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Computer aided design of sequencing problem – the concept of Paint Shop 4.0

Komputerowe wspomaganie procesu sekwencjonowania – koncepcja Paint Shop 4.0

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Presented is the concept of paint shop operation for the automotive industry – Paint Shop 4.0, based on the ideas of Industry 4.0 and Digital Factory. A new approach to the issue of car body sequencing, taking into account the actual structure of the paint shop department with buffers, has been presented. In the created application, proprietary car body sequencing algorithms were implemented.
KEYWORDS: car production, painting process, sequencing, buffer, Industry 4.0, Paint Shop 4.0

Car production is a technologically and logistically complex process. A large selection of available equipment options, a wide range of exterior colors and a variety of functional solutions mean that one car model can exist in hundreds of variants. In addition, several car models can be produced at the same time. This means that multi-assortment and multi-variant production planning is used in the automotive industry. In addition, the vast majority of cars are made to individual order ("make to order"). The customer decides about the model, color, equipment and expectations of order fulfillment in the shortest possible time.

Characteristic for multivariate and multi-product production is production planning in smaller batches by sequencing (mixing) of product variants within the same process (mixed model production). The problem of sequencing has become one of the main challenges of production optimization in the car industry, and in the literature it is known as the car sequencing problem (CSP) [1]. Researchers proposed many assumptions simplifying the structure of production systems, but the time to obtain solutions using the algorithms they proposed was so long that these approaches were not suitable for implementation in industry.

Several research areas can be distinguished, in which sequencing was assessed using various indicators:

- car sequencing at the final assembly department [1] – minimizing the number of violations of the bandwidth limitation of the assembly line,
- car sequencing simultaneously for paint shop departments and final assembly [2] – minimization of violations of the bandwidth limit of the assembly line and the number of color changes,
- car body sequencing in the paint shop – minimization of the number of color changes and the consumption of varnish and the factor used to clean the spray nozzles [3],
- car sequencing and scheduling at the final assembly department – minimizing the number of violations of the bandwidth limitation of the assembly line and even load of stations with assembly operations (balancing the assembly line) [4, 5].

The authors of the article consider the real problem of controlling the process of car body sequencing at the paint shop department, including buffers with different construction solutions. The real data were used to test the developed sequencing algorithms. During the tests, the car body flow through the buffer was also monitored to detect specific buffer filling situations deemed as unacceptable under real conditions.

The Paint Shop 4.0 project is carried out for one of the foreign car manufacturers in cooperation with the Gliwice ProPoint company. Due to the protection of non-public industrial data, the article does not specify the place of project implementation or detailed information on the implementation of algorithms.

Control problems of the paint shop department

The problem of effective car body sequencing at the paint shop department results from the specifics of the production process and from the structure of the production line. The painting process is complex, multi-stage, and energy and cost-intensive [6]. From the perspective of its optimization, it does not matter what color the bodywork will be painted on, but the bodywork sequence determines the number of re-toolings of the lane nozzles, which take part in two stages of the process: painting with base and base paint.

The large number of colors used makes it much more difficult to plan the car body painting process (over the years, the color palette has widened: from four colors in 1908–1913 to 64 colors currently available). Therefore, taking into account the vehicle's character, which is the color, it is necessary to set the subsequent bodywork

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sequences in such a way that the number of changeovers of the paint nozzles is as small as possible.

To ensure continuity of production, inter-unit buffers are located between the welding plant, paint shop and assembly. Additionally, within the paint shop department, a buffer preceding the process of painting the bodywork with base paint is used, which is used for the current sequencing of the bodywork. This raises the question: how to create an optimal sequence from the point of view of the optimization criteria of the painting process using the optimal sequence for the welding department? This problem was considered by the authors as Car Sequencing Problem with Buffers [7].
According to the authors of the article in auto factories, determining the sequence of car bodies directed to la-targeting is not automated. Decisions are made by an experienced operator based on information from various sources.

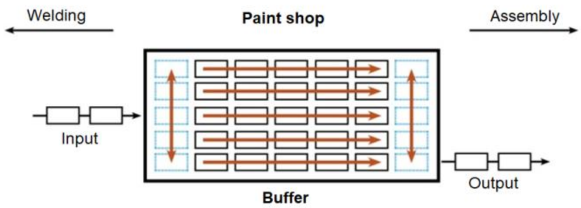

Fig. 1. Buffer structure without recessing the body

Part of the information (production plan, current state of the buffer, QR code of the car body at the entrance) is displayed on several monitors, in applications that do not cooperate with each other. Additional information (e.g. hardware failure, lack of paint) is provided to the operator by phone.

In the currently developed concept of Industry 4.0, people will have to change their role from the operator to the coordinator-specialist [8]. The automation of the paint shop's painting process is consistent with the requirements of Industry 4.0.

In the implemented project of the automatic control system, the paint shop department uses a buffer with the structure shown in fig. 1. This is the most difficult structure due to the consequences of making decisions.

Planning paint shop work is a complicated process, and an additional difficulty is knowing the production plan for a period not longer than three-four hours. Decisions are made each time on the basis of current information on one car body at the entrance, 3-, 4-hour production plan, buffer status and availability of resources.

The system's task is to sequencing the car body using the algorithms proposed by the authors. The general algorithm is to direct the body located on the buffer input to the appropriate transmission line and to discharge the car body from the buffer in such a way that the number of color changes between subsequent periodic cleaning nozzles is as small as possible. These assumptions arise from economic reasons – any change in color is connected with the necessity to clean the paint system, loss of paint and time, which increases production costs. In addition, due to the necessity to perform periodical cleaning of the nozzle in order to ensure the correct quality of the painting process, the aim is to synchronize the changeovers resulting from the change of color with these cleaning operations.

Virtual start in Industry 4.0

One of the most important requirements for systems of modern industrial automation is the ability to effectively supervise, collect and transparently present data from technological facilities, which ensures a functionally integrated management system of production resources. The high level of advancement of the technological process control systems is connected with the necessity of organizing an efficient and highly reliable exchange of information between the devices and their operators *via* the industrial Internet of Things (IIoT).

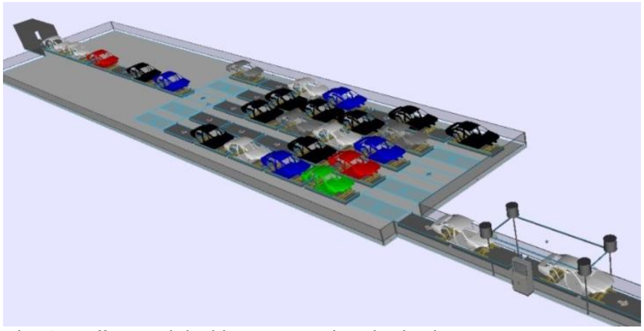

Fig. 2. Buffer model without recessing the body

Process data has been available in factories for many years, but nowadays it can be used more and more effectively if it has a network that transmits this information in real time. In an enterprise in which a production process is carried out, it is necessary to implement and maintain systems that should perform all activities in the area of production flow control. The most important in the implementation process of these systems is the detailed recognition, analysis and organization of all business processes taking place in a given company.
The ERP, APS, MES and SCADA systems cooperate in the company, creating a hierarchical, informative and decision-making planning structure in the scope of information flow regarding the current state of the production system [9].

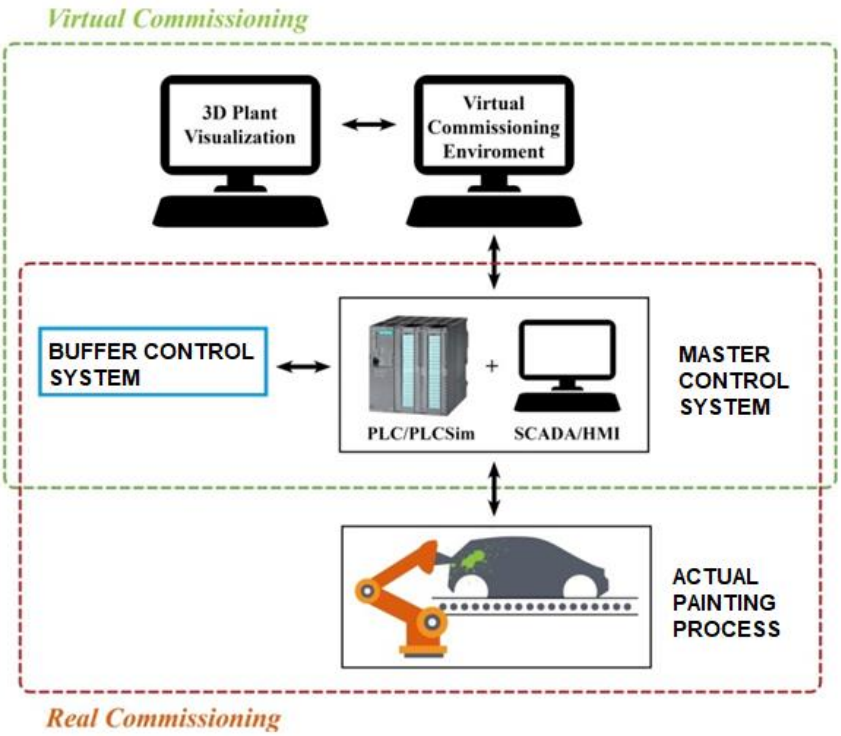

Fig. 3. Configuration of the paint shop control system

One of the key innovations enabling the fourth industrial revolution is the use of simulation techniques for the functioning of real objects in their virtual representations (mappings) using the process data delivered and processed in real time. This approach allows designing, testing and optimization of the configuration of production processes before they are physically activated. The following tools were used in the implemented project:

- Virtual Engineering (VE) – modeling of production systems with the use of 3D tools, without taking into account the control software (fig. 2), in order to validate the processes.
- Virtual Commissioning (VC) – enables designing and testing of a new production system without the need to suspend the work of a real object. Based on the production system models created as part of the VE stage, the control system software is verified in accordance with the HiL (Hardware in the Loop) approach. VC enables preliminary assessment, optimization and validation of the entire production system, and in particular the integration of all resources: product, process, mechanical and electrical components and software [10].

Description of the buffer control system application

The buffer control system application consists of six information and communication modules shown in fig. 4. These are:

1. Connection Control – a module responsible for connecting and transferring data between the application and the PLC.
2. Simulation Control – a module enabling starting or stopping the simulation, resetting the current simulation status and defining the Tper parameter, which specifies the periodic cleaning period. In order to monitor the current state of production, the actual number of bodywork that was delivered to the paint shop (CarIN) is displayed, as well as the number of bodywork for which the painting process was completed (CarOUT) in relation to the production plan.
3. Base Algorithm – a module presenting basic information about the optimal sequence for a given production plan.
4. Current Algorithm – module informing about the results of attempts to optimize the flow control of the body by means of the selected sequencing algorithm.
5. Algorithm Control – a module designed to choose a combination of developed sequencing algorithms out of three heurists defining the method of filling the buffer (Loading Site Active) and six heuristics determining in which order the car bodies leave the buffer (Unloading Site Active).
6. Output Counter – module for monitoring the current state of production.

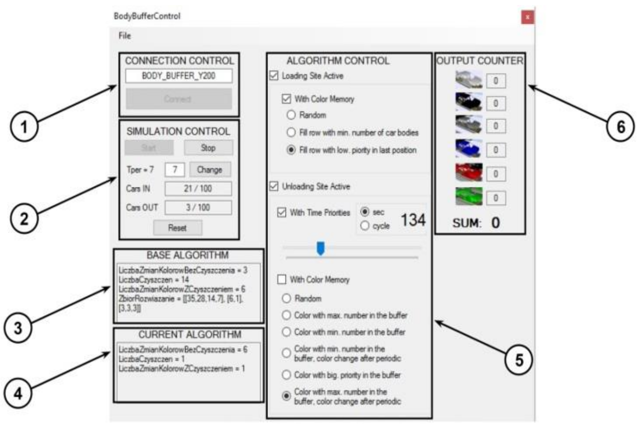

Fig. 4. View of the main application panel (description in the text)

Conclusions

Among the key technical innovations enabling the fourth industrial revolution, the use of simulation techniques and tools of the virtual environment is mentioned which, based on real data, enable testing and optimization of industrial process configurations prior to their physical activation.

The article presents the practical application of virtual environment tools for the automotive industry. The real problem of controlling the car body sequencing process at the paint shop department has been analyzed, including the buffer with a rigid structure.

Using the simulation tool, a buffer function model was created, and then, using the innovative method of virtual start-up, various car body sequencing algorithms were tested in the paint shop department. An innovative application has been presented for the automatic creation of car body sequences directed to varnishing. The aim of the optimization is to minimize the number of color changes between subsequent cleaning of periodic spray nozzles. In addition, the aim is to synchronize the changeovers with these cleanings.

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