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Procedia CIRP 72 (2018) 774–779

www.elsevier.com/locate/procedia

51st CIRP Conference on Manufacturing Systems

Variant flexibility in assembly line balancing under the premise of feasibility robustness

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Abstract

The final assembly of vehicles is frequently designed as a mixed model line which produces effectively at a fixed ratio of variants. Market forecasts indicate a volatile future demand for different types of vehicles such as electrified vehicles. The resulting uncertainty of demand affects the task of line balancing assembly lines. This paper presents a new planning method to provide decision support for line balancing with inherent variant flexibility while maintaining feasibility robustness. Therefore a combined approach of scenario analyses and line balancing optimization is developed. This approach is applied to a use case in automotive industry.

Keywords: planning; variants assembly; flexibility; feasibility robustness; line balancing

1. Introduction

The steady growth of product variants in automotive industry has become a challenge for automotive companies [1]. This trend is additionally driven by the expanding amount of electric variants [2; 3]. Especially in the premium segment, the amount of variants increases rapidly due to additional car architectures and equipment [4]. As a result of this demand for individualized products [5], hardly two completely identical cars are produced. In order to maximize the efficiency of car assembly under these circumstances, assembly lines thus have to be designed with respect to various product variants.

Line balancing is carried out in an early planning phase, whereby the underlying information on future variant demands is subject to uncertainty. Uncertainty in demand quantity can be faced by adjusting shift and working hours models [6] while uncertainty regarding model mix shares and optional equipment directly affects the design of the assembly system as assembly times and assembly equipment depend on a specific product variant [7].

The objective of car assembly is the production of the planning period's entire production program. If the actual production program does not correspond to the production program on the basis of which the line balancing planning was carried out, takt time violations may occur. In order to counteract this risk, vehicle assembly can be designed to be changeable, making it easier to adapt the line balancing according to changes in demand [8]. In order to avoid these subsequent adaptations, the system can be designed to be robust against a defined amount of fluctuations in the product mix [9]. As a result of robust planning, cost advantages especially in volatile markets can be obtained, since subsequent changes to the line balancing require relatively high financial efforts [10].

FISEL developed an approach to design cost-efficient line balancing configurations of a variant flow production line depending on potential model mix scenarios [11]. Hereto, a multi-criteria optimization is applied. The objectives comprise minimizing the cost of a greenfield line balancing configuration, minimizing scenario-dependent change costs and maximizing the robustness of the line balancing regarding

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Peer-review under responsibility of the scientific committee of the 51st CIRP Conference on Manufacturing Systems.
10.1016/j.procir.2018.03.049

volatility within the variant mix. This approach allows to model the trade-off between cost, changeability and robustness of line balancing and therefore supports decision making. The presented approach describes the robustness of the line balancing within this overall approach. If a decision-maker focuses on the robustness of an assembly line's balancing, the presented objective function has to be weighted comparatively strongly in the overall approach.

Therefore, an approach for increased robustness in multi variant line balancing problems is presented. In order to depict uncertainty of future demand, the share of product variants is represented by stochastic input parameters. These parameters are derived from a structured analysis of model-mix scenarios, which then determines the requirement for system immanent robustness. By solving a line balancing optimization problem using these stochastic input parameters, a robust line balancing configuration can be obtained. The paper closes with a case study showing robust line balancing for a compact class vehicle.

2. Robustness in line balancing

The planning of variant flow production in the automotive industry can be divided into three phases: line balancing, production program planning and sequencing (Fig. 1) [12].

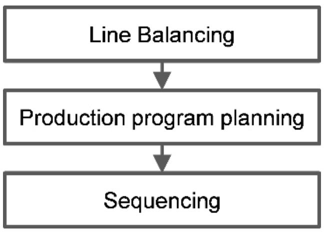

Fig. 1. Steps of assembly line planning [12]

The core task of assembly line balancing is the assignment of assembly tasks and their required resources to one station of the assembly line. Usual objectives are the minimization of the necessary workstations or the takt time [13]. This basic problem is referred to as the Simple Assembly Line Balancing Problem (SALBP) [14]. The subsequent planning of the production program assigns a rough production date to the customers' orders in the planning period [15]. Based on this, the customers' orders of the planning period are transferred into a production sequence [12].

A valid solution to the line balancing problem is characterized by the following properties: The elementary assembly steps are assigned to exactly one assembly station. The precedence constraints are fulfilled. The average assembly times at each station do not exceed the takt time [7].

If these properties are expanded by the application of additional constraints, the research area is extended to the General Assembly Line Balancing Problem (GALBP) [16]. This includes extensions to the core problem, e. g. the assembly of several products [16; 17], parallel stations [12] or dynamic [18; 19] and stochastic process times [20].

Changing basic conditions such as changes in the product mix of the production program have a disturbing effect on the assembly system, as the design was based on different premises. Problems such as a reduction of the output quantity may result from this conflict [9]. In order to avoid this, the line balancing can be designed robustly.

HAZIR & DOLGUI define the robustness of assembly lines as „the insensivity of line performance with respect to disruptions" [9]. This is in line with the feasibility robustness described by Scholl, which evaluates to what extent the calculated plan is feasible for each possible scenario [21]. Within the context of the present work, a solution is considered valid if a valid plan for processing the production program can be found by means of a sequencing algorithm.

In order to achieve complete feasibility robustness with regard to changes in the model mix of the production program, it is necessary to avoid overloading of the line balancing, e. g. by adding a buffer to the average assembly time [12]. This means that the assembly time of a station cannot be exceeded for any combination of variants in the production program, but this can also lead to an increase in the number of assembly stations required. In contrast, the design of the line balancing for the proportionately weighted variant average depends on the forecast quality of the future model mix [22]. Due to the reduced number of assembly stations this may result in reduced feasibility robustness. In the automotive industry, line balancing is often conducted on the basis of the average variant [22; 23].

Within the present paper, an objective is to provide decision support for this trade-off from the lowest possible cost for the assembly system which are determined by the amount of assembly stations and the highest possible feasibility robustness. The presented method therefore provides solutions to this trade-off.

3. Method for feasibility robust line balancing

The following information must be held available before executing the method: In order to set up model mix scenarios the variants to be produced by the assembly system have to be defined. The assembly process of these variants has to be split into assembly steps that cannot be further subdivided, whereby the assembly sequence is described by precedence constraints [24] (Fig. 2).

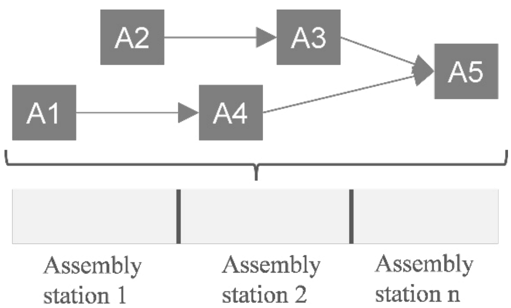

Fig. 2. Elementary assembly steps and precedence constraints

The proposed approach is divided into two steps. In the first step, a scenario analysis of the future model mix in the production program is carried out. Hereby a worst-case evaluation of the scenario-inherent uncertainty is conducted in order to derive an adequate robustness requirement. As a result, assembly task specific time buffers are derived from the expected fluctuations in the model mix.

In solving line balancing optimization problems, methods of operation research can be used [25], whereby the problem of line balancing is a non-deterministic polynomial-time hard problem (np-hard) [7]. The proposed optimization algorithm on the one hand aims to distribute the different assembly times of individual assembly tasks in such a way that the aggregated possible fluctuation of all assembly steps assigned to a station is minimized. On the other hand the objective is to minimize the amount of assembly stations.

3.1 Scenario based robustness requirements

The line balancing is focused on the future production program [26]. Due to strategic decision the production program may be predefined and variations in model mix or optional equipment are covered by designated assembly lines. Hence robustness is not a requirement in these cases.

Otherwise the requirements of the line balancing have to be derived from an uncertain production program. By conducting a scenario analysis, it is possible to describe potential future production programs and thus obtain possibility ranges for each variant in the model mix, which further define the required robustness.

A scenario's share of the production program for each variant is described with an expected value (EV) and a level of uncertainty. Hereto a variant's share is modelled by using a normal distribution (Fig. 3). The expected values of all variant shares to be assembled on the respective assembly line have to sum up to the total production capacity, which is indicated by 100%.

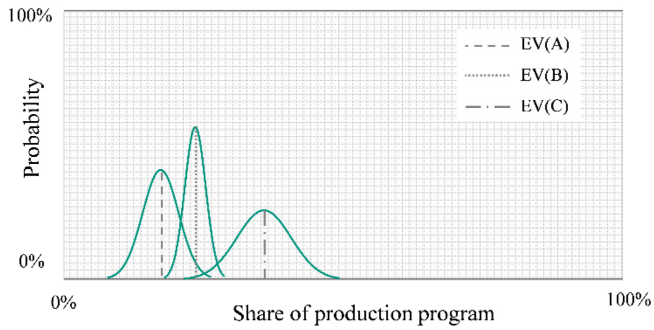

Fig. 3. Example of normal distributed shares of product variants

The assembly line's robustness requirement is derived from this scenario analysis. The variant (k) specific assembly times of individual assembly tasks are extended by a task-specific robustness buffer. As shown in Algorithm 1, the variance of the normally distributed variant shares in the model mix is used as an indicator for dimensioning the robustness buffer.

By applying this procedure, a time buffer to reduce the probability of takt time violations can be implemented specifically at the level of assembly tasks. The thereby determined task durations are used as input parameters for the line balancing optimization algorithm.

Algorithm 1: Deriving t_{robust} for an assembly task

```
initialize all parameters
repeat
  lower bound_k = expected share_k − Variance_k
  upper bound_k = expected share_k + Variance_k
  slack_k = upper bound_k − lower bound_k
  share_k = lower bound_k
until all variants processed
build list of variants by descending assembly times
slack_total = 100% − ∑ lower bound_k
repeat
  select variant with highest rank
  if slack_total < slack_k, then
      slack_k = slack_total
  end if
  share_k = share_k + slack_k
  t_robust,k = share_k * assembly time_k
  slack_total = slack_total − slack_k
  remove variant from list
until all variants removed
t_robust = ∑ t_robust,k
```

3.2 Optimization model for increased feasibility robustness

By definition, takt time violations never occur in a perfect deterministic line balancing problem without overload of takt time. However, if assembly task times are subject to stochastic behaviour and overload of takt time is possible, takt time violations may occur. To reduce this risk, a trivial approach is to plan sufficient buffer time at each assembly station by reducing the given takt time or by increasing individual assembly task times [12].

A more detailed approach for increasing robustness is given by identifying an assembly station's individual volatility and hence its extra need for robustness. This approach presents an extension for the general SALBP that minimizes the amount of work stations in operation [14] and further maximizes robustness at work stations with volatile task times by minimizing volatility at each station. Consequently, it is classified as a GALBP.

As a first step the volatility of single assembly tasks vol_i is to be determined. Therefore the weighted variance of task $i \in I$ is being used (Formula 1). For each assembly task i, the value of vol_i is calculated as the quadratic deviation of each possible optional equipment $s \in S$ of each product concept $k \in K$ (regarding its relative occurrence in the production schedule w_{iks}) from the task time $t_{robust,i}$.

$$vol_i = \sum_{k \in K} \sum_{s \in S} w_{iks} * \left(t_{iks} - t_{robust,i}\right)^2 \quad \forall i \in I \qquad (1)$$

ALTEMEIER proposed alternative volatility measures of which solely the measure of inefficiency weights deviations in a non-linear manner [27]. Since this measure compares the volatility throughout multiple stations it is not suitable for a station-related approach.

In order to minimize an assembly station's volatility an according measure vol_j is implemented. Assuming stochastically independent assembly tasks i, this measure represents the aggregation of each vol_i which is assigned to station j (Formula 2).

$$\text{vol}_j = \sum_{i \in I} vol_i * x_{ij} \qquad \forall j \in \text{J} \qquad (2)$$

Since the volatility of a station depends on its assigned tasks a dynamic approach that calculates vol_j during the algorithms execution is aspired. Therefore |J| constraints are used to determine the vol_j per station according to the algorithms decision variables assignment.

To increase feasibility robustness, the optimizations objective is to minimize the volatility of each assembly station (Formula 3). Therefore the |J| volatility constraints get equated with vol_j which is part of the objective function (Formula 4). In order to avoid constant terms of volatility in the objective function every instance of vol_j is squared.

$$\sum_{j \in J} vol_j^2 \qquad (3)$$

$$\sum_{i \in I} vol_i * x_{ij} \le vol_j \qquad \forall j \in J \qquad (4)$$

The program is formulated as a mixed integer linear program with a quadratic term in the objective function (MIQP). This program is based on SALBP and enhanced by the introduced objective function term including its corresponding constraints.

$$\min \sum_{j \in J} \Theta_1 * j * y_j + \sum_{j \in J} \Theta_2 * vol_j^2 \qquad (5)$$

$s.t.$

$$\sum_{i \in I} x_{ij} * t_i \le c \qquad \forall j \in J \qquad (6)$$

$$\sum_{j \in J} x_{ij} = 1 \qquad \forall i \in I \qquad (7)$$

$$\sum_{j \in J} (j * x_{aj}) - \sum_{j \in J} (j * x_{bj}) \le 0 \qquad \forall a, b \in I \mid E(a,b) = 1 \qquad (8)$$

$$\sum_{i \in I} x_{ij} \le |I| * y_j \qquad \forall j \in J \qquad (9)$$

$$\sum_{i \in I} vol_i * x_{ij} - vol_j \le 0 \qquad \forall j \in J \qquad (10)$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in I, j \in J \qquad (11)$$

$$vol_j \in \mathbb{R}_+, y_j \in \{0,1\} \qquad \forall j \in J \qquad (12)$$

x_{ij} represents the allocation of task $i \in I$ to station $j \in J$. Whether a station j is used in the line balancing configuration is determined by binary variable y_j. The predecessor constraint (Formula 8) is relevant for all tasks $a, b \in I$ if a is predecessor of b in the precedence graph P. Furthermore, Θ_1 and Θ_2 are normalization factors as in [28] that normalize the two objective terms to the interval [0,1] each.

4. Case Study

The described approach for a robust line balancing configuration is applied to a case study with data from a German automotive company. Therefore the algorithm got implemented into MathWorks MATLAB and solved with IBM ILOG CPLEX Optimization Studio. The actual input data is collected from a final assembly line for compact cars. In total, two product variants are to be produced on the focussed assembly line which is characterised by 100 assembly tasks (Fig. 4).

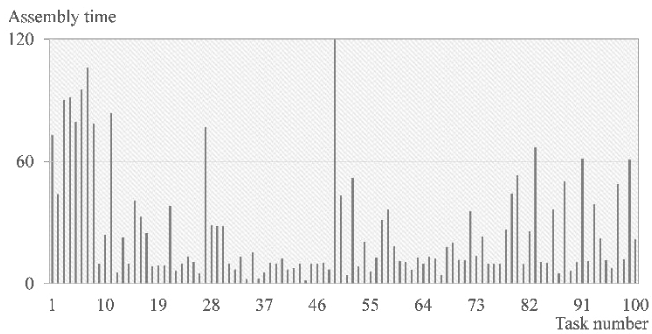

Fig. 4. Distribution of t_{robust} for focused assembly line (model mix ratio 1:1)

The obtained robust assembly time spans from below 5s up the maximum of 120s. These assembly tasks have to be allocated to a maximum of 30 assembly stations while the takt time of the assembly line is set to 120 seconds. The use case contains the following three operation point scenarios OPS_1, OPS_2, OPS_3 which are to be analysed:

Table 1: Operation point scenarios of the use case

Scenario	Ratio variant A/B	Standard deviation variant A/B
OPS_1	25% / 75%	5% / 5%
OPS_2	50% / 50%	5% / 5%
OPS_3	75% / 25%	5% / 5%

In order to generate additional results to the line balancing problem by applying the presented approach S_{robust} for comparison, two other approaches have been implemented. Both approaches use a standard SALBP optimization program without the proposed objective term to reduce station specific volatility (Formula 4). This procedure results in various solutions with the same target value for assembly stations. Hence, as supposed by ALTEMEIER [27; 11] the algorithm chooses the solution with the best horizontal smoothing throughout the stations' total assembly times. Line balancing in the first comparative approach is focussed on the average variant as described in chapter 2 and therefore produces line balancing solutions S_{avg}. In contrast to that, the line balancing in the second comparative approach is using the maximum assembly time of each assembly task and hereby produces solutions S_{max}. This approach prevents overload of the takt time and thus eliminates the risk of takt time violations for any model mix scenario.

In order to evaluate whether a production program can be produced on an assembly line with a certain line balancing configuration, the car sequencing problem is solved. Thereby the objective is to identify a sequence of products in which no overload, i. e. no violation of the takt time, occurs [12]. If a valid solution for the sequencing problem can be found, the line balancing configuration is considered to be valid in terms of the respective production program. Invalid solutions are rejected for further planning steps. Regarding the assembly system it is assumed that the employee's speed of return to the starting point of the station is infinite. Furthermore, it is assumed that there are no set-up times when changing variants and the increment for operation point feasibility analysis regarding variant A and B is set to 5%.

This analysis leads to a feasibility corridor that is limited by the largest feasible deviation from the OPS. In comparison, a more robust solution is characterized by a larger feasibility corridor. Figure 5, 6 and 7 show the feasibility corridors for each of the three operation point scenarios OPS_1, OPS_2 and OPS_3. The labelling of the bars indicates the algorithm used and the amount of stations which have to be opened when applying the solution. For comparison purposes, the solutions S_{avg} are used as reference solutions and hereto a light grey area is applied in the diagrams. Furthermore, the OPS is marked with a black line.

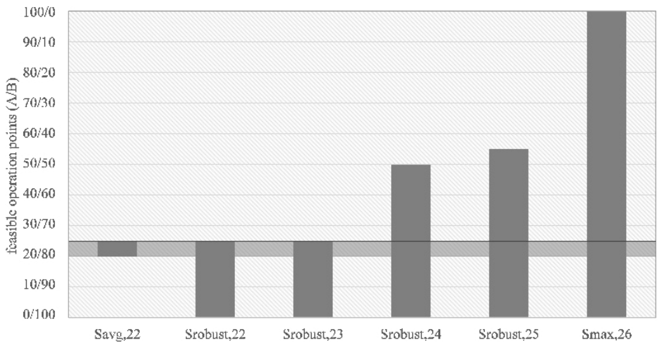

Fig. 5. Feasibility corridors for OPS 1

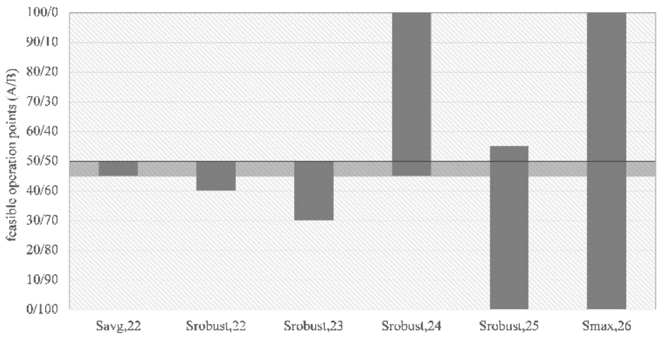

Fig. 6. Feasibility corridors for OPS 2

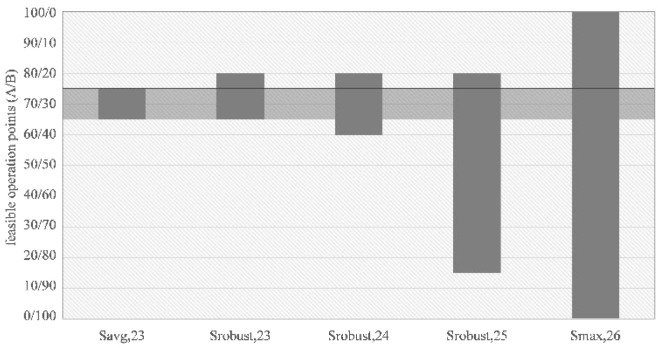

Fig. 7. Feasibility corridors for OPS 3

Within one OPS setup, several $S_{robust,j}$ were generated by varying the objective function's weighting parameters Θ_1 and Θ_2. The solution $S_{max,26}$ represents the limit of stations and feasibility robustness as no further robustness can be achieved and thus no further assembly station needs to be opened. This limit of stations can be applied as a comparison to each OPS since it holds the maximum feasibility robustness regarding all variants.

By comparing the solutions $S_{avg,j}$ to the solutions $S_{robust,j}$ with minimal stations, it can be observed that by applying the proposed approach a gain in feasibility robustness can be obtained at no additional costs through more stations. This effect can be observed especially in OPS_1 where the initial range of operating points from 20% to 25% of variant A, respective from 75% to 80% of variant B, could be extended to the range of 0% to 25% of variant A and 75% to 100% for variant B. On the one hand no further feasibility could be achieved by opening one more additional station in this case. On the other hand a general observation indicates that by adding more stations, feasibility robustness regarding variant fluctuations increases for each model mix scenario.

5. Conclusion and outlook

The described approach can be used to design robust line balancing with respect to specific production program scenarios. This results in a trade-off regarding costs incurring for assembly stations and required feasibility robustness towards fluctuations in the production program.

For this purpose, a combined approach is chosen. In the first step, a worst case scenario analysis of an uncertain production program is conducted. As a result, assembly task specific time buffers are derived from the expected fluctuations in the model mix. Subsequently, the line balancing problem is solved by the proposed algorithm. This algorithm focuses the described trade-off. It aims to distribute the different assembly times of individual assembly tasks in such a way that the aggregated possible fluctuation of all assembly steps assigned to a station is minimized. Furthermore, the number of assembly stations is to be kept to a minimum. By presenting the possible resolve options of this trade-off, it is possible to show which options for action are open to a decision-maker.

The described approach can be further detailed by including additional aspects of planning. In Algorithm 1, the normal distribution's variance is utilized to obtain the upper and lower boundary of the respective assembly time. It is yet to analyze whether different measures such as a multiple of the standard deviation or different distribution functions such as triangular distribution allow for a better robustness behavior.

Figures 4-6 show that the orientation of the feasibility robustness corridor is not included in the decision. Criteria can be developed to evaluate the orientation of this corridor.

Furthermore, the cost analysis can be carried out in more detail. In this approach, the car sequencing algorithm is used to determine the order sequence of the production program, which does not allow an overload of the takt time. By using mixed model sequencing, overload can be allowed [12]. This may, for example, be resolved by using springers and evaluated in terms of costs. The costs thus received can subsequently be compared to the costs of an additional assembly station. In addition to that, the occurring costs may further be detailed by taking the equipment into account, which is used at one station for several assembly tasks and therefore has to be purchased in a smaller quantity.

Lastly, the presented approach focuses on countering possible fluctuations in a predicted model mix by the integration of feasibility robustness. The integration and evaluation of reconstruction measures of the assembly system, due to exceedances of the robustness corridor or the necessary integration of additional variants, is related to the topic of changeability in line balancing which is also the subject of further research.

Acknowledgement

The authors would like to thank the German Research Foundation DFG for the kind support and funding within the project “Kennzahlensystem zur Robustheitssteigerung verketteter Produktionssysteme (LA2351/35-1)”.

Disclaimer

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References

[1] Bär T. Flexibility Demands on Automotive Production and their Effects on Virtual Production Planning. Proceedings of the 2nd CIRP Conference on Assembly Technologies and Systems (CATS), Page 16-28, 2008.

[2] Plötz P, Wietschel M, Kühn A, Gnann T. Markthochlaufszenarien für Elektrofahrzeuge – Langfassung. Studie im Auftrag der acatech – Deutsche Akademie der Technikwissenschaften und der Nationalen Plattform Elektromobilität (AG7), Karlsruhe: Fraunhofer ISI, 2013.

[3] Schühle F. Die Marktdurchdringung der Elektromobilität in Deutschland - Eine Akzeptanz- und Absatzprognose. München: Hamp, 2014.

[4] Günthner WA. Neue Wege in der Automobillogistik. Die Vision der Supra-Adaptivität, Berlin ua., 2007.

[5] Proff He, Proff Ha. Dynamisches Automobilmanagement: Strategien für Hersteller und Zulieferer im internationalen Wettbewerb“. Springer-Verlag, 2008.

[6] Möller N. Bestimmung der Wirtschaftlichkeit wandlungsfähiger Produktionssysteme. Vol. 212. Herbert Utz Verlag, 2008.

[7] Scholl A. Balancing and sequencing of assembly lines, 1999.

[8] Pröpster M. Methodik zur kurzfristigen Austaktung variantenreicher Montagelinien am Beispiel des Nutzfahrzeugbaus. Vol. 314. Herbert Utz Verlag, 2016.

[9] Hazır O, Dolgui A. Robust assembly line balancing: state of the art and new research perspectives. Sequencing and Scheduling with Inaccurate Data, 2014, p. 211-223.

[10] Dombrowksi U, Medo M. Varianten im Takt–Gift für die Produktivität?. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, Vol. 101, Nr. 12, 2016, p. 715–718.

[11] Fisel J, Arslan A, Lanza G. Changeability focused planning method for multi model assembly systems in automotive industry. Procedia CIRP, 63, 2017, p. 515-520.

[12] Boysen N. Variantenfließfertigung. (Vol. 49) Deutscher Universitätsverlag, 2005.

[13] Becker C, Scholl A. A survey on problems and methods in generalized assembly line balancing. European journal of operational research 168.3, 2006, p. 694-715.

[14] Baybars, I. A survey of exact algorithms for the simple assembly line balancing problem. Management science 32.8, 1986, p. 909-932.

[15] Besenfelder C, Uygun Y, Kaczmarek S. Service-oriented integration of intercompany coordination into the tactical production planning process. Robust Manufacturing Control. Springer, Berlin, Heidelberg, 2013, p. 301-314.

[16] Thomopoulos NT. Mixed model line balancing with smoothed station assignments. Management science 16.9, 1970, p. 593-603.

[17] Dörmer J. Produktionsprogrammplanung bei variantenreicher Fließproduktion: Untersucht am Beispiel der Automobilendmontage. Springer-Verlag, 2013.

[18] Boucher TO. Choice of assembly line design under task learning. International Journal of Production Research 25.4, 1987, p. 513-524.

[19] Chakravarty AK. Line balancing with task learning effects. IIE transactions 20.2, 1988, p. 186-193.

[20] Tempelmeier H. Practical considerations in the optimization of flow production systems. International Journal of Production Research, Vol. 41, No. 1, 2003, p. 149–170.

[21] Scholl A. Robuste Planung und Optimierung – Grundlagen, Konzepte und Methoden. Experimentelle Untersuchungen, Heidelberg, 2001.

[22] Halubek P. Simulationsbasierte Planungsunterstützung für Variantenfließfertigungen. Vulkan-Verlag, 2012.

[23] Keckl S, et al. An analytical framework for handling production time variety at workstations of mixed-model assembly lines. Procedia CIRP 41, 2016, p. 201-206.

[24] Scholl A, Voß S. Produktionsplanung – Ablauforganisatorische Aspekte. 1997.

[25] Boysen N, Fliedner M, Scholl A. A classification of assembly line balancing problems. European journal of operational research 183.2, 2007, p. 674-693.

[26] Kern W, Rusitschka F, Bauernhansl T. Planning of workstations in a modular automotive assembly system. Procedia CIRP 57, 2016, p. 327-332.

[27] Altemeier S. Kostenoptimale Kapazitätsabstimmung in einer getakteten Variantenfließlinie: unter expliziter Berücksichtigung des Unterstützereinsatzes und unterschiedlicher Planungszeiträume. Diss. Paderborn, Univ., Diss., 2009.

[28] Grodzevich O, Romanko O. Normalization and other topics in multi-objective optimization. 2006.