A HYBRID SIMULATION MODEL FOR OPTIMAL COLOR-BATCHING RESEQUENCING IN PAINT SHOP

Jinling Leng
Chun Jin

Institute of Systems Engineering
Dalian University of Technology
No.2 Linggong Road, Ganjingzi District,
Dalian, Liaoning, China
lengjinling@mail.dlut.edu.cn

Alexander Vogl

Projects & Simulation
BMW Brilliance Automotive Ltd.
No.1 BMW Avenue, Tiexi District-SEDA,
Shenyang, China
Alexander.Vogl@bmw-brilliance.cn

Dirk Wortmann

SimPlan AG
Sophie-Scholl-Platz 6,
63452 Hanau, Germany
dirk.wortmann@simplan.de

ABSTRACT

Order resequencing of sequential production lines is a critical daily challenge in automotive industry. Simulation models can evaluate production status, but it needs to be improved for more accurate resequencing visualization, simulation and optimization. In this paper, a high-fidelity hybrid simulation model is being developed to support managing of production control department. This aims to understand and control the dynamic behavior of paint shop production system with respect to hidden causes of order resequencing in daily work. Being calibrated by real-world paint shop production data resources, this model can visualize, approximate, and analyze the complex interaction in order production flow of the paint shop. Furthermore, a resequencing strategy that tackles color-batching problem is developed and implemented on the proposed hybrid model to evaluate paint shop production performance.

Keywords: hybrid model, color-batching, order resequencing strategy, paint shop, automotive industry.

1 INTRODUCTION

Vehicle manufacturers in the automotive industry strive for a high adherence to pre-scheduled assembly dates and sequences to ease the management of assembly logistics, specifically the delivery of just-in-sequence parts. That requires sophisticated strategies of planning and controlling of order production sequence (Taube and Minner 2018). At German automotive manufacturers, the Pearl Chain Concept has established to limit precise predecessor-successor sequence of production orders to achieve lean production (Lehmann and Kuhn 2018). One common Key Performance Indicators (KPI) of Pearl Chain Concept is the ratio of sequence quality (SQ) between target production orders and actual ones (Schröder and Tomanek 2015). Being an important part of four primary production processes, paint shop encounters order resequencing problems due to color-batching, random repainting caused by body rework, paralleling production lines controlling as well as buffer capacity management, which brings order sequence adherence violations and affects SQ during operation (Unger and Teich 2009). Hence, it is significant to monitor, simulate and optimize the order resequencing problem to avoid big sequence adherence violations causing unrecoverable sequence changes to downstream production of the assembly.

To manage this inevitable order resequencing problem, production controllers monitor SQ at every moment as well as the occupation of the painted body storage (PBS) (Boysen, Scholl, and Wopperer 2012). PBS is the buffer between paint shop and final assembly, which is designed to digest sequential difference between the re-sequencing finish painted bodies and the assembly required orders. However, if any production process creates big order resequencing issues, the solution is to change the position of orders in the sequence intuitively by experience. There is still no technical method can supervise detailed order resequencing status inside of paint shop, such as dynamic color-batching, body repaired time and rate, bottleneck of stock, etc. At this point, the project starts to develop a tool to understand and manage the dynamic behavior of order disturbances in paint shop and, furthermore, to measure, analyze and optimize the quantitative relationship between order resequencing and SQ. Despite Discrete Event Simulation (DES) is an efficient technique to analyze given scenarios or solutions to support the production performance management, but lacking the ability to unveil causes hidden behind the unsatisfying results via real-world production processes and data sources.

Among of all of the reasons that cause order disturbances, color-batching has the highest impact on the sequence quality of painted bodies out of paint shop by manufacturing experience and by literature (Boysen, Scholl, and Wopperer 2012). Color-batching strategies need to be controlled dynamically to reduce consumption of color in pipes when implement color changeover and loss of throughput when the color changing time is higher than cycle time of coating application. Therefore, the optimization of color-batching policy can save operational costs of plant, cycle time of paint shop any waste to environment.

In this paper, the optimization of color-batching strategy is performed based on a DES model of paint shop of BMW Brilliance Automotive plant in Shenyang, China. It has two contributions, the first contribution is the creation of a simulation model of the production process in automotive paint shop, aims at the analysis of production flow to process statistic data and explore relevant resequencing parameters during color-batching. The upper layer of model is based on macro model. It can automatically and dynamically import history data from real production system to visualize appropriate KPI which are tightly associated with painting production performance. In the second contribution, by inserting a heuristic optimizer for color-batching optimization, regular intentional sequence alteration status due to color-batching in paint shop can be improved. A hybrid simulation model is proposed in present paper to indicate the combined management of order resequencing supervision in upper DES model and lower color-batching policy optimization. The color-batching policy optimizer is integrated with policy-based order allocation approach and heuristic retrieval algorithm. It have developed in exterior environment collects input sequence from simulation model and optimizes order allocation process and body retrieval process to obtain better sequence for downstream painting applications in model. This hybrid simulation model gives modern automotive plant more opportunity to achieve mix-model, efficient and sustainable production.

In the following section, literature reviews about simulation method and painting process resequencing research are presented in section 2. In section 3, we analysis the paint shop production process and associated resequencing problem. Details of hybrid simulation approach that combines macro-based simulation model and color-batching optimization are outlined in section 4. In section 5, we describe the experiments and results. Section 6 involves our conclusions and the directions for the further research.

2 LITERATURE REVIEW

DES has been extensively implemented for simulating automotive production process over the last decades (Williams and Ülgen 2012). DES is classified as macroscopic and microscopic simulation direction. Macro simulation approach, it abstracts the equipment characteristics into a black box and simulating the input and output behavior to get the required buffer sizes between shops, work in progress and the throughput of entire plant. On the contrary, micro simulation approach builds a detailed model on shop floor level which can simulate each technology in detail, such as the quantity of carriers and possible bottlenecks (Pawlewski et al. 2012). While both of them must be built based on random generation data, which need engineers to input well prepared data distributions from production environment rather than using original historical data. Also, sophisticated parameters of the production process are required, which extend modelling time and efforts. Furthermore, less of production simulation model are based on real-world data to analysis history production operation and then to find fundamental influence parameters which effect KPI, even more, optimize these influence factors.

On the other hand, many researches proposed numbers of heuristics to optimize car resequencing problems with regard to minimize color changeover with selectivity banks (SB) buffer configuration in Figure 1 as prime storage in paint shop (Spieckermann, Gutenschwager, and Voß 2004; Lemessi, Schulze, and Rehbein 2011; Ko, Han, and Choi 2016; Taube and Minner 2018). Ko, Han, and Choi (2016) and Taube and Minner (2018) defined the releasing procedure from multi lanes of SB into a merging junction, which is a painting booth in paint shop application, as a mixed integer linear programming model. Han et al (2003) firstly proposed to use DES method to minimize the total number of paint line color changeover, but only attempted decisions making of order fill-in from 1 convey to multi lanes procedure. A US General Motors paint shop conveyor system was introduced by Elahi et al. (2015), which substantially minimize number of consecutive color changeover in less than 5 lanes SB interacted with a DES model. However, the paint shop structure was draft simulated as a conveyor system without comparison of real-world plant. In the same year, the dynamic control rules about two major intersections and two crossovers of paint shop flow of a truck plant in Canada were proposed and optimized, but include less discussion of order arriving sequence control policies or in-line buffer fill-in and release sequence control rules (Bookbinder and James 2015). Their research background is closely related to this paper due to real-world paint shop application and evaluation via DES model. However they only toke account color properties of orders and proofed the effect on samples with 3 type color (Elahi et al. 2015). Learned from above researches, this paper separated control of optimizer as allocation procedure and retrieval procedure.

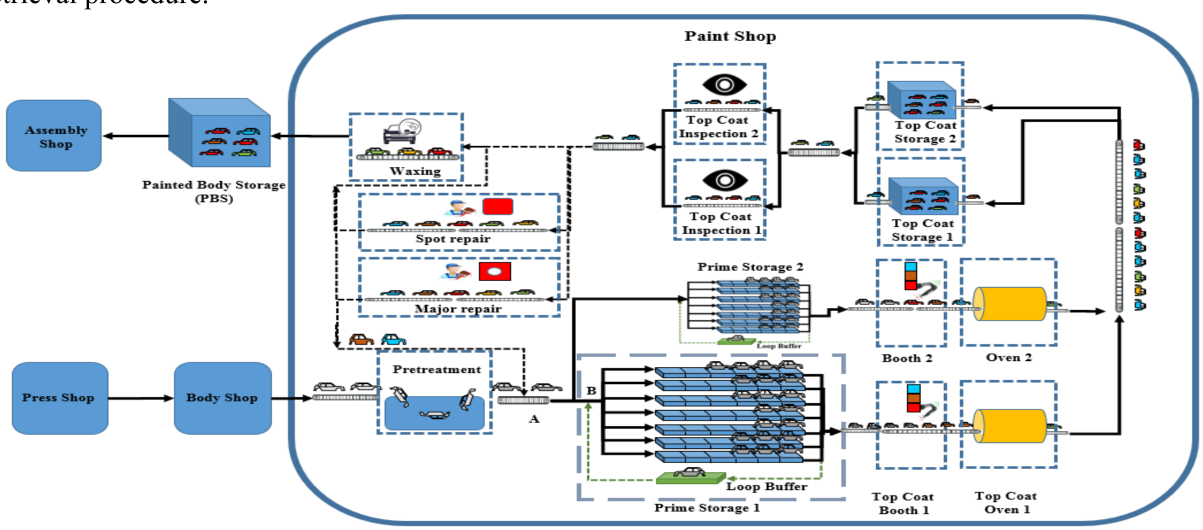

Figure 1: Macro paint shop material flow and micro color-batching process.

A storage and retrieval algorithm was applied for physical resequencing orders in PBS. A special loop buffer composition was considered to enforce the resequencing performance of SB (Moon, Cheng, and Ha 2005). SB with a loop buffer is a special buffer design in BMW plant in Shenyang, China. Therefore, based on research of Moon, Cheng, and Ha (2005), the control strategy of return loop in this paper is integrated with entire SB policy optimizer dynamically to improve the performance of color-batching. Furthermore, the literature regarding virtual resequencing in color-batching process has been study by

Epping, Hochstättler, and Oertel (2004) and Fournier and Agard (2007). An integrated physical and virtual resequencing technology was proposed to express the performance of color changeover reduction within SB and within a look-ahead area simultaneously (Sun and Han 2017). Rule-based fill approaches in Spieckermann, Gutenschwager, and Voß (2004) and Sun and Han (2017) were similar to the rule of lane allocation in this paper but with simple filling definitions, while the one in this paper considers difference body sources. Moreover, both fill-in rules and retrieval rules are improved to be more realistic and detailed in control. Thirdly, the application of virtual resequencing in look-ahead in Sun's research was unpractical. Furthermore, the setting of optimization scenarios in this paper are based on DES statistics data, which are more operable and applicable.

Summarized previous research and simulation on painting sequence and order disturbances, all vehicle arrival time is simulated by a generator rather than real-world production data. The hybrid simulation approach proposed in this paper is unique in that the representative production flow, based on real-world history data covering realistic regular shift time and emergency breakdown, assure entire paint shop runs in extremely accurate cycle time and get rid of mass workload in physical model construction. Meanwhile, the color-batching strategy can be implemented in microscopic level to improve sequence quality of finish painting bodies, in further, to optimize plant production and operation performance.

3 DESCRIPTION ON THE PAINT SHOP SYSTEM

3.1 Overall structure of the Paint Shop production flow

The simplified physical layout of the paint shop material flow is shown in Figure 1. In the case study plant and literature (Bysko, Krystek, and Bysko 2018), paint shop can be divided into different production control points. The body in white enters the paint shop, go through pretreatment, e-coat, prime coat, top coat and waxing then be delivered out of the paint shop into PBS, the assembly shop will recall painted bodies in sequence.

3.2 Resequencing problem in the Paint Shop

Analyzing the paint shop production flow in Figure 1, structure of selectivity banks (SB) and repainted bodies from defective stations are two major resequencing creators in the paint shop. For prime coat stations, phosphatized bodies in "grey" share one coming junction A and be diverted into two same selectivity banks 1 or 2 for color selection. After short time storage, bodies to be painted in top coat booths (as referring to enamel coating booth) then come into ovens and top coat storages. Through top coat inspection stations, most of colored bodies will be delivered into waxing station. Defectives will be repaired in special stations, such as spot repair stations, major repair stations or even heavy repair stations. Small defect spots in bodies can be mended in short time and back to main downstream application. However, a faction of defective colored bodies must be returned in front of SB storage and merged with no colored bodies into one of two SBs. Moreover, a loop lane located in SB returns bodies with inappropriate color assignments for queuing again. These queue-jumping action aggravates sequence disturbances before body fill in SB.

Figure 1 illustrates a amplified structure of SB 1. Selectivity banks, also named mix banks, is in format of parallel line buffers. Bodies from upstream station through one incoming conveyor then fill in parallel lanes. Each lane implements body retrieval by first in first out (FIFO) rules. Right-most bodies in lanes can be released by policy-based sequence or returned to loop buffer back to incoming conveyor in queue. This complex fill-in and release rules changes the original incoming body sequence significantly.

3.3 Color-batching for order resequencing problem

Apply color-oriented batches of bodies before top coating process due to spray robots need to be solvent and cleaned when two consecutive car bodies have to be painted in different colors. In order to minimize the consumption of paint nozzles cleaning and water pollution, production controllers should real-time rearrange sequencing contiguously the same pre-assigned color of pretreatment bodies in queue for painting application based on daily production throughput. However color-batching problem has more constraints in the entire plant. The painting color sequence abides constraints under process principle, such as colors in big diversity shall not be painted consecutively, daily production volume shall be arranged averagely, etc. Therefore, batch size shall be in range of periodical painting requirements of topcoat booth and violation between resequencing policy and assembly demand sequence inbound.

According to notations in Table 1. Symbolized each car body as an order with two attributes: color and car-model. Based on production analysis in Figure 1, color sorting happens between SBs and top coat booths. Considering order sequence at top coat $O_{tc} = \{o_1^{tc},\ o_2^{tc}, \dots o_N^{tc}\}$, with $o_i^{tc} \in O_{tc}$ for $i = 1,2,3 \dots N$. Use a binary variable (1) to denote a color change when color attribute of consecutive orders is different:

$$CC_{i,i+1} = \begin{cases} 0, & c^{o_i^{tc}} = c^{o_{i+1}^{tc}} \\ 1, & otherwise. \end{cases} \quad (1)$$

The objective of color-batching policy is to minimize the number of color changeover:

$$NC = min \sum_{i=1}^{N-1} CC_{i,i+1} \, . \quad (2)$$

Table 1: Notation of color-batching model.

Sets	**Description**
C	Set of color type in alphabet, $C = \{a, b, c, \dots\}$
M	Set of car model type
N	The length of orders
O_d	Target assembly production orders in sequence
O_{assy}	Actual assembly production orders in sequence
O_{tc}	Order sequence of entrance of top coat booth
O_b	Orders of entrance of SB
O_{np}	Orders through pretreatment application
O_{rt}	Orders through loop lane inside of SB
O_{rp}	Repainted orders through bodies repair application
p	Production control points in the production process
$o_i^p = (c^{o_i^p}, m^{o_i^p})$	Order o_i at p control point with two property, $c \in C, m \in M$.
L	Total lanes of in-line buffer
W	Total Space of each lane
$V_{l,w}$	The coordinate position in SB, $1 \leq l \leq L, 1 \leq w \leq W$
$c_{l,w}$	Color property of orders located in coordinate (l, w) of SB
$m_{l,w}$	Car model property of orders located in coordinate (l, w) of SB
$\lvert SB \rvert$	Capacity of selectivity banks
$\lvert PBS \rvert$	PBS capacity

$t_{l,w}(\mathrm{o}_{\mathrm{i}}^{\mathrm{p}})$	Waiting time of orders located in coordinate (l, w) of SB
TM	Maximum waiting time of orders in SB
$R(o_i^b)$	Number of times orders enter loop buffer, $R(\mathrm{o}_{\mathrm{i}}^{p}) \leq 2$

3.4 Performance evaluation of Paint Shop production

In the view of production control management in paint shop, Cumulated Orders out of Sequence (COS) and Sequence Quality (SQ) are two KPIs of plant to monitor, evaluate and control production status. Given capacity of $|PBS| = \infty$, the number of painted bodies into PBS is Λ with $\Lambda \leq \mathrm{N}$, the COS is the number of orders that did not start in the target sequence in the assembly shop and have hold in the COS list, $COS = |\sum_{i=1}^{\Lambda}(O_d - O_{assy})|$. A sequence violation with impact on the SQ occurs whenever an order is not inserted onto the intended target sequence in the entrance of assembly shop. Low SQ will lead to delayed delivery of the order to the assembly. Academically, violation mathematical formulations were defined to measure sequence scrambling (Gunay and Kula 2018). In this case, define SQ is the ratio when painted body comes into the assembly complies with adjacent sequence of demand list.

$$SQ = \frac{sum\ of\ bodies\ follow\ O_d}{number\ of\ painted\ bodies\ into\ Assembly} * 100\% \quad (3)$$

4 MODELLING

4.1 Macro-based simulation model

The structure of hybrid simulation model is designed like the production processes in Figure 1. The order flow behavior can be simulated rather than setting technology parameters, such as cycle time, buffer capacity, equipment availability, protection area of robots, number of carriers or even investigating production process onsite. But by importing real-time data from production line. The checking time of each order includes all above technical information. After cleaning and pre-processing data to guarantee each of the orders can be found in production control points with completed parameters: Order number, Car_model, Color, Actual_pass_time, Plan_build_time, Camera_point. An integrated order production flow table can be used for data source validation. Especially, complete the data which appears in demand list but not in history to make sure that all demand orders can be either produced from start of paint shop to the delivery to PBS or can be found in the initial stock list of any control points. All input data in this case is sequence domain data, which means the data is order related information.

4.2 Micro model: Policy-based heuristic model

Selective banks with '1-to-L-to-1' (one incoming flow to L conveyor buffers then to one out-releasing exit) system is widely utilized in the automotive industry because of low construction investment. Each lane can be reserved for a single color. But when daily production volume has more number of color than lanes, controllers have to allocate bodies to lanes with an intelligent method. The dynamic order allocation policy and iterative-searching-based retrieval policy are documented in the following sections.

4.2.1 Selectivity banks

Assume the capacity of SB is bigger than zero. All repainted bodies only flow to the first time visited SB. The space in return lane is one. And the maximal return number of times of orders is two. In particular in this case, the SB 1 (prime storage 1) shown in Figure 1 has 8 parallel lanes $|L| = 8$ and 6 spaces on each $|W| = 6$. All lanes share one fill-in junction B and one retrieval junction C. The 8th lane $l = 8$ is a special return lane, which put inappropriate bodies back to fill junction B for queuing again, therefore the capacity of SB 1 is $|SB| = (|L| - number\ of\ loop) \cdot |W| = 42$. Define the usage of space in SB:

$$V_{l,w} = \begin{cases} 0, otherwise \\ 1, occupied\ space \end{cases} \tag{4}$$

Define $w = 1$ refers to the right-most order in lane, which will be prepared to release from SB, $w = q$ refers to position of the last entrance (or left-most) order, which is also the last fill-in order in that lane. $\sum_{w=1}^{w=q} |V_{l,w}|$ is sum of spaces in lane l occupied by orders.

4.2.2 Fill-in heuristic policy for 1-to-L splitting model

For fill-in point B, the first difference between this paper and previous research is fill-in data source of SB among normal fill-in bodies and returned bodies from loop buffer with a pre-assigned color, and repainted bodies already covered with color from defective stations. Moreover, compared with previous fill control approach that only considered color similarity of incoming cars and most-recently-entered car in lane, and length of cars in queue in each lane (Sun and Han 2017; Elahi et al. 2015; Han et al. 2003), the order allocation approach in present improved to be more realistic and detailed in control.

The order source of O_b is the combination of $O_b = (O_{np}, O_{rt}, O_{rp})$. This three incoming flows design makes problem setting unique. First kind is no-color-bodies from normal pretreatment (O_{np}), another one is second round queueing no-color-bodies (O_{rt}), the third is painted-bodies with fixed color from rework (O_{rp}). Furthermore, the 1-to-L conveyor setting makes the original fill-in body sequence be altered and raises the difficulty in simulation body fill-in policy to L lanes. According to Pearl Chain Concept, the sequence of O_{np} is obedient to O_d. In this paper, setting orders to be repainted from repair stations insert next to o_i^{np} in O_d when $c^{o_i^{rp}} = c^{o_i^{np}}$. The first and second time return orders from loop buffer inserts next to o_i^{np} in O_d when $c^{o_i^{rt}} = c^{o_i^{np}}$ Update the o_i^b is the combination of orders (o_i^{np}, o_i^{rp}, o_i^{rt}) , the sequence optimization of this three order sources will be our next step research work.

The fill-in heuristic policy from one conveyor to multi parallel lanes is as following steps. Based on rolling planning horizon, $c_{l,w}$ will be updated along with fill-in orders o_i^b from point B and release orders o_i^{tc} to top coat application. Recognizing whether the color attribute of orders in left-most position of each lane $c_{l,q}$ and next coming order $c^{o_i^b}$ is same firstly, if there is only one suitable lane then put order in this lane. If more lanes in set, choose the lane with more available spaces. If no lane could be allocated, choose the lane that orders without color attribute $c^{o_i^b}$.

Step 1. Recognize lane $\in \{l|\ c_{l,q} = c^{o_i^b}, l = 1,2 \dots L, 1 \le q \le W, 0 < \sum_{w=1}^{w=q} |V_{l,w}| < W\ \}$. If $|l| = 1$, go to step 6. If $|l| \ge 2$, go to step 4. Otherwise, go to step 2.

Step 2. Choose lane $l \in \{l|\min l\,, |V_{l,w}| = 0\}$. If $|l| = 0$, go to Step 3. Otherwise, go to step 6.

Step 3. Choose lane $l \in \{l|\ \sum_{q=1}^{q-1} c_{l,q} \ne c^{o_i^b},\ \ l = 1,2 \dots L, 0 < \sum_{w=1}^{w=q} |V_{l,w}| < W\}$. If $|l| = 1$, go to step 6. If $|l| \ne 1$, go to step 4.

Step 4. Choose lane $l \in \{l|max \sum_{w=q+1}^{w=W} |V_{l,w}|\,, l = 1,2 \dots L\ \}$. If $|l| = 1$, go to step 6. If $|l| \ge 2$, go to step 5.

Step 5. Choose lane $l \in \{l|max\ (t_{l,1}), l = 1,2 \dots L\}$, go to step 6.

Step 6. Filling in order o_i^b in chosen lane, repeat rules for o_{i+1}^b.

4.2.3 Release policy for L-to-1 merging model

Assumption for return loop buffer (green conveyor in Figure 1), the holding returned body in return loop must be inserted back in queue O_b when second returned body arrive. If $o_i^b \in \left\{\{t_{l,w}(o_i^b) \ge TM\} \ne \emptyset, l =\right.$

$1,2 \dots L,\ R(o_i^b) = 2\ \}$, the body is retrieved compulsorily. The initial shuffling heuristic-based release approach of physical release approach (PRA) and virtual resequencing approach (VRA) are adopted from Sun and Han (2017). They defined a physical release policy that could consecutively retrieval maximal cars in same color and integrated a virtual method to random swap the color of two cars in same car-model to improve the physical release policy. However in this paper, the retrieval policy is redefined and a return loop is added for practical design of SB in paint shop of BMW Shenyang, China.

The retrieval heuristic policy is shown in Figure 2. Estimate waiting time of right-most orders, this time parameter is from upper simulation model. Implementing PRA for normal orders inside time restriction. In PRA, firstly, collecting color type of right-most orders as initial color candidate. According to the color restrictions condition in real-world plant, colors in big divergence e.g. black and white, white and red, could not be painted consecutively in sequence. Because of residual color impurity in pipe will lead high repair rate in real-world. Therefore, the second step rule in PRA is to restrict color *a* and *c* could not be adjacent, color *f* could not follow color *a* in retrieval policy ($\{a, , f, \dots\} \in C$), which is referenced from real-world paint shop production control department. Thirdly, in order to save color waste in pipe cleaning, given retrieval priority to color of predecessor released order. At last, update color candidate which color has the maximum orders that could be consecutively retrieved from SB, which is the only point similar like physical release rules of Sun and Han (2017). Furthermore, we consider extra situation which leaves empty color candidate, the color of right-most orders in lane with the longest waiting time will be forced to retrieved in PRA and record the number of color changeover.

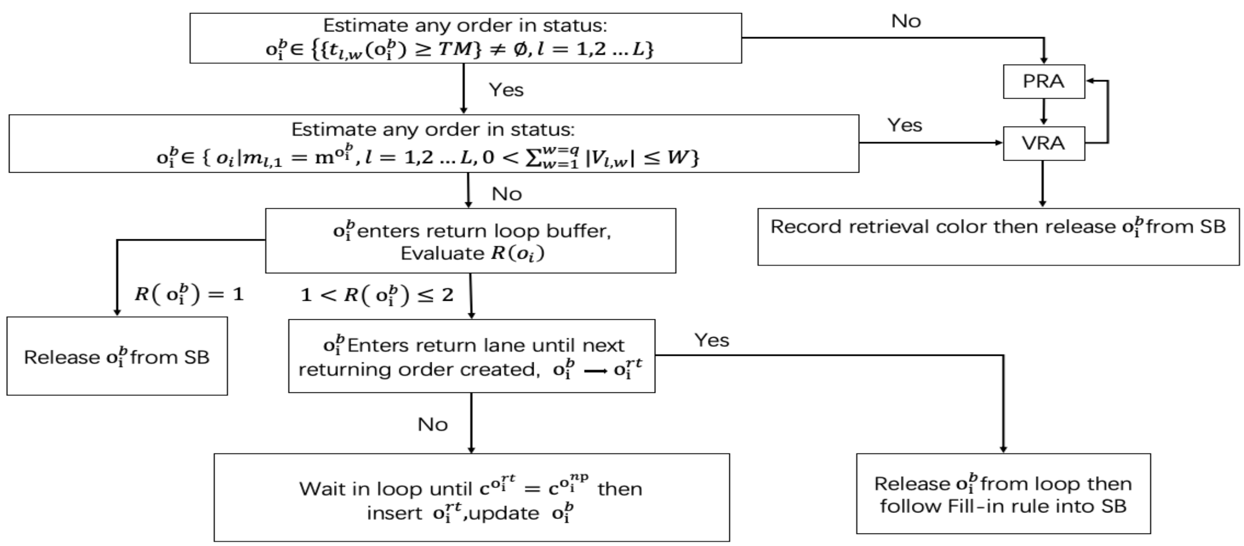

Figure 2: Process of release policy.

The virtual resequencing approach (VRA) can alter the same model type to different colors rather than bond the preassigned color to each car-model. It happens in buffer or help system do resequencing during operation without occupy extra buffer. In this paper, VRA random exchanges color of two bodies in same car-model to improve PRA until the number of color changeover is steady or maximum iterations exceeds 1000. Moreover, VRA in present could only be implemented for O_{np}, O_{rt}. O_{rp} could not be swapped due to existing color covered on bodies, which is a unique and practical setting from real-world plant.

All time exceed orders will be searching alternative orders with same car model within SB. The quality of VRA rules can be improved by setting order in right-most resequencing priority. Furthermore, for orders be returned in loop buffer for first or second time, they will be inserted back to follow fill-in rules or be retrieved to top coat booth compulsorily. Due to continuously fill-in and release process of selectivity banks, the color-batching problem can be implied as an online resequencing problem, which is based on rolling planning horizon (Boysen, Scholl, and Wopperer 2012).

4.3 Relationship between the upper and lower models

Resequencing strategy can be improved and implemented in outer JAVA model and connecting into model. By embedding the lower policy-based heuristic model in CSS modular of upper macro-based model, optimized order sequence o_i^{tc} in TC module can be updated. And by running o_i^{tc} in following module in upper model, model can export COS, SQ and PBS occupation to evaluate the quality of optimized o_i^{tc}.

5 EXPERIMENTS

5.1 Experiments design

The simulation model was developed using Plant Simulation 14.1 software. An actual case about a paint shop of BMW Brilliance Automotive, located in Shenyang in China, is studied to illustrate the actual paint shop resequencing situation in terms of color-batching production application. The main data sources needed in this model are defined as: planning production demand order in sequence, actually time step when bodies pass each production control point, initial fillings of each control point. Specifically, Original data with categories of parameters such as car model, assigned color, planning sequence, and planning be produced time, etc., which presents the domain-specific modelling properties required in this model. After importing all required files, run simulation based on historical data of two mouths to obtain statistics analysis for operational supports, incl. COS, SQ, dynamic stock of WIP, body holding time of each storage, color distribution with color type and model type, repair ratio and distribution.

5.2 Statistical data analysis

Figure 3 shows production historical records of COS, and SQ, which are KPIs to validate the precision of model. Both of them inviolate KPIs in real-world production control. Fluctuations of color batch reveal the randomness of color change during paint shop operation. Table 2 processes the relevant historical statistics data that analyzes a portion of results based on real-world color-batching situation. In realistic, the daily production volume is around 1,300 units with 2 shifts, the total production sample is around 25,000 units per parallel painting line within 2 months. Parameter settings of number of 16 color types, 12 model types in SB_1 and 17 model types in SB_2 are learned from historical data analysis from DES model. The total number of color changeover for each SB is shown in Table 2. The average batch size of both painting lines are balanced, which clues us to consider workload balance of two painting lines in future work. The average filling level of SB 1 is 88% and SB 2 is 76% of design capacity, which limits the filling parameters of color-batching optimizer. The average storage time supports the parameter TM and control of return loop.

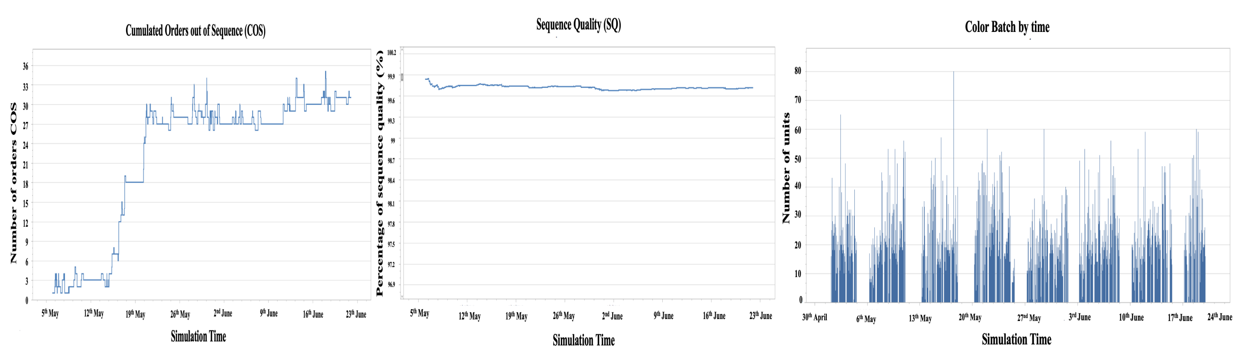

Figure 3: Statistics analysis for real-world production process.

Table 2: Statistics data

Parameters	**SB_1**	**SB_ 2**
Grand Total of orders (units)	24063	25497
Number of color changeover	2855	2788
Max batch size (units/color)	61	80
Min batch size(units/color)	1	1
Average batch size(units/color)	7.89	8.76
Average filling level (units)	37	28.8
Average storage time (mins)	44:30.7956	51:32.7854

5.3 Optimizer results and analysis

Simulation results are shown in Table 3 and Table 4. Table 3 points out results of color changeover, maximum & minimum color batch sizes in different initial filling of selectivity bank. The real-world data imported in this experiment is based on around 70% - 90% capacity of prime storage due to statistical data from model. Column R means comparison reduction with historical results. If no virtual policy used in optimizer, the optimal color-batching performance could reduce 42% and 37% compare with historical results when filling space of SBs is 70% . Concluded that initial filling has impact on color changeover. Moreover, if adding VRA to iterate with PRA, the performance reduce more to 44% and 40%, respectively, which indicate the good optimal ability of color-batching optimizer in this paper.

Table 3: Comparison results of original data and color-batching strategy.

	TC booth 1					**TC booth 2**				
	|SB|	*NC*	R	Batch size		|SB|	*NC*	R	Batch size	
				Avg(Max)	Avg(Min)				Avg(Max)	Avg(Min)
Hist_Data	88%	2855	-	61	1	76%	2788	-	80	1
PRA	70%	1663	42%	169	1	70%	1768	37%	199	1
	80%	1846	35%	202	1	80%	1938	30%	174	1
	90%	2315	19%	118	1	90%	2387	14%	89	1
VRA	70%	1593	44%	216	1	70%	1668	40%	178	1
	80%	1710	40%	257	1	80%	1799	35%	154	1
	90%	2081	27%	162	1	90%	2181	22%	123	1

Table 4 tightens the setting parameters to shown optimal results realistic and effective. Keep the filling level on 70% , average of the maximum waiting time of orders in SB is 40 minutes and 50 minutes, and sequence of painting colors restrictions. When implement VRA and TM = 40min in optimizer, the color changeover reduces 33% in SB1 and the average maximum color batch is close to historical results. Similar with another booth line. More detailed sensitivity analysis of order resequencing influences will be implemented in next step.

Table 4: Comparison results of original data and color-batching strategy with production restrictions.

	TC booth 1					TC booth 2				
	TM (min)	*NC*	R	Batch size		*TM* (min)	*NC*	R	Batch size	
				Avg(Max)	Avg(Min)				Avg(Max)	Avg(Min)
Hist_Data	37.0	2855	-	61	1	28.8	2788	-	80	1
VRA	40.0	1911	33%	86.9	1	40.0	2018	28%	72.7	1
	50.0	1930	32%	83	1	50.0	2029	27%	73.4	1

6 CONCLUSION

The hybrid model is designed to run real-world production data so that production planner and simulation engineers get a deep understanding of the production process. It can analysis and evaluate how order resequencing in paint shop can effect KPI during production, also be able to insert color-batching strategies optimization in several scenarios to control order resequencing situation, and consequently wave KPI and PBS. The performance index can be increased by improving color batch strategy without extending working in process buffer space. Integrated model can be modified by simply input demand variables rather than educated simulation engineers update model detailed objects day by day.

In future search, the experiment period will be extended to long time so that the empirical distribution module of hybrid model can be improved, which improve the feasibility of this hybrid model to be used not only for operation control of existed paint shop but also for planning phase of new plant construction. Moreover, more color-batching scenarios will be implemented in optimization module so that virtual resequencing strategy of policy-based heuristic approach will be improved.

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AUTHOR BIOGRAPHIES

Jinling Leng is a Ph.D. candidate at Institute of Systems Engineering, Dalian University of Technology, China. Master of automotive engineering from Coventry University, UK. She joined in Ph.D. Promote project of BMW Brilliance Automotive Ltd and doing research works at Projects & Simulation department since 2016. Her research interests are simulation in production operation strategy & logistics in the automotive industry. Her email address is lengjinling@mail.dlut.edu.cn.

Chun Jin is a Professor at Institute of Systems Engineering, Dalian University of Technology. He received Ph.D. degree in information and control engineering at Nagaoka University of Technology in Japan in 2000. His research interests lie in modeling, simulation and optimization on production, logistics and transport system. His email address is jinchun@dlut.edu.cn.

Alexander Vogl is an Senior Manager at Projects & Simulation of BMW Brilliance Automotive Ltd. He is a company supervisor of Ph.D. Promote project of BMW Brilliance Automotive Ltd. His email address is alexander.vogl@bmw-brilliance.cn.

Dirk Wortmann is a founder of SimPlan. He is a senior consultant and manager at SimPlan AG, Hanau, Germany, mainly working for discrete event simulation in manufacturing and business. His email address is dirk.wortmann@simplan.de.