem with the aim of determining the number of vehicles and the subset of stations to be served by each tow train. The scheduling problem was solved to decide on the number of tours as well as the start time of each tour.

Fazlollahtabar and Hassanli [13] presented a mathematical model and modified network simplex algorithm for simultaneous scheduling and routing of material handling AGVs in a manufacturing system. The aim of the study was to find the best assignment of material orders to AGVs in order to minimize the transportation cost as well as earliness and tardiness penalties.

Zhenxin and Zhuliang [14] attempted to solve the material delivery problem at mixed-model assembly lines while considering AGVs as the transportation mode and at the presence of automated storage and retrieval system. Zhenxin and Zhuliang first presented a mathematical model of material delivery system and further proposed a hybrid particle swarm optimization algorithm. The objectives of their study were to minimize the materials transportation costs, materials transportation time, and materials storage.

The material delivery at assembly lines with different transport vehicles has been the topic of interest within the literature, however, the need for a generic model capable of handling different type of transportation vehicles is significantly felt, specifically to facilitate the delivery schedule in manufacturing sectors. In this regard, this study aims at presenting a mathematical optimization model for minimizing the cost of any type of transportation vehicles (i.e. AGV, tow train, and forklift) at assembly lines through finding the best material delivery schedule.

3. Problem description

This study addresses a practical case and reports a direct observation in a manufacturing company that is progressing from mass production to mass customization. Despite the considerable advancement in manufacturing technology which facilitates mass customization, the importance and influence of logistics system has been unintentionally ignored by most manufacturers for many years.

One of the main challenges in moving toward mass customization is to have an efficient and reliable material supply process. Apart from the material handling equipment which can be chosen from a wide variety of possible options, scheduling the material delivery plays a key role for having an efficient production system and a productive plant. The main concern in any internal logistics system is to deliver the right material, to the right place, in the right quantity, in the right condition, at the right time, and at the lowest cost [15].

To overcome the challenge of material supply and to satisfy the requirements of lean philosophy, many manufacturers adopted the supermarket concept which enables them to have frequent, small lot, and JIT-based deliveries. To this end, the manufacturing company under study also takes benefit of supermarket concept, but it struggles with two critical issues of (1) the material delivery volume due to the huge number of materials as a consequence of mass customization, (2) the high frequency of material delivery as a result of implementing the supermarket and JIT concepts.

The company has four parallel assembly lines that are all supplied from a supermarket located close to them. The main problem for the company is the inability to have an efficient material delivery plan since different materials should be replenished at different times, as their consumption rates are different and the quantity needed depends on the products being produced. In such circumstances, and to avoid any shortage, the company uses a big number of vehicles to supply the assembly lines with the required materials. Therefore, the company is desperately in a need for a good material delivery schedule that enables the use of the supermarket and JIT material delivery while using an acceptable (minimum) number of vehicles. To better illustrate the concept of the supermarket and problems at hand, a schematic view of a shop floor with several assembly lines that are supplied through a single supermarket with different transportation vehicles is presented in Fig. 1.

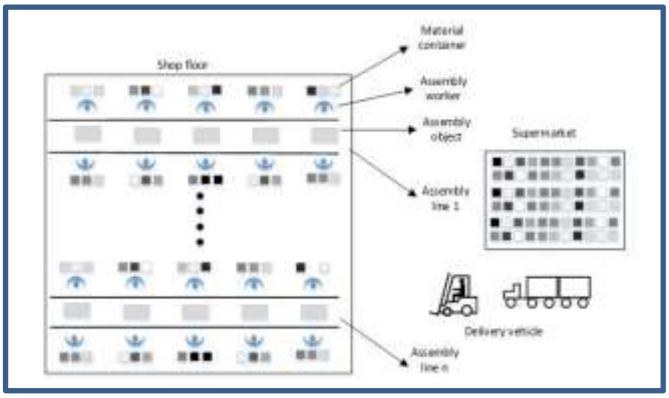

Fig. 1. Schematic view of a shop floor and supermarket.

Consistently, this study seeks to propose an optimization model for scheduling the material delivery at mixed-model assembly lines so that the transportation vehicles can be used efficiently. The model is generic in the sense it can be used for different transportation vehicles, i.e. AGV, forklift, and tow train, without any further adjustments. The use of this model will enhance the efficiency of the material delivery process at assembly lines by enabling the logistics mangers to take a set of right decisions regarding the selection of parts and the quantity to be delivered during each line visit. These decisions can be very consequential to the case company, by potentially preventing unnecessary transportation and eventually minimizing the number of vehicles required.

4. The optimization model proposed

In this section a mathematical optimization model is presented based on the real assumptions and constraints observed in the case company studied. The pretested model is a Mixed Integer Linear Programing (MILP) model. The notations used in the model are listed in Table 1.

Table 1. List of notations.

Notation	Definition
Model inputs	
i:	Part index ($i = 1, \dots, n$)
t:	Cycle index ($t = 1, \dots, T$)
k:	Vehicle index ($k = 1, \dots, K_{max}$)
C:	Vehicle capacity in bins/kits/ pallet
SC_i:	Storage capacity at the station/line requiring part i
d_{it}:	Demand for part i in cycle t
S_i:	Required safety buffer for part i
I_{i0}:	Available inventory at the begging of the first cycle
w_k:	Cost for using vehicle k
Model outputs (variables)	
P_{ikt}:	Number of bin/kit i that is delivered in cycle t by vehicle k
Y_{kt}:	Binary variable, 1 if vehicle k is used in cycle t; 0 otherwise
I_{it}:	Inventory of part i at the workstation/line after delivery of cycle t.

4.1. Assumptions

The main assumptions that have been observed in the real case study and taken into account while developing the model include:

- Only one supermarket is available to serve the assembly stations/lines.
- The storage capacity at each station is limited and known.
- Demands are known and deterministic.
- Containers of the same size are identical in shape.
- Capacity for each of the delivery vehicles is limited and known.
- Initial inventory and safety buffer at each station/line should be enough for one hour production at the beginning and end of each working shift, respectively.
- Material delivery can only be performed in fixed and regular intervals, which is called the "cycle".
- Shortage is not allowed in the entire planning horizon.

4.2. The model

$$Minimize\ Z = \left\{ \sum_{t=1}^{T} \sum_{k=1}^{K_{max}} w_k . Y_{kt} \right\} \tag{1}$$

Subject to:

$$\sum_{t=1}^{T} \sum_{k=1}^{K_{max}} P_{ikt} + I_{i0} \geq \sum_{t} d_{it} \qquad \forall i = 1, \dots, n \tag{2}$$

$$\sum_{i=1}^{M} P_{ikt} \leq C.Y_{kt} \qquad \forall t = 1, \dots, T, \ \forall k = 1, \dots, K_{\max} \tag{3}$$

$$\sum_{k=1}^{K_{max}} P_{ikt} + I_{it-1} \leq SC_i \qquad \forall i = 1, \dots, n, \ \forall t = 1, \dots, T \tag{4}$$

$$\sum_{k=1}^{K_{max}} P_{ikt} + I_{it-1} - d_{it} = I_{it} \qquad \forall i = 1,...,n,\ \forall t = 1,...,T \qquad (5)$$

$$\sum_{k=1}^{K_{max}} P_{ikt} + I_{it-1} \geq S_i \qquad \forall i = 1,...,n,\ \forall t = 1,...,T \qquad (6)$$

$$I_{it} \geq S_i \qquad \forall i = 1,...,n,\ \forall t = T \qquad (7)$$

$$P_{ikt} \geq 0 \text{ and integer} \quad \forall i = 1,...,n,\ \forall t = 1,...,T,\ \forall k = 1,...,K_{\max} \qquad (8)$$

$$I_{it} \geq 0 \qquad \forall i = 1,...,n,\ \forall t = 1,...,T \qquad (9)$$

$$Y_{kt} = 0 \text{ or } 1 \qquad \forall t = 1,...,T,\ \forall k = 1,...,K_{\max} \qquad (10)$$

The objective function, given by equation (1) minimizes the number of delivery vehicles used in each cycle. Equation (2) ensures that the number of delivered bins/kits/pallets of each material plus the initial inventory at each station/line will always satisfy their demand in each cycle. Equation (3) ensures that a bin/kit can only be delivered in a cycle if a vehicle is available. It also ensures that the total number of bins/kits assigned to each vehicle, in each cycle, does not exceed the maximum capacity of the vehicle. Equation (4) enforces storage capacity at the stations/lines. Equation (5) represents available inventory at the end of each cycle and at each station/line. It also ensures that the demands can be always satisfied. Equation (6) implies that the inventory available at each line is always adequate for one hour. Equality (7) ensures that buffer capacity will be always full at the end of the planning horizon (last cycle). Finally, equations (8) to (10) state the nonnegative, integer, and binary nature of the decision variables.

It is worth mentioning that the MILP introduced in the current study is related to previous work of Emde and Boysen [12] who proposed a model for the continuous-time scheduling of the material delivery tours as well as routing the vehicles with the aim of minimizing total inventory and vehicle cost. In the approach proposed by Emde and Boysen [12], number of cycles and their start time should be determined by following continuous-time scheduling. In the current study, however, cycles and their start time are pre-fixed and the main questions are whether or not a cycle should be selected, and what amount of which parts should be loaded on the vehicle(s). The two studies are also different in terms of the objective function, in a way the number of vehicles in Emde and Boysen's [12] study is minimized by considering the total delivery in the whole planning horizon whereas our model distinguishes between the vehicles in different cycles. Therefore, the number vehicles used, and the associated costs in each cycle could be different while the total vehicle cost is minimized. In addition, the current model includes some additional constraints and assumptions as compared to the Emde and Boysen's [12] study, which include storage capacity at stations for each part, required safety buffer for each part at the end of each cycle and at the end of the shift, and availability of only one supermarket. This means, even though the current work and the Emde and Boysen's [12] study are related, they are starkly different in terms of the formulations proposed and perspectives incorporated.

5. Numerical experiments and results

In order to validate the efficiency and the performance of the proposed optimization model, three cases taken from the real world industry have been solved. To help the decision makers to choose the best delivery vehicle, each case has been solved by considering different possible transportation vehicles. For instance, large containers can be delivered by AGVs and forklifts but not tow trains. In contrast, small containers can only be delivered by AGVs and tow trains. Different capacities have been considered for different types of vehicles. An AGV can only deliver up to two big containers at each time whereas this number is four for the forklift. The AGV can deliver 4 to 6 medium/small containers at each line visit, but, the maximum of 18 containers can be delivered by each tow train. Due the economic reasons, the maximum number of vehicles of each type has been limited to be four. Moreover, the maximum number of cycles has been defined by considering the time of a round trip from supermarket to the assembly line and vice-versa, as well as loading and unloading time at the station and supermarket.

The model has been coded in GAMS software and all the problems were solved by using the default solver CPLEX. The results of the numerical experiments are reported in Table 2, and for each problem solved we present the most important characteristics (TV: type of transportation vehicle; TD: total demand; T: maximum possible number of cycles; K_{max} : maximum number of vehicles) and solution performance (K^*: optimum umber number of vehicles; T^*: optimum number of cycles).

The analysis of the results available in Table 2 shows that the proposed model found the optimum solution for all the problems. Moreover, the model successfully found the minimum number of vehicles required to satisfy the demand. To further test the generality of the model, each problem was solved by considering two different possible delivery vehicles. As an instance, all the data for the first and second problem come from the same assembly line, and these two sets of data are identical. The only difference among these two problems is the type of vehicle that effects the delivery capacity available and the maximum number of cycles. In the first two problems, the possible vehicles are AGVs and tow trains with the capacity of 4 and 9 containers, respectively. More capacity means extra time for loading and unloading at both assembly line and supermarket, thus, less cycles. In spite of the higher delivery capacity for the tow train, the minimum number of vehicles in the first and second problems is 2. However, the number of visits in the second problem, where tow train is used, lowers by 40 as compared to the first problem, where AGV is used.

The results presented in Table 2 provide decision maker with a valuable insight about the number of various types of vehicles required. Therefore, a more efficient economical decision can be made while choosing the type of vehicles by simply considering the cost of each vehicle.

In addition to the results presented in Table 2, a detailed delivery schedule is also generated by the optimization model proposed. This schedule precisely specifies the quantity of each material/part that should be delivered by each vehicle and in each cycle. To better exemplify the output schedule of the model, a small size problem has been solved (problem # 9 in Table 2) and its detailed schedule has been reported as Table 3. A new parameter (R), is defined in Table 2 to show the number of cycles required where,

$$R = sum\left\{ \min\left(1, \sum_{k=1}^{K_{max}} Y_{kt} \right) \right\} \forall t = 1,...,T \tag{11}$$

Also, the demand in each cycle is calculated by dividing the total demand by the number of cycles, while assuming a fixed and regular time interval among the cycles.

Table 2. Computation results for the real problems solved.

Problem No.	TV^a	TD^b	T	C	K_{max}	K^*	R
1	AGV	1034	144	4	4	2	144
2	Tow train	1034	107	9	4	2	104
3	AGV	177	253	1	4	1	184
4	Forklift	177	147	3	4	1	64
5	AGV	1241	144	6	4	2	144
6	Tow train	1241	63	18	4	2	63
7	AGV	151	147	2	4	1	79
8	Forklift	151	100	4	4	1	41
9	--	100	40	5	3	1	21

a:Type of transportation vehicle; b:Total demand; K^* : Optimum number of vehicles.

The detailed material delivery schedule for the problem 9 including the quantity of each part that should be derived in each cycle and by each vehicle are presented in columns 2 to 4 in Table 3, respectively. For instance, all the 100 demand in problem 9 are related to the 5 different material types. The demand for part 1 to 5 is 21, 20, 15, 13, and 31, respectively. Considering the initial inventory of each part at the beginning of the working shift, the scheduling suggests that one box of parts number 3 and 4, and 3 boxes of part number 5 should be delivered by the first vehicle in the first cycle. It is worth nothing that a dashed line means no delivery is planned in the corresponding cycle.

Table 3. Detailed material delivery schedule

Cycle	Part No.	Quantity	Vehicle No.	Cycle	Part No.	Quantity	Vehicle No.
1	3,4,5	1,1,3	1	21	--	--	--
2	1,2,3,4	1,2,1,1	1	22	1,2,5	2,1,2	1
3	--	--	--	23	1,3,4,5	1,1,1,2	1
4	1,2,3,5	1,1,1,2	1	24	--	--	--
5	--	--	--	25	--	--	--
6	--	--	--	26	1,2,4,5	1,2,1,1	1
7	1,2,3,4,5	1,1,1,1,1	1	27	--	--	--
8	--	--	--	28	1,3	2,2	1
9	1,2,4,5	1,2,1,1	1	29	2,4,5	2,1,2	1
10	--	--	--	30	--	--	--
11	3,4,5	1,1,3	--	31	1,3,4,5	1,1,1,2	1
12	1,3,5	2,1,1	1	32	--	--	--
13	1,2,4,5	1,2,1,1	1	33	--	--	--
14	--	--	--	34	2,5	3,2	1
15	--	--	--	35	1,3,4	2,1,2	1
16	2,5	2,1	1	36	5	3	1
17	1,3,4,5	2,1,1,1		37	--	--	--
18	--	--	--	38	--	--	--
19	--	--	--	39	1,2,3,5	2,1,1,1	1
20	2,3,5	2,1,2	1	40	--	--	--

6. Conclusion remarks and future research directions

It is a common strategy for contemporary manufactures to shift their production philosophy from mass production toward mass customization due to the ever changing customer demands and market trends. Manufacturing customized products will consequently increase the importance of logistics system and specifically the material supply process. In this study, an optimization model was presented and further proven to be effective for scheduling the material delivery at assembly lines. To validate the model and evaluate its performance, some real case problems were solved. The results of the study showed that the model is capable of finding the minimum number of transportation vehicles required to satisfy the demand at assembly lines. It can also provide the user with precise delivery schedule including the information about the material and its exact quantity that should be delivered in each cycle and by each vehicle while ensuring that no material shortage occurs. The model is not only able to find the minimum number of vehicle, but, it can also decide on the time of delivery by selecting the right cycle for delivery and thus, reducing the number of line visits.

As for the future work, the model can be extended by considering other or multiple objectives such as cost of holding inventory at the line, delivery time, and so on. Moreover, the model can be further developed to cope with uncertainty in some inputs like demand. Tackling multiple objectives may also be beneficial for industry, and interesting from the scientific point of view.

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