CAR SEQUENCING PROBLEM - CONFRONTATION WITH REAL AUTOMOTIVE INDUSTRY

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Abstract

The article presents problem of sequencing multiversion car production. An issue of so-called Car Sequencing Problem, widely considered in the literature, is discussed. It is noted, that the problem presented by researchers is only a reduced problem in comparison with the problem occurring in real automotive production. Thus, some assumptions of the proposed approaches are questioned. For the sake of that, first a new formulation of sequencing problem is presented. The modified issue includes problems occurring on production line equipped with buffers and focuses on determining an order in which cars should be produced. Secondly, a new approach to the sequencing problem is proposed. The follow-up production control is suggested as a method of multiversion production sequencing.

Keywords: Sequencing, car production, buffer, multiversion production, CSP, follow-up production control

1. INTRODUCTION

Sequencing problem is considered in many fields of science, for example airplanes sequencing [1] or in biology - sequencing of DNA [2, 3]. Sequencing problem is often considered also in relation to production processes, in which many versions of the same product are manufactured. Sequencing may be considered as short-term decision-making process, which aim is to set an order of execution production variants. It is important to meet demand for all products, planned under the Master Production Schedule (MPS). The follow-up production control can be one of methods intended for sequencing of product variants in multiversion, repetitive production. The example of this production type is car manufacturing - body color and equipment for each car may be different, which indicates multiversion production. In this case, the purpose of sequencing is mixing of car variants in the same process. Regardless of science area, in which the sequencing problem is considered, this issue concerns determination of certain order, whether amino acids, or airplanes or products on production line. The use of proper sequence is a way to improve the defined Key Performance Indicators of the analyzed problem. In the case of the production process it may be, for example, the throughput, the production time or the number of changeovers of machines or robots. In this paper sequencing problem is discussed on an example of multiversion car manufacturing on a production line equipped with buffers.

2. CAR SEQUENCING PROBLEM - CASE STUDY

Car production consists of several steps that are executed one after another, according to specific order. During initial phase, steel is provided to a press shop and is used to form individual components of car body, such as: doors, floor elements, mask, roof, fenders and others. Next, in a body shop (called Body in White), robots and operators weld various parts, supplied from the press shop, to form a right structure of vehicle depending on a model of a car. Then car bodies are sent to a paint shop, where they are painted in a required color by robots equipped with painting guns. In the last phase of the process, on an assembly line, various components (e.g. sunroof, radio, air-conditioning), which form appropriate variant of equipment, are installed in a car [4]. The question is which sequence of produced cars should be used (how to organize and plan the production) in order to ensure maximum throughput of the production line and offer the largest variety of cars (models and equipment). This issue, defined as Car Sequencing Problem (CSP), has been first described by Parello et al. in 1986 [5]. The original CSP concerned sequencing cars along an assembly line, in order to install additional components in them. The solution of this problem was to find order of cars, requiring specific components, so that workstations capacity was never exceeded. This is due to the fact that each workstation is designed to handle a certain percentage of cars passing along an assembly line [4].

2.1. Definition of the original CSP

An instance of the original CSP proposed by Parello et al. is defined by a tuple (V, O, p, q, r), where:

- $V = \{v_1 \ldots v_n\}$ is a set of vehicles to be produced,
- $O = \{o_1 \ldots o_m\}$ is a set of different options,
- $p = \{p_1 \ldots p_i\}$, $q = \{q_1 \ldots q_i\}$ define the capacity constraint associated with each option $o_i \in O$; this capacity constraint imposes that, for any subsequence of q_i consecutive cars on the line, at most p_i of them may require o_i,
- $r = \{0,1\}$ defines options requirements, i.e., for each vehicle $v_j \in V$ and for each option $o_i \in O$, $r_{ji} = 1$ if o_i must be installed on v_j, and $r_{ji} = 0$ otherwise.

As can be seen, at the beginning the CSP included only problems relating to an assembly line, what was not sufficient to meet the requirement of real factories. After a few years, in 2005, it was noticed the need to expand the CSP to a problem which includes problems occurring on an assembly line as well as in a paint shop. Thus, additional parameters and constraints associated with body painting process were introduced to the primary definition of the CSP. The modified problem became a subject in ROADEF'2005 Challenge, organized by the French Society of Operations Research and Decision Analysis.

2.2. Definition of the challenge CSP

An instance of the challenge CSP based on the tuple proposed by Parello et al., but this instance was extended with following parameters and assumptions [4]:

- $O_H = \{o_{H1},\ldots,o_{Hm}\}$ and $O_L = \{o_{L1},\ldots,o_{Ll}\}$, $O_H \subset O$, $O_L \subset O$ - two subsets of options were introduced, because installation of each option has a different influence on the throughput of an assembly line,
- $C = \{c_1,\ldots,c_d\}$ - a set of colors,
- B - a batch size limit,
- σ_k - a sequence that contains the last k vehicles sequenced during a previous day,
- w_{CC}, w_{LPRC}, w_{HPRC} - weights for: color changes, low priority and high priority ratio constraint violations, where $\{w_{CC}, w_{LPRC}, w_{HPRC}\}$ is a permutation of $\{1, 10^3, 10^6\}$, such that $w_{HPRC} > w_{LPRC}$.

The cost of a feasible solution was the weighted sum (1) of the number of color changes (*NCC*), the number of high priority ratio constraint violations (*NHPRC*) and the number of low priority ratio constraint violations (*NLPRC*):

$$cost = w_{CC} \cdot NCC + w_{HPRC} \cdot NHPRC + w_{LPRC} \cdot NLPRC \quad (1)$$

Solution of the challenge CSP was to find an arrangement of vehicles in a sequence, thus defining the order in which the vehicles pass through an assembly line.

3. CAR SEQUENCING PROBLEM AND THE REQUIREMENTS OF AUTOMOTIVE INDUSTRY

Over the years, a lot of algorithms used to solve the original and modified CSP were proposed by researches. The solution was sought using both exact approaches, e.g. Constraint Programming [6,7,8], Integer Linear Programming [9], Branch and Bound method [10] and heuristic approaches, e.g. Local Search [11], Tabu Search [12], Genetic Algorithms [13]. Unfortunately, virtually, none of these proposed methods were suitable to solve the industrial Car Sequencing Problem because of the time needed to find the solution. Furthermore, in many cases several aspects, which call into questions the approach to the challenge problem, were not taken into account.

3.1. Questionable assumption of the challenge problem

Formulation of the challenge CSP was the first step towards approximating the original CSP to the real problem. However, analyzing the formula (1) carefully it is not known, how the weights were calculated. But it should be clearly explained because a combination of weights has fundamental influence on the obtained solution. Furthermore, it should be noted that the weights were not normalized. These aspects raise serious doubts about the validity and reliability of the proposed objective function. In addition, even the modified approaches, proposed by many scientists, can still not be directly used in industry. Despite taking into account additional parameters, related to the paint shop, the challenge CSP was still too simplified in comparison to requirements of modern automotive industry, as follows:

1) One of fundamental problems, which was included neither by Parello et al. nor later, is an assumption that a paint shop and an assembly line are treated as a permutation flow system. Thereby determining a sequence of cars must be specified before production start, so it is not possible to change the sequence during production, what is one of the requirements of today's automotive industry.
2) It is also important to remark that in the case of the challenge CSP the use of paint system based on filling the painting guns with portions of paint was assumed - hence it follows batch size limit. Such systems belong to solutions rarely used in the industry.
3) The painting process takes place in several steps, not as it was assumed in just one - painting on base color.

In summary, the CSP, presented by Parello et al. as well as the more expanded problem are a good example of search for solutions to the sequencing problem, but only at the academic level. The solutions to these problems are not useful for modern automotive industry, like all used exact and heuristic approaches. Consequently, this article proposes a new approach to the problem of car sequencing that reflects to problems occurring on an actual production line. This problem has been defined as Car Sequencing Problem with Buffers (CSPwB).

4. CAR SEQUENCING PROBLEM WITH BUFFERS

Despite the huge amount of research done over the last years, there is still a vast bridge between the methods considered in the literature and the current industrial problems. For this reason there are difficulties in direct use of these methods in practice. Therefore, it is suggested to modify the CSP in accordance with following remarks:

1) Currently can be observed a move away from Make To Stock production (MTS) to Make To Order production (MTO), which requires the use of mechanisms for the sequence changes during production and for adaptation sequences to incoming orders. Therefore, structure like buffers are used primarily between body shop, paint shop and assembly line, so particular departments are more independent of each other. The purpose of buffers is to ensure continuity of production and the ability to change the sequence depending on demand. Buffers are also found inside a paint shop in order to become independent of individual steps of body painting, so it is necessary to take into account parameters of buffer structures. It should be also noted that bodies are painted in several steps: painting on primary color, painting on base color and painting on colorless paint (this painting step does not affect the sequencing process because there is only one kind of colorless paint).
2) The most commonly used paint system is a system based on continuous filling the painting guns, so there is no batch size limit because the gun is not intended for storing paint, it only serves as an intermediate element in painting process. The use of such a system necessitates periodic cleaning of

painting guns what should be included in order to optimize painting process. Such cleaning may occur for example once a week or even at the end of each work shift. Each cleaning increases consumption of both the paint and the paint solvent, which is used to wash painting guns.

3) Given that car bodies are painted in different colors, an analysis of paint consumption should be conducted separately for each color. It is not only important, how many times robots had a changeover, as suggested in the Challenge, but also how much paint (remaining in the painting guns) was not used because of changeovers and what color was the paint. The analysis should include both the primary color and the base color. Conducting such a statistics allows in turn to optimize management of stock and production resources and to provide with material requirement planning.

Taking into account the observations presented above, it is proposed to formulate a new instance for the proposed Car Sequencing Problem with Buffers.

5. PROBLEM FORMULATION

Table 1 presents input parameters for CSPwB specifying order details, technological constraints in paint shops (periodic cleanings) and on assembly line (capacity constraints).

Table 1 Input parameters

Order	Description	Lines/ buffers	Description	Technological limitations	Description
NV	Number of vehicles subject to sequencing	*NiBS*	Maximum number of indexes in body shop	*NVPerClnPrPS*	Frequency for periodic cleanings in primary paint shop
NP	Number of car parameters	*NiPrPS*	Maximum number of indexes in primary paint shop		
NM	Number of possible models	*NiBsPS*	Maximum number of indexes in base paint shop	*NVPerClnBsPS*	Frequency for periodic cleanings in base paint shop
NCf	Number of possible configuration	*NiAL*	Maximum number of indexes on assembly line		
NCp	Number of possible components	*NrBPrCl, NcBPrCl*	Dimensions of buffer for primary paint shop	*xNPossVLSubS*	Assembly line constraints defined for each component
NPrCl	Number of possible primary color	*NrBBsCl, NcBBsCl*	Dimensions of buffer for base paint shop		
NBsCl	Number of possible base color	*NrBAL, NcBAL*	Dimensions of buffer for assembly line		

The proposed cost function is the weighted sum (2) of the total number of cleanings in primary paint shop (*tnClnPrPS*), the total number of cleanings in base paint shop (*tnClnBsPS*) and the total number of violations of assembly line capacity constraints (*tnViolAL*):

$$F = w_1 \cdot tnClnPrPs + w_2 \cdot tnClnBsPs + w_3 \cdot tnViolAL \rightarrow \min, \quad (2)$$

where $\{w_1, w_2, w_3\}$ is a set of weights for sum components.

As can be see, before solving the problem weights in function (2) should be appropriately chosen, what is a subject of future research. The solution to CSPwB is to find not one sequence but six: an input/output sequence into the buffer for primary color, an input/output sequence into the buffer for base color and an input/output sequence into the buffer for assembly line. The division into six sequences ensures that individual departments are independent of each other. To find these sequences, it is proposed to use the follow-up production control.

6. FOLLOW-UP PRODUCTION CONTROL

The follow-up production control (FUPPC) [14] is one of the methods that can be used for ongoing decision making in the paint shop. These decisions concern tasks (sequences) which are assigned to execution at the time of completion of tasks performed previously. In the FUPPC method each order for a production system appears at the beginning of a certain current period of operational planning and contains a process ID, which informs about the tasks to be performed. In the analyzed process, the order contains information about the number of cars and color, on which they should be painted. In addition, in the variant of the FUPPC, intended for sequencing, future orders are determined together with forecasts of time of arrival to the system and planned due times. In the event of overcapacity of the paint shop, the load-planning algorithm may transfer a part of the orders to later periods. It can be interpreted as division of production orders or their parts into smaller orders. Car bodies that are assigned to these orders, need to be kept in a buffer, located before the paint shop.

The follow-up production scheduling (FUPPS) method is a local algorithm in a hierarchical production control system. It is intended for current generation of executive plans implemented in a paint shop in such a way that these plans follow-up the operational plans, coming from the coordination unit of the system. Calculation of load planes is an operational planning, while executive planning is generated by the follow-up production scheduling. The decisions of the FUPPS method are based on the state of the algorithm, which consists of previously taken decisions and the state of arrears in the implementation of the operational plans by the executive plans. The arrears are cumulative differences between these plans in subsequent periods of executive planning. The operational plans are introduced with a regular period, which is a multiple of the executive planning period. The FUPPS algorithm works in a feedback system analogous to a tracking system, whereby operational plans act as target values, executive plans act as follow-up values. In the analyzed process the operational plans are production orders. Every reading of the operational plans causes an increase of a backlog (the number of car bodies to be painted). The subsequent executive plans generated by FUPPS algorithm reduce these backlogs. In general case, the FUPPS algorithm, which operates at the end of working period or during downtime of production cells, makes a current decision, whether to work or stop. Due to the nature of production process, carried out in the paint shop, only a decision to work should be excepted. Stoppage will be permitted in the absence of sufficient number of production orders. In the case of work, it is a decision on a sequence of car bodies to be painted.

Due to the main purpose of the current control of the paint shop, it may seem that the decision to work should always be made when there are any backlogs in the implementation of the operational plans and the length of the sequence should be as large as possible. The batch size of the individual color in a sequence should be equal to the arrears. The paintng process can be conducted in smaller batches, but it should be noted that color change is a time-consuming and coslty process, therefore the size of a batch should be carefully selected.

In the process of making a decision on the sequence for current working period (how many car bodies, what colors, what orders) following priority rules can be used:

- LPT - *Longest Processing Time,*
- SPT - *Shortest Processing Time*,
- FIFO - *First In - First Out,*
- LIFO - *Last In - First Out*.

Applaying these rules to the proposed sequencing problem requires some modifications in accordance with following: the LPT rule selects the color for which the number of car bodies in the buffer is the largest; the SPT rule specifies the color for wich the number of car bodies in the buffer is the smallest; the FIFO rule chooses the color for which the number of car bodies in the buffer at the earliest reaches the threshold of backlogs, the LIFO rule determines this color to execution for which the number of car bodies in the buffer at the lates reaches the threshold of backlogs

7. CONCLUSIONS

The Car Sequencing Problem, widely considered in the literature, is only a simplification of problem occurring in automotive industry. The expansion of the CSP to a real problem requires inclusion of many parameters and access to actual data, based on which the studies can be carried out. A new formulation of the original Car Sequencing Problem is introduced in the article. This problem has been defined as Car Sequencing Problem with Buffers (CSPwB). It is necessary to use different sequencing methods to solve the proposed real problem. The articles presents the possibility of using the follow-up production control to find appropriate order of cars.

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