Abstract

Manufacturing companies are facing high variant diversities of their products. The degree of variant diversity increases along the value chain. Hence, assembly is forced to deal with the highest diversity. These fluctuating workloads affect the utilization rate in multi model assembly lines. Thereby, constant cycle times lead to losses in time due to the model mix. Furthermore, losses can result from gaps between exact workloads and human capacities in the workstations. Optimal operating points are defined as the ideal combination of concurrent sub goals like utilization rate and throughput rate. The identification of such operating points for assembly lines with planned product sequences shows up as a task for capacity planning and line balancing. Several analytic line balancing methods were developed in the past aiming for instance at minimal cycle times. However, methods for operational decisions on cycle time and overall production capacity are still rare. Simulation methods show potential to fill this gap. They allow the modeling and simulation of specific and complex production systems. This paper describes a planning method and a simulative tool for the identification of optimal operation points. The aim of optimal operating points is a reduction of time losses due to the model mix. Based on current approaches for simulative line balancing, a planning tool has been developed. Working with defined product sequences, this tool supports the variation of parameters like the cycle time. Effects on productivity and time losses can be analyzed. Optimal operating points can be identified. Furthermore, the tool can visualize specific product sequences with corresponding workloads during the shift. It supports staff decisions on improvements in production. Moreover, results can be used for decisions on staff planning and staff development. The tool has been validated by a case study in a truck assembly line.
1.2. State of the art

The assembly line of trucks is flow-oriented and the operations are executed in different stations by specialized workers. The typical transport system of such assembly lines is a conveyor belt, which leads to a linear material flow. Originally, assembly lines were developed for cost-efficient mass-production of standardized products [4]. Assembly line balancing aims at the assignment of work to a station within the assembly line, to assure that waiting, respectively idle times are low. A rising variant and product variety leads to difficulties in line balancing. Mathematical algorithms were developed to optimize these assignments. Though, studies show a lack of application in practice. They are seldom used in the automotive industry due to high efforts for data acquisition and the difficulty of modeling essential cause variables [5]. In addition, some simulative approaches for the automobile or truck assembly were developed. Pröpster et al. describe a dynamic line balancing system which considers specific production programs and sequences, work planning and worker flexibility. As a result, different flexibility strategies for workers can be deducted [6]. Furthermore, the approach allows the simulation of scenarios for staff assignment [7]. Dombrowski and Medo combine the analytic approaches of line balancing with worker qualification. They recommend to group and allocate workers according to their qualification. This approach utilizes simulation as well [8]. Nevertheless, real production systems are specific and not limited to one multi model assembly line. For instance, truck assembly sites can be equipped with pre-assemblies, which supply the main production line directly. Such pre-assemblies can deliver other production lines in parallel, which can increase the complexity of capacity planning. Dombrowski et al. extend the approach of dynamic line balancing to a method for the definition of optimal operating points [9].

1.3. Objectives

The objective of this paper is to expand the method that was developed by Dombrowski et al. to define optimal operating points. General planning variables and a simulative tool are described within this paper. Finally, the paper illustrates results of an evaluation of the tool in the industry.

The method and the tool are described in chapter 2. The third chapter includes the evaluation. A case study was executed in cooperation with the MAN Truck & Bus AG. The case and its results are presented in chapter 3.

2. Materials and Methods

Optimal operating points are not defined consistently in production management. However, the terminology is used similarly in different areas of production planning and scheduling. In the following, different definitions are discussed and a terminology is proposed. Based on this terminology and the work in different domains of production planning and scheduling, a method for defining operating points was developed. Moreover, a software tool for its support was realized. After proposing a terminology for optimal operating points in section 2.1, the method is described in section 2.2. In section 2.3, requirements on the tool following from this method are clarified and the implementation is described.

2.1. Proposed Terminology

Optimal operating points are clearly defined in mechanical engineering. The power and the energy consumption of an engine depend on the combination of speed and torque. This can be visualized as a torque-speed characteristic curve. In one point of each curve, the energy usage shows a minimal value. If this optimal operating point equals the main purpose of the drive system, energy usage during operations is minimal [10].

In production management, optimal operating points are not defined that precisely. Schickmair defines the optimal operating point as ideal combination of competing sub goals in terms of a specific target, respectively the aims that were set for a production situation [11]. In contrast, Roscher defines the optimal operating point of as the output quantity leading to minimal unit costs [12]. Nyhuis et al. employ operating points to describe combinations of logistic objectives in a production system [14]. Based on Gutenberg’s scheduling dilemma and likewise to previous statements [15], [13], [16], [17], they point out that managers have to balance different logistic objectives instead of optimizing one certain objective [14].

![Fig. 1: Operating points and their sub goals (based on [11], [13], [14])](image)

In the theory of logistics operating curves dependencies between such logistic objectives in a generalized production system are shown [18]. Throughput times, delivery reliability, work-in-progress levels as well as output rate and utilization are considered. Nyhuis et al. use these target dimensions to describe operating points for production systems [14].

While Schickmair’s definition of optimal operating points does not comprise specific dimensions, Roscher uses the terminology for one target. Nyhuis et al. do not define optimal operating points. They state that operating points have to be the result of a trade-off between different logistics objectives. However, they specifically name such objectives.

In this paper, Schickmair’s definition is adapted. Though, it is extended by the logistic objectives used by Nyhuis et al. to describe operating points. Accordingly, optimal operating points are defined as the combination of competing sub goals in terms of a target that has been specified for the specific case. Generally, the logistics objectives output rate and utilization, throughput time, delivery reliability and work-in-progress have to be considered for the description of operating points. Fig. 1 shows the terminology, which is used in this paper.
2.2. Method for improving operating points

In the preceding section different target dimensions of operating points were identified. In the following, a method for the improvement of operating points is presented. Firstly, the advantages of simulation for performance prediction in complex systems in comparison to analytic approaches are shown. Secondly, production management disciplines and variables that have to be addressed by the method are worked out. Finally, a stepwise method is presented.

Simulation as method for computational decision support

To analyze interdependencies between variables in production systems different computational modeling methods for performance analysis and prediction were developed in the past. Such performance prediction methods aim at the formal description of real processes and the support of configuration decisions [2], [3]. In the following, different methods are characterized and the choice of simulation and knowledge-based planning as parts of the proposed method are justified. At that, the quality of modelling, the adaptation possibilities and the acceptance by management are discussed.

Analytic methods mathematically describe the behavior of a system. Under the aim of performance prediction, different methods were based on queuing models [2]. They assume ideal work stations and describe probabilities for system states [13]. An advantage is that models and parameters are deduced from elementary coherences. The basic model is generally valid for idealized work stations [19]. However, the modeling depends on simplifications and requires high amounts of data [2]. The possibilities to adapt analytic models to complex systems with cross-linked structures are limited. This leads to constraints regarding practical relevance and to a high level of abstraction. The comprehension of prediction systems by decision makers and the acceptance of results can be restricted [2], [19].

Analytic-empirical methods expand analytic ones. They use analytic models to describe theoretical relationships of ideal systems. To allow the analysis of real systems, they include parameters derived by simulative studies. Such parameters describe dependencies in real systems. Parameterization allows the transfer of general models to similar systems without specific simulations [2], [19]. Analytic-empirical methods show the advantage that they are usable for similar systems with less modeling effort than analytic methods. Though, models must exist for a specific problem and a similar system. If a system does not equal an ideal model sufficiently, it cannot be adapted. The creation of new models needs time and requires know how. Quality and acceptance of results depend on the similarity between reality and ideal model [2], [13].

Analytic as well as analytic-empirical methods are restricted regarding the application in complex systems. For performance analysis and prediction in such systems, simulation has evolved. It allows modeling of real systems and experimental studies [20]. Results of such experiments support system comprehension and the development of measures [21]. Simulation allows describing dynamic systems [22]. Strengths of simulation are the possibilities to describe parallel processes and stochastic influences [21]. In contrast to analytic methods, it supports the detailed analysis of complex systems [23].

Nyhus et al. emphasize adaptation possibilities of models, a high prediction quality in specific cases and a high acceptance of results. In contrast to these strengths, they state that new applications require new models. They highlight the application effort and the aspect that general conclusions cannot be drawn from specific studies [14], [19]. Especially if analytic methods require assumptions or cannot be used due to computational costs, simulation can be advantageous [24].

Although decision support methods exist, practitioners often plan statically using standard times [2], [3]. Such times follow from average or maximal process values, e.g. to define process times. Static planning does not model dynamic dependencies [3]. Breakdowns or other dynamic effects are estimated by standard surcharges [25]. Accordingly, the quality of results is restricted [2], [3]. Though, a knowledge-based, static planning with empiric values is simple and shows a reasonable abstraction level. This leads to a good tangibility, uniqueness in interpretation and high practical relevance [2].

High potentials were identified for performance prediction with simulation above. Simulation is characterized as method that submits the modeling of complex systems. It allows model abstractions and leads to highly accepted results. In parallel, a high practical acceptance was stated for knowledge-based planning. Thereby, a suitable methodological direction for defining optimal operating points in specific production systems was defined. To identify definite problems, which should be supported when planning operating points and to provide a general parameter structure, a review of planning disciplines and respective problems for multi model assembly lines was executed. Its results are summed up in the following.

Identification of planning problems and variables

To increase the efficiency of decision support methods, problems can be partitioned [4], [26]. Hierarchical planning uses such partitioning of planning problems. Problems are differentiated regarding the grade of detail and the effective time horizon [27]. This work considers two decision levels. Tactical decisions aim at the utilization and adaptation of existing capacities, e.g. by decisions on general employment of flexible staff [29]. They can also lead to changes of capacities. Operative decisions aim at the full utilization of given potentials [28]. For instance, it includes the allocation of tasks to capacities [29]. While tactical decisions affect periods of months, operative decisions aim at days or weeks [3]. Planning the operating point of a production system requires the consideration of tasks on both production decision levels.

Relevant disciplines within these decision levels can be developed from the sub goal utilization which was shown in Fig. 1. The utilization rate is influenced by demand and capacity. Though, the planning of product sequences is not considered in this work. For instance in truck assembly lines such sequences are highly restricted by technical conditions and created by analytic optimization methods [7]. The overall demand is determined by markets as pointed out in chapter 1. Accordingly, the utilization planning has to be focused in capacity adjustment. Different researchers proposed aspects that have to be considered when planning flexible capacities of multi model assembly lines. Roscher identifies three areas for the creation of volumetric and occupancy flexibility. He states
that flexibility can be planned by parameters of operating hours, whereas the lengths and the model of shifts are named. Additionally, he mentions cycle time as well as integration and disintegration of cycles. To control these aspects, line balancing and structural system changes are proposed [12]. Askar differentiates the planning of shift models, staff flexibility, changes to cycle time and system configuration [30]. He uses the length and quantity of shifts, the part of flexible workers and the shifting of demand to influence targets [31]. Both authors plan flexibility by adjusting capacities in a tactical production and staff planning. This tactical adjustment of existing capacity and workload is summed up as capacity planning in the context of this paper.

In addition to tactical capacity planning, approaches of dynamic line balancing were developed to analyze a dynamic adaption of cycle times or human capacities. Davis et al. developed an analytic method to assign workers to work cycles during the daily shift [32]. Others developed an indicator system to evaluate line balancing and flexibility strategies [33]. They analyze staff assignment scenarios in a simulative approach [7]. A method for developing cycle time scenarios was proposed, aiming at the adaptive use of different cycle times and shift models. The developers base their method on a continuous monitoring of the projected load [6]. Dombrowski and Medo embedded the aspect of staff assignment and development in a simulative dynamic line balancing approach. Their method differentiates workers according to their qualification, allows recommendations for the staff development and assigns workers to tasks during the shift [8].

Six steps for improving operating points

This paper proposes a method and tool for the improvement of operating points, which combines simulation as well as knowledge-based planning. According to the identified planning problems in the preceding paragraph, aspects of capacity planning and line balancing have to be regarded within method and tool. To define a method that combines these approaches, the methodological framework, which had been developed by Dombrowski et al. in a previous work [9], was adapted and expanded. Dombrowski et al. developed a method consisting of five steps. Firstly, they propose to define system boundaries. Secondly, they recommend defining variables. For the third step, they propose to identify dependencies between the variables. The fourth and the fifth step of their method generally describe the identification of optimal operating points as well as the development of measures to adjust the production [9]. The first three steps and the last step were inherited into the method proposed with this paper. The method was expanded regarding two aspects. Firstly, a computational method was identified to support the improvement of operating points. Due to argumentation in the beginning of section 2.2, simulation was positioned in the method. Secondly, based on the hierarchical management concept tactical and operative planning problems and variables with relevance for the planning of operative points were identified above. Fig. 2 shows the method which is proposed in this paper. In the following, the steps are described. Thereby, planning functions and variables that have to be considered are depicted.

As pointed out in section 2.1, the definition of optimal operating points is only possible when the analysis is based on a given system. Accordingly, in the first step of each analysis, boundaries of the analyzed production areas and included planning disciplines must be defined (see Fig. 2). When system boundaries are defined, sub goals and variables which shall be considered for the specific case are defined. The general targets that have to be regarded were described in Fig. 1. To support the tactical capacity planning, as discussed above, the parameters workload, production program, cycle time and capacity (length and amount of shifts) have to be taken into account. A planning with average empirical values is recommended. As argued above, this is reasonable due to high acceptance of knowledge-based planning. To support the planning of cycle times, staff qualification and assignment, the proposed method recommends the short term operative analysis of planned product sequences. A variation of cycle times and their influence on idle times should be simulated to identify the best cycle time for the projected product sequence. In addition, possible improvements regarding worker assignment and qualification should be identified. This can be prepared by supporting shop floor management with visualizations of product sequences and standard times for upcoming shifts across different work stations. In the third step of the proposed method, dependencies between the chosen variables and sub goals have to be defined. These can be different, e.g. depending on the existence of pre-assemblies and their delivery structure in parallel to the main multi model assembly line. In the fourth step, simulation models of the proposed tool are adapted to the specific case. A general basic model depending on the aforementioned variables and sub goals was developed and is shown in the evaluation section of this paper. As attributes of specific production systems can differentiate, the model has to be adjusted to the case. According to the problem areas as well as defined variables and sub goals, two planning modules were developed with the tool. The tactical planning module is based on average values and focuses the overall capacity planning. The operative module supports the analysis of changes in idle times and staff decisions by analyzing given product sequences and simulating different cycle times. Within the fifth and sixth step, the adapted simulation modules are utilized. Optimal operating points are defined and measures are developed. Steps five and six can be repeated in the sense of a monitoring process.
2.3. Development of the Tool

The developed method differentiates tactical and operative planning tasks, variables and sub goals (see Fig. 2). In the sense of hierarchical planning, it proposes the development of two simulative tool modules. The requirements which follow from the previous section 2.2 can be summarized as follows:

**General requirements:**
- Usability for shop floor and tactical management to support knowledge based planning
- Adaptability and expandability
- Collective view on whole production system
- Consideration of output rate, work-in-progress, throughput time and utilization

**Requirements for the tactical planning module:**
- Basis: Mean productivity / production programs (Empirical data gathered from organizational experience)
- Variable: shift model, worker assignment, demand shifting

**Requirements for the operative planning module:**
- Based on standard times of fixed product sequences
- Analysis of cycle time and idle time
- Support of line balancing, staff assignment and staff development planning, bottom-up support tactical planning

According to these requirements, a simulative model was developed and implemented in Microsoft (MS) Excel and Visual Basic for Applications. Using MS Excel allows a tool, which is accessible without additional licenses for a broad group of managers and staff in production. The software enables the adaption and expansion of planning modules with low effort und programming skills. The tool is designed so that the dependencies between tactical variables and sub goals can be customized to specific cases with little programming skills. The implemented simulation surface, that required higher initial efforts for development, can be used without any changes. The operative module supports the import of product sequence data from MS Access. By using this data, standard proceeding times for given product sequences can be visualized for operative workers. Different cycle times can be simulated for a given sequence. Variations of idle times resulting from different utilization rates become transparent for daily or weekly planned shifts. These results coming from the operative management support the tactical planning.

3. Evaluation

The tool was employed at the MAN Truck & Bus AG Salzgitter plant. Its assembly is structured into a main multi model assembly line and pre-assembly areas for modules. Pre-assemblies are located close to the main line, which enables a just-in-sequence delivery of modules. The modules are demanded by different customers, namely the main assembly line and a completely knocked down (CKD) production. In contrast to the main assembly, the CKD production does not assemble complete trucks. Modules are packed into containers before shipped abroad. The trucks are assembled afterwards. The existence of two internal customers leads to specific complexity for capacity planning in pre-assembly areas.

Fig. 3: Modeling of the tactical planning module for the case study

Due to organizational regulations, identical shift models have to be planned for the whole production and pre-assemblies. The planning problem is getting more difficult by variable cycle times and demand structures. For instance empty cycles emerge when particular pre-assemblies do not deliver certain CKD-types while other pre-assemblies produce. In addition to these dependencies, the demands for completely built trucks in the main line fluctuate dependent on the product. Tactically, optimal combinations of shift model, cycle time and CKD demand have to be identified. The application of the tool shows locally optimal operating points for different demand structures in a tactical sense. The following paragraph gives an example of results. Fig. 3 sums up the dependencies that were described with the tactical model for this pilot case.

Fig. 4: Results for the tactical analysis of the utilization rate

According to the method, operating points were analyzed from a tactical as well as operative point of view regarding the sub goals that were developed in section 1. Fig. 4 shows simulation results for the utilization rate, which were obtained in the tactical analysis by variations of shift lengths. According to Fig. 4, the maximal utilization rate follows from the combination of one shift with six hours and a second shift with 6.25 hours. Utilization rates differ by more than 10 % by
changes in the shift lengths. To analyze such results in the overall context, different variables were simulated and analyzed regarding the defined sub goals.

In addition to the tactical analysis perspective, weekly projected production sequences were analyzed regarding a variation of cycle times and their effect on idle times. The exemplary results in Fig. 5 can be explained as follows. Total idle times follow from the aspect that the number of workers per workplace follows from rounding. For instance, the assembly of wheels at a certain cycle time requires 2.5 workers. The assigned work can only be processed by three workers. Hence, one of three has a utilization of 50%. The summation of the idle times for the entire main assembly line can be simulated by the operative tool. The results of cycle time simulation in Fig. 5 show four effects. Firstly, the total loss increases analogously to the cycle time. Secondly, there are local optima at which fewer losses by idle times occur. At specific points additional workers are needed. Thirdly, when rounding to half workers assuming that they work within the overall context, different variables were simulated and analyzed regarding the defined sub goals.

The results of cycle time simulation in Fig. 5 show four effects. Firstly, the total loss increases analogously to the cycle time. Secondly, there are local optima at which fewer losses by idle times occur. At specific points additional workers are needed. Thirdly, when rounding to half workers assuming that they work within the overall context, different variables were simulated and analyzed regarding the defined sub goals.

4. Conclusion

The paper introduced a definition for optimal operating points. An approach for improving operating points was derived based on simulation and knowledge-based planning. Planning targets as well as variables were adapted from different disciplines of production planning and scheduling. A methodological approach in six steps was developed. This approach allows the definition of optimal operating points by supporting decisions on capacity planning and line balancing. Finally, the methodological approach was transferred into a tool. This tool can be used to support decisions of tactical capacity planning as well as the operative short term analysis of product sequences. An evaluation in a truck assembly of the MAN Truck & Bus AG confirmed potentials of the developed method and the respective tool.

References


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Fig. 5: Results for cycle time simulation with the operative module