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Assembly line balancing: Which model to use when?

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Abstract

Assembly lines are flow-line production systems which are of great importance in the industrial production of high quantity standardized commodities and more recently even gained importance in low volume production of customized products. Due to high capital requirements when installing or redesigning a line, configuration planning is of great relevance for practitioners. Accordingly, this attracted the attention of researchers, who tried to support practical configuration planning by suited optimization models. In spite of the great amount of extensions of basic assembly line balancing (ALB) there remains a gap between requirements of real configuration problems and the status of research. This gap might result from research papers focusing on just a single or only a few practical extensions at a time. Real-world assembly systems require a lot of these extensions to be considered simultaneously. This paper structures the vast field of ALB according to characteristic practical settings and highlights relevant model extensions which are required to reflect real-world problems. By doing so, open research challenges are identified and the practitioner is provided with hints on how to single out suited balancing procedures for his type of assembly system.

Keywords: Configuration of assembly lines; Assembly line balancing; Classification

1. Introduction

An assembly line is a flow-oriented production system where the productive units performing the operations, referred to as stations, are aligned in a serial manner. The workpieces visit stations successively as they are moved along the line usually by some kind of transportation system, e.g. a conveyor belt.

Originally, assembly lines were developed for a cost efficient mass production of standardized products, designed to exploit a high specialization of labour and the associated learning effects (Shtub and Dar-El, 1989; Scholl, 1999, p. 2). Since the times of Henry Ford and the famous model-T, however, product requirements and thereby the requirements of production systems have changed dramatically. In order to respond to diversified costumer needs, companies have to allow for an individualization of their products. For example, the German car manufacturer BMW offers a catalogue of optional features which, theoretically, results in 10^{32} different models (Meyr, 2004). Multi-purpose machines with

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automated tool swaps allow for a facultative production sequence of varying models at negligible set-up times and costs. This makes efficient flow-line systems available for low volume assembly-to-order production (Mather, 1989) and enables modern production strategies like mass customization (Pine, 1993). This in turn ensures that the thorough planning and implementation of assembly systems will remain of high practical relevance in the foreseeable future.

Under the term assembly line balancing (ALB) various optimization models have been introduced and discussed in the literature which aim at supporting the decision maker in configuring efficient assembly systems. Since the first mathematical formalization of ALB by Salveson (1955), academic work mainly focused on the core problem of the configuration, which is the assignment of tasks to stations. Subsequent works however, more and more attempted to extend the problem by integrating practice relevant constraints, like U-shaped lines, parallel stations or processing alternatives (Becker and Scholl, 2006; Boysen et al., 2006a).

Considering the large variety of regarded extensions, which are referred to as general assembly line balancing (GALB), it is astonishing that there remains a very considerable gap between the academic discussion and practical applications, up to now. Empirical surveys stemming from the 1970s (Chase, 1974) and 1980s (Schöniger and Spingler, 1989) revealed that only a very small percentage of companies were using a mathematical algorithm for configuration planning at that time. The apparent lack of more recent scientific studies on the application of ALB algorithms indicates that this gap still exists or even has widened.

One reason for this deficit might originate from the fact that research papers often regard single or only just a few extensions of ALB in an isolated manner (Boysen et al., 2006a). Real-world assembly systems require a lot of these extensions in many possible combinations. Thus, flexible ALB procedures are required, which can deal with a lot of these extensions in a combined manner. Typically, there is a trade-off between flexibility and efficiency of an optimization procedure. Accordingly, by identifying typical combinations of extensions which often arise jointly in real-world assembly systems, procedures can be developed which exactly fit these requirements, while decreasing the required flexibility to a minimum. Moreover, practitioners might be provided with valuable advices on how to use already existing models and procedures for their special assembly system.

For that purpose this paper is structured as follows. At first, Section 2 summarizes ALB research by describing ALB in its very basic form (Section 2.1) and then classifying further extension from that starting point (Section 2.2). Finally, the classification serves as a basis for assigning these extensions to typical assembly systems (Sections 3–7). This way, already existing ALB models and procedures are identified being valuable for the different types of real-world assembly systems and future research challenges are recognized.

2. ALB

2.1. Basic problem of ALB

An assembly line consists of (work) stations $k = 1,\dots,m$ usually arranged along a conveyor belt or a similar mechanical material handling equipment. The workpieces (jobs) are consecutively launched down the line and are moved from station to station. At each station, certain operations are repeatedly performed regarding the cycle time (maximum or average time available for each work cycle).

Manufacturing a product on an assembly line requires partitioning the total amount of work into a set $V = \{1,\dots,n\}$ of elementary operations named tasks. Performing a task j takes a task time t_j and requires certain equipment of machines and/or skills of workers. The total workload necessary for assembling a workpiece is measured by the sum of task times t_{sum}. Due to technological and organizational conditions precedence constraints between the tasks have to be observed.

These elements can be summarized and visualized by a precedence graph. It contains a node for each task, node weights for the task times, arcs for the direct and paths for the indirect precedence constraints. Fig. 1 shows a precedence graph with

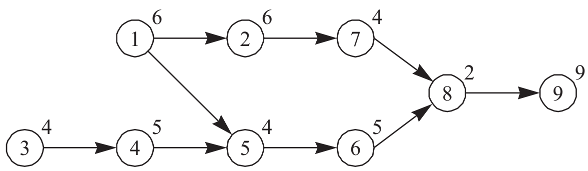

Fig. 1. Precedence graph.

$n = 9$ tasks having task times between 2 and 9 (time units).

Any type of assembly line balancing problem (ALBP) consists in finding a feasible line balance, i.e., an assignment of each task to a station such that the precedence constraints (Fig. 1) and further restrictions are fulfilled. The set S_k of tasks assigned to a station k $(=1,\ldots,m)$ constitutes its station load or work content, the cumulated task time $t(S_k) = \sum_{j \in S_k} t_j$ is called station time.

When a fixed common cycle time c is given (paced line), a line balance is feasible only if the station time of neither station exceeds c. In case of $t(S_k) < c$, the station k has an idle time of $c - t(S_k)$ time units in each cycle. For the example of Fig. 1, a feasible line balance with cycle time $c = 11$ and $m = 5$ stations is given by the station loads $S_1 = \{1,3\}$, $S_2 = \{2,4\}$, $S_3 = \{5,6\}$, $S_4 = \{7,8\}$, $S_5 = \{9\}$.

Because of the long-term effect of balancing decisions, the used objectives have to be carefully chosen considering the strategic goals of the enterprise. From an economic point of view cost and profit related objectives should be considered. However, measuring and predicting the cost of operating a line over months or years and the profits achieved by selling the products assembled is rather complicated and error-prone. A usual surrogate objective consists in maximizing the line utilization which is measured by the line efficiency E as the productive fraction of the line's total operating time and directly depends on the cycle time c and the number of stations m. In the most simple case, the line efficiency is defined as follows: $E = t_{\text{sum}}/(mc)$.

The basic problem described so far is called simple assembly line balancing problem (SALBP) in the literature (cf. Baybars, 1986). Four versions are defined by using different objectives (cf. Scholl, 1999, Chapter 2.2): SALBP-E maximizes the line efficiency E, SALBP-1 minimizes the number m of stations given the cycle time c, SALBP-2 minimizes c given m, while SALBP-F seeks for a feasible solution given m and c. A recent survey of solution procedures for these basic problems is given by Scholl and Becker (2006).

2.2. A classification of ALBP extensions

SALBP is based on a set of limiting assumptions which reduce the complex problem of assembly line configuration to the "core" problem of assigning tasks to stations. The balancing of real-world assembly lines will, however, require the observation of a large variety of additional technical or organizational aspects, which will heavily affect the structure of the planning problem. Among the extensions considered in the literature are parallel work stations and tasks, cost synergies, processing alternatives, zoning restrictions, stochastic and sequence-dependent processing times as well as U-shaped assembly lines. For a recent survey see Becker and Scholl (2006).

A recent attempt in structuring the field of ALB is the classification scheme provided by Boysen et al. (2006a). They introduce a tuple notation which is an adoption of the famous $[\alpha|\beta|\gamma]$ classification for machine scheduling of Graham et al. (1979) to ALB. A specific assembly system with all its relevant extensions can now be briefly characterized by a tuple. A summary of this classification scheme is presented in Fig. 3.

In the following, the notation of this scheme is used in order to assign typical attributes to different aspects of real-world assembly systems. By doing so, joint occurrences of SALBP extensions can be identified which are especially characteristic for certain groups of assembly systems in the real world. Furthermore, a comparison with the existing literature can clarify if solution procedures for these typical cases already exist or if their development remains up for future research. Fig. 2 summarizes the kinds of assembly systems considered in the following five sections.

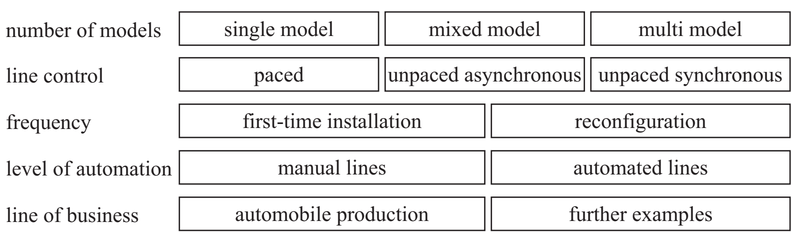

Fig. 2. Investigated kinds of assembly lines.

Precedence Graph Characteristics

Product specific precedence graphs: $\alpha_1 \in \{mix, mult, \circ\}$	
α_1=mix	Mixed-model production
α_1=mult	Multi-model production
$\alpha_1 = \circ$	Single-model production

Structure of the precedence graph: $\alpha_2 \in \{spec, \circ\}$	
α_2=spec	Restriction to a special precedence graph structure
$\alpha_2 = \circ$	Precedence graph can have any acyclic structure

Processing times: $\alpha_3 \in \{t^{sto}, t^{dy}, \circ\}$*	
$\alpha_3 = t^{sto}$	Stochastic processing times
$\alpha_3 = t^{dy}$	Dynamic processing times (e.g. learning effects)
$\alpha_3 = \circ$	Processing times are static and deterministic

Sequence-dependent task time increments: $\alpha_4 \in \{\Delta t_{dir}, \Delta t_{indir}, \circ\}$*	
$\alpha_4 = \Delta t_{dir}$	Caused by direct succession of tasks (e.g. tool change)
$\alpha_4 = \Delta t_{indir}$	Caused by succession of tasks (tasks hinder each other)
$\alpha_4 = \circ$	Sequence-dependent time increments are not considered

Assignment restrictions: $\alpha_5 \in \{link, inc, cum, fix, excl, type, min, max, \circ\}$*	
α_5=link	Linked tasks have to be assigned to the same station
α_5=inc	Incompatible tasks cannot be combined at a station
α_5=cum	Cumulative restriction of task-station-assignment
α_5=fix	Fixed tasks can only be assigned to a particular station
α_5=excl	Tasks may not be assigned to a particular station
α_5=type	Tasks have to be assigned to a certain type of station
α_5=min	Minimum distances between tasks have to be observed
α_5=max	Maximum distances between tasks have to be observed
$\alpha_5 = \circ$	No assignment restrictions are considered

Processing alternatives: $\alpha_6 \in \{pa^{\lambda}, \circ\}$	
$\alpha_6 = pa^{\lambda}$	Processing alternatives; with $\lambda \in \{\circ, prec, subgraph\}$
	$\lambda = \circ$: Processing times and costs are altered
	λ=prec: Precedence constraints are additionally altered
	λ=subgraph: Subgraphs are additionally altered
$\alpha_6 = \circ$	Processing alternatives are not considered

Objectives

Objectives: $\gamma \in \{m, c, E, Co, Pr, SSL^{\lambda}, score, \circ\}$*	
γ=m	Minimize the number of stations m
γ=c	Minimize cycle time c
γ=E	Maximize line efficiency E
γ=Co	Cost minimization
γ=Pr	Profit maximization
$\gamma = SSL^{\lambda}$	Station times are to be smoothed; with $\lambda \in \{stat, line\}$
	λ=stat: Within a station (horizontal balancing)
	λ=line: Between stations (vertical balancing)
γ=score	Minimize or maximize some composite score
$\gamma = \circ$	Only feasible solutions are searched for

Station and Line Characteristics

Movement of workpieces: $\beta_1 \in \{\circ\lambda\upsilon, unpac^{\lambda}\}$	
$\beta_1 = \circ\lambda\upsilon$	Paced line; with $\lambda \in \{\circ, each, prob\}$ and $\upsilon \in \{\circ, div\}$
	$\lambda = \circ$: (Average) work content restricted by cycle time
	λ=each: Each model must fulfill the cycle time
	λ=prob: Cycle time is obeyed with a given probability
	$\upsilon = \circ$: Single global cycle time
	υ= div: Local cycle times
$\beta_1 = unpac^{\lambda}$	Unpaced line; with $\lambda \in \{\circ, sync\}$
	$\lambda = \circ$: Asynchronous line
	λ=syn: Synchronous line

Line layout: $\beta_2 \in \{\circ, u^{\lambda}\}$	
$\beta_2 = \circ$	Serial line
$\beta_2 = u^{\lambda}$	U-shaped line; with $\lambda \in \{\circ, n\}$
	$\lambda = \circ$: The line forms a single U
	λ=n: Multiple Us forming an n-U line

Parallelization: $\beta_3 \in \{pline^{\lambda}, pstat^{\lambda}, ptask^{\lambda}, pwork^{\lambda}, \circ\}$*	
$\beta_3 = pline^{\lambda}$	Parallel lines
$\beta_3 = pstat^{\lambda}$	Parallel stations
$\beta_3 = ptask^{\lambda}$	Parallel tasks
$\beta_3 = pwork^{\lambda}$	Parallel working places within a station
$\beta_3 = \circ$	Neither type of parallelization is considered
$\lambda \in \{\circ, 2, 3, \ldots\}$: Maximum level of parallelization; $\circ$=unrestricted	

Resource assignment: $\beta_4 \in \{equip, res^{\lambda}, \circ\}$*	
β_4 =equip	Equipment selection problem
$\beta_4 = res^{\lambda}$	Equipment design problem; with $\lambda \in \{\circ, 01, max\}$*
	λ=01: If two task share a resource, investment costs are reduced at a station
	λ=max: Most challenging task defines the needed qualification level of a resource
	$\lambda = \circ$: Other type of synergy and/or dependency
$\alpha_6 = \circ$	Processing alternatives are not considered

Station-dependent time increments: $\beta_5 \in \{\Delta t_{unp}, \circ\}$	
$\beta_5 = \Delta t_{unp}$	Unproductive activities at a station are considered
$\beta_5 = \circ$	Station-dependent time increments are not regarded

Additional configuration aspects: $\beta_6 \in \{buffer, feeder, mat, change, \circ\}$*	
β_6=buffer	Buffers have to be allocated and dimensioned
β_6=feeder	Feeder lines are to be balanced simultaneously
β_6=mat	Material boxes need to be positioned and dimensioned
β_6=change	Machines for position changes of workpieces required
$\beta_6 = \circ$	No additional aspects of line configuration are regarded

Fig. 3. The classification scheme for ALB of Boysen et al. (2006a).

3. ALB in dependency of the number of models

3.1. Single-model assembly lines

In its traditional form, assembly lines were used for high-volume production of a single commodity ($\alpha_1 = 0$). Nowadays, products without any variation can seldom attract sufficient customers to allow for a profitable utilization of the assembly system. Advanced production technologies enable automated set-up operations at negligible set-up times and costs. If more than one product is assembled on the same line, but neither set-ups nor significant variations in operating times occur, the assembly system can be treated as a single model line, as is the case in the production of compact discs (Lebefromm, 1999, p. 3) or drinking cans (Grabau and Maurer, 1998) for example. Single-model production is the standard assumption of SALB and many generalized ALB problems and has been considered by a vast number of publications. A recent literature overview is provided by Scholl and Becker (2006) as well as Becker and Scholl (2006).

3.2. Mixed-model assembly lines

In mixed-model production, set-up times between models could be reduced sufficiently enough to be ignored, so that intermixed model sequences can be assembled on the same line ($\alpha_1 = \text{mix}$). In spite of the tremendous efforts to make production systems more versatile, this usually requires very homogeneous production processes. As a consequence, it is typically assumed that all models are variations of the same base product and only differ in specific customizable product attributes, also referred to as options.

The installation of varying options typically leads to variations in process times. In automobile production, for instance, the installation of an electrical sunroof requires a different amount of time than that of a manual one. Therefore, station times will depend heavily on the specific model to be assembled. If several work intensive models follow each other at the same station, the cycle time might be exceeded and an overload occurs, which needs to be compensated by some kind of reaction (line stoppage, utility workers, off-line repair or higher local production speed; Wild, 1972, p. 164). These overloads can be avoided if a sequence of models is found where those models which cause high station times alternate with less work-intensive ones at each station. This leads to a short term sequencing problem (cf. Yano and Bolat, 1989; Sumichrast and Russell, 1990; Sumichrast et al., 1992; Bard et al., 1992; Tsai, 1995; Merengo et al., 1999).

The balancing and the sequencing problem are heavily interdependent. While the line balance decides on the assignment of tasks to stations and thus determines the work content per station and model, the production sequence of a given model mix is arranged on this basis with regard to minimum overloads. The amount of overload by itself is a measure of efficiency for the achieved line balance. That is why some authors have proposed a simultaneous consideration of both planning problems (McMullen and Frazier, 1998a; Kim et al. 2000b, c, 2006; Miltenburg, 2002; Sawik, 2002; Bock et al., 2006).

A simultaneous approach is, however, only viable under very special conditions as both planning problems usually have completely different time frames. The balancing decision is a long to mid-term planning problem with a typical planning horizon of several months, so that the short-term model mix (e.g. on a daily basis) is typically not known at this point in time. Detailed prognoses of future model sales are often bound to heavy inaccuracies, especially if the assembled products are in an early phase of their life cycle. It, thus, seems more meaningful to generally anticipate the sequencing decision at the higher balancing level within a hierarchical planning approach (Scholl, 1999, Chapter 3.4; Boysen et al. 2006b).

In order to reduce the difficulties in sequence planning, the line balancing can, for instance, seek to minimize variances in station times over all models, known as horizontal balancing ($\gamma = \text{SSL}^{\text{stat}}$; Merengo et al., 1999). Various different objectives which address this issue in some form have been proposed in the literature (Thomopoulos, 1970; Domschke et al., 1996; Bukchin, 1998; Scholl, 1999, Chapters 3.3 and 3.4; Matanachai and Yano, 2001; Boysen, 2005, Chapter B.2).

Alternatively, line balancing can enforce that all models observe the cycle time at every station ($\beta_1 = \text{each}$; Merengo et al., 1999). This approach ensures that overloads can never occur and thus make sequence planning trivial. However, it leads to higher cycle times and thus lower output of the assembly system in exchange. It might therefore be better to only enforce an observation of the cycle time for a certain percentage of models, weighted by their estimated occurrence in typical model mixes ($\beta_1 = \text{prob}$; Vilarinho and Simaria, 2002).

In ALB the mixed-model case is usually transformed to the single-model case by the use of a joint precedence graph (Thomopoulos, 1970; Macaskill, 1972; van Zante-de Fokkert and de Kok, 1997). Here, the process times of tasks which vary for certain models are averaged with regard to the occurrence of respective models in the estimated model mix and are then composed to form a unique precedence graph. If precedence relationships differ among models, this procedure might lead to conflicts which can nevertheless be resolved by duplicating nodes (Ahmadi and Wurgaft, 1994).

In some fields of business, the product variety is too large to allow reliable estimations. German car manufacturer Daimler Chrysler delivers its C-Class model in 2^{27} theoretically possible specifications (Röder and Tibken, 2006). A model-based prognosis is thus impossible. Instead, only reliable estimations of option occurrences over all models can be provided, e.g., the percentage of cars with air conditioning (Röder and Tibken, 2006). Consequently, the determination of joint precedence graphs should be based on these prognoses, which requires an assignment of tasks to product attributes (see Boysen et al., 2006c).

The use of a joint precedence graph implies that those similar tasks which are performed on different models are always assigned to the same station. The economic justification is that similar tasks usually require identical resources, which would need to be purchased and installed multiple times, otherwise (Thomopoulos, 1967). However, this approach is not necessarily efficient. Instead, the increased investment costs ($\beta_4 = \text{res}^{01}$), which result from an assignment of similar or identical tasks to different stations ($\beta_3 = \text{ptask}$; Pinto et al., 1975), can be considered explicitly to allow for an improved balance, for instance in the form of a lower cycle time. Like this, the trade-off between higher investment costs and potentially higher revenues due to increased output should be regarded in mixed-model ALB (Bukchin and Rabinowitch, 2006).

Although a mixed-model production implies set-up times to be very low, tool swaps between models might be necessary which just consume a fraction of the cycle time ($\alpha_4 = \Delta t_{\text{dir}}$; Wilhelm, 1999). As these swaps consume some part of the operating time of a station, they might nevertheless be of great relevance in practice.

As a summary of the argumentation, it follows that ALB problems designed for mixed-model production, in particular, should cover the following cases:

$$[\text{mix},\ \Delta t_{\text{dir}}|\text{ptask},\ \text{res}^{01}|\text{Co},\ \text{SSL}^{\text{stat}}]\ \text{or}$$
$$[\text{mix},\ \Delta t_{\text{dir}}|\text{prob},\ \text{ptask},\ \text{res}^{01}|\text{Co}].$$

Table 1 displays a selection of valuable research papers for ALB problems arising in mixed-model assembly lines.

3.3. Multi-model assembly lines

In multi-model production, the homogeneity of assembled products and their production processes is not sufficient to allow for facultative production sequences. In order to avoid set-up times and/or costs the assembly is organized in batches ($\alpha_1 = \text{mult}$). This leads to a short term lot-sizing problem which groups models to batches and decides on their assembly sequence (cf., e.g., Burns and Daganzo, 1987; Dobson and Yano, 1994).

Especially if lot sizes are large, the line balance can in principle be determined separately for each model, as the significance of set-up times between batches is comparatively small. However, also in multi-model production a certain degree of similarity in production processes should be inherent. Typically, the different models are manufactured by use of the same resources, e.g. machines or operators. If line balances are determined separately, those resources which are shared by models ($\beta_4 = \text{res}^{01}$) might need to be moved to other

Table 1
ALB for mixed-model assembly lines

Source	Notation	Source	Notation
Merengo et al. (1999)	[mix|each|m, SSL$^{\text{line}}$, SSL$^{\text{stat}}$]	Domschke et al. (1996)	[mix| |E, SSL$^{\text{stat}}$]
Bukchin et al. (2002)	[mix|ptask|score]	Askin and Zhou (1997)	[mix|pstat|Co]
Visich et al. (2002)	[mix|u|SSL$^{\text{stat}}$]	Erel and Gökcen (1999); Gökcen and Erel (1998)	[mix|div|m]
Bukchin and Rabinowitch (2006)	[mix|div, ptask, res^{01}|Co]	Vilarinho and Simaria (2002)	[mix, link, inc|prob, pstat|m, SSL$^{\text{line}}$, SSL$^{\text{stat}}$]
Thomopoulos (1970)	[mix| |m, SSL$^{\text{stat}}$]	Roberts and Villa (1970)	[mix, link|each, ptask|m]
Matanachai and Yano (2001)	[mix| |SSL$^{\text{line}}$, SSL$^{\text{stat}}$]	McMullen and Frazier (1997, 1998b), McMullen and Tarasewich (2003)	[mix, t^{sto}|pstat|Co, SSL$^{\text{line}}$, score]
Macaskill (1972)	[mix| |E]		

Table 2
ALB for multi-model lines

Source	Notation	Source	Notation
Chakravarty and Shtub (1985)	[mult|div|Co]	Pastor et al. (2002)	[mult, cum, fix| |c, SSL$^{\text{line}}$, SSL$^{\text{stat}}$]
Chakravarty and Shtub (1986)	[mult, t^{sto}|div|Co]	Kimms (2000)	[mult, spec|unpac, equip|Co]
Dar-El and Rabinovitch (1988)	[mult, t^{dy}| |Co]	Cohen and Dar-El (1998)	[mult, t^{dy}|unpac|Pr]

stations whenever the production system is set-up for a new batch or have to be installed multiple times. This increases set-up times and/or costs. If this interdependency is regarded in the line balance, the set-up times might be reduced considerably, which in turn allows for a formation of smaller lots with all associated advantages ($\gamma = \text{Co}$).

The same trade-off can be observed when manual labour is considered. If line balances are determined separately, the work content of an operator can change considerably with any new batch. This leads to a lower specialization of labour and can result in increased training costs and additional waste whenever operators need to adapt to their new tasks. By and by the operators will learn to master their new work content, so that processing times are likely to decrease over time. Thus, dynamic task times ($\alpha_3 = t^{\text{dy}}$) should be considered when balancing multi-model lines to account for these learning effects (e.g. Cohen and Dar-El, 1998) after a new batch is released.

If all models in a multi-model line are to be balanced simultaneously, different production targets for each model need to be taken into account. Accordingly, cycle times can vary with each model considered ($\beta_1 = \text{div}$; Gökcen and Erel, 1998). An investigation of the case [mult|div, res^{01}|Co] seems to be especially suitable for multi-model assembly. Up to now, only a few publications deal with multi-model lines (see Table 2).

4. ALB in dependency of line control

4.1. Paced line

In a paced assembly production system typically a common cycle time is given which restricts process times at all stations ($\beta_1 = \circ$). The pace is either kept up by a continuously advancing material handling device, e.g. a conveyor belt, which forces operators to finish their operations before the workpiece has reached the end of the respective station, or by a so called intermittent transport, where the workpiece comes to a full stop at every station, but is automatically transferred as soon as a given time span is elapsed. The real-world implementation does usually not influence the balancing decision.

If the transportation of workpieces is continuous, station lengths need to be defined in accordance with the line balance. The length of a station might be subject to technical restrictions, e.g. by space requirements of assigned machinery, but should also be considered from a planning point of view. If the length of a station (multiplied by the movement rate of the line) exceeds the cycle time, the resulting extra time can be used to compensate for deviations in task times either due to a mixed-model production ($\alpha_3 = \text{mix}$) or caused by stochastic variations ($\alpha_3 = t^{\text{sto}}$). Accordingly, the cycle time should not always be observed strictly at a station. In the case of stochastic task times it is sufficient to fulfill the cycle time restriction with a certain probability ($\beta_1 = \text{prob}$). The selection of an appropriate probability is highly dependent on the amount of extra time available and the costs which arise whenever operations could not be completed (e.g., costs of line stoppage, use of utility workers or external completion of workpieces; Wild, 1972, p. 164). An explicit consideration of these cost factors can, for instance, be found in Carter and Silverman (1984), Gökcen and Baykoc (1999), Henig (1986), Kottas and Lau (1981), Lau and Shtub (1987), Lyu (1997), Sarin and Erel (1990), Sarin et al. (1999), Shtub (1984) as well as Silverman and Carter (1986).

Instead of assigning a global cycle time, locally diverging cycle times are useful ($\beta_1 = \text{div}$) to allow for, e.g., an installation of test stations which examine the quality of workpieces. If such a test station identifies a defect, the corresponding workpiece is taken off the line, repaired and then reexamined, before it can replace another defect workpiece at the successive station (Lapierre and Ruiz, 2004). A consideration of different target production quantities in multi-model production also requires diverging cycle times (Gökcen and Erel, 1998).

4.2. Unpaced asynchronous line

In unpaced lines, workpieces are transferred whenever the required operations are completed, rather than being bound to a given time span ($\beta_1 = \text{unpac}$). Buzacott and Shanthikumar (1993) further distinguish as to whether all stations pass on their workpieces simultaneously (synchronous) or whether each station decides on transference individually (asynchronous).

Under asynchronous movement, a workpiece is always moved as soon as all required operations at a station are completed and the successive station is not blocked anymore by another workpiece. After transference the station continues to work on a new workpiece, unless the preceding station is unable to deliver (starving). In order to minimize waiting times, buffers are installed in-between stations, which can temporarily store workpieces ($\beta_6 = \text{buffer}$). When deciding on buffer installation one has to consider the trade-off between installation costs and achievable throughput, because the latter tends to increase by installing more and larger buffers.

Buffers can only be used to compensate for temporary deviations in task times. If a station is generally faster than another one, the buffer storage will soon be filled to capacity and lose its function (Buzacott, 1971; Buxey et al., 1973). Accordingly, the use of unpaced asynchronous lines with buffers is only meaningful, if station times are subject to variations which might stem from stochastic task times ($\alpha_3 = t^{\text{sto}}$) and/or machine breakdowns which are relevant even in case of deterministic task times. Nonetheless, in ALB it only seems suggestive to consider stochastic task times either caused by (i) variations in the speed of manual labour and/or by (ii) the model mix ($\alpha_1 = \text{mix}$) (Tempelmeier, 2003). Instead of incorporating such singular events like machine breakdowns, that have low probability but enormous consequences on the operation of the line, in the long-term to mid-term planning task of ALB, planning effort should rather be spent on eliminating the causes of breakdowns and placing and dimensioning buffer storages adequately.

In unpaced lines, the production rate is no longer given by a fixed cycle time, but is rather dependent on the realised task times. These can be estimated as long as the distribution functions are known which are, however, considerably influenced by buffer allocation. Thus, the configuration planning of an unpaced asynchronous assembly system needs to: (1) determine a line balance, (2) allocate buffer storages, (3) estimate throughput (and/or further measures of efficiency).

Due to the strong interdependencies between all three planning problems, a simultaneous solution would certainly be desirable. So far, approaches in the literature avoid the resulting complexity and rather investigate isolated parts. The majority of publications deals with problems (2) and (3) and seeks an optimal relation of buffer cost and production rate (cf. Buzacott, 1968; Suhail, 1983; Baker et al., 1990; Hillier and So, 1991; Hillier et al., 1993; Malakooti, 1994; Powell, 1994; Dolgui et al., 2002). In these approaches, the line balance is typically given, so that station times and their respective distribution functions are known. The successive planning of line balance and buffer allocation will most likely not lead to a global optimum of the whole system. Already slight changes in the work content at a station might lead to a more efficient buffer allocation and improve the system's overall performance. Optimal buffer allocations could thus be determined repetitively for varying line balances or both problems might be solved simultaneously, e.g. in a simulation-optimization approach. The appropriate integration of all three problems is certainly a challenging field for future research.

In any case, also in asynchronous unpaced systems, line balancing is essential for ensuring smooth station loads, at least in the long run. Thus, it seems to be adequate to restrict station times by a cycle time, just like in paced lines, even though the job movement will not be controlled by the cycle time later on. Nevertheless, it remains to be investigated which extensions of SALBP are most suitable for considering the special requirements of asynchronous unpaced lines. It is for instance not necessarily required that the stochastic nature of operating times is always accounted for in a stochastic ALB model. The use of a deterministic model might be justified as ALB mainly seeks for a long-term balance of station loads (see Sphicas and Silverman, 1976). This in turn allows for a further integration of additional extensions, such as parallelization or equipment selection, which have so far not been regarded in stochastic ALB models.

The analysis of asynchronous lines revealed an interesting attribute, generally referred to as "bowl phenomenon" (cf. Hillier and Boling, 1966, 1979; Hillier and So, 1993), according to which the throughput of a line can be improved by assigning

Table 3
ALB for unpaced asynchronous assembly lines

Source	Notation	Source	Notation
Johnson (1983)	[type|div, ptask|m]	Nakade et al. (1997)	[t^{sto}|unpac, u,Δt_{unp}|c]

smaller station loads to central stations than to those located at the beginning or end of the line. This effect is the stronger, the higher the stochastic deviations of processing times (Smunt and Perkins, 1985). The same concept applies to buffer allocation, if buffer storages in the centre (or at bottleneck stations) are increased in size (Conway et al., 1988; for a more recent overview see Harris and Powell, 1999). In this context, the use of a global cycle time seems inappropriate, and should thus be replaced by station-specific local cycle times to account for this phenomenon ($\beta_1 = \mathrm{div}$; Johnson, 1983), which assign a lower work content to central stations or alternatively enforce a higher probability of regarding the cycle time in case of a stochastic model. The appropriate determination of these local cycle times is still up to future research. ALB for asynchronous assembly lines should thus further investigate the case:

[t^{sto}|div, prob, buffer|m].

The few approaches in the literature which treat at least parts of the mentioned extensions from the ALB's point of view are summarized in Table 3.

4.3. Unpaced synchronous line

Under synchronous movement of workpieces, all stations wait for the slowest station to finish all operations before workpieces are transferred at the same point in time ($\beta_1 = \mathrm{unpac}^{\mathrm{syn}}$). In contrast to the asynchronous case, buffers are hence not necessary.

If task times are deterministic, the unpaced synchronous line can be treated just like a paced line with intermittent transport, as the cycle time is determined by the slowest station. In the stochastic case ($\alpha_3 = t^{\mathrm{sto}}$), there further exist strong similarities to a paced line, which is stopped whenever the cycle time is exceeded. An unpaced line can, however, advance if operations were performed unexpectedly fast and need not have to wait for a fixed time span to elapse. That is why an unpaced synchronous line promises a higher output than its paced counterpart.

The variable output, nevertheless, complicates line balancing considerably. Some approaches in the literature deal with estimating throughput in such a setting (cf. Lau and Shtub, 1987; Buzacott and Shanthikumar, 1993; Kouvelis and Karabati, 1999). These approximations allow for a selection of line balances out of a given set of predetermined alternatives; however, sophisticated optimization models need to integrate throughput determination and line balancing. So far only Karabati and Sayin (2003) as well as Urban and Chiang (2006) proposed combined models and solution procedures (see Table 4). There is, thus, still a wide gap for future research concerning these assembly systems.

5. ALB with regard to its frequency

5.1. First time installation

Whenever an assembly production system is installed for the first time and resources have not been purchased yet, stations can in fact be treated as abstract entities, to which a certain number of tasks can be assigned. Typically, only the desired product with all its attributes and variants is already determined. The exact production process is often not yet fixed or not even fully substantiated.

This can be taken into account in two different ways: The classical approach is to select and fix all tasks and their respective processing modes prior to the balancing decision to form a single precedence graph before the ALB problem is solved. Alternatively, this successive planning can be replaced by selecting the processing alternatives simultaneously with the balancing decision. The latter approach requires the survey of all (or a reasonable subset of) alternative processes which lead to the desired product(s), which are hence passed on to the balancing problem. The assignment of tasks to stations is then influenced by the simultaneous selection of processing alternatives. This approach promises a better overall solution and is especially suitable for a first time installation ($\alpha_6 = \mathrm{pa}$; Pinto et al., 1983; Pinnoi and Wilhelm, 1998; Bukchin and Tzur, 2000).

Table 4
ALB for unpaced synchronous assembly lines

Source	Notation	Source	Notation
Karabati and Sayin (2003)	[mix|unpac^{sync}|score]	Urban and Chiang (2006)	[t^{sto}|unpac^{syn}|m]

Table 5
ALB for the first-time installation of an assembly line

Source	Notation	Source	Notation
Capacho and Pastor (2004)	[pa^{subgraph}| |m]	Zäpfel (1975)	[link, inc| |Pr]
Chakravarty (1988)	[t^{dy}| |E]	Rosenblatt and Carlson (1985)	[| |Pr]

Processing alternatives can influence the determination of the precedence graph in different ways. Often, different machinery or differently skilled operators can carry out the same task at varying performances and costs. Typically, there exists a time-cost trade-off, such that the more expensive resource promises lower task times. Additionally, processing alternatives might directly influence the precedence relationships ($\alpha_6 = \text{pa}^{\text{prec}}$), as the transformation carried out by a particular task might impede the implementation of an automated procedure while a manual operation is still available. Finally, whole subgraphs might be substitutable ($\alpha_6 = \text{pa}^{\text{subgraph}}$; Capacho and Pastor, 2004). This is the case whenever the assembly of different single options can be replaced by a purchased module or subassembly with the same attributes. All mentioned forms of influences are especially relevant for a first time installation and should thus be considered in the respective ALB problems.

As processing alternatives typically generate different implementation costs, these costs need to be considered explicitly in the objective function ($\gamma = \text{Co}$). At this point in time, sales forecasts are moreover subject to considerable inaccuracies, so that it can be reasonable to model the trade-off between investment costs and expected revenues raised by a varied output ($\gamma = \text{Pr}$; Zäpfel, 1975; Klenke, 1977; Rosenblatt and Carlson, 1985; Martin, 1994; Boysen and Fliedner, 2006) instead of a cost minimization for a given cycle time (and, thus, output).

With regard to the long life time of the assembly line, the expected learning effects ($\alpha_3 = \text{t}^{\text{dy}}$), which are even favoured by the high specialization of labour, can have a considerable impact on determining the long-term efficiency of the production system. If those learning effects are neglected, capacities might be heavily overestimated, so that excess capacities in later phases of the product life cycle might force the company to grant heavy discounts, as can be witnessed in the German automotive industry at present (Krcal, 2005). The accurate quantification of learning effects is afflicted with difficult forecasts, however, some approaches can be found in the literature (Boucher, 1987; Chakravarty, 1988; Cohen et al., 2006). In order to account for the particularities of a first time installation appropriately, models and algorithms for the following cases seem to be most promising:

[t^{dy}, pa^{subgraph}| |Pr] or [t^{dy}, pa^{subgraph}| |Co].

Existing research treating at least some of the relevant SALBP-extensions is summarized in Table 5.

5.2. Reconfiguration

The majority of real-life line balancing problems stem from a reconfiguration rather than from a first time installation (Falkenauer, 2005). A reconfiguration becomes necessary whenever there is a substantial change in the structure of the production programme, e.g., a permanent shift in the demand for models. In a reconfiguration, stations have identities in the form of allotted resources and a physical location in the workshop.

As stations are already existent, the minimization of the number of stations as an objective is less important. Furthermore, the cycle time is often determined based on sales forecasts. As a consequence, the retrieval of a feasible solution which observes the given number of stations and the cycle time is sufficient. As a supplementary goal it is often proposed to distribute the work content as evenly as possible among the stations ($\gamma = \mathrm{SSL}^{\mathrm{line}}$; Agnetis et al., 1995; Pinnoi and Wilhelm, 1997b; Merengo et al., 1999; Rekiek et al., 2001, 2002). This promises a higher product quality, which might otherwise be endangered at stations with extraordinarily high workloads.

Once resources are allotted to stations, heavy machinery might not be reallocated. In this case, all tasks which require this resource need to remain at their previous station, which can be enforced by assignment restrictions ($\alpha_5 = \mathrm{fix}$). Often, the movement of a machine is, however, not technically impossible, but rather associated with movement costs. In this case, movement costs might need to be considered explicitly ($\gamma = \mathrm{Co}$; Gamberini et al., 2004, 2006). Additionally, space constraints need to be observed whenever a machine is moved ($\alpha_5 = \mathrm{cum}$; Bautista and Pereira, 2007). The space at a station might be limited, so that two tasks each of which requires a large machine cannot be assigned to the same station ($\alpha_5 = \mathrm{inc}$).

But not only the machinery, but also the operators of the assembly line have been assigned to a certain station. They may have been especially trained to carry out the respective work content, so that a change will additionally be associated with training costs. It might thus be desirable, that the new line balance remains as close as possible to the previous one, in order to save training and movement costs. This aspect has so far not been taken up in the literature.

If in the previous balance, a station or a whole section of the line was parallelized ($\beta_3 = \mathrm{pstat}$; Pinto et al., 1981), this can be considered by local cycle times ($\beta_1 = \mathrm{div}$), which are multiples of the global one, so that the parallelized stations can take up a higher work content.

The majority of papers (implicitly) treat the case of a first time installation of an assembly system. This might be the more important case, as it deals with the investment in machinery as well as the selection of processing alternatives and thus leads to cost intensive decisions which influence the company for a longer period in time. However, just due to the higher frequency with which reconfigurations become necessary, this field has a high relevance in practice. There is thus a need for models and algorithms for the following case:

$[\mathrm{fix},\ \mathrm{inc},\ \mathrm{cum}|\mathrm{div}|\mathrm{Co},\ \mathrm{SSL}^{\mathrm{line}}]$.

Papers regarding some extensions which are especially valuable for the reconfiguration of assembly systems are summarized in Table 6.

6. ALB and the level of automation

6.1. Manual lines

In spite of the major advances in the automation of assembly processes, there are still many assembly systems which mainly or completely rely on manual labour. Manual lines are especially common, where workpieces are fragile or if workpieces need to be gripped frequently, as industrial robots might lack the necessary accuracy (Bi and Zhang, 2001). In countries where wage costs are low, manual labour can also be a cost efficient alternative to expensive automated machinery.

Task times under manual labour are often subject to stochastic deviations ($\alpha_3 = t^{\mathrm{sto}}$), as the performance of human workers depends on a variety of factors, like motivation, work environment or the mental and physical stress (Tempelmeier, 2003).

The lack of motivation and the low level of satisfaction, which is typically caused by the high repetitiveness of elementary operations, have been considered as a major disadvantage of assembly production (Shtub and Dar-El, 1989). It is therefore desirable to assign packages of cohesive tasks to workers, like the total assembly of a particular product option. So far, the level of cohesiveness of a task set has been roughly measured by the number of direct precedence relationships between included tasks (Agrawal, 1985; Lee et al., 2001). This approach seems to be somewhat imprecise or at least requires an empirical validation. An explicit consideration of the tasks' cohesiveness with regard to modules and subassemblies is provided by Shtub and Dar-El (1990).

The physical (e.g. grip strength) and psychological (e.g. fatigue) stress an operator has to face can be modelled as additional node weights in the precedence graph. To each task a certain stress indicator is assigned, which may not exceed or fall below a certain total level over all tasks assigned to a worker ($\alpha_5 = \mathrm{cum}$; Carnahan et al., 2001). Another major factor influencing manual labour is the individual experience of a worker. That is why learning effects gain a special importance in manual labour as they might result in dynamic task times ($\alpha_3 = t^{\mathrm{dy}}$).

Due to their complexity and the problems in quantification it is questionable whether a detailed

Table 6
ALB for assembly line reconfiguration

Source	Notation	Source	Notation
Raouf and Tsui (1982)	[t^{sto}, fix, excl|prob|m, SSL^{stat}]	Pastor et al. (2002)	[mult, cum, fix| |c, SSL^{line}, SSL^{stat}]
Buxey (1974)	[Δt_{dir}, link, inc, max|pstat|score]	Arcus (1966)	[mix, Δt_{dir}, cum, fix|$\text{res}^{\max}$, Δt_{unp}, pwork|E]
Rekiek et al. (2001)	[Δt_{dir}, link, inc, fix, type, pa| |Co, SSL^{line}]	Pastor and Corominas (2000)	[link, inc, type, max| |SSL^{line}]
Agnetis et al. (1995)	[spec, inc, fix | |SSL^{line}]	Johnson (1983)	[type|div, ptask|m]
Rekiek et al. (2002)	[link, fix, pa| |Co, SSL^{line}]	Deckro (1989)	[link, inc, max| |m, c]
Park et al. (1997)	[spec, inc, pa^{prec}| |c]	Gamberini et al. (2004, 2006)	[t^{sto}|u|Co, score]

consideration of all mentioned aspects leads to meaningful ALB models. Another characteristic aspect of manual labour might be more easily utilized: the unmatched level of flexibility. Operators of adjacent stations might for instance support each other in case of an overload. This can be directly exploited by certain line layouts, like the U-line ($\beta_2 = u$; Miltenburg and Wijngaard, 1994; Nakade et al., 1997; Aase et al., 2004) or n-U-line ($\beta_2 = u^n$; Miltenburg, 1998; Sparling, 1998), which stems from the famous Toyota-Production-System (Monden, 1998). In such a line both wings are positioned close to each other to form a rather narrow U, so that workers can carry out tasks on both wings in the same production cycle. This increases the degrees of freedom of the balancing decision considerably (Scholl and Klein, 1999). The time it takes a worker to move from one side to the other might need to be considered nevertheless whenever it reaches a certain level ($\beta_5 = \Delta t_{\text{unp}}$; Sparling, 1998; Sparling and Miltenburg, 1998).

Typically, wage costs constitute the highest cost factor if manual labour is used extensively ($\gamma = \text{Co}$). It needs to be investigated, however, if the line balance has a direct influence on wage costs. If all operators are already employed, as is typically the case in a reconfiguration, and alternative jobs for workers outside the line are not available, the line balance might not have any impact on wage costs. Sometimes the wage cost might be influenced due to different levels of qualification necessary by the most demanding task a worker has to carry out ($\beta_4 = \text{res}^{\max}$; Steffen, 1977; Rosenberg and Ziegler, 1992; Amen, 2000a, b, 2001, 2006; Scholl and Becker, 2005). In this case, the assignment of tasks to workers can alter wage costs considerably by aggregating the most challenging tasks as much as possible.

The quality of workpieces is also of special importance if operations are carried out manually. As the appropriate quantification of quality is rather difficult, it can, however, only be considered indirectly (Robinson et al., 1990). Under manual labour, quality often suffers if operators are overloaded with work and thus need to work faster. Consequently, it is desirable to ensure that the total workload is distributed as evenly as possible among the stations ($\gamma = \text{SSL}^{\text{line}}$). It follows that manual assembly lines require models and algorithms for the following case:

$[t^{\text{sto}},\ t^{\text{dy}},\ \text{cum}|u,\ \text{res}^{\max},\ \Delta t_{\text{unp}}|\text{Co},\ \text{SSL}^{\text{line}}]$.

All ALB approaches which at least treat some of the above mentioned extensions are provided in Table 7.

6.2. Automated lines

Fully automated lines are mainly implemented wherever the work environment is in some form hostile to human beings, as for instance in the body and paint shops of the automobile industry, or where industrial robots are able to perform tasks more economically and with a higher precision (e.g. metal-processing tasks). The higher precision of machines typically justifies the assumption of deterministic task times ($\alpha_3 = \circ$). If only specialized machinery (each task requires his own machine or tool) is employed, very little other particularities (e.g. space restrictions; $\alpha_5 = \text{inc, cum}$) arise merely from the fact that machines carry out tasks.

However, the increasing differentiation of products, which share the same line ($\alpha_1 = \text{mix}$) gives rise to flexibility even in automated assembly systems. This leads to flexible transfer lines where multi-purpose machines with automated tool swaps

Table 7
ALB for manual lines

Source	Notation	Source	Notation
Amen (1997, 2000a, b, 2001, 2006)	$[\|res^{max}\|Co]$	Ajenblit and Wainwright (1998)	$[\|u\|m, SSL^{line}]$
Arcus (1966)	$[mix, \Delta t_{dir}, cum, fix\|res^{max}, \Delta t_{unp}, pwork\|E]$	Sparling and Miltenburg (1998)	$[mix\|u, \Delta t_{unp}\|m, SSL^{stat}]$
Sparling (1998)	$[\|u'', pline, \Delta t_{unp}\|m]$	Carnahan et al. (2001)	$[cum\| \|c, score]$
Wilson (1986)	$[t^{sto}, pa\| \|Co]$	Miltenburg (1998)	$[fix\|u'', \Delta t_{unp}\|m, score]$
Bukchin et al. (1997); Bukchin and Masin (2004)	$[\|pwork\|m, score]$	Miltenburg and Wijngaard (1994)	$[\|u\|m]$
Rosenberg and Ziegler (1992)	$[\| res^{max} \|Co]$	Shtub and Dar-El (1990)	$[\| \|m, c, score]$
Boysen and Fliedner (2006)	$[t^{sto}, link, inc, cum, pa\|u, pstat, ptask, res^{01}, res^{max}\|Pr]$		

can perform a number of different tasks at varying speed. Due to the high investment costs of universal machinery, the objective of cost minimization considerably gains in importance ($\gamma = $ Co).

If more than one multi-purpose machine can carry out a task with different performance, processing alternatives need to be considered ($\alpha_7 = $ pa). As a consequence, the assignment of tasks to stations is augmented by a selection problem of the equipment at each station ($\beta_4 = $ equip; Pinnoi and Wilhelm, 1998; Bukchin and Tzur, 2000). This selection, hence, determines the task times at the respective station as well as the investment costs (Graves and Lamar, 1983).

Furthermore, assignment restrictions often need to be considered, as some tasks might only be carried out by a subset of available machines ($\alpha_5 = $ type) or cannot be performed on the same machinery ($\alpha_5 = $ inc) at all. The automated tool swap might as well take a certain period of time which might further be dependent on the sequence of workpieces and their required tools ($\alpha_4 = \Delta t_{dir}$; Wilhelm, 1999). Likewise, workpieces often need to be loaded into the station, before any operation can be performed ($\beta_5 = \Delta t_{unp}$; Bard, 1989). Eventually, tool magazines might be limited in size, so that the available capacity becomes a limiting factor when assigning tasks to a station ($\alpha_5 = $ cum; Kim and Park, 1995; Pinnoi and Wilhelm, 1997a).

Additionally, modern multi-purpose machines enable new forms of parallelization. A machine might for instance employ several spindle heads, which are able to perform operations on the same workpiece simultaneously ($\beta_3 = $ pwork; Dolgui et al. 1999, 2001a–c, 2003, 2006).

In an automated line, breakdowns of machinery become a relevant planning issue not only in short-term planning and control but also in configuration planning of assembly lines. Nonetheless, it seems questionable if ALB is the right place to account for these breakdowns. The present lack of research on ALB considering default of machinery is a further indicator that ALB misses suited instruments to attenuate the effects of breakdowns. Instead, a respective placement and dimensioning of buffers seems even more appropriate to maintain throughput in spite of breakdowns (Section 4.2; furthermore see, e.g., Hillier and So, 1991; Tempelmeier, 2003).

It follows that automated lines will mainly benefit from new models and algorithms for the case:

$$[mix, \Delta t_{dir}, inc, type, cum, pa|equip, \Delta t_{unp}|Co].$$

Table 8 summarizes research papers dealing with different aspects of automated assembly systems.

7. Line of business specific ALB

7.1. Automobile production

The final assembly of cars is mainly carried out on paced[1] mixed-model lines ($\alpha_1 = $ mix) with a high proportion of manual labour (Meyr, 2004). In spite of the rather low level of automation, the assumption of deterministic task times is nevertheless often justified ($\alpha_3 = \circ$). Especially, in the German car industry task times are subject to mutual agreements between the employer and the respective trade union, which usually result in very detailed regulations based on standardized time measurement methods concerning the exact amount of time

[1]Urban and Chiang (2006), however, report an example of an unpaced synchronous automobile assembly line ($\beta_1 = unpac^{syn}$).

Table 8
ALB for automated lines

Source	Notation	Source	Notation
Dolgui and Ihnatsenka (2004), Dolgui et al. (1999, 2001a–c, 2003, 2006)	[link, inc|pwork|Co]	Rubinovitz and Bukchin (1993)	[pa|equip|m]
Pinnoi and Wilhelm (1997a)	[mult, link, inc, cum, type, pa|div, equip, pstat, pwork|Co]	Nicosia et al. (2002)	[pa|equip|Co]
Pinnoi and Wilhelm (1998)	[pa|equip|Co]	Levitin et al. (2006)	[pa|equip|c]
Bukchin and Rubinovitz (2003)	[pa|pstat, equip|Co]	Wilhelm (1999)	[Δt_{dir}, pa|equip|Co]
Bukchin and Tzur (2000)	[pa|equip|Co]		

a worker is granted for performing any given type of task.

Balancing of automobile assembly lines needs to deal with a number of peculiarities, most of which are related to the fact that workpieces are comparatively large. As a consequence, a station can often be subdivided into parallel workplaces, where operators work simultaneously on the same workpiece ($\beta_3 =$ pwork; Akagi et al., 1983). This phenomenon also occurs in related industries, like in the production of trucks, buses and construction vehicles (Bartholdi, 1993; Lee et al., 2001). Typical workplaces in car assembly are the front and the rear, left and right, the interior, the roof as well as the underbody of the car. Workers can work in parallel at several workplaces or even change their workplace during a production cycle. This requires the observation of precedence constraints between tasks within a station, as waiting times can for instance arise whenever a worker needs to wait for the completion of another task at another workplace in the same station, before he can continue. In this case, station times cannot be determined anymore by simply summing up task times. Instead a scheduling problem needs to be solved at every station (Falkenauer, 2005; Scholl et al., 2006).

In addition to that, extra times might need to be considered, whenever a worker changes his workplace ($\beta_5 = \Delta t_{\mathrm{unp}}$), operations at different workplaces are impeding each other or if two workers are required to carry out a task jointly, for instance to install the car's axle (Arcus, 1966) or the cockpit. Furthermore, the workpiece itself might be required in a particular position in order to perform a task (e.g. lifted, in order to work underneath the car). As a consequence, some tasks might be incompatible at a certain type of station. ($\alpha_5 =$ type; Johnson, 1983, 1991; Kim et al., 2000a). As position changes can only be realized by heavy machinery, the allocation of such devices becomes part of the balancing process ($\beta_6 =$ change).

Eventually, in automobile production some of the tasks are carried out across more than one station. For instance, a CD player might be installed by a worker who remains in the interior of the car while it visits several stations (Arcus, 1966; Falkenauer, 2005). In order to carry out this task on all vehicles, several workers are allotted, which all work in parallel shifted by a cycle ($\beta_3 =$ pstat; Inman and Leon, 1994).

Hitherto, research was limited to two sided lines ($\beta_3 = \mathrm{pwork}^2$; Bartholdi, 1993; Kim et al., 2000a; Lee et al., 2001). An in-depth investigation of the aforementioned requirements of automobile assembly has not yet been performed. In particular models are needed which comprise the following extensions:

$$[\mathrm{mix},\ \mathrm{type}|\mathrm{pwork},\ \mathrm{pstat},\ \Delta t_{\mathrm{unp}},\ \mathrm{change}|\mathrm{SSL}^{\mathrm{stat}}].$$

Table 9 provides an overview on those research papers which deal with applications in the automobile industry (or related industries).

7.2. Further examples

As no other industries could be identified which require such far reaching extensions as the automobile production and would therefore justify an in-depth discussion, in the following an overview on those research papers is given which are explicitly concerned with practical applications.

7.2.1. Electronic industry

The majority of research papers treating practical applications stem from the appliance industry.

Table 9
ALB in automobile production and related industries

Source	Line of business	Notation
Pastor and Corominas (2000)	Motor cycle production	[link, inc, type, max| |SSL^{line}]
Arcus (1966)	Automobile production	[mix, Δt_{dir}, cum, fix|res^{max}, Δt_{unp}, pwork|E]
Bartholdi (1993)	Small utility vehicles	[fix, type|$pwork^2$|m]
Kim et al. (2000a)	Automobile production	[fix, type|$pwork^2$|m]

Table 10
Practical applications of ALB

Source	Line of business	Notation
Hautsch et al. (1972)	White goods	[link|$pwork^2$, res^{max}, feeder|E]
Malakooti (1991)	Lamp production	[| |m, c, Co]
Agnetis et al. (1995)	Car heaters	[spec, inc, fix| |SSL^{line}]
Kim and Park (1995)	Camcorder, VCR decks	[cum|equip|m]
Park et al. (1997)	Electronic home appliances	[spec, inc, pa^{prec}| |c]
Rekiek et al. (2001, 2002)	Car alternator	[Δt_{dir}, link, inc, fix, type, pa| |Co, SSL^{line}]
Bautista and Pereira (2002)	Bicycles	[inc, Δt_{dir}| |m, score]
Pastor et al. (2002)	White goods	[mult, cum, fix| |c, SSL^{line}, SSL^{stat}]
Lapierre and Ruiz (2004)	Appliance industry	[link, inc, type|div, $pwork^2$, feeder|m]
Lapierre et al. (2006)	Home appliances	[type|$pwork^2$|m]

If workpieces are sufficiently large, as in the production of white goods (refrigerators, etc.) parallel workplaces might be installed just like in automobile production. Due to the comparatively smaller size, this application is usually limited to two sided lines ($\beta_3 = \text{pwork}^2$; Hautsch et al., 1972; Lapierre et al., 2006). As electronic devices usually consist of a number of electronic subassemblies, which need to be assembled themselves, feeder lines are often considered ($\beta_6 = \text{feeder}$; Hautsch et al., 1972; Lapierre and Ruiz, 2004). A possible strategy in such a setting is to balance the main line first and use the resulting cycle time as an input value for balancing the feeder lines later on. It is questionable, however, if such a decomposition will result in a global optimum. This issue is even more critical, if operators can work on tasks on both the main line and the feeder line at their connection points (Lapierre and Ruiz, 2004). The practical applications furthermore employ various assignment restrictions ($\alpha_5 = $ link, inc, fix, type, max) as is summarized in Table 10.

7.2.2. Bicycle production

Bautista and Pereira (2002) consider the manufacturing of bicycles on a paced single model line with mainly manual labour. Apart from assignment restrictions ($\alpha_5 = \text{inc}$) especially the position changes of workpieces need to be regarded. Depending on a particular task the bicycles need to be rotated around the x- or y-axis. On the one hand, this operation takes additional time, on the other hand it means physical stress for the worker. This could have been modelled explicitly by sequence dependent task time increments ($\alpha_4 = \Delta t_{dir}$) or work content restrictions at stations ($\alpha_5 = \text{cum}$). In their case study, Bautista and Pereira (2002) chose to minimize the number of position changes in the objective function ($\gamma = \text{score}$).

8. Conclusions

Thus far, ALB has been an active field of research over more than half a century. This led to a massive body of literature covering plenty of aspects of assembly line configuration. With regard to this tremendous academic effort in ALB, it is astounding that only 15 articles could be identified which explicitly deal with line balancing of real world assembly systems. In comparison to the 312 different research papers treated in the latest review articles of Scholl and Becker (2006), Becker and

Scholl (2006) as well as Boysen et al. (2006a) this is less than 5%. This relation is another indicator for the aforementioned gap between the status of research and the requirements of real-world configuration problems. This article is intended to be a first step towards closing this gap in the future. The assignment of the various SALBP extensions presented in the literature, to typical kinds of real-world assembly systems provides insights for two important questions:

(i) Which SALBP extensions occur jointly in what kind of assembly system and should be regarded in future research on balancing procedures?
(ii) How are existing balancing models and procedures employed most efficiently for solving real-world ALB problems?

There remain some more steps to be done to close the gap. First and foremost, an empirical study on practical line balancing problems needs to confirm whether the theoretical findings in this work are valid in the real world. Furthermore, research should focus even more on solving real-world balancing problems and journals should increasingly publish such case studies. Lastly, if the requirements of practical line balancing are identified, user-friendly computer software is to be developed, which is flexible enough to be successfully applied to these real-world problems.

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