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Reducing physical ergonomic risks at assembly lines by line balancing and job rotation: A survey

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ABSTRACT

Factors such as repetitiveness of work, required application of forces, handling of heavy loads, and awkward, static postures expose assembly line workers to risks of musculoskeletal disorders. As a rule, companies perform a post hoc analysis of ergonomic risks and examine ways to modify workplaces with high ergonomic risks. However, it is possible to *lower* ergonomic risks by taking ergonomics aspects into account right from the planning stage. In this survey, we provide an overview of the existing optimization approaches to assembly line balancing and job rotation scheduling that consider physical ergonomic risks. We summarize major findings to provide helpful insights for practitioners and identify research directions.

1. Introduction

Ergonomics addresses the ways to create a working environment that optimizes the worker's well-being and the overall performance of the organization (cf. IEA, 2016). Workplace ergonomics depends on physical (e.g. repetitiveness of work, the weight of handled loads), cognitive (e.g. variability and complexity of tasks) and organizational factors (e.g. communication patterns, teamwork). In this paper, we focus on *physical ergonomic risks*, or risks of developing occupational musculoskeletal disorders, since psychological and psychosocial ergonomic risk factors are mostly absent in the ergonomic measurement methods currently adopted by companies.

According to some estimations, about 44 million workers in Europe suffer from occupational musculoskeletal disorders (Nunes, 2009). The occupation of the assembly line operator is associated with above-average ergonomic risks. According to the Fourth European Survey on Working Conditions, 35% of plant and machine operators and assemblers report having regular backaches and muscular pains (Schneider & Irastorza, 2010). Several studies of assembly operators in different countries indeed confirm high prevalence rates of musculoskeletal disorders (e.g. Bao, Winkel, & Shahnavaz, 2000; Pullopdissakul, Ekpanyaskul, Taptagaporn, Bundhukul, & Thepchatri, 2013).

Especially in view of the ageing of the working population in a number of countries, the reduction of physical ergonomic risks has emerged as a priority topic on the agenda of production managers at assembly line plants in recent years. On the one hand, legislation requires companies to regularly measure ergonomic risks and to document actions to reduce the latter (cf. 2006/42/EC, 89/391/EEC). On the other hand, improvements in workplace ergonomics often translate into higher financial and social performance indicators of the company. Several case studies have found a strong relationship between poor workplace ergonomics and quality at assembly lines (e.g., Eklund, 1995; Erdinç & Yeow, 2011; Ivarsson & Eek, 2016). For example, the case study of Falck, Örtengren, and Högberg (2010) of an automobile producer measures about eight times higher costs to perform necessary corrections of quality defects originated at stations with medium and high ergonomic loads compared to stations with low ergonomic loads. Overall, an assembly station with a high ergonomic load has been estimated to cost for the Volvo car company €90,000 additionally per annum to cover absenteeism, employee turnover etc. (Sundin, Christmansson, & Larsson, 2004). According to a survey of case studies on cost-benefit analysis of ergonomic interventions, the pay-back period of the ergonomic investments amounts to less than one year on average because of fewer reported work-related disorders, fewer lost workdays, increased productivity and quality as well as decreased turnover and absenteeism (Goggins, Spielholz, & Nothstein, 2008).

Currently, most companies perform a post hoc estimation of ergonomic risks of the existing workplaces. The recent academic literature draws attention to the possibility of *preventive* reduction

of ergonomic risks, where operational planning takes ergonomics aspects into account. In this survey, we review articles that consider physical ergonomic risks and propose optimization models and algorithms on the assembly line balancing, which describes the task-to-station assignment in paced assembly lines, and on the job rotation scheduling, which describes worker-to-station assignment.

To our best knowledge, the available literature surveys on assembly line balancing (e.g. Battaïa & Dolgui, 2013; Becker & Scholl, 2006; Boysen, Fliedner, & Scholl, 2007; Boysen, Fliedner, & Scholl, 2008; Scholl, 1999; Scholl & Becker, 2006) as well as personnel scheduling and job rotation (Burke, De Causmaecker, Berghe, & Van Landeghem, 2004; Ernst, Jiang, Krishnamoorthy, Owens, & Sier, 2004a; Ernst, Jiang, Krishnamoorthy, & Sier, 2004b; Van den Bergh, Beliën, Bruecker, Demeulemeester, & Boeck, 2013) do not discuss ergonomic risks in detail. Several available surveys study organizational aspects on how to integrate ergonomics into the planning processes of the company, for example, via stakeholder participation or performance indicators (e.g. Jensen, 2002; Neumann & Village, 2012). These surveys do not discuss optimization models. Neumann and Dul (2010) summarize results of the case studies that compare human effects (mostly physical workload and health) and system effects (mostly productivity and quality) of different operations management initiatives. Dul, de Vries, Verschoof, Eveleens, and Feilzer (2004) sum up requirements of ergonomics standards relevant for manufacturing companies. To our best knowledge, very few articles provide a literature survey on optimization approaches to reduce ergonomic risks. Lodree, Geiger, and Jiang (2009) examine ergonomics aspects in the literature on scheduling. Grosse, Glock, and Neumann (2017) and Grosse, Glock, Jaber, and Neumann (2015) summarize the literature on human factors in order picking.

In the following, we provide a short introduction to physical ergonomic risk estimation methods (Section 2) and describe methodology of the literature search (Section 3). Sections 4 and 5 survey the literature on the assembly line balancing and on the job rotation scheduling problems, respectively. We discuss major findings from the literature and provide recommendations for industrial engineers (Section 6), outline future research opportunities (Section 7) and conclude the performed study (Section 8).

2. Physical ergonomic risks and their measurement

The level of physical ergonomic risks depends on the intensity, frequency, and duration of the exposure to such physical workload factors as lifting of heavy loads, awkward postures, prolonged sitting or standing, repetitive movements, vibrations, as well as environmental factors such as temperature, humidity, noise and lighting. Assessment of these factors aims to detect and evaluate health risks at work. There are several widely used ergonomics assessment tools including direct methods, observational methods, subjective methods, and other psychophysiological methods. We refer the interested reader to Stanton, Hedge, Brookhuis, Salas, and Hendrick (2004) for more details on measurement methods and to Dempsey, McGorry, and Maynard (2005) and Pascual and Naqvi (2008) for discussions on validity and implementation of the ergonomics measurement methods in the industry.

In the following, we briefly introduce risk assessment methods which are most frequently used in the articles of this literature survey (see Sections 4.1 and 5.1):

- for lifting tasks: the National Institute for Occupational Safety and Health lifting equation (*NIOSH-Eq*) (Waters, Putz-Anderson, Garg, & Fine, 1993) and the Job Strain Index (*JSI-L*) (Liles, Deivanayagam, Ayoub, & Mahagan, 1984),

- for assessment of postures: the Rapid Upper Limb Assessment (*RULA*) (McAtamney & Corlett, 1993) and the Rapid Entire Body Assessment (*REBA*) (Hignett & McAtamney, 2000),
- for risk assessment of upper extremities: the OCcupational Repetitive Action tool (*OCRA*) (Occhipinti, 1998) and the Job Strain Index (*JSI*) (Moore & Garg, 1995),
- for noisy workplaces: the Daily Noise Dosage (DND) (NIOSH, 1998; OSHA, 1993),
- and general risk assessment tools: the Ergonomic Assessment Work Sheet (EAWS) (Schaub, Caragnano, Britzke, & Bruder, 2013) and the energy expenditure method (EnerExp) (Garg, Chaffin, & Herrin, 1978).

The lifting index (*LI*) of *NIOSH-Eq* displays the ratio between the handled load and a recommended load. The latter depends on the weight of the handled object, horizontal and vertical locations, distance, angle of symmetry, frequency of lift, duration and the coupling between hands and the object. High values of *LI* indicate elevated ergonomic risk. Since *LI* is limited to jobs with similar lifting tasks, several researchers refine the lifting index and adapt it for jobs with multiple tasks (e.g. Waters, 2006; Waters, Lu, & Occhipinti, 2007; Waters, Occhipinti, Colombini, Alvarez-Casado, & Fox, 2016). In contrast to NIOSH-Eq, *JSI-L* takes individual physical capacity of workers into account. The physical capacity of the worker is predicted based on his/her fitness and body size.

RULA offers worksheets for rapid assessment of ergonomic risks of upper limbs, neck and trunk. It requires just seven steps to compute the final score. The final score depends on the applied forces, awkward and static postures and on the frequency of repetition. *REBA* is an extension of RULA to assess ergonomic risks of the whole body.

OCRA evaluates repetitive handling at high frequency performed by upper limbs and it is calculated separately for each hand. The final OCRA index is computed as the ratio between the actual and the recommended frequency of actions measured as the number of repetitions per minute. The recommended frequency of actions depends on the applied forces, postures and additional risk factors, such as vibration. Higher value of the OCRA index indicates higher ergonomic risks. *JSI* uses a methodology similar to that of OCRA with two additional parameters: speed of work and duration of strain.

DND describes the time-weighted average of the combined sound level at the workplace. OSHA (1993) and NIOSH (1998) recommend different limits for noise pressure accumulated by workers of 90 dBA and 85 dBA, respectively.

EAWS assesses postures, action forces, manual material handling as well as other whole-body risk factors and repetitive loads of upper limbs. The results of the EAWS estimation are two aggregate risk values: risk points for the whole body and risk points for upper limbs. Higher risk points indicate higher risks for musculoskeletal disorders. *EnerExp* estimates metabolic rates for material manual handling tasks. It considers individual parameters of the worker (e.g. gender, body weight), geometry of material handling tasks, postures, speed of work, load weight and task duration. Excessive levels of energy expenditure are associated with high ergonomic risks.

3. Methodology of the literature review

We performed literature search in the databases Web of Science: Science Citation Index Expanded (from 1945), Social Sciences Citation Index (from 1956), Arts & Humanities Citation Index (from 1975) and Emerging Sources Citation Index (from 2015). We also performed additional search in Google Scholar.

We used 54 search combinations of keywords (see Table 1), which define the optimization problems under investigation (category A) and aspects of physical ergonomics (category B). Keywords in category A represent well-established terminology in Operations Research (cf. Battaïa & Dolgui, 2013; Lodree et al., 2009; Scholl, 1999). We developed keywords on physical ergonomic risks from several intersecting semantic groups to achieve a good coverage of the relevant literature:

- general description of ergonomics (e.g., ergonomics, human factors),
- general description of occupational disorders (e.g., musculoskeletal disorder, lower back pain) as well as
- description of risk factors that are most widespread at assembly lines (e.g., repetitiveness, application of forces, awkward and prolonged postures and vibration, cf. Cohen, Gjessing, Bernard, & McGlothlin 1997; Punnett and Wegman, 2004).

We carefully use asterisks (as a placeholder of an arbitrary combination of letters) and quotes (to denote that we look for the whole phrase rather than separate words) in framing our keywords. As a result, we have found 72 articles written in English language and published in peer-reviewed journals with our search in the databases of Web of Science.

We also performed a supplementary search in Google Scholar databases the search algorithms of which look throughout the whole text of articles. For this supplementary search, we combined the word "ergonom∗" which had by far the most hits in our main search with the keywords in category A in Table 1. The resulting three combinations of search words have identified 77, 574 and 67 articles, respectively.

We also performed a detailed snowball search for the articles located with Web of Science and Google Scholar.

Our scope is to review articles that consider physical ergonomic risks and propose optimization models or algorithms on the assembly line balancing and on the job rotation scheduling for paced assembly lines. This topic is especially interesting for industrial engineers and factory management looking for data-driven planning approaches. As a consequence, we filtered the articles according to the following selection criteria:

- Articles had to be written in English language and published in peer-reviewed journals.
- Articles had to investigate the (dis-)assembly line balancing problem for paced assembly lines or the job rotation scheduling problem. For instance, they had to contain a sufficiently precise description of the objective function and constraints.
- Articles had to contain an explicit measure of physical ergonomic risks.

As a result, we have selected 16 articles on assembly line balancing and 26 articles on job rotation scheduling for the survey.

Table 1
Categories of words utilized for the literature search.

Category A	Category B
job rotation scheduling, assembly line balancing, disassembly line balancing	ergonom∗, "human factor∗", "manual handling", "occupation∗ disorder", "occupation∗ disease∗", "musculoskeletal disorder∗", "musculoskeletal disease∗", "upper extremity disorder∗", "upper extremity disease∗", "low∗ back pain", posture, application∗ force∗, exposure∗ force∗, "repet∗ strain", "repet∗ motion", vibration, fatigue, "energy expenditure"

Note. We combine words in categories A and B resulting in $3 \times 18 = 54$ search combinations.

Some recently published papers which are not in the scope of our literature survey should be nevertheless mentioned in this paper. For instance, Battini, Faccio, Persona, and Sgarbossa (2011) provide a general overview on factors influencing ergonomics and productivity in assembly lines. Although psychological and psychosocial ergonomic risk factors are mostly absent in the ergonomic risk measurement methods adopted by companies, they may have a profound influence on workers' productivity (cf. Lundberg, Granqvist, Hansson, Magnusson, & Wallin, 1989). Bhadury and Radovilsky (2006), Azizi, Zolfaghari, and Liang (2009), and Ayough, Zandieh, and Farsijani (2012) consider boredom in creating job rotation schedules. Also further human factors like learning (e.g., Li & Boucher, 2016; Otto & Otto, 2014b) or skills and abilities of workers (e.g., Costa & Miralles, 2009; Moreira & Costa, 2013) are relevant in the context of assembly lines. For instance, although Costa and Miralles (2009), Moreira and Costa (2013) do not employ explicit measurement of ergonomic risks, they introduce assignment restrictions for workers with disabilities to stations. Due to differences in modelling and solution approaches, research on paced and unpaced assembly lines mostly belong to two distinct communities. We refer the readers interested in studies on unpaced lines taking into account ergonomics to Al-Zuheri, Luong, and Xing (2013), Al-Zuheri, Luong, and Xing (2014) and Anzanello, Fogliatto, and Santos (2014).

As Fig. 1 illustrates, the surveyed articles are predominantly published in general journals on Engineering (e.g. IIE Transactions, Computers & Industrial Engineering) rather than in specialized ergonomics journals (e.g. Ergonomics, Applied Ergonomics). Further important journal types include Production and Operations Management (e.g. Journal of Operation Management, International Journal of Production Economics) and Operations Research (e.g. European Journal of Operational Research, Annals of Operations Research). It should be noted that we have counted each journal only once and have classified interdisciplinary journals according to the first key word in the description of their scope. Most occurrences of authors in the articles belong to Thai, American and Spanish research institutions (see Fig. 2).

Most articles cited in this survey consider a few established ergonomic risk measurement methods. Thus, 12 articles (or about 30% of 42 articles) use DND, five articles (or 12% of cases) use OCRA. RULA method and EnerExp has been used four times each. Several studies formulate general task-specific parameters of physical load (14% of cases). Only 17% of articles utilize measures not described in Section (2), which are mostly different measures of fatigue or expert evaluations of ergonomic risks.
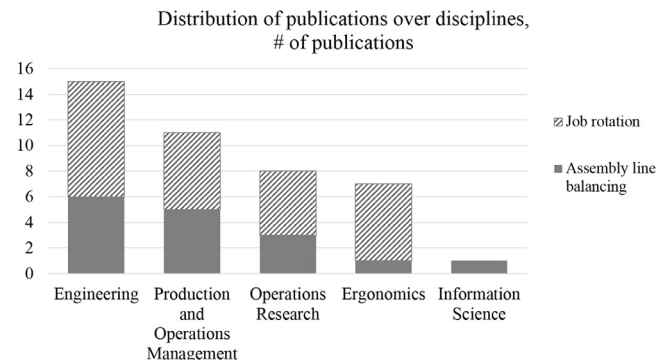
Fig. 1. Distribution of publications over disciplines. *Note.* Interdisciplinary journals are classified according to the first key word in the description of their scope. For example, IJPE is counted as a journal in Production and Operations Management, whereas C&IE and IIE Transactions are considered as engineering journals.
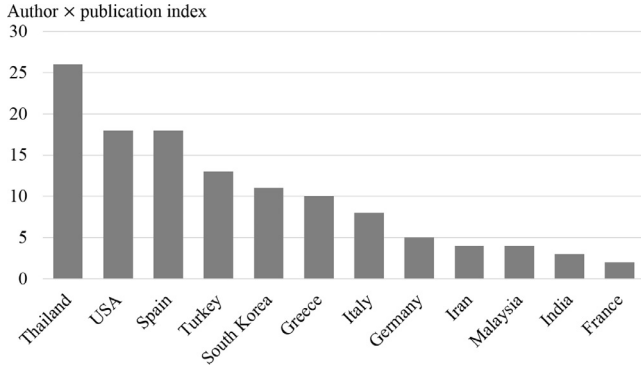
Fig. 2. Distribution of contributors per countries. *Note.* We compute the index as the number of occurrences of authors from particular countries in journal publications.

4. Reducing ergonomic risks by assembly line balancing

The assembly line balancing problem is to find an assignment of assembly tasks to stations to optimize the specified objective function. In the following, we describe the basic variant of the problem, called the *simple assembly line balancing problem (SALBP)*.

Formally, the simple assembly line balancing problem is to partition the set of *tasks* $V = \{1, \ldots, n\}$ with deterministic operation times t_j, $j \in V$, into disjoint subsets $S_k \subseteq V$ assigned to *stations* $k \in \{1, \ldots, K\}$ (see Scholl, 1999). SALBP describes straight assembly lines, where workpieces are transferred along a set of *stations*. The amount of time, called *cycle time c*, that each workpiece can spend at each station is constant. The assignment of tasks has to respect cycle time and precedence constraints. The first group of constraints states that the *station time* should not exceed the cycle time: $t(S_k) = \sum_{j \in S_k} t_j \leqslant c, \forall k \in \{1, \ldots, K\}$. The second group of constraints enforces *precedence relations* between the tasks. Precedence relations arise due to technological and organizational constraints. A *precedence relation* $(i, j) \in A$ states that task $i \in V$ must be performed before task $j \in V$, task i is called *predecessor* of task j and set A is the set of precedence relations. Task parameters can be visualized as a *precedence graph* with tasks V depicted as nodes, task times depicted as node weights and precedence relations A depicted as directed arcs.

Let us consider the precedence graph in Fig. 3. If cycle time equals $c = 20$, then assembly line balance $\{1, 5\}, \{4\}, \{3\}, \{2, 6\}, \{8\}, \{7\}, \{10\}, \{9\}, \{11\}$ with 9 stations is feasible. For example, the station time of station 4, containing tasks 2 and 6, is $6 + 6 = 12 \leqslant 20$. As a consequence, the cycle time constraint is respected. All the predecessors of tasks 2 and 6, which are tasks 1 and 3, are performed in the earlier stations (station 1 and station 3). The conventional objective functions of SALBP are to minimize the number of stations for the given cycle time (which is SALBP of type 1 or SALBP-1) and to minimize the cycle time for the given number of stations (which is SALBP of type 2 or SALBP-2).
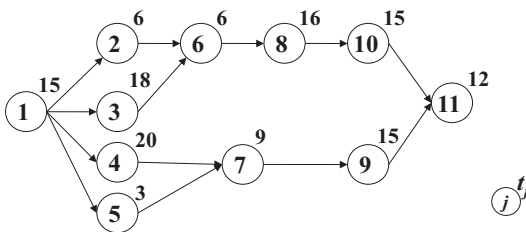
SALBP is a combinatorial optimization problem and its instances have, as a rule, a large number of optimal solutions, as we illustrate below. For SALBP-1, this is due to the fact that a lot of different task assignments correspond to the same number of workstations. Therefore we can, for example, consider an ergonomic objective lexicographically and select an assembly line balance with the lowest ergonomic risks. This is illustrated in the following computational study. We consider SALBP with the objective to minimize the number of stations given the cycle time. We have randomly generated instances with $n = 10$, 15, 20 and 25 tasks with the problem generator SALBPGen (Otto, Otto, & Scholl, 2013), 20 instances per each setting, which makes 80 instances in total. Tasks have precedence relations of medium strength (order strength equals 0.5, cf. Scholl, 1999). Operation times of tasks are randomly generated from the bimodal distribution described in Otto et al. (2013), which is a typical distribution observed in practice (cf. Kilbridge & Wester, 1961). Note that we analyze only solutions with stations maximally packed with tasks (cf. max load rule in Scholl, 1999). Fig. 4 reports the average number of optimal solutions per instance. Observe that it increases exponentially in the size of the instance.

Some assembly line balances may have lower ergonomic risks than other line balances. For example, we may collect *idle time* at stations containing especially demanding tasks. In our example in Fig. 3 with $c = 20$, station time of station four equals 12, so that $20 - 12 = 8$ time units remain idle. Further, we may avoid accumulation of the harmful effect of some risk factors with time. For example, performing tasks requiring holding arms above head for the whole cycle time is much worse (more than three times worse) than performing such tasks for a third of the cycle time (cf. EAWS).

4.1. Survey of the literature

Otto and Scholl (2011) provide a general overview of widespread ergonomics methods and describe how to model them in the context of the assembly line balancing problem. They dub the class of problems with ergonomic constraints or objectives as ERGO-SALBP and examine several possible objective functions: minimization of average ergonomic risks, minimization of the number of stations with high ergonomic risks and minimization of deviations from acceptable levels of station physical loads. In their computational experiments, Otto and Scholl (2011) examine ERGO-SALBP of type 1 and minimize ergonomic risks as a second-tier objective. They propose a two-stage heuristic: at the first stage, the minimal possible number of stations is found with the well-known branch-and-bound procedure SALOME (see Scholl & Klein, 1997; Scholl & Klein, 1999), at the second stage, a simulated annealing technique supplemented by a local search algorithm constructs solutions with the minimal number of stations and low ergonomic risks.

Xu, Ko, Cochran, and Jung (2012) propose to linearize risk measurement functions of the existing ergonomic risk measurement
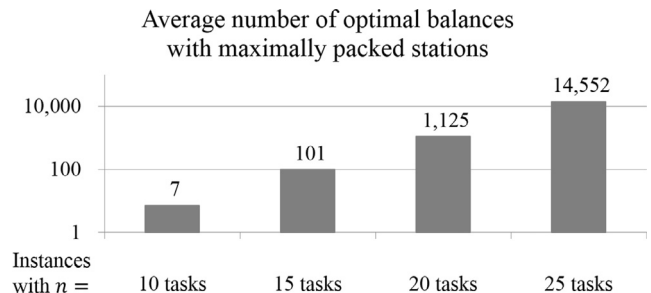

Fig. 3. Example of a precedence graph.

Average number of optimal balances with maximally packed stations

Fig. 4. The average number of optimal line balances for instances of different size.

methods, which are often nonlinear, in order to make the resulting models suitable to a rich toolbox of the linear programming approaches. The authors consider ergonomic measures for upper extremities recommended by the guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH, 2010) and introduce ergonomic constraints on hand exertion frequency, duty cycle, normalized peak force, vibration acceleration and vibration duration into the simple assembly line balancing model. Thereby they convert step functions into linear equations by standard mathematical programming techniques. The authors test the developed methodology on a case study of a blender producer and solve the problem instance with the off-the-shelf software IBM ILOG Cplex.

If ergonomic risks at stations are measured as a simple sum of task-specific parameters of the assigned tasks, then the resulting assembly line balancing problem belongs to the class of the Time and Space Constrained Assembly Line Balancing Problem (TSALBP). Bautista, Alfaro-Pozo, and Batalla-García (2016) set up a TSALBP with the given number of stations and task-specific ergonomic parameters of tasks. They consider two problem variants differing in their objective function: to minimize the maximum ergonomic risks for a station and to minimize absolute deviations between ergonomic risks of stations. The authors propose to measure ergonomic risks along several dimensions and to aggregate them only in the computation of the objective function. Each dimension may represent, for example, an existing risk measurement method, such as OCRA, RULA or NIOSH-Eq. The authors design a multistart metaheuristic GRASP and compare it to IBM ILOG Cplex for a case study of a power train plant in Spain. Similarly, Bautista, Batalla-García, and Alfaro-Pozo (2016) investigate a TSALBP with space restrictions and task-specific ergonomic parameters. The authors propose a number of mathematical formulations for the objective functions describing station times, space requirements and physical ergonomic risks at each station and perform a case study for the power train plant of Nissan Spanish Industrial Operations (NSIO) in Barcelona, Spain. The formulated mixed-integer linear program is solved with off-the-shelf software IBM ILOG Cplex for instances with different scenarios for demand, different values of the maximum allowed ergonomic risks at a station and different numbers of stations. In their computational analysis, the authors examine the impact of the product mix on the assembly line balances and the "robustness", or "resilience", of assembly line balances towards variations in demand.

Several studies propose to use holistic, custom-designed expert ratings of ergonomic risks instead of available universal risk measurement approaches. For example, Choi (2009) formulates 13 different parameters describing physical load for each task. These parameters belong to three categories: environmental parameters (such as inappropriate temperature, light, noise, vibration, and exposure to chemicals), physical load of awkward and static postures (such as bending, or twisting), physical load of other factors (such as weight of the handled load, or frequency of actions for gripping tasks). Experts measure ergonomic parameters of each task with a five-point ordinal scale. Afterwards, an index for each category of ergonomic risks is constructed as a sum of the respective ergonomic parameters. Physical loads of each station in each category of risks equal the sum of physical loads of the assigned tasks. Choi (2009) sets up a Chebyshev goal program, in which he compares the physical load of each station to the recommended load limits. The first term of the objective function aims at equalizing the station times. The second term aims at balancing the station physical loads. Mutlu and Özgörmüş (2012) introduce fuzzy constraints limiting the physical load of each station. The authors use expert estimates of physical demands of tasks on a nine-item ordinal scale ranging from 0 ("Nothing at all") to 9 ("Very strong"). They apply a fuzzy linear programming model in a case study of a textile company and solve it with the off-the-shelf software IBM ILOG Cplex.

Most articles consider a weighted sum of two groups of objective functions: ergonomic and economic. Thus, Carnahan, Norman, and Redfern (2001) propose a ranking heuristic and two genetic algorithms for the assembly line balancing problem with the objectives of minimizing the local muscle fatigue and the cycle time. Both objectives are taken as a weighted sum. They estimate fatigue due to gripping demand with the methods of Woods, Fisher, and Andres (1997), taking into account the applied force, duration of the gripping and the individual capacities of the assembly operators. Also Jaturanonda and Nanthavanij (2006) and Jaturanonda, Nanthavanij, and Das (2013) formulate in their two similar studies an assembly line balancing problem with two objectives taken as a weighted sum: the objective of balancing the distribution of station times (measured by the coefficient of variance) and of balancing ergonomic risks among stations (measured by the coefficient of variance of station-specific ergonomic risk estimates). Both articles estimate risks with RULA. The authors combined the priority rule heuristic of Kilbridge and Wester (1961) with an iterated local search procedure based on task swaps and shifts. Barathwaj, Raja, and Gokulraj (2015) look for an assembly line balance with the given cycle time and minimize the objective function computed as the sum of three components: the number of stations, the average deviation of the station idle times and the total ergonomic risks. The authors apply RULA and examine the designed genetic algorithm for an instance with 21 tasks originated from a case study of an automobile part supplier. Battini, Delorme, Dolgui, Persona, and Sgarbossa (2016) perform a detailed study on the trade-offs between economic and ergonomic objectives for different time and energy parameters in a case study on the assembly of garden appliances. The authors consider two time-oriented and two ergonomic objective functions –– minimization of the variance of station times, minimization of the cycle time, minimization of the variance of the energy expenditures at stations and minimization of the maximal energy expenditure at a station –– for the assembly line balancing problem with the given number of stations. Battini et al. (2016) refine the EnerExp method and adapt it to the assembly lines.

Along with arranging economic and ergonomic functions lexicographically or taking their weighted sum, goal programming is another approach often chosen in the surveyed articles. Thus, Rajabalipour Cheshmehgaz, Haron, Kazemipour, and Ishak Desa (2012) develop a goal programming model with three objectives and design a genetic algorithm. The first objective function aims to minimize the maximal deviation of station times from the ideal cycle time, which is the lowest achievable cycle time in case of preemptive tasks. The second objective penalizes deviations of station physical loads from the average physical load of the entire line. The third objective minimizes the maximal value of an ergonomic estimate for accumulated risks of postures. Gunther, Johnson, and Peterson (1983) also formulate a goal programming model with several lexicographically arranged objectives and propose a branch-and-bound algorithm. Each task has a physical demand parameter stating the amount of energy required to perform this task. The total physical demand of the station, which is the sum of the task-specific demand parameters, should not exceed the individual physical tolerance of the worker (as soft constraints). To the best of our knowledge, this article represents the first attempt to integrate ergonomic risks into the assembly line balancing problem.

Sternatz (2014) formulates the assembly line balancing problem that describes typical constraints in automobile productions, such as multiple workplaces per station, task-to-station assignment restrictions, sequence-dependent setup times and ergonomic constraints prohibiting station loads with high ergonomic risks. To

solve this problem, Sternatz (2014) adapts the multi-Hoffmann heuristic of Fleszar and Hindi (2003). In the simulation, based on a part of the final automobile assembly line, the multi-Hoffmann heuristic finds feasible solutions containing stations only with low and medium ergonomic risks for instances with a wide range of settings.

Several studies achieve more degrees of freedom in reducing ergonomic risks by treating assembly line balancing and worker-to-station assignment simultaneously. Thus, Kara, Atasagun, Gökçen, Hezer, and Demirel (2014) consider a worker-to-station assignment and assembly line balancing problem with multiple-manned stations. They estimate psychological demands of tasks with the task rigidity measure and assess the energy expenditure of tasks. Workers differ in their skills and their daily energy expenditure rates. The objective function is to minimize the total cost (e.g. annual wages, cost of equipment or cost of extensive illumination). Thus, tasks requiring similar illumination levels, similar equipment and the same working posture (such as standing or sitting) should be preferably assigned to the same station. The ergonomic constraints ensure that the sum of task rigidities of each station does not exceed the recommended limit. Moreover, individual limits on the total energy consumption should be satisfied. In their case study, Kara et al. (2014) solve a problem instance with 30 tasks and seven workers with off-the-shelf software XPRESS Solver Engine. Akyol and Baykasoğlu (2016) consider simultaneous worker-to-station assignment and assembly line balancing with several lexicographically arranged objective functions. The first-tier objective is to minimize cycle time for the given number of stations. Further objectives are ergonomic objectives (such as to minimize average ergonomic risks, to minimize average deviation of ergonomic risks among stations and to minimize the number of stations with high risks). For each worker, there is a set of tasks that he/she can perform given his/her abilities and physical restrictions. The authors measure ergonomic risks with OCRA and propose a multi-start greedy heuristic algorithm to solve the formulated problem.

Table 2 provides a general overview of the contributions. For each article, it summarizes the employed ergonomic risk measurement methods, notates whether the models contain ergonomic risks as a part of the constraints or as a part of the objective functions and provides information on the designed customized solution methods.

5. Reducing ergonomic risks via job rotation scheduling

Assembly line balancing may not be able to eliminate stations with high ergonomic risks. Therefore job rotation schedules should prevent workers from spending the whole shift at workplaces with high demands and ensure a balanced distribution of risks among individual work assignments. Indeed, higher ergonomic risks denote not only higher risks for musculoskeletal disorders, but also higher risks for more severe diseases, so that balancing ergonomic risks among individual work assignments is important.

Let triple $(i, k, p) \in \Theta$ denote that in rotation period $p \in P$ worker $i \in I$ is employed in station $k \in \{1, \ldots, K\}$. In other words, set of triples Θ describes an assignment of workers to jobs in rotation periods. The number of workers equals the number of stations: $|I| = K$. A feasible assignment Θ' satisfies the following constraints:

- For each pair of values $p' \in P$ and $k' \in \{1, \ldots, K\}$, there is exactly one triple $(i, k', p') \in \Theta'$, i.e. exactly one worker is assigned to each station in each rotation period.
- For each pair of values $p' \in P$ and $i' \in I$, there is exactly one triple $(i', k, p') \in \Theta'$, i.e. each worker is employed at exactly one station during each rotation period.

Observe that there are $|P| \times K$ triples in any feasible assignment. Further, let $E(\Theta', i)$ be a function that computes ergonomic risks for worker $i \in I$ given some feasible assignment Θ'. In its basic formulation, the job rotation scheduling problem aims to find a feasible

Table 2
Summary of the contributions to the assembly line balancing that consider physical ergonomic risks.

Reference	Measurement of ergonomic risks	Ergonomic risks considered as…		Designed solution method
		Const-raints	Obj. function	
Gunther et al. (1983)	EnerExp	x	x	B&B
Carnahan et al. (2001)	Fatigue (Woods et al., 1997)		x	GA, heuristic
Jaturanonda and Nanthavanij (2006)	RULA		x	Heuristic (LS)
Choi (2009)	Environmental parameters, awkward and static postures, force loads (check-list of 13 risk factors)		x	–
Otto and Scholl (2011)	NIOSH-Eq, OCRA, JSI, EAWS	x	x	Heuristic (SA, LS)
Rajabalipour Cheshmehgaz et al. (2012)	Awkward and static postures		x	GA
Mutlu and Özgörmüş (2012)	Parameters[a]	x		–
Xu et al. (2012)	Force loads, repetitiveness, vibration (ACGIH, 2010)	x		–
Jaturanonda et al. (2013)	RULA		x	Heuristic (LS)
Kara et al. (2014)	Task rigidity, energy expenditure, quality of illumination	x		–
Sternatz (2014)	Awkward and static postures, force loads (internal method of a firm)	x		Heuristic
Barathwaj et al. (2015)	RULA		x	GA
Akyol and Baykasoğlu (2016)	OCRA		x	Heuristic
Battini et al. (2016)	EnerExp		x	–
Bautista, Alfaro-Pozo et al. (2016)	OCRA, RULA, NIOSH-Eq		x	GRASP
Bautista, Batalla-García et al. (2016)	Parameters[a]	x	x	–

Notes. B&B – branch-and-bound algorithm, GA – genetic algorithm, LS – local search, SA – simulated annealing, GRASP – greedy randomized adaptive search procedures, heuristic – other construction heuristic, heuristic(xyz) – heuristic with elements of xyz. We use a dash "–" if no customized solution method was proposed, for example, if the article utilized an off-the-shelf solver
[a] General job-specific physical demand parameters.

assignment Θ', so that the maximum ergonomic risks $max_{i \in I} E(\Theta', i)$ is minimized.

We call as the *basic job rotation scheduling problem* the job rotation scheduling problem with ergonomic risk function computed as a sum of ergonomic parameters e_{ikp} of jobs assigned to workers, $E(\Theta', i) := \sum_{k \in \{1,\ldots,K\}, p \in P | (i,k,p) \in \Theta'} e_{ikp}$. Indeed, according to widespread methodologies that do not consider dynamic effects, ergonomic risks for an individual work assignment are computed as a sum of time-weighted ergonomic points of the respective jobs (cf. EAWS).

Consider an instance of the basic job rotation scheduling problem in Fig. 5 with 3 stations, 3 workers and 2 rotation periods. Ergonomic risks at each station are measured as points (EP), larger ergonomic points indicate higher ergonomic risks. Worker 1 spends the first rotation period at station 1 with 80 EP and the second rotation period at station 2 with 10 EP, so that time-weighted ergonomic points of jobs for worker 1 are $\frac{80 \cdot 4}{4+4} = 40$ and $\frac{10 \cdot 4}{4+4} = 5$ EP, respectively and the ergonomic risks of the work assignment equal $40 + 5 = 45$ EP. In the job rotation schedule in Fig. 5, work assignments of workers 1, 2 and 3 have ergonomic risks of 45, 45 and 40 EP, respectively. Observe that if each worker would stay at the same station for the whole shift, the risks of the work assignments would equal 80, 10 and 40 EP, respectively. Such schedule exposes worker 1 to excessive risks for severe musculoskeletal disorders. Therefore, the job rotation schedule illustrated in Fig. 5 is preferred.

The job rotation scheduling problem is a combinatorial problem, with a large number of distinct feasible job rotation schedules, which increases exponentially with the number of workers. The off-the-shelf software is often not able to solve instances of practice-relevant size to optimality. Therefore, customized algorithms need to be designed.

Field studies confirm that job rotation is positively evaluated by workers and that it reduces the *perceived* physical load (Kuijer, van der Beek, van Dieën, Visser, & Frings-Dresen, 2005; Kuijer, Visser, & Kemper, 1999; Rissén, Melin, Sandsjö, Dohns, & Lundberg, 2002). Moreover, several studies found a positive effect of job rotation on worker satisfaction as well as reduced monotony and boredom (Neumann, Winkel, Medbo, Magneberg, & Mathiassen, 2006; Triggs & King, 2000). From an organizational point of view, the rotation of workers means that they are suitably trained to carry out different jobs. Job rotation should be regularly implemented to maintain skills of workers, and so that the company has the flexibility to change their work assignments in response to variations in demand or to cope with a high level of absenteeism.

Several field studies examine the effect of job rotation on the actual risks for musculoskeletal disorders. Job rotation reduces exposure to awkward and static postures (Hinnen, Läubli, Guggenbühl, & Krueger, 1992; Kuijer et al., 1999), cardiovascular load (Kuijer et al., 1999), muscle fatigue (Raina & Dickerson, 2009) and therefore the need for recovery (Kuijer et al., 2005). In some studies, however, job rotation has been found to increase risks for back injuries (Jeon, Jeong, & Jeong, 2016; Kuijer et al., 2005; Leider, Boschman, Frings-Dresen, & van der Molen, 2014; Wells, McFall, & Dickerson, 2010). The negative effect of job rotation can be potentially explained by neglecting the dynamics of exposure and peak physical loads, as well as using aggregate ergonomic estimates instead of tracking ergonomic risks of specific body segments.

In our survey, we consider studies on job rotation scheduling even if the authors have not explicitly designed their optimization approaches for assembly line production systems. Indeed, the existing approaches to job rotation scheduling can be easily adapted for assembly lines.

5.1. Survey of the literature

Carnahan, Redfern, and Norman (2000) pioneer the application of operations research techniques in job rotation scheduling with ergonomic objectives. The authors develop an integer programming formulation for the job rotation scheduling problem with the objective of minimizing the highest risk for lower back injuries. Carnahan et al. (2000) measure ergonomic risks with JSI-L. They design several genetic algorithms, which can also cope with stochastic ergonomic parameters (such as uncertain frequency of lifts or uncertain weights). The authors consider a case study of a manufacturing cell with four jobs and four groups of workers, a five-day workweek and 1-h job rotation intervals. They examine the solutions of genetic algorithms by clustering techniques to find simple worker-to-station assignment rules.

A number of studies consider the *basic job rotation scheduling problem*. Thus, Otto and Scholl (2013) investigate structural properties of the problem. The authors prove the formulated problem to be NP-hard in the strong sense. Exploiting the problem structure, Otto and Scholl (2013) develop a fast and effective smoothing heuristic as well as a tabu search algorithm. A few articles illustrate the applicability of the basic job rotation scheduling problem to reduce risks for hearing loss. For example, Nanthavanij and Kullpattaranirun (2001) and Kullpattaranirun and Nanthavanij (2005) propose genetic algorithms and Yaoyuenyong and Nanthavanij (2003) design a greedy heuristic with an integrated local search. The objective is to minimize accumulated noise dosage by workers during a shift. Yaoyuenyong and Nanthavanij (2003) show that although the original risk measurement function of DND is nonlinear, its monotonic transformation is a linear function; so that the authors formulate the basic job rotation scheduling problem. Tharmmaphornphilas, Green, Carnahan, and Norman (2003) linearize the DND risk measurement function as well by minimizing the maximum or the average time-weighted sound level exposure among work assignments. They perform detailed simulations and show that the designed job rotation schedules reduce the maximum daily exposure by about 60% and significantly lower the time-weighted average level of exposure compared with the status quo job rotation schedule. The basic job rotation scheduling problem with linear risk measurement function is also suitable for manual material handling tasks as explained by Tharmmaphornphilas and Norman (2004). The authors apply the basic problem setting in two case studies. The first one contains jobs with a high share of manual material handling activities and uses JSI-L to measure risks within job rotation periods. The second one studies a sawmill and measures risks with DND. The authors perform detailed computational studies of job rotation schedules with a different number of rotation periods. Afterwards, they perform statistical analysis of the computational results to find the most appropriate length of job rotation intervals. Seçkiner and Kurt (2007, 2008) design a simulated annealing algorithm and an ant colony optimization algorithm for the basic job rotation scheduling problem, respectively.

	Station 1 (80 EP*)	Station 2 (10 EP)	Station 3 (40 EP)
Rotation period 1 (4 hours)	★ Worker 1	▲ Worker 2	⬟ Worker 3
Rotation period 2 (4 hours)	▲ Worker 2	★ Worker 1	⬟ Worker 3

Fig. 5. Example of a job rotation schedule. *Ergonomic points (EP) measure physical ergonomic risks.

A number of studies compute ergonomic risks as an aggregate of several dimensions representing groups of risk factors. Aryanezhad, Kheirkhah, Deljoo, and Mirzapour Al-e-hashem (2009) develop a multi-objective integer programming model to simultaneously minimize the maximum occupational noise exposure measured with DND and to minimize the maximal risks for lower back injuries measured with JSI-L. They consider workers with varying levels of skills and individual exposure limits. The model's constraints prohibit individual workloads to exceed individual exposure limits. The authors combine normalized objective functions as a weighted sum into a single objective function and compute schedules for different levels of weights. Asensio-Cuesta, Diego-Mas, Cremades-Oliver, and González-Cruz (2012) propose a genetic algorithm for the job rotation scheduling problem. In the stated model, the fitness of alternative schedules negatively depends on the sum of risks for the right and the left upper extremities measured with OCRA as well as on the monotony index measured as the number of repetitions of the same job multiplied with a psychosocial coefficient of monotony. The authors consider worker-job incompatibilities due to disabilities and individual limits on the ergonomic load depending on the state of health. The authors test the developed genetic algorithm on 6 industrial cases. Song et al. (2016) formulate a job rotation scheduling problem with a wide range of risk factors, such as workloads of single anatomical segments and the workload in manual material handling activities. The risk estimations depend on the state of health of workers. The authors design a heuristic algorithm and present a case study where the computed job rotation schedules outperform the status quo job rotation schedule used in the company.

Some studies develop holistic criteria to find the best match between job requirements and capacities of workers in a job rotation schedule. For example, Diego-Mas, Asensio-Cuesta, Sanchez-Romero, and Artacho-Ramirez (2009) compare the required movements in jobs to individual capacities to perform these movements, mental requirements of jobs to mental abilities of workers, communication requirements to communication abilities as well as general requirements, such as application of forces, climbing, or driving vehicles, to the respective general capacities. Experts measure the requirements and the capacities on ordinal scales (e.g. "necessary" vs. "not necessary" and "without limit" vs. "with limit"). Additionally, workers may express their preferences and name jobs that they do not want to perform. The objective function penalizes mismatches between job requirements and workers' capacities as well as the assignment of workers to the jobs that they dislike. Moreover, penalties arise if the same job has been performed by the same worker for several rotation periods. The authors propose a genetic algorithm and illustrate their approach in a case study for an automobile parts supplier assembly plant with 18 jobs and four rotation periods. Asensio-Cuesta, Diego-Mas, Canós-Darós, and Andrés-Romano (2012a) consider 39 criteria to characterize alternative job rotation schedules. The criteria take physical demands on different muscle groups measured with the method of Rodgers (1992), physical capacities of workers and skills of workers into account. Based on these criteria, the authors calculate ergonomic scores for work assignments. The algorithm looks for the best match between workers and the skills required to perform the jobs. The authors propose a genetic algorithm and apply it to design a job rotation schedule for a set of 16 jobs in an assembly plant of an automobile parts supplier.

In contrast to other studies, Yoon, Ko, and Jung (2016) minimize the variance of individual workload in their job rotation scheduling model. They assess workload with REBA and solve the formulated quadratic integer program with IBM ILOG Cplex. The proposed model is successfully tested at three automotive assembly lines for chassis, trim, and finishing. However, because of the quadratic objective function, the computation times are quite long.

Besides ergonomic objectives, researchers also formulate economic objectives, such as to minimize costs or to increase the resulting output. For example, Tharmmaphornphilas and Norman (2007) consider objectives to minimize the maximum and the total expected number of lost days due to lower back pain. The authors introduce uncertain task demands, different worker profiles and propose heuristic methods. Michalos, Makris, Rentzos, and Chryssolouris (2010) develop a job rotation re-scheduling model, which is designed to enhance the adaptability of the shop workforce to variations in market demand. Thereby the objective function can be interpreted as a utility function; it is computed as a weighted sum of several criteria: competence, fatigue, distance travelled, cost and repetitiveness of tasks. Competence is measured with a fuzzy membership function that describes whether operators have skills to perform certain jobs. Fatigue is estimated by the dynamic estimation tool of Ma, Chablat, Bennis, and Zhang (2009). Costs reflect varying individual wage rates and individual differences in the speed of performing certain tasks because of skill levels. Repetitiveness depends on the maximum number of consecutive repetitions of the same job. The model takes current positions of workers and the required distance to the location of their next job into account. The authors develop an enumeration-based solution procedure in MATLAB to generate and evaluate alternative job rotation schedules. The tool is tested on a case study of a final assembly line for trucks. On the basis of their previous work, Michalos, Makris, and Mourtzis (2011) implement a web based tool for the generation of job rotation schedules. Michalos, Makris, and Chryssolouris (2013) point out that the accumulated fatigue could result in frequent human errors and therefore in the reduction of the product's quality, and that job rotation schedules differ in the probability of error occurrence. Utilizing the approach of Elmaraghy, Nada, and Elmaraghy (2008), the authors calculate human error probability as a function of the competence of the worker. They measure accumulated fatigue with the dynamic method of Ma et al. (2009) and the repetitiveness of work as the number of repetitions of the same job. Michalos et al. (2013) evaluate several job rotation scenarios for a case study of a heavy vehicle producer. Their findings indicate that the adoption of job rotation techniques could significantly enhance product quality by drastically reducing the total number of assembly errors. Mossa, Boenzi, Digiesi, Mummolo, and Romano (2016) describe a job rotation scheduling problem, in which productivity rates depend on the skill profiles of workers. The authors estimate ergonomic risks with OCRA. The total output, which depends on the assignment of workers to jobs, has to stay within the preferred limits. The authors formulate two mixed-integer nonlinear models. The first model aims to maximize the number of produced product units so that the maximal individual workload measured with OCRA as well as the variance of the individual workloads do not exceed the recommended exposure limits. The second model aims to minimize the average ergonomic risks for the target level of the output. The models are applied to an industrial case study of a car seat producer. The results show that it is possible to increase productivity as well as to reduce and balance ergonomic risks simultaneously by an appropriate rotation of workers.

Asawarungsaengkul and Nanthavanij (2006) and Asawarungsaengkul and Nanthavanij (2008b) propose a hierarchical planning approach to reduce ergonomic risks due to noise and formulate mixed-integer programming models for this purpose. At the tactical planning level, managers should select appropriate engineering controls for noise reduction (e.g. isolation of noise emitting machines, barriers blocking noise transmission paths) given location of sources of noise, location of workers, budget constraints and acceptable noise doses that workers are allowed to accumulate during a shift. Afterwards, as a part of operational planning, job rotation should be implemented taking into account

ergonomic risks. Finally, appropriate individual hearing protection devices should be acquired. As a part of this hierarchical planning scheme, the authors set up two variants of the job rotation scheduling problem. The first one is to design a job rotation schedule so that the number of cases, when employees work at different stations in two consecutive periods is minimized. In the second one, the number of available workers in each rotation period may exceed the number of stations. The objective is to set up a job rotation schedule with the minimum number of workers, so that ergonomic risks accumulated by each worker during a shift do not exceed the recommended limits. In several further papers, Suebsak Nanthavanij together with co-authors investigate the formulated job rotation scheduling problems. Asawarungsaengkul and Nanthavanij (2008a) propose a genetic algorithm for the first job rotation problem with the objective of minimizing workplace changeovers. Yaoyuenyong and Nanthavanij (2008) develop a construction heuristic with an integrated local search and Yaoyuenyong and Nanthavanij (2006) design several further algorithms, including a greedy multi-start heuristic, local search procedure, enumeration-based heuristic and a branch-and-bound procedure, for the second job rotation scheduling problem. Thereby, Yaoyuenyong and Nanthavanij (2008) show that the formulated model is suitable for ergonomic measurements with Ener-Exp. Nanthavanij, Yaoyuenyong, and Jeenanunta (2010) take varying skills of workers into account. Similar to Yaoyuenyong and Nanthavanij (2006), they consider job rotation schedules that respect ergonomic limits. However, instead of minimizing the number of assigned workers, they maximize the total competencies of the hired workers in the jobs assigned to them. The authors propose a hierarchical heuristic approach to solve the formulated problem: decisions on the number of employed workers, on the

selection of the desired number of workers from the pool of available workers and scheduling of the selected workers are made consecutively.

Table 3 provides a general overview of the contributions. Similar to Table 2, it describes for each contribution the measurement of ergonomic risks, how ergonomic risks are included into the model and the designed customized solution methods.

6. Managerial insights

Based on the surveyed literature, we make the following recommendations for practitioners.

First of all, it is important to consider ergonomics aspects right from the planning stage, as this *preventively* reduces health risks for workers. The existing papers have persuasively shown that various established ergonomic risk estimation methods can be integrated into assembly line balancing and job rotation scheduling models. The optimization algorithms developed are able to find solutions better than the status quo task-to-station and worker-to-station assignments within acceptable computational times. For instance, significant improvements to the production processes have been illustrated with detailed simulations for the production of automobiles (Otto & Scholl 2011; Sternatz, 2014), automotive parts (Bautista, Batalla-García et al., 2016; Diego-Mas et al., 2009; Gunther et al., 1983), textile (Jaturanonda & Nanthavanij, 2006; Mutlu & Özgörmüş, 2012) and appliances (Battini et al., 2016; Xu et al., 2012). Recall that in the context of the assembly line balancing problem, the reduction of ergonomic risks may require higher cycle time or additional workstations and thus the assembly line productivity indicators can be deteriorated. Never-

Table 3
Summary of the contributions to the job rotation scheduling that consider physical ergonomic risks.

Reference	Measurement of ergonomic risks	Ergonomic risks considered as...		Designed solution method
		Const-raints	Obj. function	
Carnahan et al. (2000)	JSI-L		x	GA
Nanthavanij and Kullpattaranirun (2001)	DND		x	GA
Tharmmaphornphilas et al. (2003)	DND		x	–
Yaoyuenyong and Nanthavanij (2003)	DND		x	Heuristic (LS)
Tharmmaphornphilas and Norman (2004)	JSI-L, DND		x	–
Kullpattaranirun and Nanthavanij (2005)	DND		x	GA (LS)
Asawarungsaengkul and Nanthavanij (2006)	DND	x		–
Yaoyuenyong and Nanthavanij (2006)	DND	x		Heuristic (LS), B&B
Tharmmaphornphilas and Norman (2007)	JSI-L		x	Heuristic (LS)
Seçkiner and Kurt (2007)	Parameters[a]		x	SA
Asawarungsaengkul and Nanthavanij (2008a)	DND	x		GA (LS)
Asawarungsaengkul and Nanthavanij (2008b)	DND	x		–
Seçkiner and Kurt (2008)	Parameters[a]		x	ACO
Yaoyuenyong and Nanthavanij (2008)	Parameters[a], DND, EnerExp	x		Heuristic (LS)
Aryanezhad et al. (2009)	JSI-L, DND	x	x	–
Diego-Mas et al. (2009)	Force loads, awkward and static postures, repetitiveness, capacities of workers		x	GA
Michalos et al. (2010) and Michalos et al. (2011)	Fatigue, repetitiveness		x	Heuristic
Nanthavanij et al. (2010)	DND	x		Heuristic (LS)
Asensio-Cuesta, Diego-Mas, Canós-Darós, et al. (2012)	Force loads (Rodgers, 1992)		x	GA
Asensio-Cuesta, Diego-Mas, Cremades-Oliver et al. (2012)	OCRA, monotony		x	GA
Michalos et al. (2013)	Fatigue (Ma et al., 2009), repetitiveness		x	Heuristic
Otto and Scholl (2013)	EAWS		x	Heuristic (LS), tabu search
Mossa et al. (2016)	OCRA	x	x	–
Yoon et al. (2016)	REBA		x	–
Song et al. (2016)	NIOSH-Eq, force loads (Rodgers, 1992), geometry of tasks		x	GA (LS)

Notes. ACO – ant colony optimization, GA – genetic algorithm, LS – local search, SA – simulated annealing, heuristic – other construction heuristic, heuristic(x,y,z) – heuristic with elements of xyz. We use a dash "–" if no customized solution method was proposed, for example, if the article utilized an off-the-shelf solver
[a] General job-specific physical demand parameters.

theless, in the simulations of Otto and Scholl (2011), ergonomic risks have been reduced in about 90% of the tested instances even if the productivity indicators have been kept at the theoretically best possible levels. For about 50% of instances, acceptable levels of ergonomic risks have been achieved for all the stations. This result is relevant for companies in highly competitive environments that cannot allow even a temporary deterioration in assembly line performance.

Secondly, the majority of the articles propose very flexible models that can be straightforwardly extended to solve problems with different ergonomic risk estimation functions. Unfortunately, no recommendation is possible on the best performing solution algorithms, because most authors neither compare their methods to the existing ones, nor estimate the remaining gap to optimality for the solutions achieved with their algorithms.

Thirdly, the existing literature also addresses potential implementation issues of the preventive planning approach at companies. One of the widespread implementation issues is the absence and poor quality of the required data. Klindworth, Otto, and Scholl (2012) and Otto and Otto (2014a) suggest an efficient methodology on how to collect the sufficient amount of accurate data on precedence relations between tasks at low cost. Comprehensive ergonomic estimation tools, such as EAWS, require detailed information that may not be documented at companies, such as geometrical dimensions or weights of parts and tools. In this case, planners may use expert estimates of the physical demands of tasks as described by Mutlu and Özgörmüş (2012). Alternatively, planners can limit the analysis of risks to a few most prominent risk factors at the studied production site, e.g. noise (cf. Tharmmaphornphilas et al., 2003) or a general analysis of postures with REBA (cf. Yoon et al., 2016).

The first step to apply optimization techniques to assembly line balancing and job rotation scheduling in practice is to work out an appropriate formal model, i.e. a precise formulation of the planning problem, including a set of feasible alternatives and objective functions. We refer an interested reader to Boysen et al. (2008) for a guidance on modelling aspects of assembly line balancing. We comment on the selection of ergonomic objective functions below and discuss some modelling aspects of ergonomic risk measurement methods in Section 7.

Overall, existing studies examine several possible ergonomic objective functions, such as minimization of the average ergonomic risks (cf. Mossa et al., 2016), minimization of the variance in distribution of ergonomic risks among stations (cf. Jaturanonda & Nanthavanij, 2006), minimization of the deviation from acceptable levels of ergonomic risks (cf. Choi, 2009) and minimization of the maximum ergonomic risks (cf Battini et al., 2016), to name a few.

It is important, however, that the choice of particular objective functions suits not only the company's criteria, but also the particular ergonomic risk estimation method and the problem setting. For example, minimization of the average ergonomic risks may assign demanding tasks unequally among workers, resulting in work assignments with extremely high ergonomic risks. Also, minimization of the variance of ergonomic risks should be avoided if ergonomic risks are estimated with methods that take the maximum or minimum evaluation of several risk factors. For example, let us balance an assembly line with cycle time of $c = 10$, four tasks with operation times 5 each and no precedence relations between the tasks. Tasks 1 and 2 require dorsal flexion of the wrist, whereas tasks 3 and 4 require a wide hand grip for the whole duration of the task. Fig. 6 depicts simplified examples of linear functions for postural ergonomic risks, higher points indicate higher ergonomic risks. In some ergonomic risk estimation methods, where postural risks are measured for wrist and palm separately, the final risk estimate is equal to the maximum of individual estimates (cf. OCRA). In this case in balance 1, dorsal flexion of the wrist is performed 100% of time at station 1 and wide hand grip lasts for 100% of time at station 2, so that ergonomic risks equal 2 points for each station and the variance of ergonomic risks is 0. In balance 2, ergonomic risks equal $\max\{1; 1\} = 1$ point at each station and the variance of ergonomic risks is 0 as well. So that the objective function treats both assembly balances as equal, although in reality ergonomic risks of balance 2 are lower.

7. Outlook and research opportunities

We suggest that future research should address the following challenges: working out guidelines on specific preventive ergonomic interventions, adaptation of ergonomics estimation methods to the needs of preventive planning as well as advancement of modelling and solution approaches.

The identified research topics for further investigation will require close collaboration between production managers, ergonomists and operations researchers.

7.1. Guidelines on ergonomic interventions

The literature suggests numerous possible ergonomic interventions into the organization of assembly lines and work schedules. These include flexible assignments of workers to stations (e.g.
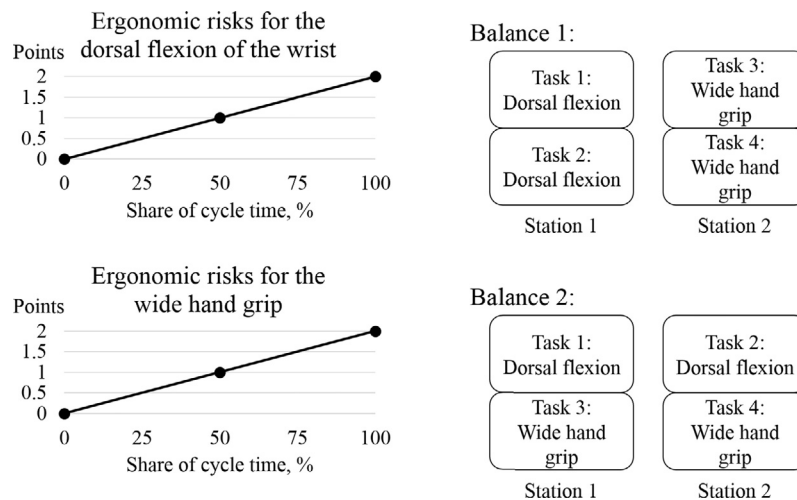
Fig. 6. Illustrative example of two assembly line balances.

workers process each second workpiece during two consecutive cycles or workers are allowed to move from station to station during the cycle time, cf. Battaïa et al., 2015), or changing the assembly line layout to facilitate working at different stations (e.g. to a U-type layout). Some studies suggest that in highly customized production systems, sequencing workpieces may be a factor influencing ergonomic risks because the latter depend on the dynamics of exposure due to accumulated fatigue (cf. Ding, Wexler, & Binder-Macleod, 2000; Rohmert, 1973). The length and timing of the rotation periods can be adjusted (cf. Tharmmaphornphilas & Norman, 2004). Furthermore, preferences of workers may be taken into account in assembly line balancing and job rotation scheduling (cf. Diego-Mas et al., 2009). Production managers need guidelines on particularly important interventions in specific production environments. With the incorporation of ergonomic risk measurement into assembly line balancing and job rotation scheduling models, it becomes possible to examine ergonomic interventions in detailed computational experiments. Although unlike field studies, computational experiments cannot represent all facets of real-world assembly lines, they enable to change one parameter at a time and therefore estimate the resulting effect.

Besides physical ergonomic risks, preventive planning approaches should also take into account cognitive load such as learning and forgetting effects (cf. Jaber & Glock, 2013; Otto & Otto, 2014b) as well as boredom and variability of tasks (cf. Asensio-Cuesta, Diego-Mas, Cremades-Oliver et al., 2012; Digiesi, Kock, Mummolo, & Rooda, 2009; Gunther et al., 1983).

7.2. Ergonomic risk estimation methods

Most existing methods for ergonomic risk estimation have been developed to perform analysis of existing work assignments, for instance, to make them suitable for a rapid pen-and-pencil application at the production site. This necessarily has led to some simplifications as well as compromises between alternative risk estimation routines. The requirements of preventive planning are different, since the latter relies on ergonomics estimation methods to design *new* work assignments. Optimization algorithms are *blind* in the sense that they evaluate alternative work assignments solely based on the information supplied by the risk estimation method. Consider the following example presented in Fig. 7 with cycle time of $c = 15$, nine tasks each of operation time 5 and no precedence relations between the tasks. Task 1, 2 and 3 require dorsal flexion of the wrist, wide hand grip and elbow flexion for the whole duration of the task, respectively. Tasks 4 to 9 require walking and standing and we assume their ergonomic risks to be 0. We assume the ergonomic risk function for elbow flexion to be the same as for the dorsal flexion of the wrist in the example in Fig. 6. Recall that some existing ergonomic risk estimation methods compute the final risk estimate as the maximum of individual estimates, in this example these are estimates for the elbow, wrist and hand. In this case, many objective functions (such as minimization of the devi-

ation from acceptable levels of ergonomic risks or minimization of the average ergonomic risks) prefer balance 1 over balance 2. Indeed, ergonomic risks of stations 1, 2 and 3 are 2/3, 0 and 0 for balance 1 and 2/3, 2/3 and 2/3 for balance 2, respectively. However, most production managers would prefer balance 2 over balance 1. Consequently, the existing risk estimation methods have to be adjusted to the requirements of preventive planning. For instance, risks of each anatomical segment may be considered in the optimization model as separate soft or hard constraints.

Also risk estimation methodologies in case of job rotation need adjustment. To compute ergonomic risks for a worker, most current risk estimation methodologies recommend taking the *average* of ergonomic risk estimates of the jobs performed during the shift weighted by time. However, several field studies highlight the importance of putting more weight on the maximum physical load of a work assignment during the shift at least in some production settings (cf. Frazer, Norman, Wells, & Neumann, 2003; Kuijer et al., 2005).

Furthermore, it is essential to explore whether the design of sufficiently accurate ergonomic risk estimation methods with "nice to have" mathematical properties, such as linearity or convexity, is possible. As already discussed, the assembly line balancing problem and the job rotation scheduling problem are combinatorial problems with, as a rule, an extremely large number of feasible solutions for instances of practice relevant size. So that even modern computers cannot enumerate and compare all the feasible solutions within acceptable time limits. Also metaheuristics, which most articles recommend using, may offer solutions with a large gap to the optimality. Certain functional forms of ergonomic risk estimation may help to design efficient solution algorithms that achieve good average performance within available run times. To sum up, ergonomic risks of solutions found by metaheuristic algorithms and comprehensive risk estimation functions should be compared to solutions found by exact solution algorithms based on simplified estimation functions. The Predetermined Motion Energy System of Battini et al. (2016) is an example of an ergonomic risk estimation tool with "nice to have" mathematical properties.

7.3. Modelling and solution approaches

Only a few articles propose good-quality lower bounds and provide information about the optimality gap of the proposed solutions (cf. Bautista, Batalla-García et al., 2016; Otto & Scholl, 2013; Sternatz, 2014). Therefore, future research has to focus on the design of fast exact solution algorithms. On the one hand, optimal solutions that exhaust all the available potential to increase productivity and reduce ergonomic risks. On the other hand, the quality of optimal solutions is a more natural criterion to compare alternative interventions, because it does not depend on the algorithm used to compute these solutions.
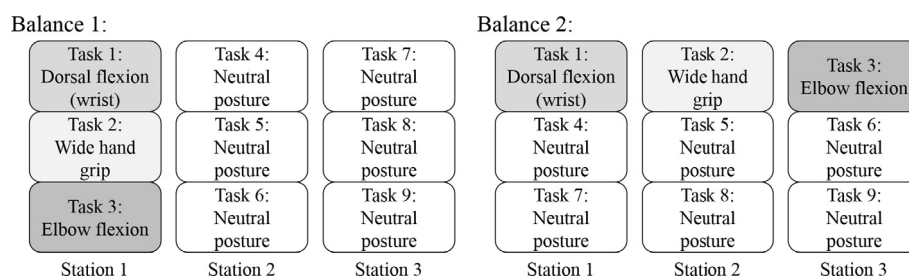
Fig. 7. Illustrative example of two assembly line balances.

8. Conclusion

In this survey, we examine the optimization models incorporating physical ergonomic risks for assembly line balancing and job rotation scheduling. Computational studies illustrate that the ergonomic risks at assembly lines can be significantly reduced, if they are considered in the planning of work assignments. Sometimes it is even possible to completely eliminate the exposure to excessive ergonomic risks without any deterioration in the productivity indicators of the assembly line.

For each article, we provide a short summary of the modelling approach, including an outline of the ergonomic risk estimation functions, and of the solution algorithms designed. We summarize major insights for practitioners and provide some references on how to overcome the problem of missing data, which is a major hindrance for the implementation of optimization methods in practice. Based on our detailed literature survey, we consider the following research topics to be promising: working out guidelines on preventive ergonomic interventions, adaptation of risk estimation methods to the needs of preventive planning and further advancement of modelling and solution approaches (especially the development of lower bounds and fast exact solution methods). We expect close cooperation between ergonomists, production managers and operations researchers in the coming years to address the specified research challenges.

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