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Preventing ergonomic risks with integrated planning on assembly line balancing and parts feeding

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In this paper, we advise to perform assembly line balancing simultaneously with decision-making on parts feeding. Such integrated planning may open additional potential to reduce labour costs. Additional planning flexibility gained with the integrated planning may be used to mitigate ergonomic risks at workplaces. We formulate the integrated assembly line balancing and parts feeding planning problem, propose a mixed-integer model and compare integrated planning to a common hierarchical planning approach in a detailed case study on the assembly of a self-priming pump. Our case study illustrates that workplaces with high ergonomic risks may emerge even in productions that involve handling parts and workpieces of low weights and avoid static and awkward postures. We also show that the proposed integrated planning approach may eliminate excessive ergonomic risks *and* improve productivity indicators simultaneously.

Keywords: assembly line balancing; part feeding; mixed-integer linear programming; ergonomic risks; case study

1. Introduction

Occupational ergonomic risks lead to higher risks of musculoskeletal disorders for workers and higher compensation costs, but also to lower productivity, lower quality and higher absenteeism for companies (Eklund 1995; Beevis 2003; Sundin, Christmansson, and Larsson 2004; Goggins, Spielholz, and Nothstein 2008; Falck, Örtengren, and Högberg 2010; Ivarsson and Eek 2016). Available estimations reveal significant economic consequences of occupational musculoskeletal disorders for national economies: they cost the US economy between \$45 and \$54 billion annually (NRC 2001) and decrease the gross national product of EU by up to 2% (Schneider and Irastorza 2010). Workplaces with high ergonomic risks are frequent in paced assembly systems because of one-sided strain due to repetitiveness of work (Schneider and Irastorza 2010; Thun, Lehr, and Bierwirth 2011; Schaub et al. 2013).

Recent articles have shown that we can significantly lower ergonomic risks if we take them into account preventively in the operational planning. In this way, we can sometimes decrease ergonomic loads of workers *without* deteriorating key productivity indicators (e.g. Colombini and Occhipinti 2006). For instance, in *assembly line balancing*, or assignment of tasks to assembly operators, we may allocate some additional time for relaxation after especially strenuous tasks and avoid assigning several tasks to a worker that impact the same anatomical segments (cf. Otto and Scholl 2011; Battini et al. 2016b). Still workplaces with significant ergonomic risks may remain if we perform assembly line balancing without considering closely related planning decisions. At least partially, the remaining ergonomic risks are associated with picking parts from difficult to reach containers due to required (severe) bending and high weights of some parts.

In this article, we argue that from economic and ergonomic perspectives, the assembly line balancing should be considered jointly with *parts feeding*, i.e. delivery system of parts to the assembly line. We examine two widespread alternative modes of parts supply (see illustration in Figure 1):

- *direct* supply of parts in containers
- and *indirect* supply of parts in so-called *station kits*, which are repositories containing all the parts needed to process one workpiece at an assembly station.

Directly supplied parts are delivered directly from the warehouse to the assembly line in large containers, each storing one part variant. So, several directly supplied parts will be delivered in several containers. It may be problematic

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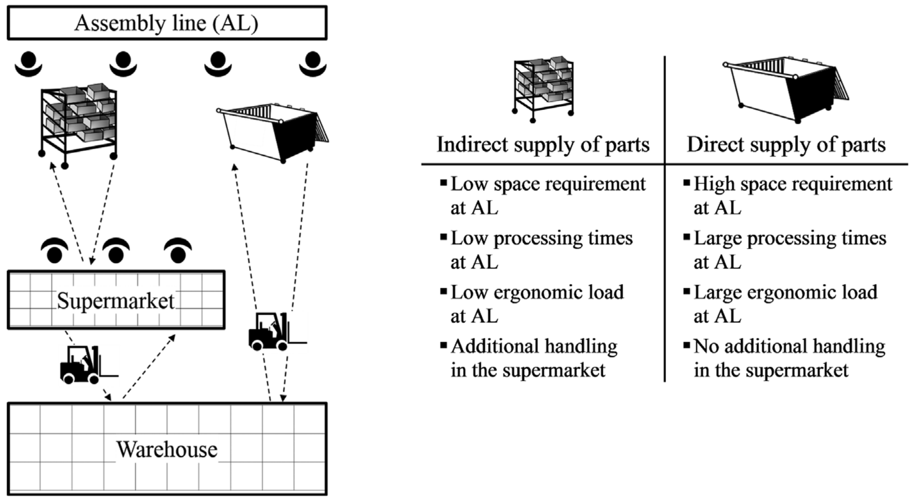

Figure 1. Alternative parts feeding policies: indirect supply of parts in station kits and direct supply of parts in containers, each container stores a single part variant. AL – assembly line.

because the space at the assembly line is limited. Moreover, reaching for parts stored in such bulky containers requires bending, sometimes severe bending, and it takes much time. Additionally, assembly operators may have to unpack the parts.

Indirectly supplied parts have additional handling in an intermediate smaller in-house warehouse located close to the assembly line, called *supermarket*. Supermarket operators re-package parts into ergonomically designed station kits. Therefore, if all the parts are supplied indirectly, each station will accommodate only a few station kits instead of several bulky containers. The ergonomic design of station kits enables assembly operators reaching for the parts fast and in most convenient postures. On the negative side, indirect supply requires additional handling in the supermarket. Because of repetitive re-packaging motions, working assignment of supermarket operators may pose elevated ergonomic risks. To sum up, decisions on parts feeding policies have a profound influence on space and time requirements at the assembly line and in the supermarket, as well as on ergonomic risks for assembly and supermarket operators.

Hierarchical planning, when planners perform assembly line balancing first and make decisions on parts feeding for the given assembly line balance afterwards, is currently widespread in firms (cf. Sternatz 2015). We argue that hierarchical planning can forfeit a lot of potential in reduction of ergonomic risks and therefore should be replaced with *integrated planning*, where assembly line balancing and parts feeding are considered simultaneously.

In this paper, we propose a mixed-integer model for simultaneous planning of assembly line and supermarket operations. We examine the case when operations at the assembly line and in the supermarket are synchronised. Synchronisation is a part of the so-called lean production philosophy and is widespread at manufacturing firms. We estimate the benefits of *integrated planning* compared to the state-of-the-art *hierarchical planning* in a case study of self-priming pump production. We comment on the generalisability of our observations.

The motivation of the current study was first presented at the 8th IFAC Conference on Manufacturing Modelling, Management & Control (Battini et al. 2016a). The conference paper proposed an optimisation model for a special case when supermarket operators may prepare kits only for consecutive assembly stations. In this paper, we extend the model for a general case, when each supermarket operator may serve any assembly station. In the present paper, we also carefully examine the impact of integrated planning in a case study of self-priming pump assembly.

In the following, we proceed with a literature review in Section 2 and develop an optimisation model in Section 3. Section 4 analyses the developed concepts for the assembly of a self-priming pump. We conclude with a summary and outlook of future research directions in Section 5.

2. Literature review

To the best of our knowledge, this article is the first study to examine potential in reduction of ergonomic risks from integrated planning on assembly line balancing and parts feeding. Recent literature surveys and classifications of the assembly line balancing problems can be found, for example, in Becker and Scholl (2006), Scholl and Becker (2006), Boysen, Fliedner, and Scholl (2007, 2008, 2009) and Battaïa and Dolgui (2013).

Overall, parts feeding planning and assembly line balancing are treated as separate problems in the literature. Recently, Sternatz (2015) introduced a model on joint assembly line balancing and parts feeding for automobile industry. He proposed a heuristic solution approach based on partial enumeration. In contrast to our study, the model of Sternatz (2015) does not take ergonomic risks into account. Moreover, the model does not consider synchronisation of assembly line and supermarket operations for just-in-time supply of parts, i.e. it neglects possible idle time of supermarket operators.

Several articles analyse ergonomics aspects in assembly line balancing decisions (e.g. Gunther, Johnson, and Peterson 1983; Carnahan, Norman, and Redfern 2001; Akyol and Baykasoğlu 2016; Bautista, Alfaro-Pozo, and Batalla-García 2016a, 2016b). Case studies and computational experiments show that alternative solutions, which are optimal with respect to productivity criteria, may differ a lot in terms of ergonomic risks they impose on assembly operators (see Colombini and Occhipinti 2006; Otto and Scholl 2011; Battini et al. 2016b). However, in many cases, assembly line balancing cannot eliminate ergonomic risks by re-planning tasks without hiring additional resources. Thus, for 50% of instances in Otto and Scholl (2011), additional stations had to be introduced to eliminate workplaces with excessive ergonomic risks. Especially, in case of medium assembly lines with a few stations, the required deterioration of productivity parameters to receive solutions with only acceptable ergonomic risks may be high (Battini et al. 2016b). We refer the interested reader to a recent survey of Otto and Battaïa (2017) on ergonomic aspects in planning paced assembly lines.

Starting with Bozer and McGinnis (1992), a number of articles proposed evaluation approaches for parts supply policies, mostly along such decision criteria as space requirements and handling costs (see Kilic and Durmusoglu 2015 and Boysen et al. 2015 for literature reviews). Among those is a high-level evaluation procedure of Battini et al. (2009), which includes decisions on decentralisation of parts storage (i.e. storage in one or several warehouses), location of warehouses and selection of parts supply modes. Hua and Johnson (2010) and Hanson and Brolin (2011) study the transfer from direct supply to indirect supply qualitatively and discuss them on case studies from electronics and automotive industries. Caputo and Pelagagge (2011) propose descriptive models to design the best policies and delivery systems for assembly systems, also extending them with economic considerations (Caputo, Pelagagge, and Salini 2015) and by taking into account parts features (Caputo, Pelagagge, and Salini 2016). Mixed-integer optimisation models on how to select between several modes of parts supply are elaborated by Limère et al. (2012), Limère, Van Landeghem, and Goetschalckx (2015) and Sali and Sahin (2016). The existing studies, however, assume the assignment of tasks to stations as given. Moreover, to our best knowledge, they do not consider ergonomics aspects.

Several articles examine how selected aspects of parts logistics relate to ergonomic risks. For example, Christmansson et al. (2002) investigate typical movements, postures and forces in picking parts in two alternative kitting configurations. Hanson and Medbo (2016) analyse driving factors for duration of material kitting activities. Battini et al. (2016c) and Otto et al. (2017) examine the impact of slotting, i.e. assignment of parts to shelves in warehouses, on ergonomic risks. Ciriello (2003), Neumann and Medbo (2010), Hanson et al. (2016), Andriolo et al. (2016), Calzavara et al. (2017) study the impact of box sizes, parts configuration and workplace layout on ergonomic risks from picking parts. The results of these studies suggest significant influence of parts supply modes on picking time and ergonomic risks.

3. The integrated assembly line balancing and parts feeding planning

In this section, we explain the estimation of ergonomic risks (Section 3.1), provide a general problem formulation for *the integrated assembly line balancing and parts feeding planning problem* (IALBFP) (Section 3.2) and specify a mixed-integer model (Section 3.3). We also describe the hierarchical planning approach, which is currently widespread in practice, in Section 3.4.

3.1 *Estimation of ergonomic risks*

We estimate ergonomic risks based on energy expenditure of workers, which allows to describe all the three main ergonomics dimensions during physical work: level, repetitiveness and duration. Energy expenditure is closely related to the heart rate of workers (Spurr et al. 1988; Li, Deurenberg, and Hautvast 1993). Excessive energy expenditure is associated with metabolic stress, fatigue and discomfort (Waters et al. 1993; Dempsey 1998). Energy expenditure is closely related to the repetitiveness of work, which, according to pathomechanical studies, may lead to inflammatory processes and tissue degeneration, especially with age (Geronilla et al. 2003; Baker et al. 2007). Moreover, workers change muscle recruitment patterns in order to compensate for fatigue from repetitive work (Marras and Granata 1997), which may result in awkward postures. Overall, energy expenditure is routinely used by certified professional ergonomists as an appropriate tool to estimate ergonomic risks at workplaces (David 2005; Dempsey, McGorry, and Maynard 2005) and is a major component of ergonomic checklists and aggregate indices, such as the NIOSH equation (Waters et al. 1993). We refer the interested reader to Marras and Karwowski (2006) for further details and discussions of widespread ergonomic risk estimation methods.

Our basic concept, which dates back to seminal papers of Rohmert (1973) and Price (1990), is to provide additional time for rest, called rest allowance, to workers according to their energy expenditure. We measure energy expenditure with formulas of Battini et al. (2016b) and Calzavara et al. (2016), who adapted comprehensive and flexible regression models of Garg, Chaffin, and Herrin (1978) to manual tasks at assembly lines and to picking activities, respectively. The formulas describe energy expenditure rates for common manual tasks and body movements. The energy expenditure rate is a sum of two terms: energy demand for maintaining a certain body posture (e.g. standing, sitting) and energy demand for performing activities (e.g. arm lifting, holding, pushing). The formulas consider different parameters, such as gender, body weight, handled load weight, vertical heights of lifting or lowering, grade of the walking surface and speed of walking.

We estimate e_j^d, which is the energy expenditure rate for performing task j at the assembly line if the corresponding part j is supplied directly; e_j^i, which is the energy expenditure rate for task j at the assembly line if part j is supplied indirectly; and, finally, e_j^s, which is the energy expenditure rate for handling indirectly supplied part j in the supermarket. Energy expenditure rates are measured in kcal.

Based on energy expenditure rates of individual tasks, we compute energy expenditure indices $\dot{E}$ for each worker as proposed by Price (1990) and Battini et al. (2016a, 2016b). Energy expenditure index $\dot{E}$ is a ratio of the average rate of energy expenditure rate E and the duration T of the manual activities:

$$\dot{E} = \frac{E}{T} \tag{1}$$

If energy expenditure index $\dot{E}$ of the workplace exceeds the limit of 4.2927 kcal/min, then we have to add rest allowance term RA to the task times to provide sufficient recovery time to the worker (Price 1990). The new times $\hat{T}$, corrected by RA with the formulas of Rohmert (1973) and Price (1990), are:

$$\hat{T} = T \cdot (1 + \mathrm{RA}) \tag{2}$$

Because $\mathrm{RA} = \frac{41 \cdot \dot{E} - 176}{100}$, we can express $\hat{T}$ as follows:

$$\hat{T} = \begin{cases} 0.41 \cdot E - 0.76 \cdot T & \text{if } \dot{E} > 4.2927 \\ T & \text{otherwise} \end{cases} \tag{3}$$

Observe that if $\dot{E} > 4.2927$, then $0.41 \cdot E - 0.76 \cdot T > T$ holds. Therefore, we can rewrite (3) as follows:

$$\hat{T} = \max\{T, 0.41 \cdot E - 0.76 \cdot T\} \tag{4}$$

Based on (4), we define the following ergonomic parameters for IALBFP: $\eta_j^d = 0.41 \cdot e_j^d - 0.76 \cdot t_j^d$ for assembly task j with directly supplied parts, $\eta_j^i = 0.41 \cdot e_j^i - 0.76 \cdot t_j^i$ for assembly task j with indirectly supplied parts and $\eta_j^s = 0.41 \cdot e_j^s - 0.76 \cdot t_j^s$ for operations in the supermarket to prepare parts for assembly task j. Thereby, t_j^d and t_j^i are processing times of task j at the assembly line if part j is supplied directly or indirectly, respectively; t_j^s is additional processing time of the part of task j in the supermarket.

The higher the energy expenditure index, the higher the risks of getting musculoskeletal disorders become (Hoozemans et al. 1998). Ergonomic risks are excessive, if the *average* energy expenditure index for a continuous period of work exceeds 4.2927 (Price 1990; Westgaard and Winkel 1996). At the paced assembly line with homogeneous products, workers repeat the same set of operation at each workpiece. Therefore, the average energy expenditure index of tasks within a cycle should be within the limit of 4.2927 kcal/min. Based on (4), we require that sufficient time should be reserved at each assembly station k for performing the assigned set of tasks J^k:

$$\max\left\{\sum_{j\in J^k \cap J^{dir}} t_j^d + \sum_{j\in J^k \cap J^{ind}} t_j^i, \sum_{j\in J^k \cap J^{dir}} \eta_j^d + \sum_{j\in J^k \cap J^{ind}} \eta_j^i\right\} \le c, \tag{5}$$

where J^{dir} and J^{ind} are the sets of tasks with directly and indirectly supplied parts, respectively.

In our case study in Section 4, we report energy expenditure indices for each station. For example, energy expenditure index for assembly station k is:

$$\dot{E}_k = \frac{\sum_{j \in J^k \cap J^{dir}} e_j^d + \sum_{j \in J^k \cap J^{ind}} e_j^i}{c} \tag{6}$$

Observe that the integration of the described energy expenditure-based risk measurement in the line balancing problem leads to a simpler formulation compared to other possible ergonomics risk estimation techniques, for example, NIOSH or OCRA (Waters, Putz-Anderson, and Garg 1994; Occhipinti 1998; Waters et al. 2016), so that the resulting linear integer programme can be solved with standard off-the-shelf solvers. Energy expenditure can also be easily estimated in practice using simple instruments (Battini et al. 2017). Note, however, that energy expenditure-based equations may underestimate impact of some awkward postures and infrequent handlings of heavy weights (cf. Waters et al. 1993). Therefore, at assembly lines involving handling of heavy parts, additional ergonomic constraints may have to be introduced.

3.2 *Problem statement*

We consider paced assembly lines where homogeneous workpieces are processed at sequentially arranged single-manned stations. They are launched at equal time intervals, called *cycle time* c, so that each workpiece spends c time units at each station. The assembly of a workpiece requires completion of the set of tasks J.

In IALBFP, we make three kinds of decisions simultaneously:

- On parts feeding policy for each assembly task,
- On assembly line balancing,
- On assignment of re-packaging tasks to the supermarket operators

We assume that supermarket operations are perfectly synchronised with the assembly line. We also assume that some delivery system periodically transports prepared station kits to the assembly stations and picks up empty station kits. Synchronisation is a part of the lean principle and is being adopted by firms to increase transparency on the status of processes, for example, to make delays and the process variability visible. The periodicity of the kits exchange depends on the distance from the supermarket, utilised technology and organisational arrangements. It may be as often as once in a one-minute cycle. For example, when a proper automated feeding system, which is able to supply the material rapidly, has been set up, or when the kitting area is very close to the corresponding assembly stations, as in the case of the fishbone supermarket (Battini et al. 2009; Caputo and Pelagagge 2011). In some other arrangements, the periodicity of kits exchange may be less frequent, once in several cycles. In the latter case, several kits are exchanged at once.

Parts feeding policy. For each task $j \in J$, we decide whether the required parts associated with this task should be supplied directly, i.e. in containers, or indirectly, i.e. as a part of a station kit. In other words, we partition set J into two disjoint sets: $J = J^{dir} \cup J^{ind}$, J^{dir} contains tasks with directly supplied parts and J^{ind} contains tasks with indirectly supplied parts. To streamline our exposition, we assume that each task is associated with *exactly one* part. In the following, we often refer to the part associated with task j as 'part j'.

As discussed in Section 1, decisions on the parts feeding policy have consequences on (i) processing times, (ii) ergonomic load and (iii) space requirements at assembly line stations; moreover, indirectly supplied parts require additional processing in the supermarket (iv). The processing time of task j is higher in case of direct supply, i.e. $t_j^d \geq t_j^i$. Ergonomic load for an assembly operator, quantified as described in Section 3.1, equals to η_j^d and η_j^i in case of direct and indirect supply, correspondingly, thereby $\eta_j^d \geq \eta_j^i$. For $j \in J^{dir}$, space bb_j should be reserved for the container of part j. In case of indirect supply, parts are supplied as a part of a station kit and space BK should be reserved at the assembly stations containing tasks with indirectly supplied parts.

Each part $j' \in J^{ind}$ requires additional processing time $t_{j'}^s$ in the supermarket, it imposes ergonomic load $\eta_{j'}^s$ on a supermarket operator and requires space $nb_{j'}$. Also, the total space requirements of the parts with indirect supply should not exceed the available space BS: $\sum_{j' \in J^{ind}} nb_{j'} \leq$ BS.

Assembly line balancing. Observe that because of organisational and technological constraints, *precedence relations* may restrict the processing sequence of the tasks. We notate a precedence relation as a pair of tasks (i, j), where i has to be completed before we can start processing j. We denote the *set of precedence relations* as $A := \{(i, j) | j \in J, i \in J, i \text{ has to precede } j\}$. The assembly line balancing is to determine the number of stations K and to find a partition $\bigcup_{k=1}^{K} J^k$ of the set of tasks J into K pairwise disjoint sets which we call *station loads*, such that:

- The total processing time of each station load does not exceed the cycle time: $\sum_{j\in J^k\cap J^{dir}} t_j^d + \sum_{j'\in J^k\cap J^{ind}} t_{j'}^i \le c \forall k \in \{1, \ldots, K\}$,
- The total ergonomic load of each station load does not exceed the recommended limit E^{lim}: $\sum_{j\in J^k\cap J^{dir}} \eta_j^d + \sum_{j'\in J^k\cap J^{ind}} \eta_{j'}^i \le E^{\lim} \forall k \in \{1,\ldots,K\}$,
- Partition $\bigcup_{k=1}^{K} J^k$ does not violate precedence relations: for all $(i,\ j) \in A, i \in J^k$ and $j \in J^{k'}$ it follows that $k \le k'$.
- The total space requirements of station load J^k do not exceed the available space B_k at station k. In other words, each station should have enough space for containers of parts directly supplied to this station and, in case it contains some indirectly supplied parts, for station kits: $\begin{cases} \sum_{j\in J^k\cap J^{dir}} bb_j \le B_k & \text{if } J^k \cap J^{ind} = \emptyset \\ \sum_{j\in J^k\cap J^{dir}} bb_j + BK \le B_k & \text{if } J^k \cap J^{ind} \ne \emptyset \end{cases}$.

Assignment of re-packaging tasks to supermarket operators. We also have to assign re-packaging tasks to supermarket operators. In other words, we have to determine the number of assembly operators R and find a partition $\bigcup_{r=1}^{R} \tilde{J}^r = J^{ind}$ of the set of parts with indirect supply into R subsets each forming a workload of a supermarket operator, such that:

- The total processing time of parts in each subset does not exceed the cycle time: $\sum_{j'\in\tilde{J}^r} t_{j'}^s \le c \forall r \in \{1,\ldots,R\}$,
- The total ergonomic load in each subset does not exceed the recommended limit E^{lim}: $\sum_{j'\in\tilde{J}^r} \eta_{j'}^s \le E^{\lim} \quad \forall r \in \{1,\ldots,R\}$.
- A kit for one station is prepared by one supermarket operator: if $J^k \cap \tilde{J}^r \ne \emptyset$ then $\left(J^k \cap J^{ind}\right) \subseteq \tilde{J}^r$ $\forall k \in \{1,\ldots,K\}, \forall r \in \{1,\ldots,R\}$

See Table 1 for the summary on the introduced notation.

3.3 *Mixed-integer problem formulation*

Let enumerate the supply modes of parts with coefficient s: $s = 1$ for direct supply and $s = 0$ for indirect supply. We introduce the following decision variables. Binary variables x_{jks} denote whether task j is assigned to station k and its part is supplied with supply mode s ($x_{jks} = 1$) or not ($x_{jks} = 0$). Similarly, assignment variables y_{jkr} express whether supermarket operator r processes part j which is assigned to assembly station k ($y_{jkr} = 1$) or not ($y_{jkr} = 0$). For each assembly station k, we also use instrumental variables z_{kr} to track whether it contains tasks with indirectly supplied parts processed by supermarket operator r ($z_{kr} = 1$) or not ($z_{kr} = 0$).

We streamline our model with the following preprocessing steps: (i) for each task j, we compute the earliest E_j and the latest L_j station, to which this task can be assigned as well as (ii) we compute the set of tasks assignable to each station k as $A_k : \{j \in J | k \in \{E_j, L_j\}\}$ (cf. Scholl 1999; Scholl and Becker 2006). To streamline our model and without loss of generality, we require that set J contains dummy sink task n, which has to be performed last. We also require that if any part j is supplied indirectly, then the last supermarket operator processes part n. Parameters $\bar{K}$ and $\bar{R}$ denote upper bounds on the number of assembly line stations and on the number of supermarket operators, respectively, for example, $\bar{K} = \bar{R} : |J|$. As we show in Section 4, the formulated model solves the problem instances of our case study in just a

Table 1. Parameters of IALBFP.

J	Set of jobs/parts, $J = \{1, \ldots, n\}$	$\bar{K}$	Upper bound on the number of assembly stations
t_j^d, t_j^i	Processing times of task j at assembly line in case of direct and indirect supply, respectively	c	Cycle time
η_j^d, η_j^i	Ergonomic loads of task j at assembly line in case of direct and indirect supply, respectively	BK	Space requirements of a station kit
A	Set of precedence relations, $A := \{(i,j) \mid i \text{ precedes } j; i,j \in J\}$	B_k	Space restriction of station k
		t_j^s, η_j^s	Processing time and ergonomic load of part j in the supermarket
bb_j	Space requirements of task j at assembly line		
s	Supply mode: $s = 1$ for direct supply, $s = 0$ for indirect supply	$\bar{R}$	Upper bound on the number of supermarket operators
E_j, L_j	The earliest and the latest stations, to which task j can be assigned	nb_j	Space requirements of part j in the supermarket
A_k	Set of tasks that can be assigned to station k, $A_k := \{j \in J \mid k \in \{E_j, L_j\}\}$	BS	Space restrictions in the supermarket

couple of seconds of time. Observe, that for large problem instances, the model can be further streamlined, for example, by introducing constraints described by Pastor and Ferrer (2009) and Ritt and Costa (2015).

A mixed-integer model of IALBFP is:

$$\text{Minimise } F(x,z,m) = \sum_{k\in E_n}^{L_n} \sum_{s\in\{0,1\}} k\cdot x_{nks} + \sum_{k\in E_n}^{L_n} \sum_{r=1}^{\bar{R}} r\cdot y_{nkr} \tag{7}$$

$$\sum_{k\in\left\{E_j,L_j\right\}} \sum_{s\in\{0,1\}} x_{jks} = 1 \qquad \forall j\in J \tag{8}$$

$$\sum_{j\in A_k}\left(t_j^d\cdot x_{j,k,1} + t_j^i\cdot x_{j,k,0}\right)\le c \qquad \forall k\in\{1,\ldots,\bar{K}\} \tag{9}$$

$$\sum_{j\in A_k}\left(\eta_j^d\cdot x_{j,k,1} + \eta_j^i\cdot x_{j,k,0}\right)\le c \qquad \forall k\in\{1,\ldots,\bar{K}\} \tag{10}$$

$$\sum_{r=1}^{\bar{R}} z_{kr} \ge \frac{\sum_{j\in A_k} x_{j,k,0}}{|A_k|+1} \qquad \forall k\in\{1,\ldots,\bar{K}\} \tag{11}$$

$$\sum_{j\in A_k} bb_j\cdot x_{j,k,1} \le B_k - BK\cdot\sum_{r=1}^{\bar{R}} z_{kr} \qquad \forall k\in\{1,\ldots,\bar{K}\} \tag{12}$$

$$\sum_{k\in E_j}^{L_j} \sum_{s\in\{0;1\}} k\cdot x_{jks} \le \sum_{k\in E_l}^{L_l} \sum_{s\in\{0;1\}} k\cdot x_{lks} \qquad \forall (j,l)\in P \tag{13}$$

$$\sum_{k\in E_j}^{L_j} \sum_{r=1}^{\bar{R}} y_{jkr} \le 1 \qquad \forall j\in J \tag{14}$$

$$\sum_{j\in J} \sum_{k\in E_j}^{L_j} t_j^s\cdot y_{jkr} \le c \qquad \forall r\in\{1,\ldots,\bar{R}\} \tag{15}$$

$$\sum_{j\in J} \sum_{k\in E_j}^{L_j} \eta_j^s\cdot y_{jkr} \le c \qquad \forall r\in\{1,\ldots,\bar{R}\} \tag{16}$$

$$\sum_{k\in E_j}^{L_j} \sum_{r=1}^{\bar{R}} r\cdot y_{jkr} \le \sum_{k\in E_n}^{L_n} \sum_{l=1}^{\bar{R}} l\cdot y_{nkl} \qquad \forall j\in J\backslash\{n\} \tag{17}$$

$$x_{j,k,0} \le \sum_{r=1}^{\bar{R}} y_{jkr} \qquad \forall j\in J,\ \forall k\in\left\{E_j,\ldots,L_j\right\} \tag{18}$$

$$\sum_{r=1}^{\bar{R}} z_{kr} \le 1 \qquad \forall k\in\{1,\ldots,\bar{K}\} \tag{19}$$

$$|A_k|\cdot z_{kr} \ge \sum_{j\in A_k} y_{jkr} \qquad \forall k\in\left\{E_j,\ldots,L_j\right\}, r\in\{1,\ldots,\bar{R}\} \tag{20}$$

$$\sum_{j\in J}\sum_{k\in E_j}^{L_j} nb_j \cdot x_{j,k,0} \leq \text{ BS} \tag{21}$$

$$x_{jks} \in \{0;1\} \qquad \forall j \in J, \quad k \in \{1,\ldots,\bar{K}\}, \quad s \in \{0;1\} \tag{22}$$

$$y_{jkr} \in \{0;1\} \qquad \forall j \in J, \quad \forall k \in \{E_j,\ldots,L_j\}, \quad r \in \{1,\ldots,\bar{R}\} \tag{23}$$

$$z_{kr} \in \{0;1\} \qquad \forall k \in \{1,\ldots,\bar{K}\}, r \in \{1,\ldots,\bar{R}\} \tag{24}$$

Objective function (7) is to minimise the number of required assembly and supermarket operators.

Constraints (8-13, 22) are assembly line balancing constraints. Each task has to be assigned to exactly one station (8), the processing duration of tasks of a station cannot exceed the cycle time (9) and the ergonomic load cannot exceed the ergonomic limit (10). Recall that according to the energy expenditure method described in Section 3.1, the ergonomic limit $E^{\text{lim}} := c$. Constrains (13) enforce precedence relations between tasks and constraints (11) set sum of variables $\sum_{r=1}^{\bar{R}} z_{kr}$ to 1 if station k contains at least one task with indirectly supplied parts. The space requirements should not exceed the available station space (12).

Constraints (14–17) are supermarket constraints. Each part is re-packaged by at most one operator (14), time load and ergonomic load of each supermarket operator does not exceed the cycle time (15) and the ergonomic limit (16), respectively. Recall that, as explained in Section 3.1, E^{lim}: = c. In Constraints (17), we enforce that if any part j is supplied indirectly, then the last supermarket operator processes dummy part n.

Constraints (18) and (20) link values of decision variables and require that each indirectly supplied part is processed by at least one supermarket operator (18) as well as that if supermarket operator r serves task j of station k then instrumental variable z_{kr} is set to 1 (20). Constraints (19) require that each station kit is prepared by one supermarket operator. Constraint (21) describe the space restriction in the supermarket. Constraints (22–24) set domaines of the decision variables.

Observe that we can further improve our planning by looking for a balance with the minimum average ergonomic risks among the optimal balances of model (7–24). In this case, we modify objective function (7) as follows:

$$\text{Minimise } F'(x,z,m) = F(x,z,m) + \frac{\bar{K}+\bar{R}}{c\cdot(\bar{K}+\bar{R}+1)} \cdot \frac{\sum_{j\in A_k}\left(\eta_j^d \cdot x_{j,k,1} + \eta_j^i \cdot x_{j,k,0}\right) + \sum_{j\in J}\sum_{k\in E_j}^{L_j} \eta_j^s \cdot y_{jkr}}{\bar{K}+\bar{R}} \tag{7a}$$

In (7a), we extend objective function (7) by adding the weighted average ergonomic load per workplace. Observe that because of weight $\frac{\bar{K}+\bar{R}}{c\cdot(\bar{K}+\bar{R}+1)}$, the second summand never exceeds 1 and we always prefer a feasible solution with a lower number of the required workers to a feasible solution with lower average ergonomic risks.

3.4 *Hierarchical planning approach*

In our analysis, we compare *integrated planning* according to model (7a, 8–24) with *hierarchical planning*, which is currently a state-of-the-art procedure in industries. At the first stage of hierarchical planning, planners perform assembly line balancing. Thereby they reserve enough time to enable direct supply of all the parts, but ignore space restrictions. The first stage can be described with constraints (8, 9, 13, 22) with modified constraints (8) as $\sum_{j\in A_k} t_j^d \cdot x_{j,k,1} \leq c$ for all$k \in \{1,\ldots,\bar{K}\}$, reduced domain for parameter $s \in \{1\}$ and the objective function to minimise $F''(x) = \sum_{k\in E_n}^{L_n}\sum_{s\in\{1\}} k \cdot x_{nks}$. At the second stage of hierarchical planning, planners examine overcrowded stations with too many bulky containers in the limited station space and re-assign some parts to indirect supply to receive a feasible solution. Ergonomic risks are generally neglected in such planning approach.

4. Evaluation of the benefits of integrated planning in a case study

In our case study, we examine assembly of a self-priming pump. It is an example of a light production system, which is generally regarded as production with low ergonomic risks. It involves handling of rather small weights (up to about 2 kg), moderate repetitiveness of work and does not involve awkward postures except for bending in case of picking parts from bulky containers. In our analysis, we show that even at such assembly lines, high ergonomic risks may be present at some workplaces. Therefore, the selected case study presents a conservative estimate of the potential benefits of the proposed integrated planning approach.

We solve the optimisation models with off-the-shelf software IBM ILOG CPLEX 12.7.1 with default settings (e.g. parallelisation, automatic selection of the optimisation method). All the examined models have been solved in just a few seconds, and computational time never exceeded 1 minute. Thereby, the IALBFP for the preassembly phase required the longest time of 53 seconds, while the simple assembly line balancing as part of hierarchical planning was solved in less than 1 second.

In the following, we describe parameters of the case study in Section 4.1, examine ergonomic risks emerging in the two planning approaches (Section 4.2) and evaluate further benefits of integrated planning (Section 4.3). Afterwards, we provide a short overview of the performed pieces of analysis in Section 4.4. In Section 4.5, we compare our findings with the existing research and suggest some insights for calibration of artificial data sets in Section 4.5.

4.1 *Description of the case study*

The self-priming pump is assembled in a manual paced assembly system. The assembly consists of three processes: preassembly, painting and finishing. While the first phase deals with the actual assembly of mostly the entire product, the latter includes final assembly, refinement tasks, quality control and packaging. The preassembly process has 27 tasks, painting is coded as one task (task 28), while the finishing process has 23 tasks. Preassembly, painting and finishing are largely independent production subprocesses decoupled by buffers. Therefore, we consider these processes independently. Figure 2 shows the respective precedence graphs, where nodes denote tasks and arcs (i, j) between node i and node j indicate that task i should precede task j. We do not examine painting in the present analysis, because it represents a process that cannot be meaningfully broken down into a set of assembly tasks. Therefore, we do not visualise task 28 in Figure 2.

Table A1 reports characteristics of each task: the weight in kilogrammes of the handled object – it can be a part, or, in some cases, the entire assembled product, – processing times and energy expenditure rates. For each task, we report times and energy expenditure rates for parts picking and assembly separately. For example, t_j^w, t_j^{dp} and t_j^{ip} are the assembly time of task j, the picking time of part j from a bulky container and the picking time of part j from a station kit, respectively, so that $t_j^d := t_j^w + t_j^{dp}$ and $t_j^i := t_j^w + t_j^{ip}$. We measured assembly times t_j^w with stopwatches during regular production activities and took the average of six different estimates. We estimated parts picking and handling times t_j^{dp}, t_j^{ip} and t_j^s by combining direct measurements with the stopwatch and experimental results (see Hanson et al. 2016; Calzavara et al. 2017). Because of low variance in the received estimates, we assume parts handling times to be the same for all the tasks, specifically $t_j^{dp} := 0.15\,\text{min}, t_j^{ip} := 0.05\,\text{min.}$ and $t_j^s := 0.12\,\text{min.}$ for all tasks $j \in J$ that require a part. If task j does not require a part, times t_j^{dp}, t_j^{ip} and t_j^s are zero. We calculate energy expenditure rates of task j as the

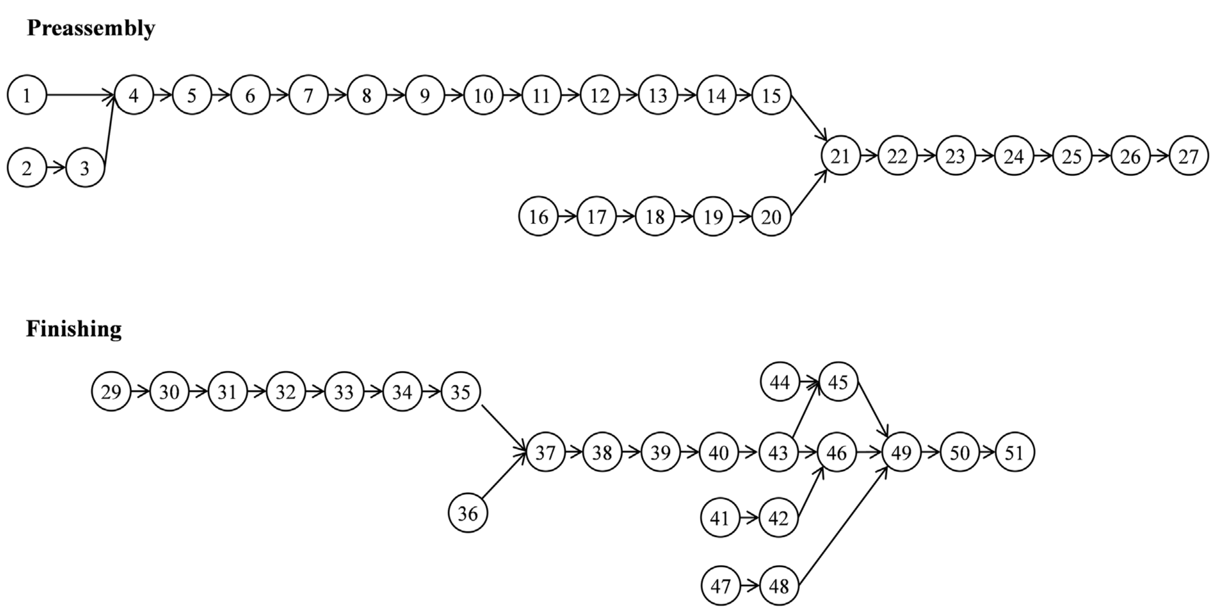

Figure 2. Precedence graphs for preassembly and finishing assembly lines.

total energy of all the constituent activities, which we estimate as described in Section 3.1. We calculate energy expenditure rates for a 75-kg male operator. Note that at the planning stage of assembly line balancing, assignment of workers to stations is unknown and will be fixed in a downstream planning task. Overall, the calculated energy expenditure rates represent an optimistic scenario, since they will be higher for heavier operators and for female operators.

Directly supplied parts are always supplied in EURO-pallets or EURO-cages, i.e. bb_j: = 0.96 m^2 for all $j \in J$. The dimension of a station kit is 0.24 m^2 and because station kits are delivered each five cycles, we set $BK := 0.24 \cdot 5 = 1.2$ m^2. Indirectly supplied parts of each type $j \in J$ are stored in bins of size $nb_j := 0.48$ m^2 in the supermarket area. Assemblies for preassembly and finishing are spatially separated and each requires a distinct supermarket.

4.2 *Ergonomic risks in light productions*

As discussed above, the case study is an example of a light production with much lower ergonomic risks than at many other assembly lines. It does not require high repetitiveness of tasks in contrast, for example, to meat processing assemblies where highly repetitive movements are common. It also does not require awkward postures except for bending to pick parts from bulky containers. Awkward postures are common, for example, in automobile industry where operations on the undercarriage require working over shoulders and operations in the engine compartment require bending.

In this section, we show that even in such productions as our case study, task assignment to workers may result in high ergonomic risks.

In this piece of analysis, we assume moderate size of assembly stations and set $B_k := 3.12$ m^2 so that in each station, the space for three EURO-pallets (or EURO-cages) or two EURO-pallets and station kits is available. We do not pose any restrictions on the size of the supermarket area and provide enough space to supply all the parts indirectly by setting $BS := 17$ m^2.

Table 2 reports energy expenditure indices $\bar{E}_j = \frac{e_j^d}{t_j^d}$ for tasks j in preassembly and in finishing in case of direct supply of its part. In our case study, the main source of high energy expenditure is the weight of the handled workpiece and/or parts. Only six tasks have energy expenditure indices over the critical level of 4.2927 kcal/min and combination of these tasks in one station may result in excessive ergonomic risks. These are tasks 2, 3, 16, 21, 26 in preassembly and tasks 44, 51 in finishing, among them tasks 2, 3, 16 and 44 require handling a part (see Table 2). Indirect supply reduces the energy expenditure index of tasks by about 20% on average.

In hierarchical planning, too high ergonomic risks may emerge for cycle times $c \in [0.73, 0.81]$ min when tasks 2, 3 and 16 in preassembly are assigned to the same station.

Figure 3 illustrates examples of integrated and hierarchical planning for $c = 0.75$. Observe that all the parts are supplied directly in case of hierarchical planning, because no station space restrictions are violated after the first planning stage. Figure 3 shows that hierarchical planning leads to one workplace with excessive ergonomic risks.

Integrated planning reduces the total energy expenditure by 12% without requiring any additional worker (see Figure 3). Moreover, the highest energy expenditure index of 3.61 (at assembly station 14) after integrated planning is about 23% lower than the maximum energy expenditure index of 4.69 (at assembly station 1) in case of hierarchical planning. Note that reduction of ergonomic risks at most exposed workplaces is extremely important because higher ergonomic risks translate not only to higher prevalence of occupational diseases, but also risks of having more severe forms of occupational diseases become higher.

4.3 *Factors influencing relative advantages of integrated planning*

In the following, we examine further factors influencing relative advantages of the integrated planning compared to hierarchical planning: space restrictions at assembly stations, cycle time and space restriction in the supermarket. On the

Table 2. Energy expenditure rates $\dot{E}_j^d = \frac{e_j^d}{t_j^d}$ in case of direct supply of part j for tasks that require handling parts (bold values for tasks exceeding 4.2927 kcal/min).

j	1	2	3	4	5	6	7	8	9	10	12	13	14	15	16	17	18
$\dot{E}_j$	3.96	**5.05**	**4.74**	3.67	3.48	3.80	2.72	3.11	3.19	3.70	3.70	3.37	3.45	3.67	**5.59**	2.72	3.32
j	19	20	27	30	33	34	35	36	37	38	39	40	41	42	44	47	48
$\dot{E}_j$	3.41	2.71	3.50	3.70	3.66	3.50	3.32	3.50	3.70	2.72	3.50	3.56	3.32	3.43	**4.47**	3.30	3.39

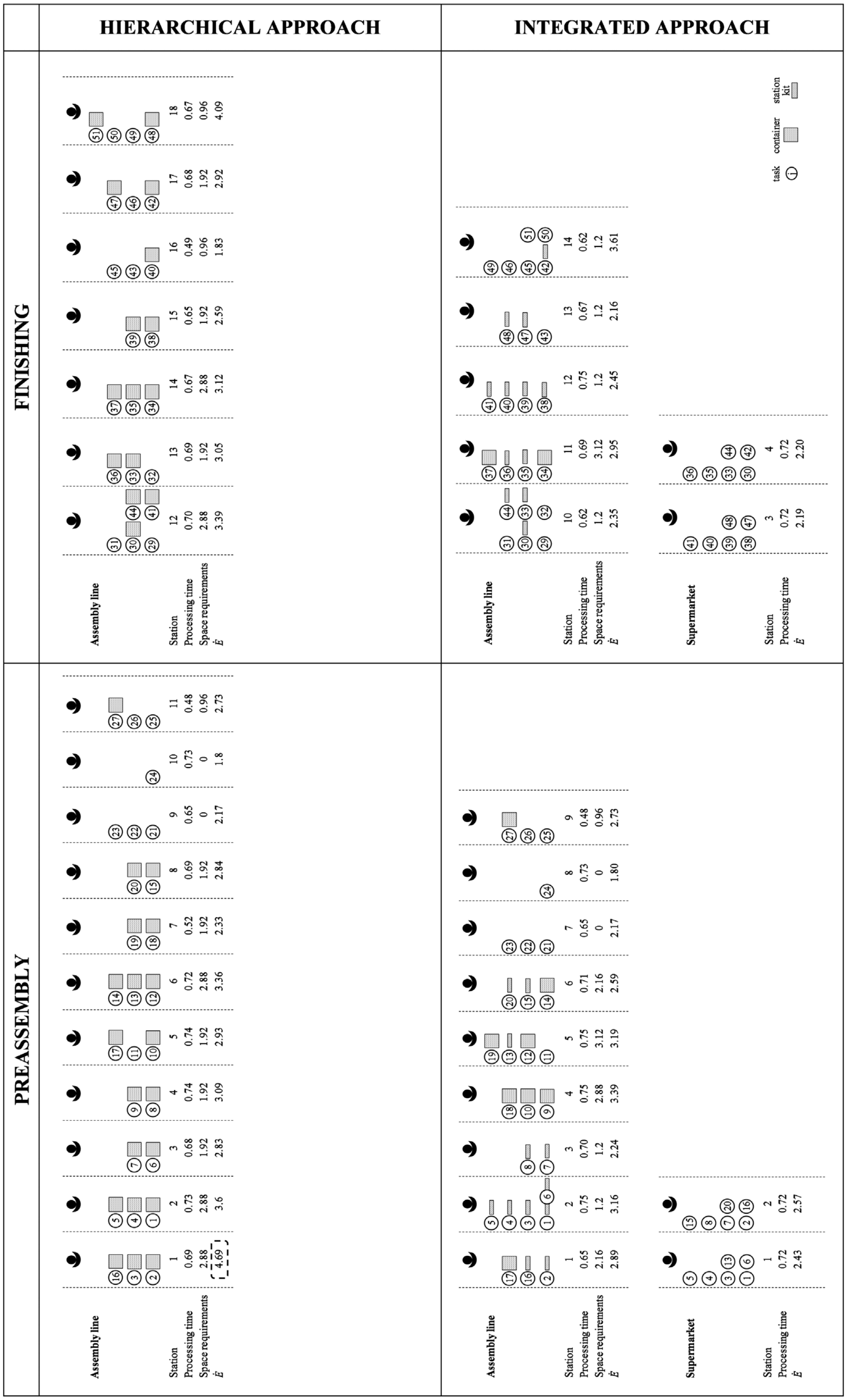

Figure 3. Results of hierarchical and integrated planning for c: = 0.75 min, B_k: = 3.12 m^2, BS: = 17 m^2.

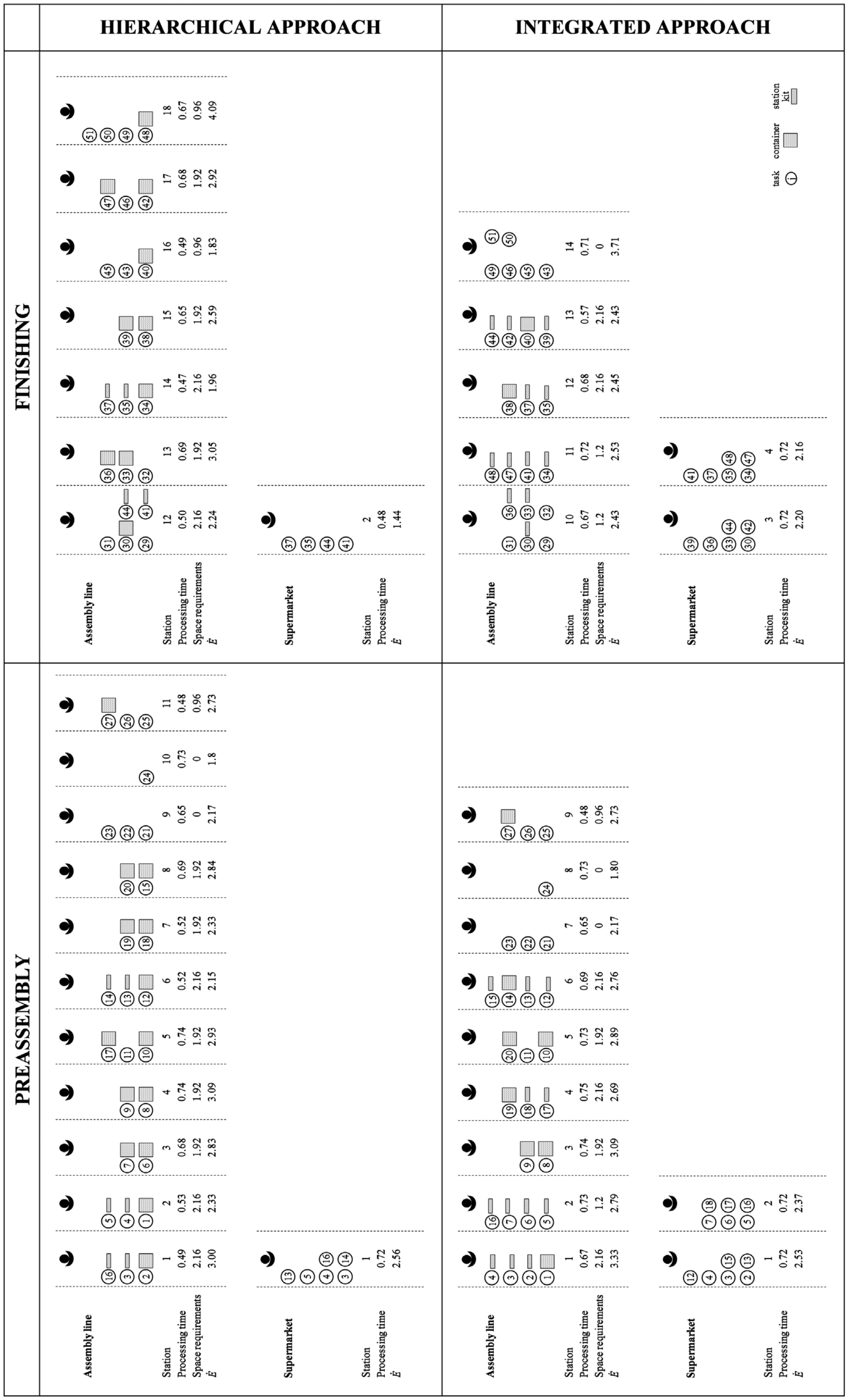

Figure 4. Results of hierarchical and integrated planning for c: = 0.75 min, B_k: = 2.16 m^2, BS: = 17 m^2.

example of our case study, we illustrate that relative advantages of integrated planning measured in the required number of workers get generally higher with less space available at stations B_k, higher cycle times c and more space available for the supermarket BS.

Analysis 1. Figure 4 illustrates the results of integrated and hierarchical planning in case of more restrictive station space of $B_k := 2.16$ m^2 that provides space for maximally two EURO-pallets or one EURO-pallet and station kits.

The first stage of hierarchical planning results in the same assembly line balance as depicted in Figure 3. With lower B_k, space requirements are violated at stations 1, 2, 6 in preassembly and 12, 13 in finishing, so that several tasks from these stations have to be assigned to indirect supply to restore feasibility of the plan in planning stage 2. Hierarchical planning requires two additional supermarket operators (see Figure 4). Observe that because space constraints have become more restrictive than ergonomic constraints, ergonomic risks at all the stations are now below the critical limit.

Integrated planning requires two workers less than hierarchical planning which leads to savings of $1 - \frac{18}{20} = 10\%$ in labour costs. Interestingly, although integrated planning employs less workers, it proposes a plan with lower ergonomic risks. For example, the maximum energy expenditure index is $1 - \frac{3.71}{4.09} = 9\%$ lower and the average energy expenditure index among workers is 3% lower than in case of hierarchical planning.

Observe that relative benefits in costs of integrated planning are higher in case of $B_k := 2.16$ m^2 (10% savings in labour costs) than in case of $B_k := 3.12$ m^2 (no savings in labour costs) in our case study. Our intuition is that for randomly generated instances, this statement will be true with high probability (>50%). Indeed, in the first stage of hierarchical planning station loads are determined heuristically, without considering space restrictions and savings in processing times due to indirect supply mode. The more restrictive the station space is, more important becomes information on container sizes, which is neglected in the first stage of hierarchical planning.

Analysis 2. Figure 5 illustrates the results of integrated and hierarchical balancing in case of $c := 1.80$ min, which is a 240% larger cycle time than in the previous pieces of analysis.

Hierarchical planning results in 10 workplaces, whereas integrated planning leads to just 8 workplaces, or 20% reduction in labour costs. Although ergonomic risks increase in case of integrated planning approach (maximum energy expenditure index raises by 4% and the average energy expenditure index raises by 25%), they remain well below the recommended limit.

Observe that relative benefits of integrated planning measure in the required number of workers and labour costs are higher in case of $c := 1.80$ min (20% savings in labour costs) than in case of $c := 0.75$ min (10% savings in labour costs) in our case study. Our intuition predicts this statement to be true with high probability (>50%) for randomly generated instances. Indeed, higher cycle time leads *ceteris paribus* to more tasks per station after the first stage of hierarchical planning, so that more tasks compete for the available station space and the information on container sizes, which is neglected in the first stage of hierarchical planning, becomes more important.

Analysis 3. We also examine the results of integrated and hierarchical planning in case of limited space available for the supermarket (see Figure 6). We set the available supermarket space to be 5 m^2 for each of the two assembly lines.

In a general case, the influence of lower supermarket space is manifold. Firstly, it may lead to an infeasible problem formulation, especially in case of hierarchical planning. Secondly, however, if hierarchical planning results in a feasible solution than advantages of integrated planning over hierarchical planning measured in the number of workers are not larger (and are often lower) than in case of unrestricted supermarket space. Indeed, by decreasing BS, we eliminate a part of the solution space of problem (7a, 8-24) that may contain production plans with low costs.

To illustrate this effect, we set $B_k := 2.16$ m^2 because integrated planning lead to *positive* savings measured in the required number of workers compared to hierarchical planning in case of $B_k := 2.16$ and unrestricted supermarket area (cf. Figure 4).

In case of the restricted supermarket space, integrated planning is able to reduce the number of workers only by 1 (5% savings in labour costs). It is lower compared to a 10% reduction in labour cost if the supermarket space is unrestricted (see Figures 4 and 6).

Although integrated planning requires one worker less compared to hierarchical planning, it raises the maximum energy expenditure index only slightly (by 3%) and even reduces the average energy expenditure index a little bit (by 0.6%).

4.4 *Summary over considered cases*

Table 3 reports selected performance indicators for the examined settings of our case study. Integrated planning has reduced the lead time (or the time, a workpiece spends in preassembly and finishing) and the total occupied storage space at the assembly line for all the examined cases. The total occupied supermarket storage space was higher if integrated planning was used. Observe, however, that these results are not generalisable. For example, we expect the lead time to be lower in case of hierarchical planning than in case of integrated planning for assembly lines with large parts

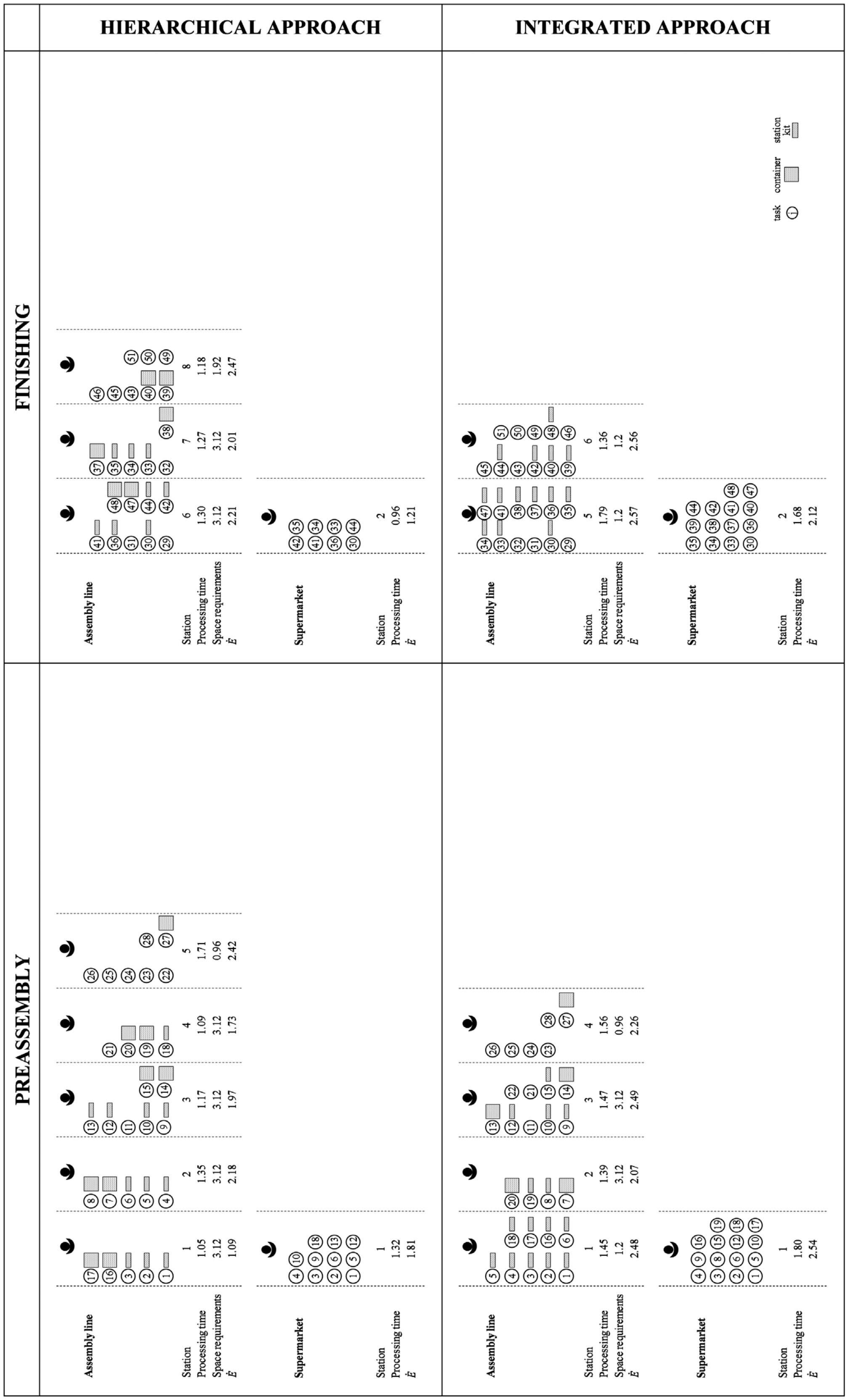

Figure 5. Results of hierarchical and integrated planning for c: = 1.80 min, B_k: = 3.12 m^2, BS: = 17 m^2.

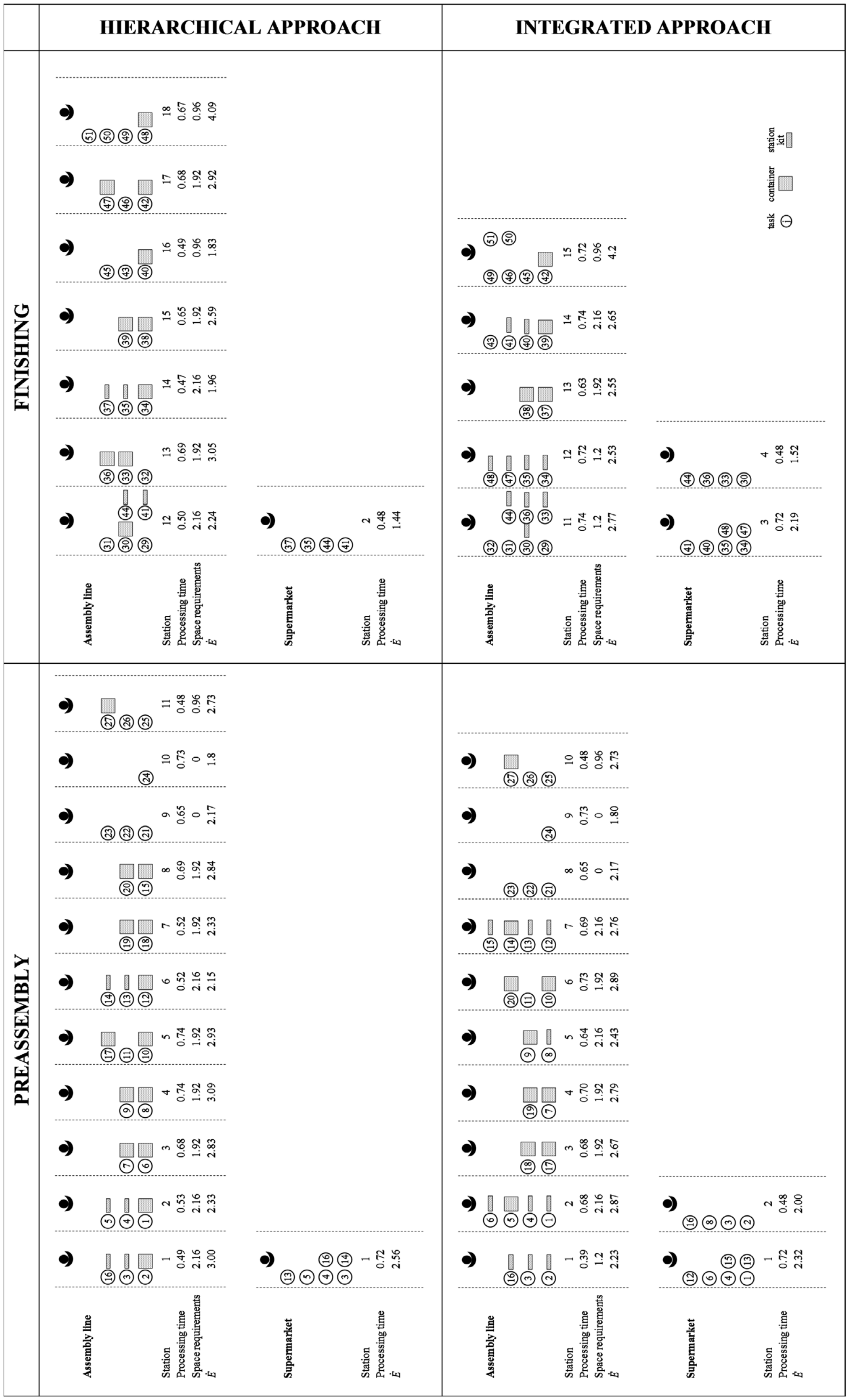

Figure 6. Results of hierarchical and integrated planning for c: = 0.75 min, B_k: = 2.16 m^2, BS: = 5 m^2.

Table 3. Comparison of integrated and hierarchical planning: absolute and relative deviations in the results.

Performance indicator	Case 1	Case 2	Case 3	Case 4
	$c := 0.75$ min $B_k := 3.12$ m^2 BS := 17 m^2	$c := 0.75$ min $B_k := 2.16$ m^2 BS := 17 m^2	c: = 1.80 min $B_k := 3.12$ m^2 BS := 17 m^2	$c := 0.75$ min $B_k := 2.16$ m^2 BS: = 5 m^2
Number of workers	0 (0%)	−2 (−10%)	−2 (−20%)	−1 (−5%)
Lead time (min)	−2.4 (−20%)	−1.4 (−13%)	−1.1 (−11%)	−1.0 (−9%)
Total idle time (min)	−0.48 (−30%)	−1.78 (−62%)	−3.70 (−66%)	−0.95 (−33%)
Total occupied line storage space (m$^{2)}$	−11.0 (−34%)	−9.8 (−34%)	−10.8 (−50%)	−7.2 (−25%)
Total occupied supermarket storage space (m^2)	+11.5 (N/A)	+6.7 (+140%)	+4.8 (+53%)	+4.8 (+100%)
Max energy expenditure index (kcal/min)	−1.08 (-23%)	−0.38 (−9%)	+0.10 (+4%)	+0.11 (+3%)
Avg. energy expenditure index (kcal/min)	−0.35 (−12%)	+0.07 (+3%)	+0.48 (+25%)	−0.01 (−0.6%)

Notes: See Section 4.2 for cases 1 and Section 4.3 for cases 2, 3 and 4. Supermarket space of BS m^2 is available for each of the two assembly lines.

(large bb_j and nb_j) because space restrictions are neglected at the first stage of hierarchical planning that decide on the number of assembly stations.

Total idle time was also lower in our case study in the solutions created with integrated planning. Idle time emerge at assembly lines because tasks are non-pre-emptive. In assembly line balancing, solutions with a lower number of workers necessarily have lower idle time. Observe that in IALBFP it is not always the case. A solution with a lower number of workers may have more parts supplied indirectly (for example, in order to decrease ergonomic risks at assembly stations), lower total task time (since $t_j^d \geq t_j^i$) and, in some constellations, higher idle time. Consequently, managers may prefer solutions of IALBFP with higher idle times to solutions with lower idle times in some situations. We conclude, that in contrast to assembly line balancing, the merit of idle time in IALBFP as a performance indicator is ambiguous.

4.5 *Insights for generation of artificial data-sets in comparison to the existing research*

Case and field studies are an important source of knowledge for calibration of the data generation process to test optimisation models. Indeed, since it takes long time to accumulate a sufficiently large pool of real-world data instances with representative parameter values and since important general insights into these parameters can be gained relatively early on, optimisation scientists create artificial benchmark data sets that mimic planning situations in practice (Otto, Otto, and Scholl 2013; Kendall et al. 2016). Therefore, we formulate some findings for the data generation process suggested by our case study. Note that these insights should be further confirmed and extended by future empirical research.

Overall, the distribution of energy expenditure rates $\dot{E}_j$ in our case study is skewed and mimics beta distribution with parameters $\alpha < \beta$. Indeed, very few tasks have energy expenditure rates under 2. These are, as a rule, some quality control tasks located at the end of the assembly line. Some tasks involve handling of large parts and even lifting the product itself (pump). They require high energy expenditure and form a long right tail of the distribution. The mean energy expenditure rates for assembly tasks (of both indirect and direct supply modes) and supermarket tasks equal 2.38 and 3.32 in our case study, respectively, whereas the mode amounts to 2.25 and 2.75. Note that ergonomic risks are rather low in our case study compared to other industries, most postures are neutral, and the tasks with the highest energy expenditure involve handling of just a 2-kg pump. For example, an extended field study of Marras et al. (2010) report an average weight handled by workers in parts logistics in automotive industry to equal 6.9 kg. Therefore, at many other assembly productions ergonomic risks at workplaces are much higher. For example, Occhipinti and Colombini (2007) studied 22 categories of workplaces from different industries, including oven assembly, refrigerator assembly, electric motors assembly and upholstering of car seats. They found the average level of ergonomic risks to exceed the acceptable level recommended by European norms in all the studied assemblies.

Overall, usually not all the tasks at the assembly line would require handling of parts. In our case study, 74% and 61% of tasks in preassembly and finishing, respectively, involved some handling of parts that could be supplied indirectly via the supermarket.

5. Conclusion

In this paper, we consider productions with synchronised operations of the assembly line and the supermarket area. We argue that decisions on assembly line balancing, supply mode of parts and scheduling of the supermarket area should be made simultaneously. Integrated planning opens additional potential for savings in labour costs and introduces flexibility into decision-making that may be used, for example, to mitigate ergonomic risks at workplaces. We formulate an optimisation problem and propose a mixed-integer model. We compare integrated planning to hierarchical planning, which is widespread in practice, in a detailed case study on the assembly of a self-priming pump.

In the case study, we show that high ergonomic risks may emerge even in light productions with moderate repetitiveness of work, low weight of handled parts and (almost) no awkward postures. We also illustrate that integrated planning may reduce the number of required workers and reduce ergonomic risks at workplaces *simultaneously* (cf. Figure 4). We compare integrated planning to hierarchical planning, which is currently widespread at firms. Overall, integrated planning outperformed hierarchical planning in a variety of settings of our case study, and for a number of performance indicators. The plans designed with integrated planning generally required more space in the supermarket area.

Overall, we expect that economic advantages of integrated planning over hierarchical planning measured in the required number of workers tend to be higher at smaller assembly stations (lower B_k), larger cycle times (larger c) and larger space available for the supermarket area (larger BS).

Several important questions remain for future research. Recall that the proposed methodology requires additional investment from companies into collection and maintenance of data on ergonomic risks. Field studies and simulations featuring typical production environments from different industries should quantify this cost and compare it to the expected benefit, such as lower production cost and reduction in ergonomic risks. Furthermore, customised solution approaches have to be developed for the IALBFP to receive optimal or good quality heuristic solutions for large problem instances, which are typical, for example, in the automobile industry. Future studies should also examine benefits and costs from extending the proposed integrated planning scheme even further, for instance, by taking into account transportation of parts from the central warehouse and the supermarket to the assembly line. Finally, the presented approach can be integrated into strategic decisions on different feeding policies, such as space reserved for the supermarket, feeding frequency, or the display of the parts on the assembly line.

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Appendix 1

Table A1. Case study of the self-priming pump: input parameters.

			Preassembly						
Task	Weight, kg	t_j^w, min	t_j^{dp}, min	t_j^{ip}, min	t_j^s, min	e_j^w, kcal	e_j^{dp}, kcal	e_j^{ip}, kcal	e_j^s, kcal
1	0.100	0.08	0.15	0.05	0.12	0.22	0.69	0.19	0.30
2	0.250	0.05	0.15	0.05	0.12	0.19	0.82	0.24	0.37
3	0.300	0.12	0.15	0.05	0.12	0.42	0.86	0.25	0.39
4	0.100	0.12	0.15	0.05	0.12	0.30	0.69	0.19	0.30
5	0.005	0.08	0.15	0.05	0.12	0.18	0.62	0.17	0.26
6	0.100	0.10	0.15	0.05	0.12	0.26	0.69	0.19	0.30
7	0.005	0.28	0.15	0.05	0.12	0.55	0.62	0.17	0.26
8	0.100	0.32	0.15	0.05	0.12	0.77	0.69	0.19	0.30
9	0.005	0.12	0.15	0.05	0.12	0.24	0.62	0.17	0.26
10	0.050	0.08	0.15	0.05	0.12	0.20	0.65	0.18	0.28
11	–	0.08	0.00	0.00	0.00	0.18	0.00	0.00	0.00
12	0.040	0.08	0.15	0.05	0.12	0.20	0.65	0.18	0.27
13	0.040	0.12	0.15	0.05	0.12	0.26	0.65	0.18	0.27
14	0.001	0.07	0.15	0.05	0.12	0.15	0.61	0.17	0.26
15	0.100	0.12	0.15	0.05	0.12	0.30	0.69	0.19	0.30
16	0.400	0.07	0.15	0.05	0.12	0.29	0.94	0.28	0.44
17	0.005	0.28	0.15	0.05	0.12	0.55	0.62	0.17	0.26
18	0.010	0.10	0.15	0.05	0.12	0.21	0.62	0.17	0.26
19	0.050	0.12	0.15	0.05	0.12	0.27	0.65	0.18	0.28
20	0.005	0.27	0.15	0.05	0.12	0.52	0.62	0.17	0.26
21	0.470	0.15	0.00	0.00	0.00	0.67	0.00	0.00	0.00
22	–	0.15	0.00	0.00	0.00	0.30	0.00	0.00	0.00
23	–	0.35	0.00	0.00	0.00	0.66	0.00	0.00	0.00
24	–	0.73	0.00	0.00	0.00	1.35	0.00	0.00	0.00
25	–	0.18	0.00	0.00	0.00	0.36	0.00	0.00	0.00
26	1.666	0.08	0.00	0.00	0.00	0.92	0.00	0.00	0.00
27	0.005	0.07	0.15	0.05	0.12	0.15	0.62	0.17	0.26

Table A1. (*Continued*).

Finishing									
Task	Weight (kg)	t_j^w (min)	t_j^{dp} (min)	t_j^{ip} (min)	t_j^s (min)	e_j^w (kcal)	e_j^{dp} (kcal)	e_j^{ip} (kcal)	e_j^s (kcal)
29	–	0.03	0.00	0.00	0.00	0.09	0.00	0.00	0.00
30	0.003	0.05	0.15	0.05	0.12	0.12	0.62	0.17	0.26
31	–	0.05	0.00	0.00	0.00	0.12	0.00	0.00	0.00
32	–	0.12	0.00	0.00	0.00	0.24	0.00	0.00	0.00
33	0.150	0.20	0.15	0.05	0.12	0.55	0.73	0.21	0.32
34	0.003	0.07	0.15	0.05	0.12	0.15	0.62	0.17	0.26
35	0.010	0.10	0.15	0.05	0.12	0.21	0.62	0.17	0.26
36	0.010	0.07	0.15	0.05	0.12	0.15	0.62	0.17	0.26
37	0.005	0.05	0.15	0.05	0.12	0.12	0.62	0.17	0.26
38	0.005	0.28	0.15	0.05	0.12	0.55	0.62	0.17	0.26
39	0.010	0.07	0.15	0.05	0.12	0.15	0.62	0.17	0.26
40	0.050	0.10	0.15	0.05	0.12	0.24	0.65	0.18	0.28
41	0.005	0.10	0.15	0.05	0.12	0.21	0.62	0.17	0.26
42	0.000	0.08	0.15	0.05	0.12	0.18	0.61	0.17	0.25
43	–	0.22	0.00	0.00	0.00	0.42	0.00	0.00	0.00
44	0.100	0.02	0.15	0.05	0.12	0.07	0.69	0.19	0.30
45	–	0.02	0.00	0.00	0.00	0.06	0.00	0.00	0.00
46	–	0.08	0.00	0.00	0.00	0.18	0.00	0.00	0.00
47	0.100	0.22	0.15	0.05	0.12	0.53	0.69	0.19	0.30
48	0.050	0.13	0.15	0.05	0.12	0.30	0.65	0.18	0.28
49	–	0.22	0.00	0.00	0.00	0.42	0.00	0.00	0.00
50	–	0.05	0.00	0.00	0.00	0.12	0.00	0.00	0.00
51	2.167	0.12	0.00	0.00	0.00	1.58	0.00	0.00	0.00

Notes: Picking times of part *j* from a bulky container and from a station kit are t_j^{dp} and t_j^{ip}, respectively. Processing time of task *j* excluding the part pick time is t_j^w. Energy expenditure rates are denoted as e_j^{dp}, e_j^{ip} and e_j^w. So that $t_j^d = t_j^w + t_j^{dp}$, $t_j^i = t_j^w + t_j^{ip}$, $e_j^d = e_j^w + e_j^{dp}$ and $e_j^i = e_j^w + e_j^{ip}$.