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Buffer management in solving a real sequencing problem in the automotive industry – Paint Shop 4.0 concept

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The paper presents a Car Sequencing Problem, widely considered in the literature. The issue considered by the researchers is only a reduced problem in comparison with the problem in real automotive production. Consequently, a new concept, called Paint Shop 4.0., is considered from the viewpoint of a sequencing problem. The paper is a part of the previously conducted research, identified as Car Sequencing Problem with Buffers (CSPwB), which extended the original problem to a problem in a production line equipped with buffers. The new innovative approach is based on the ideas of Industry 4.0 and the buffer management system. In the paper, sequencing algorithms that have been developed so far are discussed. The original Follow-up Sequencing Algorithm is presented, which is still developed by the authors. The main goal of the research is to find the most effective algorithm in terms of minimization of painting gun changeovers and synchronization necessary color changes with periodic gun cleanings. Carried out research shows that the most advanced algorithm proposed by the authors outperforms other tested methods, so it is promising to be used in the automotive industry.

Key words: sequencing, car production, paint shop, buffer management, changeovers

1. Introduction

The article presents a selected class of sequencing problems in conditions of limited access to information on sequenced elements. These problems belong to the group of problems of discrete optimization covering a wide range of application, such as planning and controlling production flow. A special case of the problem of car sequencing in multiassortment and multiversion production

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system is presented, in particular in the paint shop. This subject is known for many years, but as it turns out, it is still very current. The problems currently occurring in practice with their assumptions go beyond the possibilities of the methods and models developed so far in the literature.

In most known cases, sequencing problems belong to the class of NP-hard problems. This means that one should not expect temporarily effective algorithms to solve them. It should be noted that the difficulty of these problems is additionally increased when considering – so often occurring in practice – limited access to information about the set of sequenced elements. In this type of problems, the set of sequenced elements already has a preset order (not always known), which needs to be changed in order to optimize the indicators relevant at a given stage of production. This is related, for example, to the minimization of the costs of the paint shop.

The paper is organized as follows. Section 2 presents the original Car Sequencing Problem and the problem proposed by Renault for the ROADEF'2005 Challenge. Section 3 includes an overview of the exact and heuristic methods, proposed in the literature, and contains a discussion about assumptions of the challenge problem. Section 4 describes the Paint Shop 4.0 concept from the point of sequencing problem view, presents background and definition of the new problem existing in the real plant. Section 5 presents selected sequencing algorithms and focuses on original Follow-up Sequencing Algorithm developed and currently tested by the authors. Section 6 includes research results and discussion about the effectiveness of proposed algorithms. The final Section concludes the paper.

2. Car sequencing problem

Car production consists of several steps that are executed one after another in a specific order (Fig. 1).

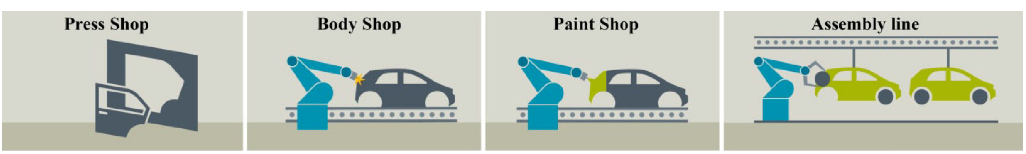

Figure 1: Stages of car production.

During the initial phase, steel is provided to a press shop and is used to form individual components of the car body, such as: doors, mask, roof, and others. Next, in the 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 the car model. Then car bodies are sent to the paint shop, where they are painted in required color by robots equipped with painting guns. In the last phase of the process, on the assembly line, various components (e.g. radio, air-conditioning), which form appropriate variant of equipment, are installed in a car. 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 (in terms of models and equipment). This issue, defined as the Car Sequencing Problem (CSP), has first been described by Parello, Kabat, and Wos [38].

2.1. Definition of the original problem

The original Car Sequencing Problem concerned sequencing cars along the assembly line, in order to install additional components in them. An instance of the original problem was defined by a tuple (V, O, p, q, r), where:

- $V = \{v_1 \dots v_n\}$ is a set of vehicles to be produced,
- $O = \{o_1 \dots o_m\}$ is a set of different options,
- $p = \{p_1 \dots p_i\}$, $q = \{q_1 \dots q_i\}$ 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.

The solution of the problem was to find the sequence 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 the assembly line [45].

At the beginning, CSP included only problems related to the assembly line, what was insufficient to meet the requirements of real factories. In 2005, the need to expand CSP to a problem which includes the assembly line as well as the paint shop, was noticed. Thus, additional parameters and constraints associated with the body painting process were introduced to the primary definition of 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 problem

An instance of the challenge problem based on the tuple proposed in [38], but this instance was extended with the following parameters and assumptions [45]:

- $O_H = \{o_{H1}, \ldots, o_{Hm}\}$ 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*).

$$\text{cost} = w_{CC} \cdot NCC + w_{HPRC} \cdot NHPRC + w_{LPRC} \cdot NLPRC. \tag{1}$$

The solution of the challenge CSP was to find an arrangement of vehicles in a sequence, i.e. defining the order in which vehicles pass through the first paint shop and then the assembly line. The lower the value of the cost function, the better the solution. This problem has been shown to be NP-hard in [19, 29].

3. Overview of state-of-the-art approaches

In the literature, there are many approaches to the Car Sequencing Problem developed over the last years. Among the exact approaches, methods like: Constraint Programming (CP) [6, 10, 14, 25, 27, 33, 41], Integer Programming (IP) [15, 23], ε-constraint method [7, 42] and Branch and Bound (B&B) [15, 16, 18, 21, 49] were considered. The research was also conducted in the context of the use of methods that provide approximate solutions. The Local Search idea was considered in [12, 13, 22, 28, 33, 34, 36, 37, 39, 40]. The Beam Search and iterative Beam Search procedures were used in [4, 18, 21]. Tabu Search and iterative Tabu Search approaches were considered in [11, 34, 51]. The Simulated Annealing was subjected to research in [9, 43]. The Genetic Algorithm was used in [8, 28, 50]. In [23, 44, 45, 47, 48] the Ant Colony Optimization was investigated. The greedy approach was used to solve CSP in [5, 22, 26].

Since ROADEF'2005 Challenge CSP was not further expanded and the interest in this problem has decreased – new research on this subject has not appeared in the literature over the last years.

3.1. Questionable assumption of the challenge problem

The formulation of challenge CSP was the first step towards approximating the original CSP to the real problem, according to the statement that simulation should be based on modeling the reality [17]. However, analyzing the formula (1) it is not known, how the weights were calculated. But it should be clearly explained because a combination of weights has a great influence on the obtained solution. Furthermore, it should be noted that the weights were not normalized. These aspects raise doubts about the validity and reliability of a proposed objective function.

The modified approaches, proposed by many scientists, can still not be directly used in the industry. Despite taking into account additional parameters, related to the paint shop, challenge CSP was still too simplified in comparison to requirements of the modern automotive industry. One of the fundamental problems, which was included neither by Parello, Kabat and Wos [38] nor later, is an assumption that the paint shop and the assembly line are treated as a permutation flow system. Thereby determining a sequence of cars must be specified before a start of production, so it is not possible to change the sequence during production, which is one of the requirements of today's automotive industry. The CSP, presented in 1986 as well as the more expanded problem are a good example of a search for solutions for the sequencing problem, but only at the academic level. The solutions to these problems are not useful for the modern automotive industry, like all used exact and heuristic approaches. Thus, CSP is still considered an open problem.

This work is a part of previously conducted research on so-called Car Sequencing with Buffers (CSPwB) introduced in [1–3], which was a new approach to solve the problem of car sequencing that would reflect problems occurring in a real plant. During the research, the problem has been extended and is currently considered in the context of using modern tools, like Virtual Engineering and Virtual Commissioning, which are part of the Industry 4.0 concept. This is a part of a larger project called Paint Shop 4.0 carried out currently by the authors.

4. Problem of car sequencing in Paint Shop 4.0 concept

The Paint Shop 4.0 concept was developed in cooperation with ProPoint Sp. z o.o. Sp. k. as a response to the market situation and demand for such a solution. The studies were divided into four parts: modeling, Virtual Engineering, Virtual Commissioning and optimization of the sequencing process using buffer control system. The results of the first three stages are described in [2, 3]. This paper presents the results of the fourth stage.

4.1. Background of new problem

In real-life production, processes are very often not executed accordingly to assumed MPS. The reason for this is the occurrence of uncertainty conditions. Koh and Saad [30] defined uncertainty as any unpredictable event that disturbs the production process in a manufacturing system, that is planned by MRP (Material Requirements Planning). Therefore, the performance of typical equipment systems (serial, parallel, mixed) is most often increased by e.g. using additional capacitive elements – like buffers, small warehouses or storage tanks [35]. The basic aims of these elements are to: protect the flow capacity, reduce the level of stocks and decrease operating expenses. The process of their monitoring and improvement, as well as guidelines to its location, make up a control system [24]. Production flow in real-life manufacturing systems should be adapted to the structure of capacitive elements. Such an approach is often applied in the automotive industry.

In car factories, buffers are mostly used between the body shop, the paint shop and the assembly line (Fig. 2).

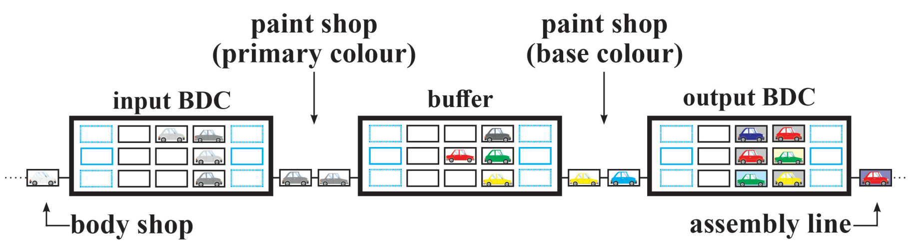

Figure 2: The structure of the production line in the paint shop.

The main purpose of the buffers is to ensure continuity of production, but from a wider point of view, they have a great significance in changing the input sequences independently for each shop and depending on their individual needs [32]. This is the reason, why in some works e.g. [46] these buffers are called selectivity banks.

Buffers occurring between shops are called Body Distribution Centers (BDC). The sequencing of orders in the "input" BDC is carried out due to optimization aims of the first step of the painting process, while the sequence of cars in the "output" BDC is adapted to requirements of the assembly line. The buffer located in the paint shop is intended to ensure the independence of the first two stages of painting and re-sequencing car bodies painted in a primary color. As can be seen, car bodies are painted in several steps: painting on a primary color, painting on a base color and painting on colorless paint, but only the first two stages are important from the viewpoint of sequencing problem.

The Paint Shop 4.0 concept focuses, among others, on controlling the buffer involved in the optimization of the sequencing in the base painting process. Because the sequencing process, which uses "input" BDC and buffer located in the paint shop differs only in terms of the number of considered colors (the number of primary colors is less than the number of base colors), the algorithms developed for the buffer located in the paint shop can be directly applied to "input" BDC. The paper focuses on the second buffer, because this component line is usually a bottleneck in many automotive companies. The peculiarity of painting process leads to a big amount of failures, which need to be reprocessed, e.g. not appropriate paint coats, workers' hairs or fibers from clothing stuck to paint coats [20]. In addition, the painting guns need to be thoroughly cleaned at every color change – because of the so-called periodic cleanings [31]. It increases the consumption of both paint and solvent, what car producers want to avoid. This is one of the Paint Shop 4.0 goals.

4.2. Definition of Car Sequencing Problem 4.0

A new look at the problem of car sequencing proposed in the paper differs from original and challenge CSP, in terms of assumptions about the production line structure. In addition, the car instance is not defined in advance, because cars arrive at the paint shop on a regular basis and their parameters are read by sensors immediately before entering the buffer. Therefore, when a car body appears at the buffer input it is necessary to decide on which buffer position it should be directed to. On the other hand, it has to be decided which body car from the buffer output should be sent for painting. A new mathematical formula of new sequencing problem is proposed.

The problem is described by input and output variables, and technological parameters. Among parameters two constants are specified:

- *NoRowBuff, NoColBuff* – number of buffer rows, columns (buffer size);
- *PerCleanInter* – periodic cleaning interval.

The input data are:

- *BuffState* – current buffer state presented as a matrix of colors;
- *cIn* – color of loaded car (loading position);
- *cNext* – color of loaded car (preloading position);
- *cOut* – color of unloaded car (unloading position);

The output data are:

- *BuffRowLoad* – row of the buffer to which loaded car is transported;

- *BuffRowUnload* – row of the buffer from which unloaded car is transported to the painting process.

The main goal of solving the problem is to find a sequence that minimizes the number of color changes occurring between periodic cleanings. It can be understood as aiming for the most frequent synchronization of changeovers with periodic cleanings, resulting from changing colors. The obtained solution is assessed based on the following quality indicators:

- *nCCUnSyn*, number of changeovers unsynchronized with periodic cleanings – the smaller the number, the better the solution,
- *nCCSyn*, number of changeovers synchronized with periodic cleanings – the larger the number, the better the solution.

5. Proposed sequencing algorithms used in buffer management

In this section, selected sequencing algorithms, understood as a way of loading and unloading the buffer, are discussed. The aim of the loading algorithm is to determine the position in the buffer to which the body car located at the buffer input is directed. The unloading algorithm is designed to create a sequence at the buffer output.

Two algorithms of loading cars and two algorithms for unloading cars are tested during research. For comparison, a theoretical situation when the buffer does not exist, i.e. it is not possible to change the sequence before the painting process, is considered.

5.1. Loading cars

Following algorithms are proposed to fill the buffer:

1) inFU (First Unoccupied) – car from an input line is directed to a first unoccupied position in the buffer;
2) inFUCM (First Unoccupied with Color Memory) – if it is possible, a car from an input line is directed to the line ending with the car of the same color; otherwise, the inFU algorithm is applied.

5.2. Unloading cars

Following algorithms are considered as methods of unloading the buffer:

1) outTtB (Top to Bottom) – an output sequence is generated accordingly to the algorithm shown in Figure 3 – cars are removed from the buffer from a specified position, from top to bottom;

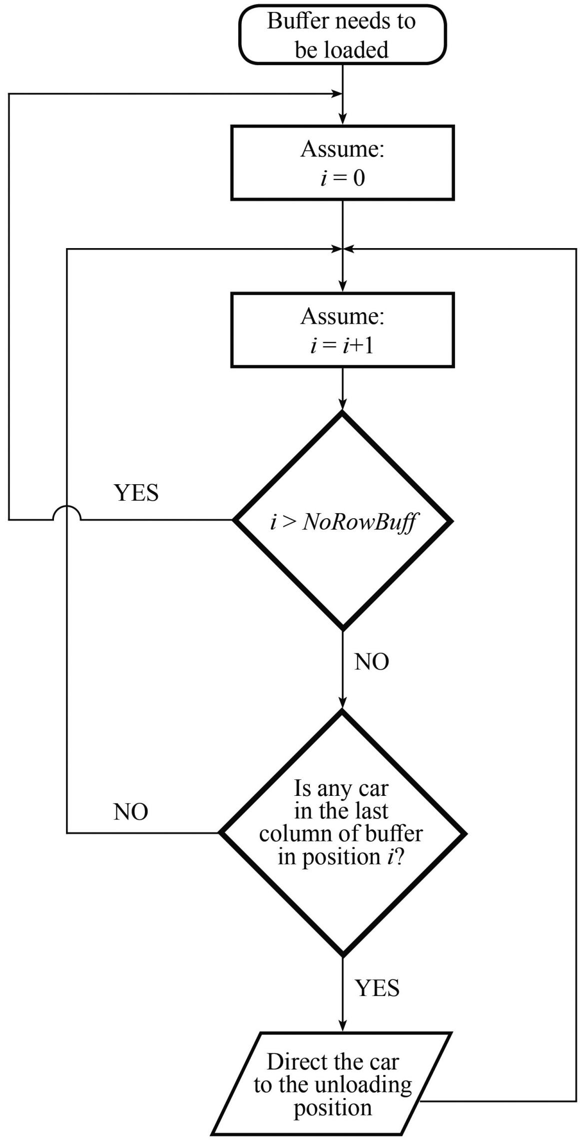

Figure 3: Block diagram of outTtB algorithm for car sequencing.

2) outCMoR (Color Memory, otherwise Random) – an output sequence is generated accordingly to the algorithm shown in Figure 4 – as far as possible, from the buffer is removed the car, which should be painted on the same color as the color of the currently painted one (grouping cars based on a feature – in this case, a color). Otherwise, to output line is directed the car placed in a random position in the last column.

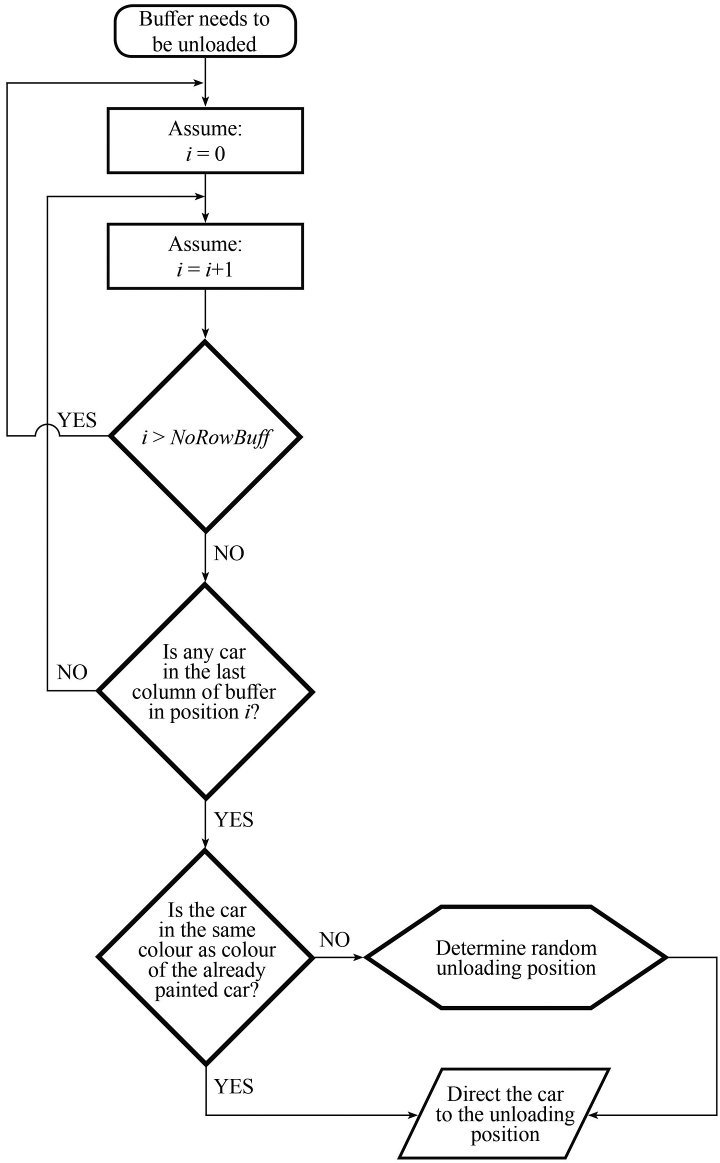

Figure 4: Block diagram of outCMoR algorithm for car sequencing.

In addition, a complex sequencing algorithm called FuSA (Follow-up Sequencing Algorithm) is considered. Due to the complexity of the FuSA, presented block diagrams show a general concept of the algorithm. The loading (Fig. 5a) and unloading (Fig. 5b) methods work parallel and are coupled together. The algorithm follows: the state at the input/output of the buffer, buffer state, occurrences of periodic cleanings and also production plan.

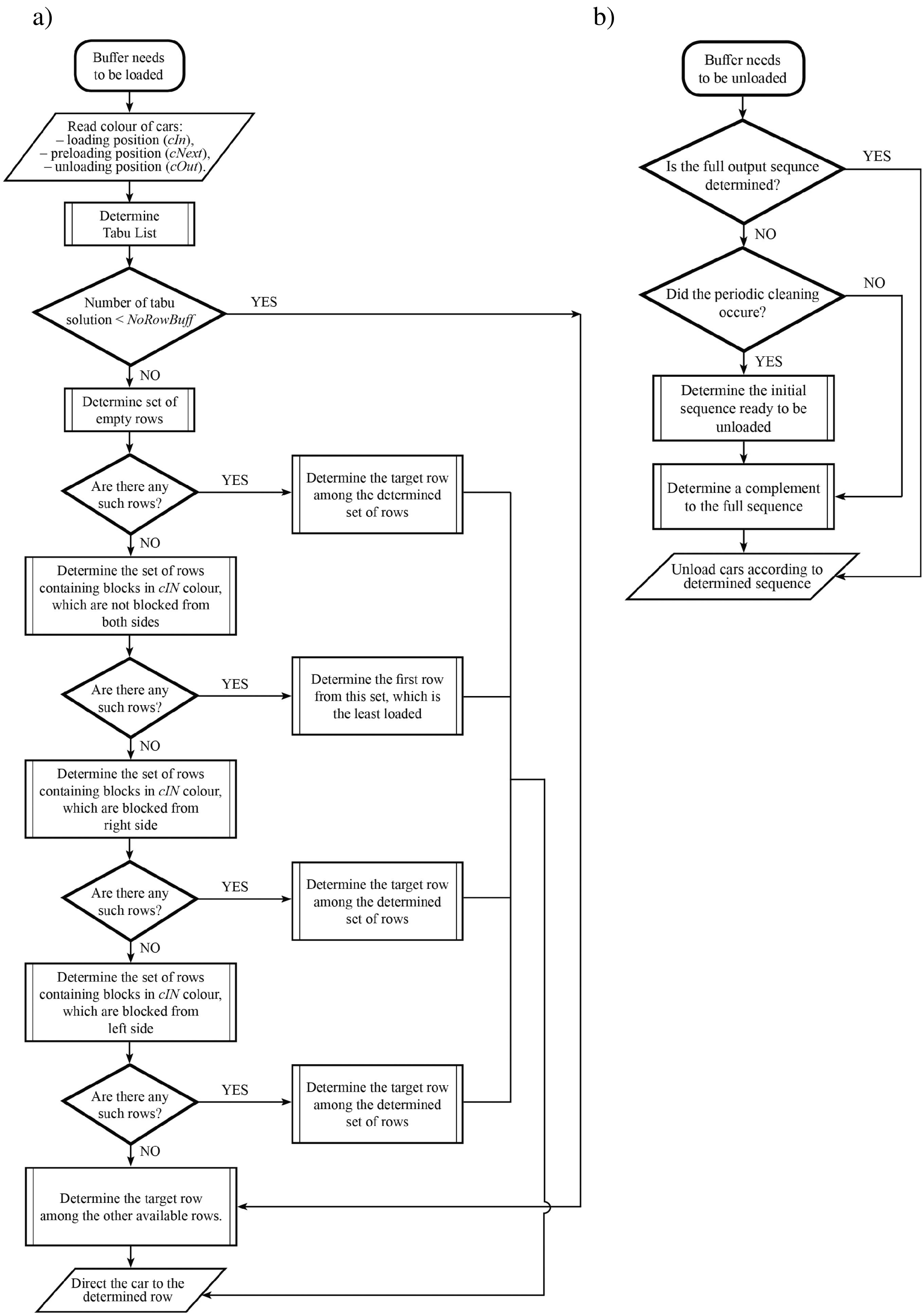

Figure 5: FuSA concept: a) loading algorithm, b) unloading algorithm.

6. Simulation research

The following algorithms were tested during simulation research: inFU + outTtB, inFU + outCMoR, inFUCM + outTtB, inFUCM + outCMoR. The main goals of carried out experiments were to:

- evaluation of the effectiveness of proposed sequencing algorithms, using *nCCUnSyn* and *nCCSyn* quality indicators,
- verification of the impact of loading algorithms (inFU, in FUCM) on the result of the sequencing process using the given unloading algorithm,
- verification of the impact of unloading algorithms (outTtB, outCMoR) on the result of the sequencing process using the given loading algorithm,
- comparison of the effectiveness of the advanced FuSA and simple proposed sequencing algorithms.

6.1. Case study assumptions

The structure of the analyzed buffer and the possible directions of internal transport (marked with orange arrows) are presented in Figure 6. The buffer consists of 25 positions (5x5), intended for car body buffering, and of 2 columns (marked in blue), used to transport the car bodies to the correct row. Inside blue columns, the movement is carried out vertically up and down, while transport between "buffering" positions is possible only horizontally to the right within individual rows. It is assumed that in the initial state the buffer is empty, but the unloading process starts only after the buffer is filled up to 60%.

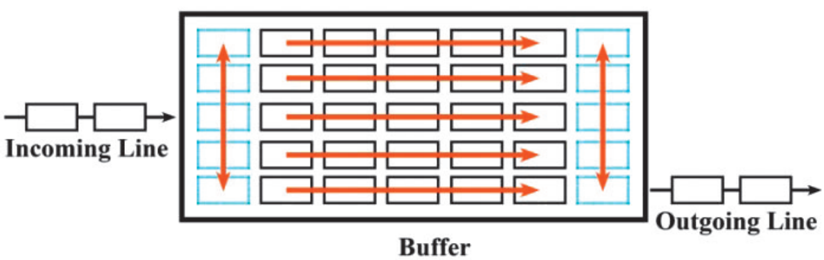

Figure 6: Structure of the analyzed buffer.

For the purpose of the research, 5 sets of real historical data were used. Each set consisted of 100 cars painted in 6 different colors. The colors distribution in each set was the same, as follows: C1: 6%, C2: 38%, C3: 29%, C4: 14%, C5: 10%, C6: 3%. In order to ensure a good quality of painting, after every 7 car bodies, the necessary periodic cleaning of guns was carried out.

6.2. Research results and discussion

In this section, experimental results are presented. Figures 7–10 show evaluation of obtained solutions.

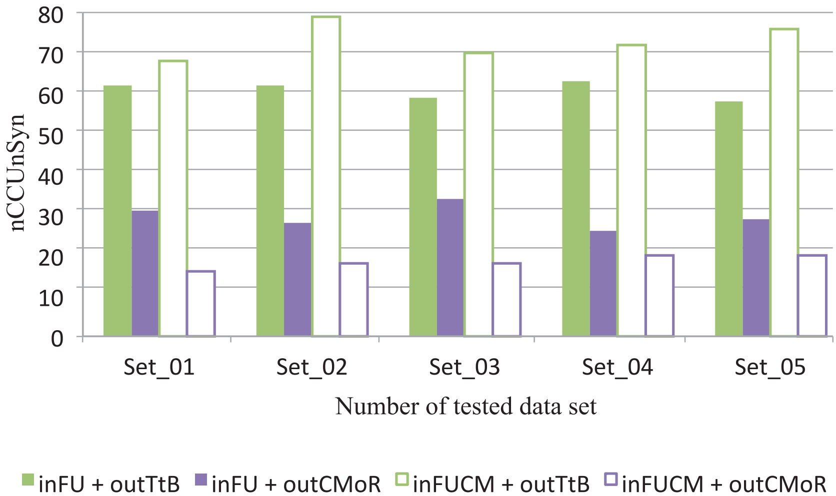

Figure 7: Evaluation of solutions in terms of the *nCCUnSyn* indicator for selected sequencing algorithms.

Regardless of the loading algorithm, the *nCCUnSyn* quality indicator reached lower values for the outCMoR algorithm. Algorithm inFU + outTtB gave slightly

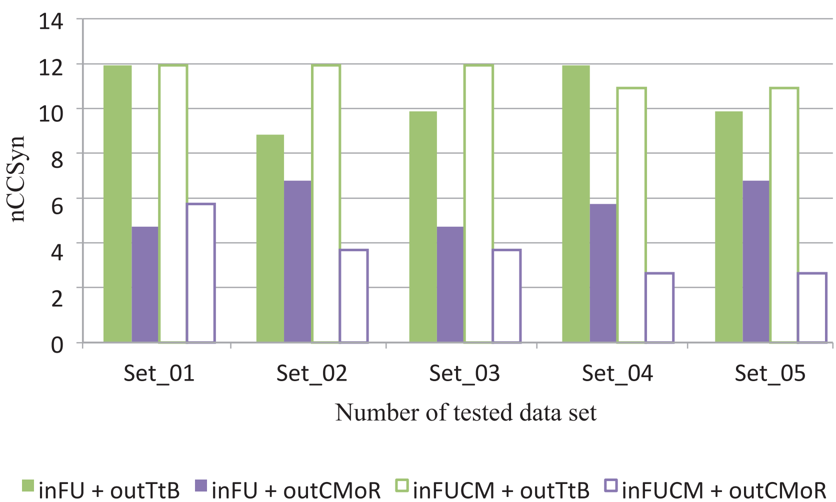

Figure 8: Evaluation of solutions in terms of the *nCCSyn* indicator for selected sequencing algorithms.

better results, whereas in the case of outCMoR using, the inFUCM algorithm was more effective. The smallest number of changeovers due to color changes occurred for the inFUCM + outCMoR algorithm.

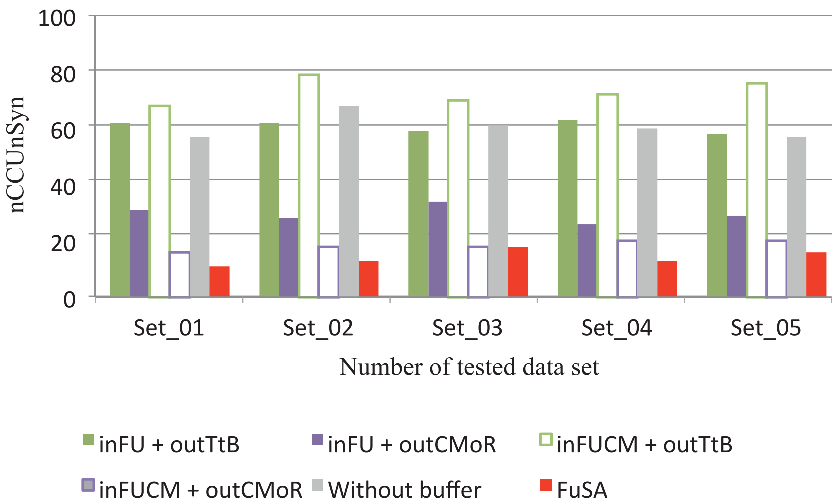

Figure 9: Evaluation of solutions in terms of the *nCCUnSyn* indicator for all tested sequencing algorithms.

Regardless of the loading algorithm, the *nCCSyn* quality indicator reached the highest value for outTtB algorithm. For most of the tested data sets, the synchronization of changeovers due to color changes and periodic cleanings

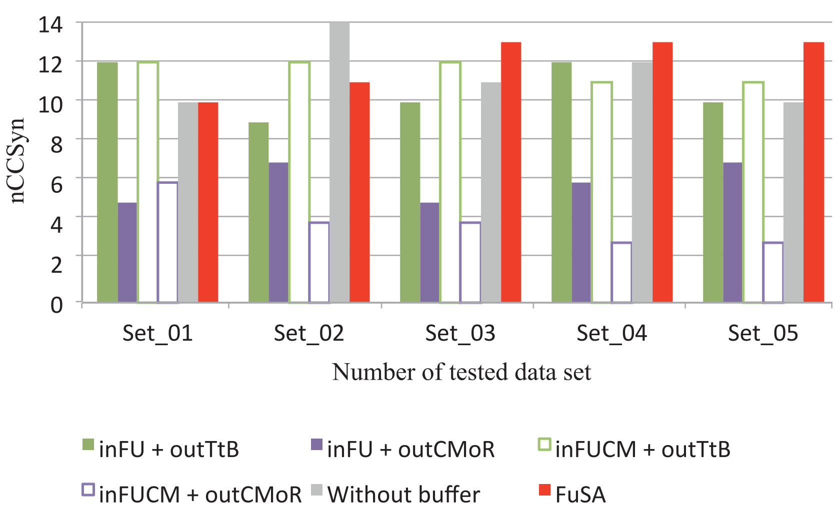

Figure 10: Evaluation of solutions in terms of the *nCCSyn* indicator for all tested sequencing algorithms.

occurred more frequently for FUCM + outTtB algorithm than for the inFUCM + outCMoR algorithm. In the case of the outCMoR algorithm, it is more profitable to use the loading algorithm inFU.

Based on the results presented in Figure 10. it can be noticed that the largest number of changeovers due to forced color changes occurred using the inFUCM + outTtB algorithm – it is even worse than in without buffer case. Among the three most effective sequencing algorithms there are: inFU + outCMoR, inFUCM + outCMoR and FuSA, while the sequencing effectiveness of advanced algorithm FuSA, is the largest.

Algorithms inFU + outCMoR and inFUCM + outCMoR gave good solutions in terms of minimizing the number of forced changeovers due to color changes, but their effectiveness form the point of changeovers and periodic cleaning synchronization view was the worst. In this respect, the inFUCM + outTtB algorithm gave good results, but FuSA works the best.

7. Conclusion

Depending on assortment produced in companies, different types of production can be distinguished. In practice, in the same industrial company at the same time, there are different types of production. Regardless of the production type carried out in the enterprises, there is always a problem of how to distribute available products in time to meet the demand for manufactured goods and to maximize used resources. It is often necessary to compromise between costs associated with the production process and meeting deadlines for customer orders. One of the examples is car production, considered in the literature from the perspective of the car sequencing problem on the production line.

Over the years, a lot of algorithms used to solve the original and modified CSP were elaborated. But in many cases, several aspects, which call into questions the approach to this problem, were not taken into account. The article presented CSP in detail in order confront the assumptions made in the context of this problem with industrial solutions. The need to define a new problem is justified, because of the large discrepancies between the structure of the production line, considered in CSP, and the lines occurring in real-life manufacturing systems. The attention is drawn to the need to develop an advanced sequencing algorithm dedicated to buffer management, taking into account the constraints of the industrial paint shop. Based on the carried out research, the presented results and the conducted discussion, it can be clearly stated that the author's algorithm FuSA is the most effective among the sequencing algorithms developed so far, both in terms of minimizing the number of forced color changes and ensuring that these color changes are synchronized with necessary periodic. The effectiveness of the FuSA algorithm was admittedly verified for 6 colors; however, according to research conducted by PPG, in 2015, a great majority of cars (nearly 75%) were painted in the conservative colors of white, black, gray and silver. This indicates the fact that the proposed algorithm could be successfully used in the practical environment of automotive manufacturers. The future research will focus on verifying the correctness of the FuSA algorithm for a larger set of colors, other production line structures, and the construction of the used buffer.

Acknowledgments

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