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CIRP Office
9 rue Mayran
75009 Paris - France
Tel: 33 1 45 26 21 80
Fax: 33 1 45 26 92 15
Email: cirp@cirp.net
Website: http://www.cirp.net

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Planning assistance for pearl chain forecasts and personnel assignment planning of sequenced assembly lines

Walter Mayrhofer [a,*], Lothar März [a,b], Wilfried Sihn (2)[a]

[a] *Vienna University of Technology, Institute of Management Science, Theresianumgasse 27, 1040 Vienna, Austria*[1]
[b] *LOM Innovation GmbH & Co KG, Kemptener Straße 99, 88131 Lindau (Lake Constance), Germany*[2]

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ABSTRACT

In sequenced automobile assembly, the assignment of personnel is done at almost all major manufacturers subordinate to the sequencing, resulting in sub-optimal utilization of personnel resources. By integrating the sequence planning with the personnel assignment planning, a significant increase in hours-per-vehicle efficiencies is possible. The presented integrated planning approach combines a sequencing solution based on constraint programming, with incident-discrete simulation. The hybrid-solution evaluates the sequence-building regarding personnel and procedural restrictions with the intent of simultaneously optimizing the vehicle sequence and the deployed assembly personnel, resulting in lower capacity demand fluctuations and increased utilization of personnel resources.

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1. Introduction

The following results are based on follow up work of the European *Eurostars* research project "Advanced Production Programme and Personnel Assignment Planning" (AProPerPlan), in which prognosis-based pearl chain planning using simulation was successfully applied at a commercial vehicle manufacturer.

1.1. Initial situation and objective

The European automotive industry is characterized by complex and customized products. This requires a production programme planning of the highest complexity to arrange the different variants in a way that worker deployment is levelled and capacity peaks are avoided. This work focuses on planning the final assembly in automobile and component factories with assembly line work of high labour intensity and low automation.

Sales forecasts, installation rates and monthly production and sales volumes are input parameters for programme planning. Operative production programme planning has to decide the manner and quantity of the variants from the existing portfolio of variants, to be manufactured for single assembly periods [1]. In many cases the production programme planning is used to break down the monthly order balance to a single day or shift program (period-oriented order stock) [2]. Thereby, on the one hand the capacity framework in the form of disposable manufacturing cycle time must be adhered to and on the other hand the availability of the used components must be considered [3].

Production programme planning is usually done cyclically or on a "floating" basis. The assignation of orders to weekly or daily periods or shifts is also called *slotting* (see Fig. 1).

Cyclical planning may ensue slotting until the sequence is fixed, which has a smoothing effect on material and capacitive dependant criteria. Under consideration of more detailed limits, single orders can be moved to other production periods and such levelling shifts are also called *balancing*. The determination of a sequence assigns a defined production position to every order of the stock (also called pool) and hence is also called sequencing. Any later changes of the sequence lead to higher expenses, because the availability of components cannot be guaranteed.

The implementation method and the sequencing goals can differ, leading to three different classes of optimization models: level-scheduling, mixed-model-scheduling and car-sequencing. *Level scheduling* is derived from the Toyota-production-system [2] and targets a level demand for materials in the production sequence. *Mixed-model sequencing* aims at avoiding resource capacity overloads of the flow system, which are minimized by

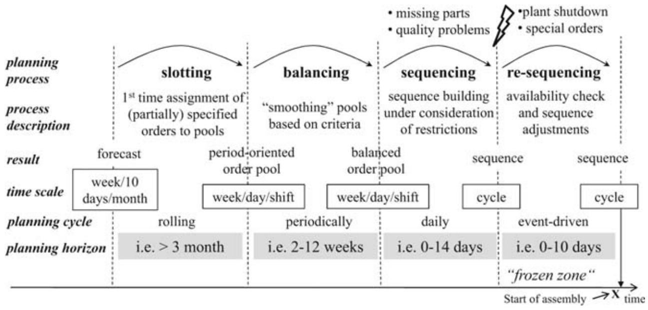

Fig. 1. Planning process of a sequenced production line.

* Corresponding author.
[1] www.imw.tuwien.ac.at.
[2] www.lom-innovation.de.

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detailed timing of the variants regarding their specific process duration at every station, defining the length of the station and cycle time. *Car-sequencing* intends to avoid overloads, by banning overload-prone sub-sequences of certain variants by means of so-called H_o–N_o-sequencing rules. Hence, maximum H_o out of N_o ensuing variants are allowed to contain the option o, otherwise overload would occur [6]. A sequencing-rule at a ratio of 1:3 for the option "sun roof" implies that only one out of three consecutive units may contain a sun roof. Most European manufacturers use car-sequencing to avoid the complex data acquisition needed for mixed-model-sequencing.

The simulation-based optimization aims to actively control the bottleneck or its capacity. This might lead to a shift of the bottleneck if personnel resources can be moved. Therefore, integrative personnel assignment and production programme planning expands the degrees of freedom of planning.

2. Approach

Most vehicle manufacturers use a sequencing solution based on the car-sequencing method. Overload is avoided by taking various restrictions into account, but dynamic dependencies are often ignored, i.e., averaging process time requirements leads to mix vehicles with longer and shorter process time. Frequently variance cannot be levelled through extra effort by the assembly line workers, requiring additional workers for one car and under-utilizing personnel with the next, twice thwarting the goal of an even work load. To analyse the interactions of the real sequence with personnel assignment planning a discrete event simulation model was developed and integrated into a web-application.

2.1. Interdependencies

Personnel assignment is illustrated with an example from the car assembly. Planning the assembly process is done by means of "time-path diagrams", depicting the physical path of a worker over time and chronologically measuring and evaluating each step. Based on the time requirements, each step can be assigned to a point of the assembly line and material withdrawal and the distances between material withdrawal and the assembly have to be bridged. Since the car-body moves with the tact-time extra stretches occur. The personnel periodically carry out similar assembly steps, necessitating that all steps at a station add up to fit within the tact-time in order to allow cyclical processing.

The number of process steps and the overall duration of the assembly process vary depending on the product variant. Due to those differences, overload can occur, if variants with high time requirements are assembled successively. This is one of the typical cases that necessitate production programme levelling.

The single process steps can be assigned to an assembly operation as a whole, i.e., the process steps material withdrawal, moving to assembly site, preparation of the assembly, catching hold of auxiliary materials, etc. are combined to one assignment (i.e. assembly of a rear-view mirror). Variants with a different process times are represented as the same assignment with accordingly adjusted assembly time and optional variants by means of distinct assembly operations. However, not every assignment has to be completed within a work cycle. Either the preceding and subsequent assignments are so short that overlong accomplishments can be performed without difficulties, or alternatively two or more workers (i.e., n) are deployed, who work overlapping on every second or n^{th} object to be assembled.

An additional opportunity is the deployment of *jumpers* (reserve pool man) in case of an overload. Such a jumper can be used for various reasons and different capacity demand scenarios:

1. Assignment of a jumper to balance the process time at a station if there is the threat of a capacity overload.
2. Using jumpers for orders with high capacity demand that follow the order through part or the whole line.

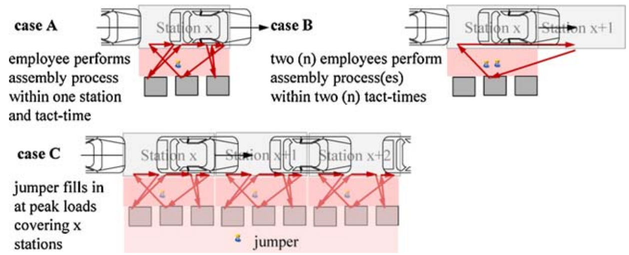

Fig. 2. Scenarios of personnel assignment with regard to the stations.

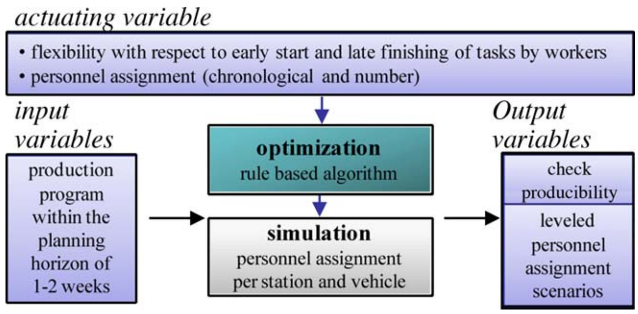

Fig. 3. Relation between simulation and optimization.

3. Drawing jumpers for tasks requiring specific skills that only occur rarely (technology caused use of jumpers).
4. Jumpers as a replacement for absentees.

The first two application scenarios of a jumper use the free capacities of the jumper at the point of occurrence. The latter two functions are not intended to support the sequence planning with a (short-term operative) capacity increase. Hence, those two options are not considered in the model, but they are considered as input parameters (no. of jumpers). The personnel assignment scenarios considered in the model are shown in Fig. 2.

The consideration of the requirements of the production programme and personal assignment planning is the combination of the sequencing solution and a simulation of personnel assignment. The resulting solution is intended to build a bridge between the need for information and the ability to solve a problem and is shown in principle in Fig. 3.

2.2. Actuating variable

In the planning horizon between middle- and short-term (i.e. one week before start of production) the system has different options to react, resulting in different actuating variables. With the premise, that the production sequence is the target parameter, the possible changes to balance a personnel deficit are

1. Utilization of group-internal flexibility.
2. Deployment of jumpers at the concerned stations.
3. Use of variable personnel capacities throughout the day.
4. Tuning of personnel scenarios at affected stations/shifts.
5. Authorization of temporary workload peaks ("moving along") and local compensating changes of sequence.
6. Shifting of work content between work stations.

2.3. Problem classes

Integrated programme and personnel assignment planning of sequenced assembly lines is a blend of an allocation problem (distribution of orders to shifts and assigning levels of personnel) and a sequencing problem (sequencing of orders). In a relaxed variant the allocation problem can be expressed as a mere linear program (see Section 3.1), which disregards the sequencing-

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constraints and the dependencies between the single stations-groups. If the constraints are integrated in the modelling, the formulation of the problem is considerably more complex. The sequencing of the automobile-production is an HP-hard problem [4]. Problems up to the size of a thousand orders can be solved efficiently. It is wise to put the constraints in hierarchical order, since in case the original problem is unsolvable some constraints can be relaxed.

3. Optimization approach and problem coding

3.1. Algorithms/systems

The planning process can classified into pooling, sequencing, simulation and analysis. Solutions of the total problem are searched with a branch-and-check-method [5]. Though pooling represents the master-problem for sequencing and simulation, sequencing represents the master-problem for sequencing.

To ease the problem, order classes, not individual orders are planned. An order class contains all orders that are similar for the planning process, i.e. this concerns all orders with the same attributes. At the end of the planning process, individual orders are represented in the positions of the respective order classes.

The varying process time requirements of the vehicles lead to model-mix-losses due to over and under utilization of the staff. No performance-related losses occur in an ideal (100%) assembly system that works at full capacity. Cycle losses normally appear because the utilization of a station to capacity, only by means of task-oriented matters, does not work out successfully. Therefore, the cycle levelling of a station is calculated as a key figure for the average over and under utilization during the planning period:

$$\tau_j = \frac{nT_j - \sum_{k=1}^{n} te_{kj}}{nT_j}$$

with:

j index stations $j = 1 \ldots m$
k index models $k = 1 \ldots n$
n number of models
T cycle time
te_{kj} process time of model k at station j
τ_j cycle levelling at station j

Under utilization during a planning period (i.e. shift) results in a positive whereas overload leads to a negative cycle levelling.

3.1.1. Pooling

As a first step orders are assigned to layers of the planning horizon and the teams needed to assemble them minimized. In this relaxed version of the total problem only capacity-constraints are considered and the station groups are observed independently. Mathematical programming was chosen to solve the pooling.

The solution of this constraint-system gives a super-optimal personnel distribution over the station groups, since an ideal distribution was assumed for every order class. Moreover, constraints between station groups were not considered and hence it is possible that, for a given solution of the pooling, no valid sequence can be found. However, the approach allows increasing the team size step by step until a valid distribution is found.

3.1.2. Sequencing

The second step of the sequencing determines the succession of orders. The sequencing solution used is one developed by flexis AG, and is based on the method of constraint programming (CP) [7,8]. The sequencer fills each position according to the specifications of its heuristics. As soon as the range of values of a position is emptied using the constraints the sequencer returns to its last choice to pick another order class.

In the course of the project more rules were added to the technical constraints (to model technical restraints of production), portraying order distribution and team size that were calculated in the pooling. A certain number of orders of a class are provided for each station group and for each shift. The actual distribution should only vary minimally from these pre-settings. This can be achieved by means of limit-constraints, which restrict the total number of orders of a class in a certain sequence section that corresponds to a shift of a station group. Deviations from this limit are allowed, but rated negative. Additional equipartition-heuristics guarantee an equal distribution of the orders and facilitates the personnel assignment throughout the simulation.

3.1.3. Simulation

The sequence of orders, given by the sequencing determines the process requirements for each station and cycle. Personnel assignment takes place during the simulation, in particular when the assignment is to be started in the simulation. In the majority of cases the workers, grouped into a team, are assigned to the scheduled tasks. The companies wish to assign the workers to the same activities, since this produces higher quality and less rework. The process time requests are aligned to the supply of capacity for each station during the simulation. If the assigned number of workers at a particular station is insufficient, workers can start early with the assembly operation during the previous cycle or finish late during the following cycle, if this is possible.

Each operation is assigned to a team. If not enough workers are available the team draws a jumper from jumper-groups, that are responsible for a number of teams. The simulation generates a virtual overflow (see Fig. 4), if no jumper is available.

3.1.4. Analysis

In the final planning step, the (wo-)manning level from the simulation is compared with the staffing level from pooling. If a reserve pool man is used in the simulation, there is a *hot spot*. This hot spot must be repaired manually by the user, because the evaluation of possible actions cannot be automated satisfactorily.

The planner decides whether more personnel are assigned to the station group (1), or additional constraints ensure, that order classes causing hot spots are sequenced with more distance to each other. If additional constraints are set, a new sequencing is required, since the constraints could have non-local effects.

3.2. Procedure

The input for the sequencing solution is the order backlog and a list of production constraints. In addition to the necessary technical restrictions, these are additional constraints, resulting from personnel assignment calculations. Personnel assignment itself results from an advance analysis of the order pool. Thereby a

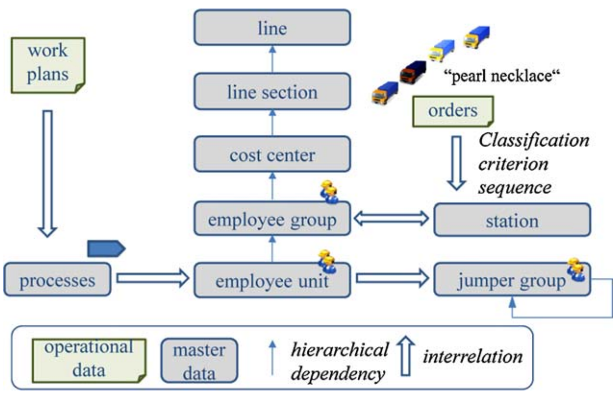

Fig. 4. Model structure of the simulation.

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levelling of the workload contained in the order pool and the available personnel capacity of the same time period takes place.

Next is the generation of an optimized sequence with regard to technical and personnel related constraints. This results in a series of personnel scenarios for each single station group that is verified by means of the simulation. The simulation model shows variant-specific assembly operations for each order considering given personnel capacities. Each order consists of a number of operations having different cycle times according to variant and equipment. One or more workers are needed for each operation and organizational data is available for every order.

The sequence serves as an input for the simulation, which in return determines the feasibility of the sequence. If the deployed personnel are insufficient, the extra number of required workers is calculated. This information can be returned to the upstream assembly. The result is an iterative process, where the sequence and defined personnel assignment are input to the simulation, which calculates the expected utilization based on fully specified job data and discloses shortfalls in disposal capacities.

4. Appraisal of the method

The presented approach combines the advantages of car-sequencing with the benefits of the mixed-modelling approach. The main advantage of car-sequencing is the restriction to a low number of characteristic product data in order to focus on the relevant criteria. Thereby the optimization algorithms are able to solve sequencing problems within limited time and acceptable quality. A further analysis of employee utilization is not possible. The accurate collection of the operational time for each variant and station allows a forecast of the load profile. Due to the iterative interplay between optimization based on characteristics and a forecast of the feasibility based on working time data, additional optimization potential can be exploited. Thereby an increase in efficiency concerning worker productivity is possible.

The simulation application was realized in the simulation software SLX. SLX excels in fast calculation and flexible model requirements illustration. Simulation runtime for 500 orders and 100 performances is under 10 s and a post-process animation with the software Proof allows visual verification.

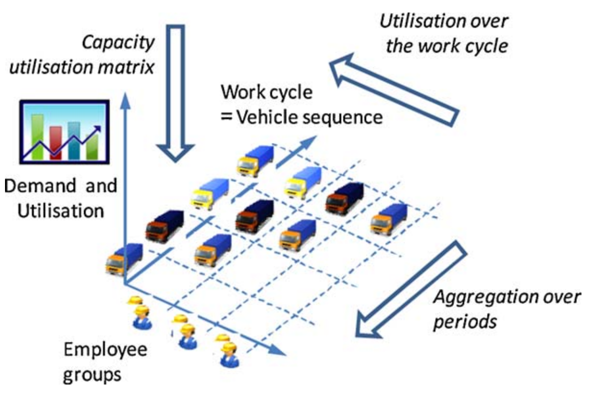

Fig. 5. Analysis of the result regarding utilization and employees.

Concerning input data a distinction is drawn between master data, which is fed into the application and edited and process and order data, which are periodically transferred from the operative planning systems. Different resulting diagrams are available to analyse the simulation (i.e. see Fig. 5). With the help of filters, regarding vehicle type and/or vehicle attributes, consequences on personnel utilization can be analysed and goal-oriented measures can be derived to improve the assembly cycle time.

5. Project results and overall benefits

Assembly workers in the automotive industry show high flexibility, but often this potential is not utilized. Integrated personnel assignment planning is able to harnesses this flexibility and hence increase productivity. The approach presented in this paper was field tested with two real-life cases in vehicle assembly. Comparing historic data from the assembly of SUVs in the first case, and of trucks in the second case, the integrated personnel assignment planning promises double-digit gains with respect to improved utilization of personnel.

Moreover, various prospects result from the ability to predict pearl chains precisely. Enabling operative personnel assignment planning, leads to efficient capacity utilization. Scenarios can be analysed regarding staffing level changes. Optional process-station-correlations and standardised process components are rateable, especially with respect to synchronization with tact-time. In a nutshell, the following advantages result from an integrated personnel and production planning:

1. Higher transparency of the personnel deployment and the assembly process.
2. Smoothing of capacity fluctuation and reduction of ‘‘hot’’ and ‘‘cold spots’’ up to 30%.
3. Increase of utilization of employee capacity.
4. Proof of technical feasibility of production programme

This results in an optimization of the production process with respect to logistics and economics and pays off with a significant increase in hours-per-vehicle-efficiency.

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