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Procedia CIRP 63 (2017) 515 – 520

www.elsevier.com/locate/procedia

The 50th CIRP Conference on Manufacturing Systems

Changeability focused planning method for multi model assembly systems in automotive industry

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Abstract

Series vehicle production is designed to produce effectively at a defined number of vehicles per period. Regarding market forecasts the overall market trend depicts an increasing demand for electrified vehicles within an uncertain propulsion concept vehicle mix. This demand cannot be predicted precisely because of volatile influencing factors such as governmental subsidies. Automotive companies are therefore confronted with the challenge of rapidly adapting their production systems accordingly. An approach to handle the variety of models within vehicle final assembly is to establish mixed model assembly lines. Since single model assembly lines are optimized for a specific production volume of one model, the subsequent integration of vehicles using alternative propulsion concepts into single model assembly lines stands as a great challenge in final assembly. Moreover, producing with optimal configured assembly systems after integrating an additional model is not ensured further on. To address this challenge, an approach for the greenfield planning of assembly lines using the concept of changeability is presented within this paper. The presented approach offers a new method to cover uncertainty regarding the future propulsion concept mix of assembly lines. This affects the initial setup of an assembly line concerning the line balancing and assembly equipment as possible subsequent changes to the assembly system increase costs. The target conflict is to minimize changes to the assembly system due to the integration of further propulsion concepts while ensuring cost efficient assembly. Hereto, the line balancing problem is solved for a fixed production volume ratio using a developed optimization algorithm. Thereafter, the production volume ratios are varied in order to identify an optimal solution for line balancing and assembly equipment. The uncertainty of volume ratios is considered in the integrated costs calculation module.

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Keywords: changeability; assembly system; planning method;

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1. Introduction

Customers of automotive companies demand an increasing amount of variants [1]. An approach of automotive companies to cover this need is to add an increased number of customizable options. This trend is further supported by the rise of electro mobility as the integration of an electric propulsion concepts can be interpreted as an additional variant to be produced.

Currently the demand for electric or hybrid vehicles is increasing [2; 3]. This demand is driven by external influencing factors such as governmental subsidies or commodity prices which are volatile. Therefore the predicted volumes to be produced vary accordingly [4]. In order to cover the resulting uncertainty a demand for highly flexible and changeable production systems occur.

The final assembly of automotive companies is confronted with several challenges concerning the assembly of different variants. The difference of the variants transfers to the difference in the bills of materials. Concerning electric mobility substantial distinctions regarding the bill of materials occur within the powertrain. Distinction in parts to be assembled leads to the conclusion, that also the assembly process is affected by different variants. Additionally the material has to

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doi:10.1016/j.procir.2017.03.148

be provided to the assembly line and moreover the order of assembly steps may be different due to other dependencies between assembly steps.

In automotive production there are two general approaches to design assembly lines – single model assembly lines (SMAL) and multi model assembly lines (MMAL) [5]. In order to handle the amount of different model variants an approach is to convert SMALs into MMALs or upgrade the amount of variants in MMALs. This approach respects the volatile but still low production volume of vehicles with electric propulsion concepts. It offers potentials for cost reduction since assembly lines operate efficiently and can be upgraded when necessary compared to setting up new assembly lines. On the other hand, the integration of new propulsion concepts causes different problems due to the optimized production flow of SMALs, limited space and assembly equipment.

Within this paper, an approach using the concept of changeability for the greenfield planning of final assembly lines within the automotive industry is presented. The concept of changeability has been applied to several topics in the field of production planning [6, 7, 8, 9, 10]. The presented approach focuses on two aspects: The line balancing under uncertainty regarding variants and model mix and the determination of the inherent flexibility of the line balancing solution.

2. Flexibility and changeability in production planning

As highlighted, final assembly lines undergo a new set of challenges due to the current overall market trend. On the one hand, the increasing number of powertrain variants that has to be respected and on the other hand, the changes in the model mix. These circumstances create pressure for the final assembly lines to keep up an effective production.

Therefore a target in final assembly planning is to plan robust assembly lines. Robust assembly systems are more resistant to changing external influences. Flexibility and changeability are two widely discussed concepts for implementing robustness [11; 12] (Fig. 1).

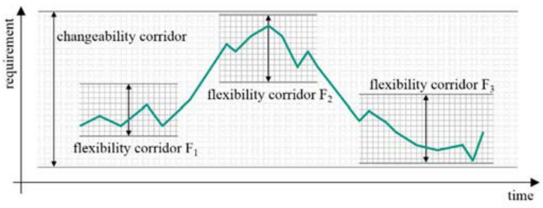

Fig. 1. Flexibility and changeability corridors [15]

2.1 Flexibility

Flexibility incorporates the possible solutions within an assembly line concept to react to small influences (e.g. fluctuations in demand or changes in model mix). Flexible solutions are characterized by quick implementation and low effort [13]. The range of flexible adjustments for such changes is defined as flexibility corridors and spans around the operating point of the system. Since adaptions in flexible systems come with low effort, the necessary resources need to be held available in advance [14]. The covered spectrum of a flexibility corridor is considered as an indicator for the robustness of the system. Therefore a larger flexibility corridor implies a more robust system.

2.2 Changeability

In case necessary modifications cannot be covered with available flexibility, changeability within the production system is a key factor for adaption. Changeability is a planned ahead solution space. It is defined as the ability to adapt to changing environmental influences by moving the flexibility corridors within the changeability corridor [15].

2.3 Costs of adaption

Regarding the planning of changeability a critical question occurs concerning the amount of changeability a system should inherently possess. A system neglecting changeability will save initial invest but in case of occurring change will result in high reconstruction and opportunity costs. In contrast a highly changeable system leads to a high initial investment but may yield operational inefficiencies, when the expected need for a change never occurs. Thus, identifying the optimal point in this trade-off is vital in strategic production planning. [16]

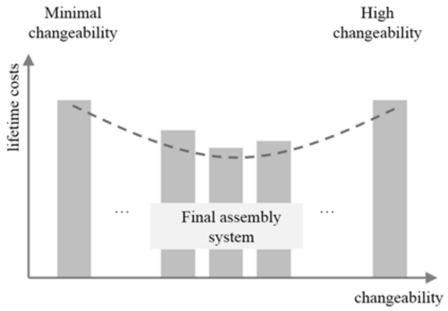

Fig. 2. Lifetime costs of changeable objects [16]

In the next chapter the method for greenfield planning that aims at investigating this trade-off through mathematical optimization is presented.

3. Methodology

The planning of final assembly consists of several tasks. The following planning methodology focusses on the uncertainty of variants and production ratios as well as on the resulting demand for a robust planning.

3.1 Deriving multi-objective optimization problem for the integration of an additional propulsion concept

The approach touches upon the field of line balancing, which is a mathematical method of allocating assembly tasks to work stations in such a way that under the consideration of precedence and other constraints a given objective function (e.g. investment costs) is minimized or maximized. Since each allocation that is not included in an optimal solution leads to unnecessary costs or inefficiencies in operations, line balancing is directly relevant to the costs of a system. In the first step, the line balancing problem of a basic variant production line (cf. greenfield planning) is modelled and solved to optimality. This illustrates the current situation. In the second step, a line balancing scenario for the integration of an additional model is created. The precedence constraints of the mixed model assembly line are created by joining those of the single models of different variants into one dependency graph. The duration of each task is thereby calculated based on the given volume ratio in the model mix. Hence, this covers the consideration of several different variants to be integrated. Subsequently, the line balancing problem of the mixed model is solved to optimality, as well.

Both problems are binary integer programmes and have a linear objective function minimizing the number of required stations given a pre-determined cycle time. The objective function has the form as in (1), where y_i is the binary variable representing the usage of workstation i.

$$min \sum_{i=1}^{k} y_i \qquad (1)$$

The constraints of the problem are given in Table 1. x_{ij} indicates the allocation of task j to workstation i, t_j the operation time for task j, and c_i the takt time of the line. While $n(J)$ represents the number of total tasks, P stands for the set of dependencies signalling whether i.e. task b is an immediate successor of task a. A Branch and Cut algorithm is deployed in order to solve the binary integer programmes in question.

Plausibly, a time delay between the current and the future scenario situations occurs. In the transition phase from the basic SMAL or MMAL to the updated MMAL, a line rebalancing approach is needed instead of a line balancing approach. Line rebalancing is the procedure of making adjustments to an already existing line so that the allocation of tasks to stations is reorganized through mathematical optimization [17].

In order to ease the transition phase, it is vital to take into consideration the future rebalancing between the basic model and the mixed model in advance. Therefore, the single model line is rebalanced in such a way that the number of allocations that are different in the mixed model line, is minimized. Accordingly, the objective function is modelled as the sum of deviations in allocations between the cases, which is to be minimized.

Table 1. Constraints of the basic problem

Constraint	Explanation
$\sum_{j \in J} x_{ij} * t_j \leq c_j, \quad \forall i$	Consideration of takt time
$\sum_{i \in I} x_{ij} = 1, \quad \forall j$	Allocation of each task to only one station
$\sum_{j \in J} x_{ij} \leq n(J) * y_i, \quad \forall i$	Maximum number of tasks per station
$\sum_{i \in I} (i * x_{ia}) - \sum_{i \in I} (i * x_{ib}) \leq 0, \ \forall a, b \in P$	Precedence constraints
$x_{ij}, y_j \in \{0,1\} \quad \forall i, j$	Binary decision variables

Concerning the effort of reallocations it is to state that every deviation in allocations generates different costs. Reallocation of some tasks to a new station might involve higher costs than that of another task. Since it is not possible to perfectly quantify prospective costs, a relative approach is followed. Respective costs are given in percentage through pair wise comparison, indicating how expensive each deviation is relatively expected to be.

Subsequently, adjustment costs are assigned to their respective reallocation and included as coefficients of the deviations in the final objective function as in (2).

$$\min \sum_{j \in J} c_j * \sum_{i \in I} \left| x_{ij}^{*} - x_{ij} \right| \qquad (2)$$

c_j represents the adjustment cost for carrying out task j at another workstation. x_{ij}^{*} and x_{ij} are binary variables, the former indicating whether task j is assigned to station i in the initial mixed line balancing problem, whereas the latter being the decision variable for the new rebalancing problem. I indicates the set of tasks, while J the set of workstations.

Although it is desired to have a line that has a high level of changeability, the basic line should still be well balanced, since the adjustments are uncertain regarding the probability of occurrence. The trade-off between the efficiency and the changeability of the single model line arises at this point. In order to take this fact into consideration, a second objective function, demonstrating the efficiency of the line, is modelled as well.

The imbalance rate of the line (3) is selected as a measure for effectiveness, indicating the variation between the maximum process duration of all stations and the total process duration of the remaining stations of the assembly line. It is preferred to have this measure as low as possible, exhibiting high efficiency [18].

$$min \sqrt{\sum_{j \in J} \left(t_{max} - t_j\right)^2} \qquad (3)$$

t_{max} gives the longest duration among tasks, whereas t_j gives the duration of task j.

A multi-objective optimization problem with two objective functions, where the first one being the minimization of the adjustment efforts between the lines (2) and the second one being the minimization of the imbalance rate of the basic model (3), is formulated. The constraints of this problem are the same as in Table 1 with the exception that y_j is not used as decision variable. Furthermore, the right hand side of the constraint on the maximum number of tasks per station is thereby reduced to only the number of total tasks $n(J)$.

The genetic algorithm NSGA-II is a fast and successful solution in dealing with multi-objective optimization problems through non-dominated sorting as well as the crowded comparison operator [19] and therefore deployed in order to solve the problem. The outcome of this procedure is the Pareto-optimal front, being the set of feasible solutions that are not dominated by any other solution. Out of the pool of non-dominated solutions, the final solution is selected by determining the minimum deviation in line efficiency from the optimal solution that was found for the basic model. This process is depicted in Fig. 3.

In order to fully implement the final allocations that the optimization problem holds, a decision on the assembly equipment is needed. Thus, an assembly equipment catalogue is generated, which contains technical information (e.g. maximum torque value) as well as related costs for every assembly process. Subsequently, the requirements of each assembly task concerning its operating equipment are identified. In a further step, the equipment requirements of the working tasks are matched with the equipment properties. Equipment that fails to fulfil the requirements is eliminated. Next, all matches between task and equipment are listed in full combinations related to a working task. The number of combinations per task is reduced through pair-wise Pareto dominance comparison. A combination dominates another combination, if it scores better in at least one feature while having equivalent or better ranking in other features.

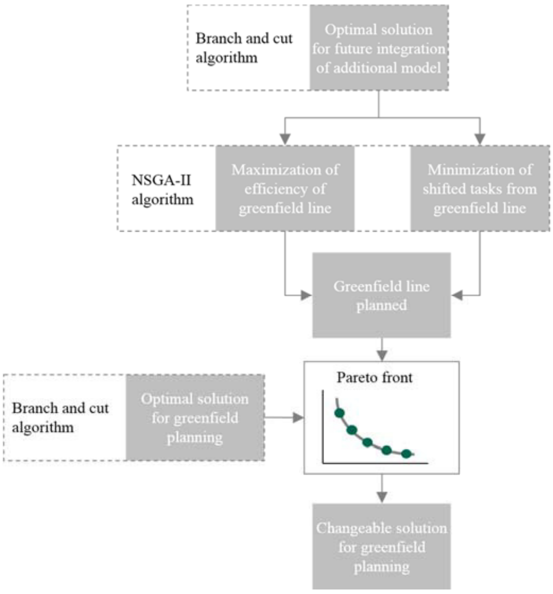

Fig. 3. Line Balancing under model uncertainty for fixed volume mix

The obtained combinations are categorized as flexible and changeable solutions. Only if a combination satisfies the requirements of both the initial SMAL or MMAL and the upgraded MMAL, it is classified as flexible. On the contrary, if a combination includes assembly equipment that requires to be changed in case of implementing further models in the assembly line, it is classified as a changeable combination.

In order to decide which assembly equipment combination to implement for each task, the related costs are taken into consideration for comparison. First of all, for each combination within the group of flexible combinations, the totals costs are obtained. Second of all, the same logic applies to each combination within the group of changeable combinations, whilst the resulting costs are calculated by multiplying the respective change costs with the likelihood of the occurrence of the change. Third of all, all combinations for each task are compared with respect to their total costs and the ones indicating the least costs are considered as the most cost efficient solution.

3.2 Identifying flexibility corridors

In the first part of the approach, a multi-objective optimization problem was modelled and solved for the integration of an additional propulsion variant with a fixed volume ratio in the mix (Fig. 3). Hereafter different volume ratios are modelled as input coefficients to the optimization problem in order to identify corresponding flexibility corridors.

In the case the model mix consisting of *n* variants, the set of the production volume ratios is *n-1* dimensional, i.e. the area of a triangle with three variants or triangular prism with four variants. The set includes all increments between the vertices of itself, of which each corresponds to a single model line producing a different basic variant. In the approach a percentage value is set as increment (e.g. 1%, 5%). The developed multi-objective problem is solved for every model mix ratio in the set. Subsequently, there are in total $\left((1/increment)+1\right)$ different cases of volume mix ratios and one solution generated for each volume mix ratio.

Throughout the optimization problems of different volume mix ratios, the average task processing time varies between the runs, since the calculation is based on a weighted sum of the task durations of the single lines. Furthermore, operation technology changes, as well.

Following this, the obtained solutions are to be structured. The target is to identify flexibility corridors compromising several model mix ratios. At first, all identical solutions are clustered. These solutions represent the flexibility of model mix ratios which can be conducted without adapting the system. Therefore these solutions form the optimal segments of the flexibility corridor. In contrast to the optimal segment a suboptimal segment can be identified. Suboptimal solutions imply that the assembly of vehicles is feasible but under suboptimal conditions (e.g. waste of production time). The representation of optimal and suboptimal flexibility corridors is depicted in Fig. 4.

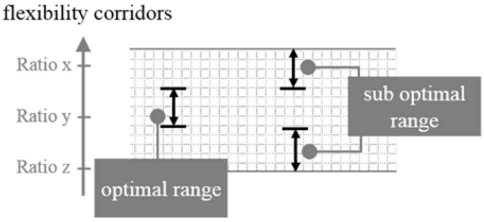

Fig. 4. Optimal and sub optimal range within flexibility corridors

In order to identify the suboptimal part of the flexibility corridor of a given volume mix, the optimization problem is rerun with the allocation results of the following increments of the volume mix. Hereby, the allocation results of the other volume mix are defined in the problem as an additional constraint (4) to those that were used as constraints in the multi-objective optimization problem.

x_{ij} is the binary decision variable of the problem to be rerun, while $\hat{x}_{ij}$ gives the allocation results of the other volume mix

$$x_{ij} = \hat{x}_{ij} \tag{4}$$

The result of rerunning the algorithm under the additional constraint is either a valid or invalid solution. (Fig 5a). An invalid solution can be derived from the algorithm run in case the algorithm does not identify a single solution to the problem. To display the results efficiently a validity matrix is generated (Fig. 5b). The ratio shown on the left hand side is the basis. The solution of the ratio shown at the top is passed to the optimization problem of the basis ratio and forms an additional constraint (see Fig 5a).

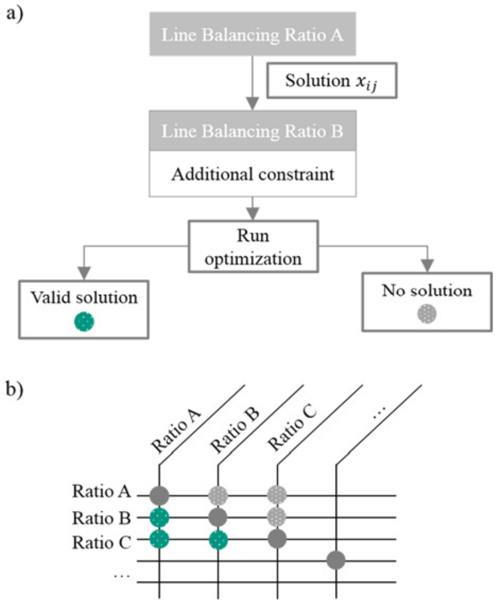

Fig. 5. (a) Feasibility check; (b) construction of validity matrix

In the next step the optimal and feasible solutions are combined in order to cover the whole set of ratios. Hereto every possible combination of corridors is considered under constraints. A combination of flexibility corridors has to cover the whole range of the ratio set. Blank spots would indicate that there is no valid solution which has to be declined if the branch and cut algorithm offers a solution (see Fig.3). An overlap of optimal solutions can be excluded since overlapping optimal solutions would be identical. This process is displayed in Fig. 6.

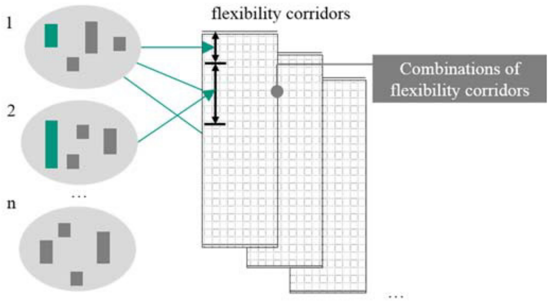

Fig. 6. Combination of flexibility corridors

Finally, all combinations of the flexibility corridors that cover the whole set of the volume ratios are generated. As a result the flexibility corridors for different model mix ratios have therefore been identified.

3.3 Consideration of change costs

As stated, flexibility and changeability are required in order for a final assembly to react to the current challenges in production planning. Optimal and suboptimal segments of flexibility corridors realize the desired robustness. In order to analyse the resulting flexibility corridors different criteria have been established [20]. Flexibility corridors which are dominated by other corridors are not considered applicable for further planning steps.

The remaining flexibility corridors form the base for further monetary analysis. As stated, flexibility corridors consist of optimal and suboptimal ranges with the optimal range being the result of the line balancing optimization (see Fig. 3). As additionally stated (see chapter 3.1) the line balancing method is conducted for each increment of the model mix ratio leading to connecting optimal ranges throughout the model mix ratio spread. This is depicted in Fig. 7 at the example of the model mix for 2 models A and B.

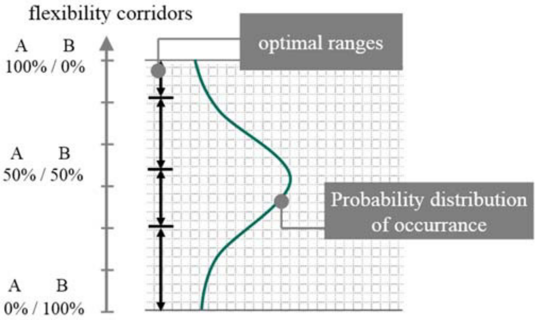

Fig. 7. Model mix ratio corridor with optimal flexibility ranges and probability of occurrence

The uncertainty regarding which model mix ratio needs to be addressed in the future is covered by the usage of probability distributions.

The optimal greenfield configuration is found under the consideration of the expected change costs [20]. First, the expected costs of changing from a given volume mix ratio in the set of the single model line to the configurations in the obtained flexibility corridor of the mixed model are calculated and summed up. Hereby, the expected change costs are calculated by multiplying the absolute change costs with the likelihood of the change occurrence (see Fig. 6). The absolute change costs are obtained by taking into account the moment of the change in question through the net present value method. The probabilities are drawn from a normal distribution. Second, the same applies to all volume mix ratios and their expected change costs are derived, accordingly. Third, the volume mix ratio with the lowest expected change costs is selected as the preferred greenfield configuration.

4. Conclusion and outlook

The presented approach addresses automotive final assembly greenfield planning under uncertainty. It offers orientation by monetarizing different degrees of changeability and therefore supports decision making. It addresses the challenge of increasing models and focusses on the integration of additional powertrain concepts but is not limited to this topic. Moreover it is applicable for other integrations, which affect final assembly planning (e.g. integration of different architectures).

At the beginning the basic concepts of flexibility and changeability were presented in order to give a general understanding of the topic. Following this, the adaption of the line balancing problem for future integration of additional models has been described. The focus idea is to solve the line balancing problem for the greenfield planning with the additional model already in mind. Therefore a Pareto-front of optimal line balancing solutions has been identified from which the preferred solution has been drawn. The second focal point of the presented approach is the identification of the flexibility corridor for each model mix ratio. In order to give a better understanding on the flexibility the flexibility corridor has been separated in an optimal and suboptimal range. The optimal range compromising solutions which are identical and the suboptimal range holding the solutions which allow for a feasible yet not optimal assembly system. The identification of feasible solutions was conducted by integrating allocation results of a line balancing solution as a restriction to the analyzed line balancing problem.

Further work can be done regarding extended optimization runs with real data. In order to conduct the branch and cut algorithm as well as the genetic algorithm, various data sets are necessary. These include the different assembly tasks, assembly times, the takt time and the demanded as well as the available assembly equipment. Additionally the cost analysis regarding the shift of assembly tasks has to be completed. Currently, a scenario in automotive industry is analyzed which holds the integration of a battery electric vehicle into a combustion engine vehicle line. Furthermore, the uncertainty is represented as probability distributions. It is yet to analyze how different distributions affect the result of the greenfield planning configuration. Therefore sensitivity analysis could be conducted. Also the approach should be transferred to the challenge of different vehicle architecture concepts. Further work can also be conducted concerning the disintegration of propulsion systems.

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