Flexibility Planning in Automotive Plants

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Abstract

The scope of this paper is the medium term capacity planning in the automotive sector. Production and labour capacity of an automotive plant are considered simultaneously in one model. The planning task is to find cost optimal capacity levels for a horizon of one to seven years using given flexibility instruments like different working time models or cycle times. The goal is to reduce fix cost by adapting capacity to the current demand. In contrast to the long term strategic planning, no additional invest in machines is considered. One major part of the problem is to find a valid coordination of production programs between the different shops of an automotive plant. An optimization approach based on dynamic programming is introduced. The approach has been implemented within the framework of a decision-support-system which is in use in several plants of the DaimlerChrysler AG. Finally a case study illustrates the benefit of the optimal usage of capacity flexibility and the advantage of different flexibility instruments.

1 Introduction

A major challenge for automotive companies is to realize a high utilization of production facilities in a dynamic and fast changing automotive market. The demand for products is influenced by the general economic situation, the product lifecycle, seasonal effects, and uncertainty in demand forecast. Due to increasing diversification and shortened lifecycles, the fluctuation in demand was enhanced in the past years. One way to react to such changing demands is to provide a high degree of flexibility within production and workforce capacities. Beside the strategic determination of the flexibility level, i.e., the available instruments to adapt capacities, it is important to use the available technical, organizational, and labour flexibility efficiently. Figure 1 illustrates the required adjustment of flexibility instruments available in an automotive plant to the flexibility demand derived from the fluctuating market. Each parameter that influences the production or labour capacity and can be changed in the mid term is viewed as a flexibility instrument.

The simultaneous medium-term planning of production and workforce capacities that is required for the efficient use of available flexibility instruments is not self-evident. The subject of planning labour flexibility is still up to date in Germany and first arose in the mid and late 80s, when the general economic situation led to a broad discussion of the topic (e.g. Rürup and Struwe (1984)). From the theoretical point of view, pioneering work was conducted by Günther (1989) and Schneeweiß (1992). Their approaches rely mostly on a linear programming model for the distribution of the annual working time in consideration of production capacities. In practice, the combination of production and workforce planning is rare but required in order to manage available flexibility optimally (cf. Dechow, Eichstädt, Hüttmann, Kloss, Mueller-Oerlinghausen (2005)).

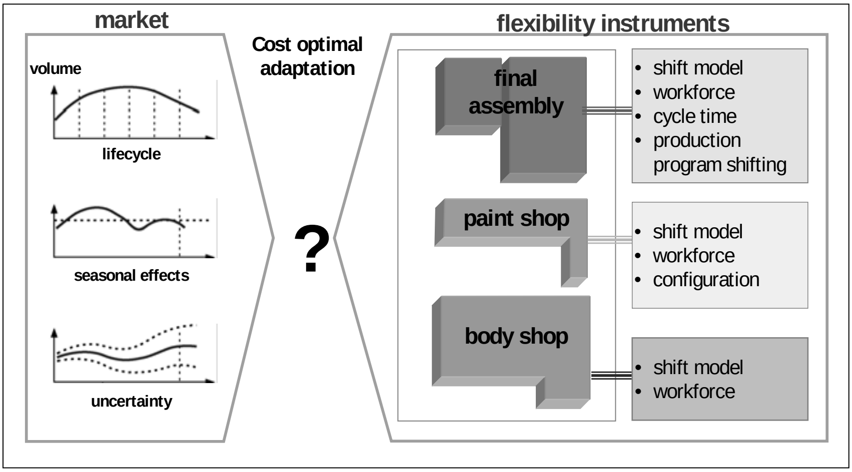

Fig. 1: Demand and supply of flexibility

Even nowadays it is not common that workforce planning aspects are considered in the context of production planning (cf. Westkämper et al. (2001), p.11). One of the reasons might be that the automotive industry has very special requirements regarding flexible workforce planning, like the determination of labour demand, which are not sufficiently covered in standard planning systems. Moreover, the complexity of the planning process increases significantly when production and workforce aspects are considered in one system at the same time (cf. Scherf (2004), p. 2). Nevertheless the question remains: “What is the optimal configuration of production and labour capacities over time with respect to given premises and market demand in an automotive plant?” In this paper, we consider in detail how to adapt the configuration by usage of given production and labour flexibility.

The paper is organized as follows: Section 2 explains the structure of an automotive plant and the different flexibility instruments that are available in each shop. In Section 3, an integrated model of production and labour capacity planning for an automotive plant is described. In particular, the complex interdependencies between production capacity and labour demand are investigated. Section 4 illustrates an optimization approach for the planning of a single production line, based on dynamic programming. Section 5 extends the approach by the coordination of multiple production lines in different shops of a plant. Finally, Section 6 presents a case study which points out the application area of the optimization approach before the paper closes with a short conclusion in Section 7.

2 Flexibility instruments of an automotive plant

Usually, an automotive plant for car manufacturing is separated in three production stages: body shop, paint shop and final assembly. The shops are each decoupled by buffers of limited size. As illustrated in Figure 2, each shop consists of one or more production lines. The production capacity of each line can be adapted by technical and organizational measures.

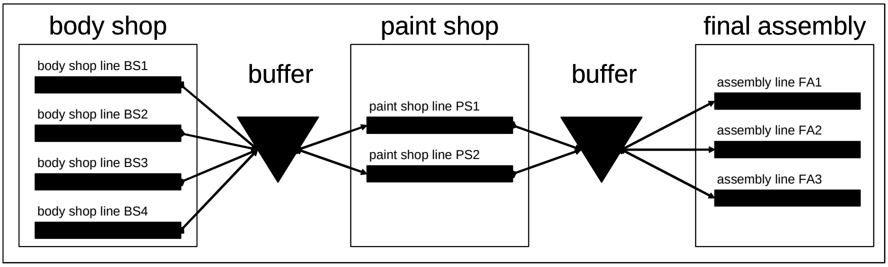

Fig. 2: General plant layout for car manufacturing

Aside from this rather complex core plant layout for the manufacturing of cars, similar flow shop production lines occur in the area of truck manufacturing and the production of modules like engines, axles and transmissions. They have an identical structure but are smaller in size, labour demand, and production capacity. Especially, in the context of optimal flexibility usage, it is of practical interest to investigate these production lines as well. They share the problem of finding an optimal adaptation for their production and labour capacity over time. Moreover, the influence of different flexibility instruments can be shown more easily because of the smaller scale.

2.1 Technical flexibility instruments

Technical adaptations are mainly realized by changing the cycle time of a production line. In general, the final assembly provides the highest degree of technical flexibility. Due to the low degree of automation in this shop, the production rate mainly depends on the available workforce and not on the available machines. Hence, the cycle time of assembly can be influenced simply by increasing or decreasing the speed of the conveyor. By doing so, a reorganization of the production processes is required, meaning that all assembly operations have to be reassigned to stations and workers. In this process costs emerge directly from the reorganization itself (e.g. modification of stations, displacement of tools, etc.). Aside from that, it takes a certain time period until the workers at the stations reach their target efficiency again. In order to compensate the loss of productivity after the reorganization, supplementary workers have to be hired during this so called learning phase.

The technical possibilities in the preceding paint shop are limited to enabling or disabling individual working stations. Another possibility is to assign fewer workers to the manual stations of the paint shop. Due to the fact that the total output of a paint shop line is determined by the slowest station, a reduction of labour capacity leads to a lower total production rate.

Another technical flexibility instrument is the reduction of the carrier assignment below 100%. Especially in the highly automated body shop this instrument is used, because the cycle time of the automated production robots normally cannot be changed. It is also available in paint shop and final assembly, but there it is only used in special situations (e.g. for the ramp up of a new product).

2.2 Organizational flexibility instruments

The following organizational flexibility instruments are available in all three shops:

- number of shift groups,
- length of shifts,
- productive time per shift, and
- number of shifts per week (especially, the availability of Saturday shifts).

Significant changes in production capacity can be achieved by adding one shift group (e.g. working with a night shift) while the adaptation of available operating time per shift is used for “fine-tuning”. Specifically, there are two ways to realize slight variations of the production capacity. Either the length of each shift or the amount of production breaks per shift can be changed. In the latter case a work rotation during the breaks has to be organized by deploying additional workers because the number and the length of breaks per worker is fixed in the labour contracts.

With regard to the planning horizon of up to seven years, the distribution of the prescribed production program to individual periods can also be used as a flexibility instrument. Based on a given sales estimate a first allocation of production capacities is calculated. In case of expensive production peaks it is possible to deviate from the capacities needed to fulfil the sales forecast. Usually, the production planning is adapted. While final assembly is affected directly by the production program, paint and body shop have to react to production changes of the succeeding shop. Different capacities and production programs in succeeding shops are possible. The buffer between two shops determines how big the difference can get and how long it can be retained. Especially, in plants with different numbers of production lines in succeeding shops differences in total production capacities of shops may occur.

In contrast to technical flexibility, organizational adaptations can be applied easily and cause little costs. Moreover, since the paint shop and the highly automated body shop have only limited possibilities for technical adaptations, capacity changes are mainly realized by organizational flexibility instruments, particularly the reduction of production breaks per shift.

2.3 Labour flexibility

Every production capacity, determined by the available operating time and the production rate, implicates a certain labour demand which has to be satisfied by the available labour capacity. The interaction between production capacity, working time, and workforce demand is highly complex, especially in labour-intensive shops such as assembly. First approaches for the optimal planning of labour capacities were presented by Faißt et al. (1991) and Faißt et al. (1992) but only applied to the service sector.

The labour capacity is specified by the number of permanent staff and temporarily hired workers. A change of labour size, i.e., hiring or laying off staff, is restricted. The maximum number of permanent staff that can be hired simultaneously is restricted by the training capacity. Laying off permanent staff is normally not allowed. In contrast, temporary workers may be hired and released as required. Aside from the possibilities described above to adapt labour capacities, worker pool concepts that allow a shifting of staff among different production lines or even between different plants are another option. They are, however, not considered in this paper.

Another aspect of the labour flexibility is given by the total working hours provided by the staff. The difference between the agreed working time according to the individual contracts and the actual total working hours, depending on the labour size and the chosen working time model, is banked in a so called working time account for each worker. If these banked hours reach a certain level, the worker has to take time off in order to reduce his individual working time account. A good overview on the history, possibilities, and potentials of the instruments of labour flexibility is given in Hoff and Weidinger (2001) and Marr (2001).

2.4 Evaluating flexibility costs

Technical, organizational, and labour flexibility instruments can be used to adapt the production and labour capacities. Each adjustment of the available flexibility instruments over time represents one adaptation strategy. Different adaptation strategies are evaluated in terms of their resulting costs. The crucial factor for the estimation of some capacity configurations are the labour costs. They are split up in wages for regular and temporary workers and additional payments (e.g., for night shifts). Also, costs for using flexibility, so called change costs, are considered. They arise from technical and organizational adaptations like cycle time changes or the training of new workers.

3 An integrated model of production and labour capacity for an automotive plant

Regarding all available flexibility instruments described above the problem consists of finding the cost optimal adaptation strategy for an automotive plant, subject to given restrictions and premises. The problem can be subdivided into shortest-path problems for each production line in all shops, as shown in Figure 3.

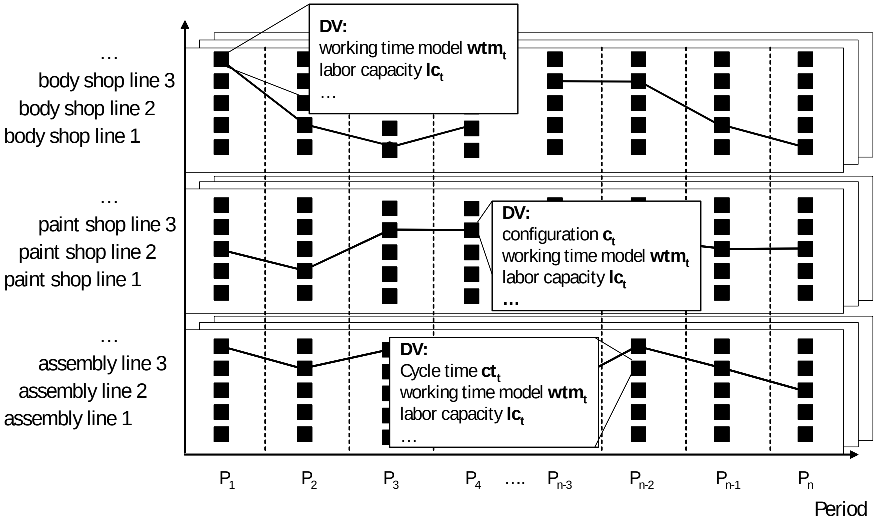

Fig. 3: Optimal adaptation strategy as a shortest-path problem

A single production line provides a certain amount of adaptation possibilities as discussed in Section 2. Each period of the planning problem (e.g., one month or one week) corresponds to one stage of the shortest-path problem. In Figure 3, each node represents a certain state of one production line, i.e., one combination of production and labour capacity, derived from the chosen values for the flexibility instruments of this line. An edge between succeeding states represents a decision for one production line and time period regarding a cycle time change, an enlargement of staff, etc.. The weight of each edge corresponds to the sum of labour and change costs that can be derived from the corresponding decision. A policy for a single production line (depicted exemplarily by the edges) consists of a set of decisions over all periods. When only a single line is considered, the task is to find the shortest path through all stages. However, in the context of the entire plant a combination of policies over all lines and stages which also fulfils the buffer restrictions has to be found. In other words, the task on plant level is to find a series of decisions for all production lines in all shops concerning the production and labour capacity which is feasible and represents a global optimum over the entire planning horizon.

Different models have been generated for describing the single line problems, where the models differ only between different shops and are equal within one shop. Due to structural similarities, such single line models can be applied to other problems than car manufacturing. In particular the assembly line model can be used for different product types (e.g. engines) and even other industries.

For each production line the demand of products for each period is given. Deviations from this demand are allowed inside prescribed upper and lower bounds, but the aggregated production program over all periods has to match the predetermined volume.

The production capacity of each line is determined by multiplying the production rate (products per time unit) with the available operating time. The latter is represented by a certain working time model. Each working time model determines the amount of shift groups, the amount of available shifts per week (especially, if Saturdays are available), and the operating time per shift. The available operating time per period is then calculated based on the chosen working time model and the amount of available shifts according to the underlying calendar. The capacity level chosen has to cover at least the production volume in the current periods.

The production rate as well as the working time model can be changed from one period to another. However, implementing such a change causes change costs. Additionally there is a restriction for the minimal number of periods between two cycle time changes.

When the interaction of subsequent lines is considered, the capacity of the production lines at each shop has to be chosen such that the production program of the succeeding shop can be produced. This means that each buffer between the different shops has to be able to balance differences of the production program of succeeding shops over time.

Each production capacity level implies a certain labour demand. It must be pointed out that the labour demand is increased during the learning phase after a cycle time change (cf. Section 2). Finally, the current state of the working time account influences the labour demand. If the average working time account for a worker has reached its upper bound, the absenteeism rate and accordingly the total labour demand increases.

Based on the available workforce at the beginning of the planning period, the number of available workers can be changed in each period, on condition that

- the maximal change in workforce from one period to another is bounded from above and below,
- the proportion of temporary workers related to the total staff must not exceed a certain fraction,
- the labour capacity has to cover at least the corresponding labour demand in each period, and
- changing the size of the staff implies variable costs depending on the quantity and kind of the change.

Each labour capacity causes certain costs. Labour costs are split up in regular wages depending on the staff size and structure[1] as well as additional payments such as night shift premiums or overtime allowances depending on the chosen working time model. Cost rates for permanent and temporary workers are different.

An adaptation strategy is determined by choosing an instantiation of the cycle time, working time model, labour capacity and structure respectively as well as the production program for each period. Each adaptation strategy is evaluated by means of the reduced, aggregated costs[2] over the periods 1 to T, in the following denoted by "Net Present Value" (*NPV*)[3]. The objective on production line level is to find the cheapest valid adaptation strategy with the lowest *NPV* for given premises. Table 1 describes the decision variables for each production line and their valid domain. The labour capacity has upper and lower bounds, which can be different in each

[1] The composition of workforce regarding permanent staff and temporary workers.

[2] Due to the planning period of up to seven years a discounted view on the cost is necessary.

[3] Although, we only consider the costs discounted to point in time zero we use the term *NPV*.

period. Also, there are discrete numbers of working time models and cycle times available in each period. Finally, the program shifting is allowed to a degree, such that the deviation from the original sales estimate does not exceed a certain range.

Table 1: Decision variables

Description	Variable	Domain
cycle time [min/unit][4]	$CT = (ct_1,..,ct_t,..,ct_T)$	$ct_t \in \{ct_t^1, ct_t^2, ..., ct_t^n\}$ $ct_t^i \in R^+$
working time model:	$WTM = (wtm_1,..,wtm_t,..,wtm_T)$	$wtm_t \in \{wtm_t^1, wtm_t^2, ..., wtm_t^m\}$
labour capacity:	$LC = (lc_1,..,lc_t,..,lc_T)$	$\underline{lc_t} \le lc_t \le \overline{lc_t}$ $lc_t \in \mathbb{N}$
program shifting[5]:	$PS = (ps_1,..,ps_t,..,ps_T)$	$msp_t(1+ps_t) = pp_t$ $pp_t \in \mathbb{N}$ $\underline{ps_t} \le ps_t \le \overline{ps_t}$ $ps_t \in R$ $\underline{ps_t} \in [-1..0]$, $\overline{ps_t} \in [0..1]$

msp = marketing and sales program
(*volume regarded from marketing and sales*)
pp = production program
(*actual produced volume*)

The objective function for one production line which has to be minimized reads as follows:

$$NPV(LC,WTM,CT) = \sum_{t=1}^{T} \left(op\_co(lc_t, wtm_t)_t + ch\_co_t(lc_t, wtm_t, ct_t) \right) \frac{1}{(1+i)^t} \qquad (1)$$

Legend:
op_co = operating costs
ch_co = change costs
i = interest rate

[4] cycle time (final assembly), configuration (paint shop) or platform assignment (body shop)
[5] Only valid for final assembly.

4 Single line optimization approach

In the following, we discuss the optimization of the single line problem regardless of the buffer constraints between the shops (i.e., we assume unlimited buffers).

The problem for one production line has three main characteristics:

1. Most of the decision variables are discrete (such as the working time model or the cycle time).
2. Many restrictions are period overlapping (e.g. the working time account or the learning phases after a cycle time change)
3. Non linear relationships regarding the working time account and the labour demand exist.

As described above, the problem can be regarded as a shortest path problem. Solving the problem with a Linear Programming approach (LP) for shortest path problems, as described e.g. by Ahuja (1993) and Chvatal (2002) is not practicable because building up the required graph is extremely complex and it would be too large to handle. This is due to the very high number of nodes and arcs required in order to model all the discrete variables and the period overlapping constraints. An alternative modelling as a Mixed Integer Problem (MIP) is also problematic because the required solution time generally would increase dramatically with the problem size. Furthermore, the non-linear constraints of the problem can only be approximated through linearization techniques, which also leads to an increase of the solution time. For these reasons, we propose a dynamic programming approach. It is well suited for discrete problems, it can handle non linear constraints and the period overlapping restrictions can be used dynamically in the solving process to reduce the state space.

The building blocks of a dynamic program are a discrete state space, a transform function, and an evaluation function. If the building blocks are defined, the underlying problem can be solved according to the well known Bellman algorithm (cf. Bellman, (1972)).

A certain number of possible states s_t exists in each period t of the planning problem where each state represents the provided production and labour capacity. In contrast to the premises of dynamic programming, each state does not only depend on the state of and the decision in the preceding period. The working time account, the learning phase after a cycle time change, and the aggregated deviation from the sales estimate are influenced by the decisions of several preceding periods. Thus, information about the decision history, i.e., decisions of several previous periods, is stored in each state in form of some status variables.[6] These are wta_t for the

[6] For details on the concept of status variables see Bertsekas (1987).

working time account, sc_t for the periods since the last cycle time change and b_t for the aggregated deviation of the production program from the sales estimate. Consequently, each state is fully specified by:

$$s_t = (ct_t, wtm_t, lc_t, sc_t, wta_t, b_t) \tag{2}$$

State s_{t+1} is determined by a so-called transformation function. The parameters of the transformation function are the state s_t of the last period and the decision made in period t. The decision consist of the choice of a certain cycle time $\hat{c}_t$, a certain working time model $\widehat{wtm}_t$, and a labour capacity $\widehat{lc}_t$. The values for ct_{t+1}, wtm_{t+1} and lc_{t+1} can be derived directly from the decision $d_t = (\hat{c}_t, \widehat{wtm}_t, \widehat{lc}_t)$. In order to reduce complexity the decision for the variable ps_{t+1} is derived from different decision variables, namely ct_{t+1} and wtm_{t+1}. Under consideration of the available production capacity a value for ps_{t+1} is chosen which provides a utilization that is as high as possible. The working time account wta_t and the shift of production program b_t depend on the current decision d_t and the state s_t of the preceding period. If $ct_{t+1} = ct_t$, the status variable sc_{t+1} is increased by one, otherwise it is set to zero. The succeeding state s_{t+1} is given by:

$$s_{t+1} = \begin{cases} c_{t+1} = \hat{c}_t \\ wtm_{t+1} = \widehat{wtm}_t \\ lc_{t+1} = \widehat{lc}_t \\ sc_{t+1} = \begin{cases} 0, & if\ c_{t+1} \neq \hat{c}_t \\ sc_t + 1, & else \end{cases} \\ wta_{t+1} = wta_t + \Delta wta(d_t) \\ b_{t+1} = b_t + ps_{t+1} * msp_{t+1} \end{cases} \tag{3}$$

Invalid decisions (e.g. reduction of permanent staff) are eliminated dynamically. After each transformation the resulting state s_{t+1} is checked in terms of feasibility regarding all constraints (e.g. validity of production and labour capacity, working time account, etc.).

Finally, the *NPV* (see Equation (1)) is used for the evaluation of each policy. After finding the cost optimal state in the last period, the *NPV*-optimal policy is determined by a backtracking procedure. As a result, the single line problem is solved to optimality in terms of the state space. For detailed explanations on the described optimization and further approaches on complexity reduction, especially by efficient discretisation of the state space, see Zimmermann et al. (2006).

5 Coordination of shops regarding buffer

Beside the separate optimization of each line, the production programs of different production lines in the different shops have to be coordinated regarding the available buffers between succeeding shops. In general, the plant capacity planning, as described in Section 3, is done in a backtracking procedure. At the beginning the capacity strategies and production programs respectively for the last shop, namely the final assembly lines, are planned. After that, the capacities of the paint shop lines are determined, while the demand for each line is derived from the production volumes of the final assembly lines. The same procedure is then applied to the body shop.

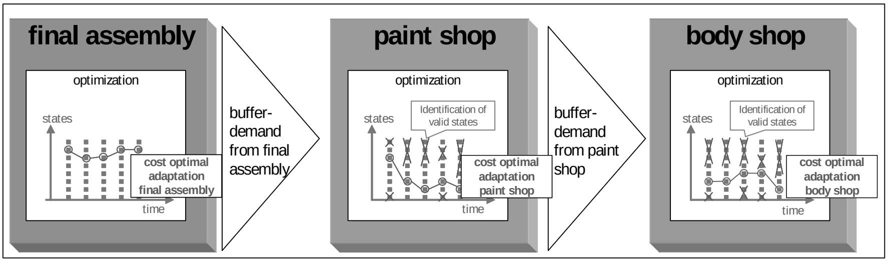

Fig. 4: Coordination of shops with rule based approach

The separate optimization of each line in all shops using dynamic programming as described in Section 4 can be extended to the case with limited buffers between shops. At first the dynamic programming approach is applied to all final assembly lines separately[7]. In an intermediate step the product specific demand for each paint shop line is then calculated from the production program of the assembly lines. It is taken as a prerequisite that each product is allocated on exactly one line. Subsequently, the optimization of the paint shop is accomplished, using the demand derived from the final assembly. The coordination between the areas of final assembly, paint shop, and body shop subject to the corresponding buffers is carried out with a heuristic procedure. The capacity strategies for all paint shop lines are optimized with respect to the optimal assembly configuration and the available buffers. Regarding these constraints, possible states in the paint shop with a high difference of production capacities[8] related to final

[7] The premise for this procedure is that there are no interdependencies between different final assembly lines in terms of capacity planning.

[8] Here the composition of the provided capacity is meant, e.g. if a capacity level is achieved by a high cycle time or long operating times.

assembly become infeasible. Thus, the valid state space for each line of the preceding shop is reduced. After finding an optimal solution (cf. Section 4) for all paint shop lines, the same is done for the body shop. The approach is illustrated in Figure 4. The validity of each capacity level in one line depends on the capacity strategy chosen in the succeeding shop.

The discrete decision variables for the cycle time and the working time model lead to discrete production capacity levels for each line. Adjusting the capacity exactly to the same level as the preceding shop is not always possible. Depending on the capacity gap between succeeding shops and the buffer size, some combinations are infeasible or only valid for a certain period. For complex plant structures with different numbers of lines in succeeding shops the problem becomes even more complicated. For example, if there are three production lines in the final assembly of which each produces one product, the possible total capacity levels for the whole shop are rising multiplicatively. If, at the same time, there is just one line in the paint shop that produces all three products, the probability to find an identical production capacity level is low, so that an approximately equal adjustment has to be chosen, depending on the buffer size. Additionally, an explicit production program regarding the three products, also called type mix, has to be determined in this shop.

The buffer constraints conduct a check of the buffer level not only at the end of each period (which would be after each week or month), but also in between one period, e.g. after each shift[9]. Let *pr* be the index for the product, *sh* the index for the current shift, $demand_{pr,sh}$ the demand from the succeeding shop of product *pr* in shift *sh*, and $b_{pr,sh}$ the buffer level of product *pr* in shift *sh*, then the buffer constraints are defined as:

$$b_{pr,sh-1} + pp_{pr,sh} - demand_{pr,sh} \geq \underline{b_{pr}} \qquad \forall\, pr,sh \qquad (4)$$

$$b_{pr,sh-1} + pp_{pr,sh} - demand_{pr,sh} \leq \overline{b_{pr}} \qquad \forall\, pr,sh \qquad (5)$$

The main task that has to be accomplished in order to consider the buffer constraints appropriately is an anticipation of the shift-wise production program planning for each shop regarding the production volume and the type mix. It is based on the capacity planning that has been implemented for the single line problem. Aside from the decision how much of the buffer is used for the compensation of cancelled shifts, it has to be defined which products use the buffer. One possibility is the formulation of fixed rules regarding shift planning and utilization that determine the pro-

[9] Especially, checking the validity of different amounts of shift groups in succeeding shops regards this granularity.

duction program planning in each shift. Three simple rules have been implemented:

1. Produce the type specific minimum buffer levels $\underline{b_{pr}}$ for each product. If the capacity is too low to produce this volume, the state is invalid.
2. If production capacity is still available, produce the type mix according to the period demand until either buffer capacity or shift capacity is reached.
3. If the shift utilization is less than some prescribed percentage, cancel the shift.

The idea of these rules is to fill all buffers to the maximum possible level so that missing capacity in the succeeding shifts can be compensated by the buffers as good as possible. The amount of infeasible states in one shop is reduced to a minimum. At the same time, the quality of the solution is enhanced because the feasible state space is not trimmed excessively.

6 Case study

It is worth mentioning that the proposed solution method has been applied and works well for an entire automotive plant. However, the complexity of the interrelationships and the effects of flexibility parameters cannot be displayed in a short case study for an entire plant.

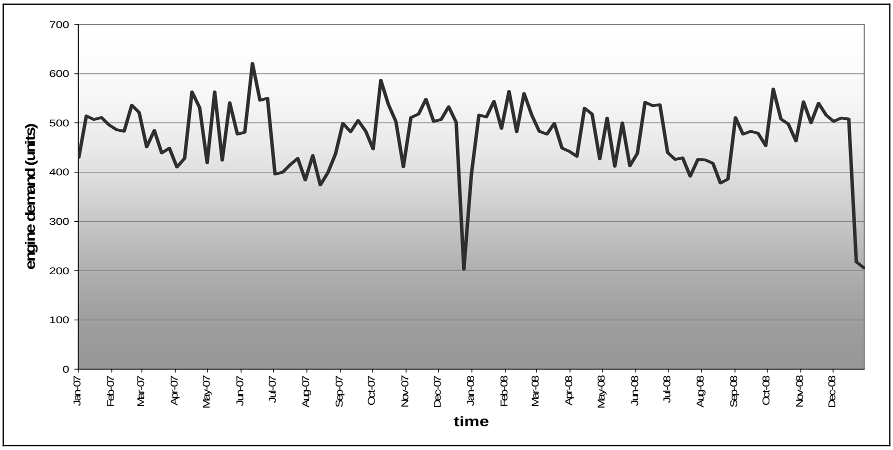

Fig. 5: Fluctuation in demand

In order to generate results that are transparent and comprehensible at first sight, we consider a single line problem. As mentioned above, the optimization approach presented in Section 4 can be applied to the manufacturing of other products. We chose a final assembly line for engines, because of the smaller scale.

In the case study a time horizon of two years (104 weeks) is considered. The demand varies in each week (cf. Figure 5). At the beginning, the situation in the plant concerning the available flexibility is that the line operates with only one possible cycle time and two shift groups at eight hours each. The maximal percentage of temporary workers related to total available workforce is 10% and shifting of the production program is not allowed.

Based on this initial situation, 108 different scenarios of available flexibility parameters have been optimized, where each one offers different organizational and/or technical flexibility to adapt the production and labour capacity to the fluctuation in demand. All constellations have been evaluated based on the NPV of labour and change costs. Afterwards they are compared to the initial scenario.

The flexibility parameters that are subject to change are:

- cycle time
- length of the shift groups
- availability of Saturday shifts
- percentage of temporary workers
- percentage of program shifting to preceding period (program shifting to the subsequent period is not possible due to sequencing restrictions)

The exact specification of the parameters is depicted in Figure 6.

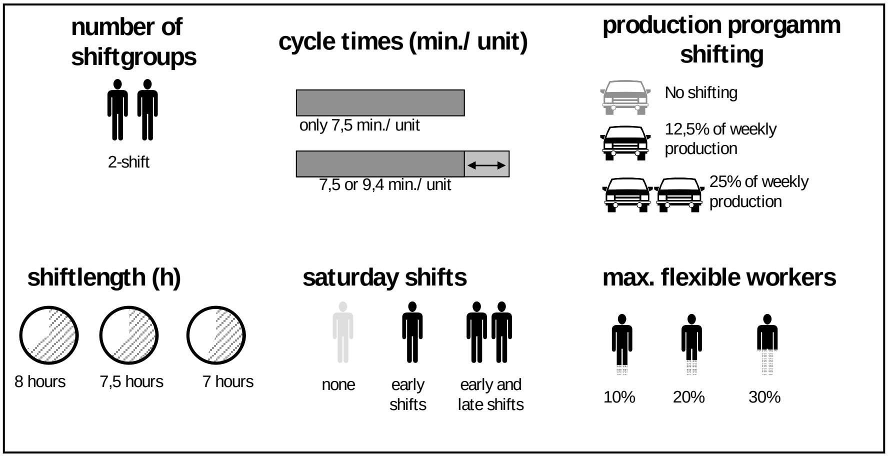

Fig. 6: Different parameter settings

Aside from the variation of the five flexibility parameters, other parameters regarding the production and workforce capacity planning and the cost evaluation are considered as constant input, i.e. they are not to be changed throughout the optimization of the problem.

The production capacity planning is done under the premise that the technical availability of the line is at 95%. When a change in cycle time occurs, the change cost is 1,000€. This amount has to be considered due to the reorganisation of the line. Afterwards the new cycle time has to be retained for at least four weeks. Learning phases due to the change in cycle time are not considered. A continuous improvement of the production process does not occur.

For the calculation of labour cost the yearly wages are considered as a constant input. The yearly wage for regular and temporary worker is set to 45,000€ and 35,000€, respectively. Training costs occur when a worker is hired. They are 1,400€ for a regular worker and 600€ for a temporary worker. The shift premiums are 15% for the late shifts, 20% for the night shifts, and an additional 5% for all shifts on Saturdays. The workers are paid for working 35 hours during the week. It is not possible to lay off regular workers. Only temporary workers can be laid off.

An analysis of the results reveals some interesting facts. An obvious correlation is that an increase in temporary workforce leads to lower costs because the line is able to reduce the total labour capacity more efficiently. Aside from that it is very important to consider the combination of available flexibility instruments.

Fig. 7: NPV for different scenarios

The variation of a single parameter seldom gives better results. It is the mix of flexibility instruments that leads to greater improvements. Especially the right combination of technical and organizational flexibility is crucial. Figure 7 depicts three scenarios that offer different degrees of flexibility.

In the three scenarios above the maximal number of temporary workers is kept at a constant level (in our example 10%). In comparison to the initial situation almost no improvement in the NPV can be made by introducing different working times and the possibility to move up to 12.5% of the weekly production program to previous periods. However, if a second cycle time is introduced additionally, the NPV can be decreased by almost 10%. The other flexibility configurations show as well that it is important to know what kind of flexibility parameters have to be combined to have an impact on the labour and change costs. Only the right combination of flexibility instruments leads to success.

The performance of the algorithm heavily depends on the state space that is built up for the specific problem. Therefore, it is difficult to give general performance results. In the following, we give some computational results for the three scenarios we already used in Figure 7, to give an impression of the solution time. The measurement took place on a computer with a 2 GHz Pentium M (Dothan core) with 2 GB of RAM running Windows XP Professional. The values for the number of realized states are average values for one period of the planning horizon. The results of the performance measurement can be found in Table 2.

Table 2: Performance example of the algorithm

	Starting configuration	**Organizational Flexibility**	**Organizational and technical flexibility**
Influence Factors	number of workers	staff size, working time, program shifting	staff size, working time, program shifting, cycle time
Max number of states	1,168	3,895	23,370
Avg. number of feasible states	27	264	11,690
Solution time	1 sec.	13 sec.	715 sec.

The number of maximal and feasible states increases with the number of available flexibility parameters. By comparing the maximum number of states and the average number of feasible states it can be seen that not all state combinations are always created within a period. The relative number increases with a growing problem size from 2% in the low flexibility case up to 50% in the high flexibility case. The numbers indicate that with an enlargement of the state space the proportion of infeasible states decreases. At the same time the solution time increases dramatically with the number of feasible states.

With the case study presented it is possible to get an insight on how different flexibility types affect the operating costs. However, it is important to consider the specific situation for which the planning is applied. E.g. a final assembly line for engines has organizational differences compared to a final assembly line for cars. Moreover basic local and regional parameters given by law or by worker union agreements have a significant influence on the results. Differences in the availability of working time models, the possibilities to change the cycle time, etc. can occur. For these reasons the proposed results regarding the effect of flexibility on costs cannot be generalized for all kinds of assembly lines. Furthermore, the performance question can only be answered for a specific scenario but not in general. As explained above a good decision support can only be realized under consideration of all specific premises and conditions.

7 Conclusions

A model for the evaluation of adaptation strategies regarding production and labour capacities has been introduced. Based on this model, an approach for optimizing each production line with simultaneous determination of production and labour capacity has been developed. Additionally, a possibility for the consideration of buffer constraints between lines of different shops was presented. This makes it possible to consider an entire automotive plant. The entire methodology is implemented in a planning tool called "Lifecycle Adaptation Planner (LAP)". The LAP provides evaluation models and optimization algorithms for each shop. The usual timeframe for those models is a planning period of one to seven years on a weekly or monthly granularity. Two major goals can be achieved with these models. On the one hand, adaptation strategies can be evaluated transparently, extensively, and very quickly. Up to now this has been a long lasting process without efficient computer based models. On the other hand, optimal adaptation strategies can be generated, which serve as a support for the decision maker. The tool LAP has been transferred to several German and international plants of DaimlerChrysler.

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