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Improving ergonomics by OR methods applied in the planning process: The example of the automobile industry

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Abstract

According to the National Safety Council, about a half of manual workplaces in US industries cause musculoskeletal disorders. The management of firms recognizes that poor workplace ergonomics results not only in high prevalence rates of diseases for workers, but also in higher costs for the firms, including costs of absenteeism and action costs. Contrary to the widespread set opinion, it is possible to improve workplace ergonomics at low costs, especially at the earlier steps of planning. Early in the planning, circumvention of ergonomic risk factors is also accompanied by raises in productivity and a higher quality. Currently, firms have difficulties to incorporate ergonomic aspects into the planning process.

In this study, we show examples of how to integrate ergonomic aspects into the planning decisions. We discuss important planning steps for the workplace ergonomics, formulate problem settings and point out the relevant models of Operations Research. For each of the planning steps, we also illustrate potential benefits from consideration of ergonomic aspects.

In order to make our illustrations more specified, we take the example of manual workplaces at assembly lines in the automobile industry. The discussed problem settings and models can also be applied to other industries and production systems.

Keywords: Operations engineering; Ergonomics; Planning; Human factors; Process Engineering; Ergonomic risks

1 Introduction

According to the definition of International Ergonomics Association (IEA Council, 2000), *workplace ergonomics* means the creation of a working environment that optimizes the worker's wellbeing and the overall performance of the organization. Workplace ergonomics gains in importance in enterprises. Ergonomics is the result of the interplay of physical (e.g. repetitivity of work, the weight of loads to be lifted), cognitive (e.g. work stress, training) and organizational factors (e.g. richness of the job, communication patterns, teamwork). Among them, the physical ergonomic risk factors are more easily measured and their consequences are better investigated than those of the other factors. It has been realized that poor physical ergonomics in the workplace results in quality losses, inefficiencies and health problems of the workers (e.g. Eklund, 1995; Moreau, 2003; Falck *et al.*, 2010). For example, for the Volvo car company, one ergonomically poor workstation is estimated to cost €90,000 yearly to cover absenteeism, personal turnover, losses of new employees etc. (Sundin *et al.*, 2004). Our study focuses on physical ergonomics. Therefore, the word "physical" is further omitted for the sake of brevity.

Product design, production and personnel planning processes are important for circumventing and mitigating the ergonomic risk factors. At this stage, there exists a high flexibility in forming the workplace design and work assignment as well as in possibilities to create or modify further organizational issues (e.g. the Framework Directive, EU, 1989; Helander, 1999; Hilla, 2006). Currently, the firms experience difficulties integrating ergonomic aspects into the planning processes (Perrow, 1983; Launis *et al.*, 1996; Broberg, 1997; Wulff *et al.*, 1999).

Recently, a regular measurement of *ergonomic risks*, or risk for health of workers, was integrated into organizational routines of firms in different industries, especially those, employing assembly line production system. However, this valuable piece of information is currently used almost solely to react on the *already existing* ergonomic problems. Thus, ergonomic risk factors are evaluated at the production stage, where the costs of their mitigation are already high. In this study we show that such estimations of ergonomic risks represent a valuable piece of information for *preventive* measures and make ergonomics easy to consider in the planning processes.

The application of the methods of Operations Research (OR) to plan and mitigate ergonomic risks was made prominent in the work of Brian Carnahan and his team (see, e.g., Carnahan *et al.*, 2000; Carnahan *et al.*, 2001). A comprehensive overview of ergonomics and possible ways of its incorporation into scheduling is provided by Lodree et al. (2009). Several studies address directly the question of the integration of ergonomic aspects into the planning processes at firms. However, their focus lies in suggesting general organizational changes that would accelerate such integration, e.g. empowering workers, providing basic training in ergonomics for production planners and designers (see Perrow, 1983; Noro and Imada, 1991; Sandberg, 1992; Hendrick, 1997; Dul and Neumann, 2009). However, an elaborate investigation of which planning decisions influence ergonomic risk factors and how to model these decision problems is still missing.

In our study, we show examples of how to integrate ergonomic aspects into the planning decisions at firms. We formulate problem settings and point out the relevant OR models. Most of such problems have been little investigated in the OR literature, so that we provide directions for further research. For each of the planning steps, we also illustrate potential benefits from consideration of ergonomic aspects. The insights that we present in this study originate from the literature, our own research and communication with car manufacturers we cooperate with.

In order to make our illustrations more precise, we refer to the manual labor workplaces at assembly lines in the automobile industry throughout our study. However, the described problem settings and models are directly applicable, possibly with a few modifications, to other industries and production systems as well. We select the automobile industry, because it is a precursor in the integration of the ergonomic risks estimation into organizational routines. Correspondingly, a lot of the existing OR models that consider ergonomic factors refer to manual workplaces at assembly lines. Manual workplaces at assembly lines, including those in the automobile industry, are heavily exposed to ergonomic risks. Along with construction workers and health care assistants, workers at assembly lines have the highest prevalence of work-related musculoskeletal disorders (see Schneider and Irastorza, 2010).

We proceed as follows. In Section 2, we provide an overview discussion on physical ergonomic risk factors, their estimation and specificity of their integration in OR models and planning decisions. In

Section 3, we report on how ergonomic aspects can be incorporated into production and personnel planning decision problems for manual workplaces at assembly lines in the automotive industry. We conclude with a discussion in Section 4.

2 OR models and quantitative estimation of ergonomic risks

Mitigating ergonomic risks is connected for many OR researchers, first and foremost, with the yes/no problem of equipment purchase and installation, such as of manipulators for lifting, ergonomic chairs or working tables of an adjustable height. The decision problem in this case is to find the right trade-off between the costs of such equipment and its benefits in terms of lower ergonomic risks for workers. However, further decisions, such as task assignment to workers, may influence the workplace ergonomics a lot. As we will see in Section 3, there exist many ways to improve workplace ergonomics at little or no cost and nevertheless receive significant benefits from the mitigation of ergonomic risks. In Section 2.1, we go through the important "drivers" of ergonomic risks and possible traditional problem settings of OR that influence them. Afterwards we provide comments on possible objective functions for OR models in Section 2.2.

2.1 Overview of ergonomic risk factors

Table 1 provides several links to widespread quantitative methods for the estimation of ergonomic risks. Ergonomic risks are usually measured in points or as an index. Higher values of points/index mean higher risks for health being present. A good overview of ergonomic risk estimation tools, including a list of industries where they have been applied, is provided in the mandatory Appendix D.1 to §1910.900 of "Final Ergonomics Program Standard" by the Occupational Safety and Health Administration (OSHA, 2000).

The ergonomic risk factors most widespread in the industries include the presence of awkward postures, application of force and high frequency of repetition (OSHA, 2000). A higher exposure to the same risk factor, such as more time spent in a certain awkward posture or accomplishment of more lifts, often leads to an exponential increase in the estimation of ergonomic risks. Task assignments that balance the ergonomic load among workers have to be preferred. Quantitative methods for ergonomic risk estimation play an important role to compare different task assignments.

Risk factors	***Example of methods*** / ***Examples for usage of the methods***
Input information: Average task assignment in a shift	
Postures	"Ovako Working Posture Analysis System" (Karhu et al., 1977) Health care (Lee and Chiou, 1995), construction workers (Kivi and Mattila, 1991)
Manual material handling (lifting)	"Revised NIOSH equation" (Waters et al., 1994) Order pickers (Dempsey, 2003)
Manual material handling	"Leitmerkmalmethode" (BAuA, 2001) Order pickers (Walch et al., 2009)
Repetitiveness	"Occupational Repetitive Action method" (OCRA) (Occhipinti, 1998) Assembly line, warehouse workers (Colombini et al., 2002)
Postures, forces, manual material handling, repetitiveness	"European Assembly Worksheet" (EAWS) (Schaub et al., 2010) Assembly line workers (Schaub et al., 2010)
Input information: Sequence of tasks, work-rest regime over a shift	
Noise	"Rapid sound-quality assessment of background noise" (Torres, 2004) Wood processing workers (Tharmmaphornphilas et al., 2003)
Fatigue	"Fatigue model" (Wood et al., 1997; Ma et al., 2010) Assembly line workers (Carnahan et al., 2001), construction workers (Hsie et al., 2009)
Input information: Shift schedule and average task assignment over several shifts	
Deviation from circadian rhythms	"HSE risk and fatigue indices" (Spencer et al., 2006) Rail sector workers, chemical industry (Spencer et al., 2006)

Table 1. Examples of quantitative methods for ergonomic risks estimation

Examples of hazardous *awkward postures* include overhead work, bending, twisting the back or bending the wrist. The risks are calculated based on the total time spent in each posture. In the language of OR, each task has an attribute – the amount of time spent in each awkward posture. By a favorable distribution of tasks with different attributes among workplaces (e.g., with help of the assembly line balancing, Otto and Scholl, 2011a), ergonomic risks of each workplace can be mitigated.

The application of *force* and *manual material handling* may place higher loads on muscles, tendons, ligaments, and joints. It may also lead to fatigue. Examples of the application of force and manual material handling include lifting objects, drilling and attaching clips. The amount of force is, as a rule, aggregated by the kind of activity (e.g., lifting vs. pushing) or the posture involved (e.g., overhead or bent). As in case of awkward postures, level and duration of the application of force and manual material handling represent the task attributes that have to be considered during the distribution of tasks among workplaces.

High *repetitiveness* of work means that similar movements are repeated with little variation and at a high frequency. High repetitiveness may lead to extreme fatigue. Work at assembly lines, operation of machines, picking small items are often connected to high frequency of repetition. Increases in the production rate or in the rate of incoming picking orders may increase ergonomic risks significantly.

The amount of risks depends not only on the level of each single factor, but also on their *interaction*. Thus, ergonomic risks from high repetitiveness of tasks further increase if awkward postures are present and/or force has to be applied. For OR it means, for example, that ergonomic risks coming from the decrease of the cycle time, that leads to a higher frequency of repetition, can be offset by a more favorable distribution of tasks among workplaces. Similarly, the application of force in an awkward posture increases the hazard significantly. Therefore, positioning of heavy items on the shelves of the medium-height, that require a neutral posture when picking, and the lighter items on the upper and lower shelves, that force overhead lifts or bending, may reduce ergonomic risks for order pickers in warehouses.

Of course, *individual characteristics* of the worker influence her health risks from performing certain tasks significantly. Among them are fitness, height and state of health of the worker. Nevertheless, it is a common practice and a legal requirement in order to avoid discrimination of workers (see, e.g., EN 614-1) to estimate the ergonomic risks at a workplace for an "average" worker at the planning stage. Still, in the certain environments, individual specificities of workers have to be taken into account, while assigning them to workplaces or tasks (see, e.g., studies of centers for disabled by Costa and Miralles, 2009).

Most of the quantitative methods, like EAWS or revised NIOSH equation, calculate ergonomic risks on the basis of one shift, taking just the average task assignment into account. If, for example, a worker has to perform 50 lifts of heavy boxes and 50 lifts of light boxes, then the sequence of lifts does not matter for these methods. Both a workplace where the lifts are performed in alternation and a workplace where the heavy lifts are performed first will receive the same estimation of ergonomic risks.

However, the *sequence of tasks* as well as the *distribution of rest pauses* may exert a significant influence on the level of ergonomic risks, especially in logistics and at multi-product assembly lines.

Only first attempts for the exact modeling of such effects are known up to now (see the fatigue models of Wood *et al.*, 1997, and of Ma *et al.*, 2010), but the research is going on. For OR it means that the sequence of tasks, the size and sequence of batches as well as the size and timing of work rest may influence the amount of workplace ergonomic risks.

Planning of the size and timing of rest pauses for each worker is also required in case of exposure to such factors, as *noise, heat, cold or vibration*. An alternative problem setting would be to determine the required number of workers, if the level of exposure never exceeds the acceptable level.

There are methods that calculate ergonomic risks over several *workshifts*, as, for example, the Health and Safety Executive (*HSE*) risk and fatigue indices (Spencer *et al.*, 2006; Folkard *et al.*, 2007). HSE indices are important whenever employees have to work at different shifts (e.g., night, early or late) in any given month. Such indices can be utilized in estimation of alternative shift schedules.

2.2 On objective functions of OR models

OR models have to *reduce* and to *balance* the distribution of ergonomic risks among workplaces. The balancing is important, because the costs incurred by the employers and employees due to poor workplace ergonomics are growing exponentially with the increase in ergonomic points (Snook, 1978; Herrin *et al.*, 1986). Such a dynamic is due to an exponential increase in both the probability of incurring and the intensity of the incurred discomfort and/or health problems. Furthermore, there is strong evidence that at high levels of physical ergonomic risks a number of organizational and psychosocial factors, such as low job control, high demands or low satisfaction with the work, may further significantly increase the risks for health (e.g., Johansson, 1995; Vandergrift *et al.*, 2011).

Significant results in reduction and balancing the ergonomic risks among workplaces can be achieved without incurring costs. Recall that most instances of the relevant OR problems, such as task assignment, worker assignment or assembly line balancing, formulated with traditional non-ergonomic objectives and constraints have *several* optimal solutions (Otto *et al.*, 2012). Therefore, we can select a solution with the lowest level of ergonomic risks among the *optimal solutions*.

Certain actions on the reduction of ergonomic risks require some costs, at least in the short term, for example, the purchase of a new piece of equipment, setting additional workplaces to achieve a more favorable balance of ergonomic risks, etc. Then the correspondent problem settings in OR require the estimation of the *trade-off* between costs and benefits of such measures. The literature on the monetary size of such trade-off, especially on the benefits from reducing ergonomic risks, is only emerging. We provide some numbers in our examples in Section 3.2.

3 Illustration: Improving ergonomic risks at the planning stage in the automobile industry

In Section 2, we provided some insights on the possibilities to mitigate ergonomic risk factors at the planning stage by the means of Operations Research. Here we will examine certain important problem settings in detail. For illustration, we take the planning process in the automobile industry.

We proceed with the description of the relevant parts of the planning process in the automobile industry in Section 3.1. Afterwards, in Section 3.2, we formulate important planning decision problems that influence ergonomic risk factors as well as point on the relevant models of OR.

3.1 Planning process in the automobile industry

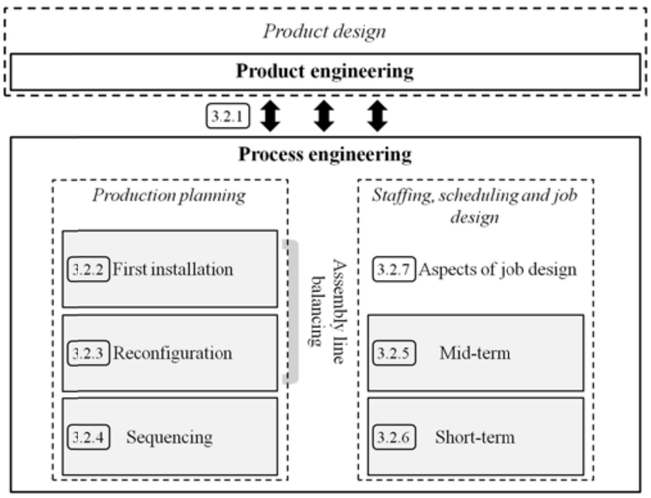

Figure 1. Elements of the product development process

The planning activities in the automobile industry from the idea about a product to its production and sells constitute the *product development process* (PDP) (Ohms, 2000). According to the study of Clark and Fujimoto (1989), PDP starts about 3.5–5 years before the start of production. Organizationally, PDP can be subdivided into two blocks: product design and process engineering. (cf. Clark and Fujimoto, 1991, see Figure 1). These blocks are overlapping and closely interrelated with each other.

Product design starts with the specification of basic functions, structures and messages to be delivered by the car to the customer (concept generation) and finishes with the *product engineering* stage, where a detailed specification of the product is developed.

On the *process engineering* stage, the specified product design is converted into manufacturing plans as well as the infrastructure necessary for production is prepared. Process engineering involves, among others, selection and acquisition of equipment and process control software, specification of standard operating procedures, set-up of the workplace design and staffing. The most important for creating a supporting working environment for assembly workers are *production planning* (in the narrow sense) and *staffing, scheduling and certain aspects of job design*. Overall, these planning fields as well as communication between process engineering and product engineering influence the most the work-place ergonomics at assembly lines. In Section 3.2, we discuss each planning step important from the view of ergonomics in a separate subsection. These steps are numbered in Figure 1.

In Section 3.2, we examine the first installation, the reconfiguration and the sequencing steps of *production planning* (cf. Fleischmann *et al.*, 2010; Boysen *et al.*, 2009a). *First installation* starts at the very beginning of the process engineering stage. The product specification is not finished yet, so that, for example, the selection between alternative operation tasks, necessary to assemble the product, still have to be done. Overall, first installation is characterized by a high degree of freedom in determining the future design of the assembly line. As a rule, first installation is "greenfield", i.e., it starts with an empty factory work floor or even with a work floor being under planning and construction. *Reconfiguration* refers to the situation, when a new product or a modified existing product has to be assembled along other product models on the existing assembly line. Reconfiguration is also performed, when the product-mix of the existing assembly line changes or when the production rate has to be modified. Both first installation and reconfiguration involve the balancing of the assembly line. *Assembly line balancing* allocates tasks that have to be performed on the product to sequentially ordered stations. In the beginning of the process engineering, assembly line balancing is included, for example, into the analysis of the selection and location of equipment. As more information becomes available, assembly line balancing provides more accurate insights into the layout of workstations (space, equipment, tools) and the required workforce. *Sequencing* plans assign the car models and model variants, that have to be produced during the shift, to the production cycles.

Staffing and scheduling planning steps can be traditionally subdivided into mid-term and short-term activities. In the *mid-term*, staffing determines how many employees are required. The staffing plans are based on the capacity planning, which provides a rough estimation of the necessary working time (Fleischmann *et al.*, 2010). Among others, the training plans to maintain the skills and to develop new skills are set-up. If the available permanent workforce is not sufficient, temporary workforce is hired. Also, in the mid-term, personal shift schedules for each worker are specified. In the *short-term*, available staffing plans are further specified and corrected according to the new information on demand and to the employment agreements (Grabot and Letouzey, 2000). The short-term scheduling includes job rotation scheduling and work sharing arrangements. Certain *aspects of the job design* are not necessarily integrated into PDP. They include, for example, a decision on the work-rest regime and a decision on the work in teams and on their size.

3.2 Incorporating ergonomic aspects into planning decision problems

In the following, we examine each of the planning steps, shown in Figure 1 and described in the previous Section 3.1. We sketch the possibilities to incorporate ergonomics into planning decision problems and point out model formulations of Operations Research. The proposed model formulations refer to the mitigation of ergonomic risks and do not depend on any specific quantitative ergonomic risk estimation method. For each of the planning steps, we also provide illustrations on the benefits that can be achieved by taking into account ergonomics information. For further illustrations of the benefits of ergonomic interventions, see the review of Neumann and Dull (2010).

In our illustrations, we sometimes refer to the traffic lights scheme. It is the “ergonomic language” of practitioners, who often classify workplaces into “green” with no significant ergonomic risks present, “yellow” with ergonomic risks present and “red” with significant ergonomic risks present. For each “red” workplace, the firm is required by legislation to document the planned and the undertaken actions for the reduction of ergonomic risks (EN 614).

3.2.1 Interface between product and process engineering

Illustration. A lot of factors that influence workplace ergonomics are already decided upon and are fixed during the product engineering. The plans and specifications of product engineering are negotiated and have to be approved by the process engineers. Almost without exceptions, product engineering and process engineering teams belong to different departments (design vs. production) and are often also geographically separated from each other (Clark and Fujimoto, 1991; Broberg, 1997; Sundin *et al.*, 2004). Therefore such negotiations provide a lot of potential to reveal, discuss and correct possible ergonomic issues. Effective negotiations and an effective information exchange between product and process engineering are the most important prerequisites also for the improvement of workplace ergonomics.

Here is an example from one of the car manufacturers we cooperate with on the importance of decisions on the product design. In the past, most rivets were replaced by clips in order to reduce the assembly time. As a consequence, the assembly workers started to complain on wrist pains, because they had to clap clips by a hit. The rate of quality errors increased as well, so that the gains in the assembly time were eliminated by the increase in action costs. However, presence of significant ergonomic risks at the workplace and the growth in costs were detected only during the serial production.

Models of Operations Research. Common problem settings for Operations Research during this step of PDP include a comparative analysis of the equipment alternatives and process alternatives connected to the changes in the product design. Process alternatives result in varying *flexibility of balancing* and differences in the *total assembly time* in achievable optimal solutions. Further decision criteria in such problems include *material and investment costs*. See, for example, models of Pinto *et al.* (1983), Capacho and Pastor (2008) and Scholl *et al.* (2009). However, it is important to add the following items: consequences for the level of *ergonomic risks*, the increase in *action costs* due to a higher error rate and in *costs from absenteeism* to the decision criteria. No such studies are known to the author.

Potential benefits. Empirical studies indicate, that information on workplace ergonomics along with the improvement in communication between product and process engineering teams, may lead to significant savings in the assembly time and costs. In the case study of chassis assembly at a bus producer conducted by Sundin *et al.* (2004), an inter-team work group was introduced, which, among other things, took ergonomic information into account. This enabled to reduce the assembly time of cable assembly on chassis by about 75%, from 56 minutes to 14 minutes. The implemented changes in the product design included, for example, a new positioning of certain details, which increased their accessibility for workers, reduced ergonomic risks and shortened assembly time.

3.2.2 First installation

Illustration. During the first installation, many decisions that influence workplace ergonomics are made. For example, whether workers will have to run along the car being moved by the conveyor belt or whether they will work on the conveyor belt? Whether the racks for lifting the car body can angle so that the workers can work on the undercarriage above shoulder level instead of overhead? Many decisions involve, besides the issues of costs, space and ergonomics, also the issue of flexibility. For example, mounting the cockpit onto the bodywork of the car can be performed fully automatically or semi-automatically. In the latter case, the cockpit is held with a manipulator which is manually operated by the worker. The roboter, which is the equipment of the first alternative, is costly to be moved to another workstation and thus restricts the degrees of freedom in the assembly line balancing. For the second alternative, the manipulator can be moved relatively easily, but it often results in a "yellow" workplace (the manipulator must be pushed).

Models of Operations Research. Problem specifications for OR are very similar to those in Section 3.2.1. The process and equipment alternatives have to be selected and located according to their costs, consequences for assembly time, restrictions on the flexibility of assembly line balancing, according to workplace ergonomic risks and action costs. The currently available models (e.g., Bukchin and Tzur, 2000; Bukchin and Rubinovitz, 2003) tend to neglect ergonomic risks and action costs.

Potential benefits. Taking into account ergonomic aspects during the first installation, may not only significantly reduce ergonomic risks, but also improve productivity. For example, the company producing emergency lighting devices considered ergonomic factors while performing transition from the multi-product assembly line production system, i.e. assembly in batches, to the mixed-model assembly line (van Rijhn *et al.*, 2005). As the result, the workers reported significantly lower levels of fatigue.

No increases were observed in postural and experienced loads. Nevertheless, the productivity raised by 44% and a reduction in the order lead time of 46% was achieved.

3.2.3 Reconfiguration and assembly line balancing

Illustration. At assembly lines, the tasks that are performed on the workpiece are partially ordered due to organizational and technological constraints. In other words, restrictions in the order of their accomplishment mostly exist. The precedence relations between the tasks may be summarized by the *precedence graph*. In the example from Figure 2, task 1 has to be completed before tasks 2 and 3 can be started. Each task is characterized by the task time, which is treated as deterministic in the automobile industry and is determined by conventional time studies, for example methods-time measurement (Bokranz and Landau, 2006). In automobile industry, the assembly line in the final assembly is paced. It means, the workpiece is available for each station for a constant period of time, called *cycle time*, afterwards it moves to the next workstation. If the cycle time equals to 60 seconds in our example from Figure 2, then one of the optimal solutions is {1,2}, {3}, meaning that the set of tasks assigned to the first station includes tasks 1 and 2 as well as that task 3 is assigned to station 2. At the first station, productive activities constitute 30 seconds of time or 50% of the cycle time, the rest of the time is *idle*. For the second station, these quantities equal to 45 seconds (75%) and 15 seconds (25%).

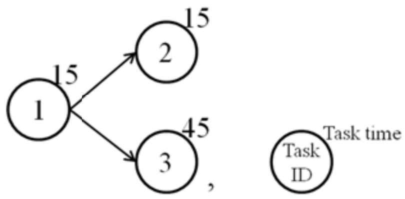

Figure 2. Example of a precedence graph

A favorable assignment of tasks to stations may lower the overall ergonomic risks associated with assembly work, measured as sum of ergonomic points of workstations. To the contrary, an unfavorable assignment of tasks to workstations may "create" risky workstations and increase the overall ergonomic risks present at the assembly line. Risks connected with the same risk factor that are combined at the same workstation (for example, several tasks requiring working overhead) *accumulate* and sometimes lead to an *exponential* increase in probability of negative effects on the worker's health (Snook, 1978; Herrin *et al.*, 1986). As a combinatorial optimization problem, ALBP has often several or even many optimal solutions (cf. Otto *et al.*, 2011). So, it is possible to choose a balance most favorable in terms of ergonomic risks without deterioration in the value of the objective function.

We illustrate the point on the following example (see Table 2 and the precedence graph in Figure 2). Let the cycle time equal to 60. Let tasks 1 and 2 require overhead work during the whole duration of the task, whereas task 3 is performed in a neutral posture. Let the primary objective be to minimize the number of workstations. For risk estimation, we utilize the method EAWS (European Assembly Worksheet) that is applied with slight modifications and under other names by the majority of European car manufacturers (see Schaub *et al.*, 2010, for details). According to EAWS, 25% of overhead activities during the cycle is evaluated with 33 points, 50% of overhead activities – with 60 points, 75% of work in neutral posture brings only 2 points. The EAWS defines the "green" zone at 0-25 points, the "yellow zone" at 26-50 points and the "red" zone at more than 50 points. Two different optimal line balances are possible, each requiring two workstations. The first one, {1,2}, {3}, consists of one "red" station and one "green" station. The second balance, {1,3}, {2} with two "yellow" stations, has to be preferred, since "red" stations with significant risks are likely to lead to significant health problems and have to be avoided if possible. See Otto and Scholl (2011a) for more examples, also on how the sum of ergonomic points can be *reduced*.

Tasks, assigned to station	Ergonomic points (according EAWS)	Comments	Time worked overhead | in neutral posture
1st Balance			
{1,2}	60	red: significant risks present	50% | 50%
{3}	2	green: acceptable risks	0% | 75%
2nd Balance			
{1,3}	35	yellow: possibly risks present	25% | 75%
{2}	33	yellow: possibly risks present	25% | 0%

Table 2. Possible assembly line balances for example from Figure 2 at cycle time of 60 seconds

The incorporation of ergonomic aspects into assembly line balancing decisions is important not only due to its potentially high effectiveness in reducing ergonomic risks, but also due to the low costs of its implementation. With available tools, as, e.g., MTMErgonomics (Schaub *et al.*, 2004), ergonomic assembly line balancing can be performed by production engineers themselves, just with basic schooling in ergonomics. The increased computational complexity can be handled with the (partial) automation of the balancing task that is currently performed manually. This starts to become possible with new methods for collection of the precedence graph information (Klindworth *et al.*, 2012).

Models of Operations Research. Most important problem variants of the assembly line balancing problem (ALBP) include the feasibility problem, which asks whether a line balance with the given number of stations and the specified cycle time is possible, and the problem of minimizing the number of workstations given the desired cycle time (see reviews of Becker and Scholl, 2006; Boysen *et al.*, 2007; Boysen *et al.*, 2008). Important constraints have to be considered (cf. Boysen *et al.*, 2009a). Just a few models (Carnahan *et al.*, 2001; Miralles *et al.*, 2008; Costa and Miralles, 2009; Otto and Scholl, 2011a) take into account ergonomic aspects, although assembly line balancing is an effective instrument for *reducing* the ergonomic risks.

Potential benefits. Colombini and Occhipinti (2006) report results of a real-world manual assembly line re-balancing, where the planner managed to reduce the number of "yellow" workplaces by 25% without increasing the number of stations and the cycle time. In their study on the conventional benchmark data set, Otto and Scholl (2011a) were able to receive a balance with only "green" workstations in 50% of cases by a simple re-assignment of tasks, keeping the number of workstations and the cycle time constant.

3.2.4 Sequencing

Illustration. Nowadays, several model variants and sometimes even several car models are produced on assembly lines. Therefore, assembly line balancing is performed for the "average" product (see Boysen *et al.*, 2009b). For example, let, according to the current task assignment to a station, the mounting of the sunroof require that work above shoulder level and overhead be performed for 50% of the cycle time and the rest 50% of the cycle time be idle. In reality, the sunroof is optional and therefore the mounting of the sunroof has to be performed only for the selected product variants (for example, variant A requires mounting of a sunroof, and variant B not). Thus, if in the current sequence ten variants A are followed by ten variants B, then the worker has to perform ten cycles with the above shoulder and overhead activities without a rest pause. Such sequence could significantly increase the risks for health for this worker.

The problem of a favorable sequence of tasks as well as of a favorable work-rest schedule arises for certain workstations in the final assembly, as shown above. But it is especially important at multi-product assembly lines, for example, at production of components for the car, where different components are processed in batches.

Overall, Wood *et al.* (1997) found out, that the fatigue and, hence, incidences of cumulated trauma disorders are minimized and the productivity is maximized at a medium length of rest and a medium intensity of work, given the same amount of work to be performed. Useful insights on the length and frequency of breaks are summarized in the literature review of Konz (1998).

Models of Operations Research. Lot sizing models for multi-product assembly lines (e.g., Dobson and Yano, 1994) and sequencing models with different objectives are proposed in the literature (see Boysen *et al.*, 2009a, 2009c, 2012). One class of such models, *mixed-model sequencing* models, tries to smooth the workload, measured in working time, incurred during the shift for each station. In many cases, mixed-model sequencing models already deliver ergonomically favorable sequences. The reason is that more risky activities often require more time. For example, according to methods-time measurement, mentioned in Section 2.1, lifting of a heavier object requires more time than lifting of a lighter one. Nevertheless, it is not always true and a direct calculation of ergonomic risks may be necessary for creating a favorable sequence.

Up to now, insights from fatigue and recovery studies were implemented only to the assembly line balancing problem setting (Carnahan *et al.*, 2001). Also, there exist models that define optimal work-rest schedules with respect to homogeneous tasks (e.g., Bechtold et al., 1984). However, studies of optimal sequencing and scheduling of batches at multi-product assembly lines incorporating ergonomic issues are still to be performed.

Potential benefits. The existing ergonomic interventions refer to the work-rest regime and not-paced work. Thus, in the study of Dababneh *et al.* (2001) at a meat-processing plant, 36 minutes of breaks additional to the regular break schedule did not lower the production rate, but reduced the feeling of discomfort of workers.

3.2.5 Mid-term staffing and scheduling

Illustration 1. Shift schedules may influence the worker’s wellbeing a lot. For example, working one week on the late shift and the next week switching to the early shift may be perceived as strenuous and hard to adapt to by many workers. The reason is that certain shift schedules may heavily disrupt the natural physiological regime, or *circadian rhythms*, and cause health problems, stress and fatigue. Among important factors influencing the risks are start time of the shift, its duration, number of consecutive shifts without the day-off as well as periodicity with which the worker switches between the shifts (Czeisler *et al.*, 1982; Spencer *et al.*, 2006; Folkard *et al.*, 2007).

Illustration 2. Overall, hiring additional staff is one of the easiest, but often one of the most expensive ways to decrease exposure to ergonomic risks. For example, introducing an additional workstation at the assembly line while keeping the cycle time constant results in more idle time, that can be seen as additional rest pauses, and less ergonomic load on average per worker. At assembly lines in the automobile industry, additional hires are less preferred than other options to reduce ergonomic risks, examined in this section. However, in certain industries, especially if employees have to work at cold or hot temperature, e.g., in refrigerated warehouses, additional staffing is a reasonable and established procedure (cf. Berufsgenossenschaft Handel und Warendistribution, BGHW, 2008, for Germany).

Models of Operations Research. A shift scheduling model for the automobile industry was proposed, for example, by Laporte and Pesant (2004). However, few models explicitly consider effects on health in the shift scheduling. For example, Kostreva *et al.* (1991) evaluated different shift schedules by their effect on the circadian rhythms.

The question of the number of additional hires that would lower ergonomic loads to the “green” level may be formulated almost in each model examined in this section. For example, in the tests of alternative assembly line balances by Otto and Scholl (2011a), a 4% increase in capacity, or in the number of workstations, was required to lower the present ergonomic risks to the acceptable levels.

Potential benefits. Unfavorable shift schedules may lead to nodding off during the work as well as to a higher rate of failures. Gold *et al.* (1992) compared nurses that either permanently worked the same shift (day or evening) or rotated the shifts. The odds, which is an established measure of probability in statistics, of the reported errors or accidents related to sleepiness were found to be twice as high for the rotators.

3.2.6 Short-term staffing and scheduling

Illustration 1. Job rotation influences directly the working assignment and thus the amount of ergonomic risks for each worker. A good job rotation schedule will balance available ergonomic risks among workers, thus avoiding high ergonomic risks for any employee. Further aspects that have to be taken into account in the job rotation schedules include learning and forgetting (by imposing the minimum required repetitions of each job within the period), boredom (by imposing the maximum required repetitions of each job), skills and assignment constraints due to health problems.

Illustration 2. If necessary, the production engineers use the flexibility of the workforce to introduce different kinds of work sharing. Work sharing smoothes an unevenly distributed workload. For example, several workstations at the assembly line may be combined into a "several-cycles-workplace". Thus, in case of a workplace that stretches over two cycles, a worker would start working on a certain product piece A in cycle 1, will proceed processing product A in cycle 2 by moving to the next station, afterwards she will return to the previous station and start working on the next product piece B in cycle 3. In other words, in this situation, the cycle time for the worker is doubled. Many firms use such organizational schemes with caution, because it complicates the supervision. Still this action is rather widespread as an effective tool for reducing and smoothing distribution of ergonomic risks.

Models of Operations Research. Job rotation scheduling as a tool to smooth and reduce the ergonomic risks was examined by Carnahan *et al.* (2000), Tharmmaphornphilas and Norman (2007), Diego-Mas *et al.* (2009), Costa and Miralles (2009) and Otto and Scholl (2011b).

Up to now, OR models treated the work sharing practices solely as a tool to reduce the cycle time (see, e.g., Anuar and Bukchin, 2006). The impact of the work sharing routines on productivity and ergonomics of workplaces has still to be examined.

Potential benefits. Job rotation leads to redistribution of ergonomic risks experienced by workers. For example, in case of one "red" and one "green" workstation, rotation will lower the level of exposure that the worker would receive otherwise on the "red" station, but will *increase* the level of exposure that otherwise would be received on the "green" station. Nevertheless, field studies report a positive effect of job rotation on the perceived load and on the need of recovery (e.g., the case of refuse collection department, Kuijer *et al.*, 1999 and 2005).

3.2.7 Aspects of the job design

Illustrations. Certain aspects of the job design either influence directly the level of ergonomic risks or restrict/improve the potential of application of other actions, described in this section. For example, low job control increases risks for health especially for “yellow” and “red” workplaces (e.g., Vandergrift *et al.*, 2011).

One of the most important aspects of the job design of manual workplaces is the opportunity to provide feedback to process and product engineers, including on the perceived discomfort coming from the tasks. An organizational scheme that enables such feedback is called participatory ergonomics (Noro and Imada, 1991).

Setting a higher size of the team increases the potential effects of job rotation. The reason is that job rotation, as a rule, is performed within a team because each team member has and has to preserve necessary skills to work at any workstation assigned to this team (Freiboth *et al.*, 1997).

The overall shift and work-rest policies of the factory are often a part of the agreement between the factory management and the trade union. The shift policy specifies the length of the working week for the worker as well as necessary and desired requirements for the shift schedule. The work-rest policy sets the start and the duration of rest pauses during each shift. A part of the pauses, relaxation allowances, can be used as an additional instrument to reduce ergonomic risks (Caragnano and Lavatelli, 2012). Instead of being a part of rest pauses, that are the same for all the workers, relaxation allowances may be allocated to workers proportionally to the amount of ergonomic risks experienced by them. For example, the required amount of the idle time within each workstation may increase proportionally to the risks associated with this workstation. The effect of this arrangement on the degree of freedom in balancing has still to be analyzed. Let in the example in Figure 2 and Table 2, a station with 60 ergonomic points have to contain at least 20% of idle time, or rest, a station with 30-35 points – 5% of idle time. Such a policy would prohibit the better second balance, because the first station with 35 ergonomic points does not contain any idle time although at least 5% of idle time is required for this station. As the result, the first balance with the presence of a 60-point “red” station but with 50% of idle time at this station will be chosen. The trade-off between a positive direct effect of more idle time per cycle and a possibly negative effect from restrictions on the set of feasible solutions is currently unknown.

Models of Operations Research. The consequences of certain aspects of the job design may be examined in the models, described in the previous sections. For example, the effect of the team size on the job rotation can be found with the help of the job rotation scheduling model (Section 3.2.6), the effect of certain work-rest policies can be studied by adjusting the assembly line balancing model (Section 3.2.3).

Potential benefits. Potential benefits differ a lot between the different elements of the job design. High benefits, for example, are brought by the participatory ergonomics. The ergonomic interventions cited in Sections 3.2.1 and 3.2.2 achieved the reported results employing participatory ergonomics.

4 Discussion

The quantitative estimation of ergonomic risks can assist planning decisions. Taking into account ergonomic risks at certain planning steps may lead to significant cost savings, e.g., of action costs or costs from absenteeism, and gains in productivity, e.g., from the decrease in the assembly time. Most importantly, it causes substantial decreases in ergonomic risks and thus in the prevalence rates of diseases and in the perceived levels of discomfort by workers.

With time, the flexibility of taking decisions decreases as product design and production processes get defined in more detail. Therefore, in general, incorporation of ergonomic aspects into the earlier steps of planning is more important and brings more gains at lower costs (Miles and Swift, 1998; Hilla, 2006). This was also shown in the cited examples in the previous section. In Figure 3, we arranged the planning decision problems, discussed in Section 3.2, according to their importance for practice, plotted on the vertical axis.

Overall, only a few OR models proposed in the literature incorporate ergonomic risks and may assist the planning of assembly lines in automobile industries. Among the least studied problem settings are such important ones as the selection of process and equipment alternatives based on the ergonomic information (see Figure 3). In addition, OR analysis considering ergonomic aspects is needed, first and foremost, in shift scheduling, sequencing and lot sizing as well as work sharing.

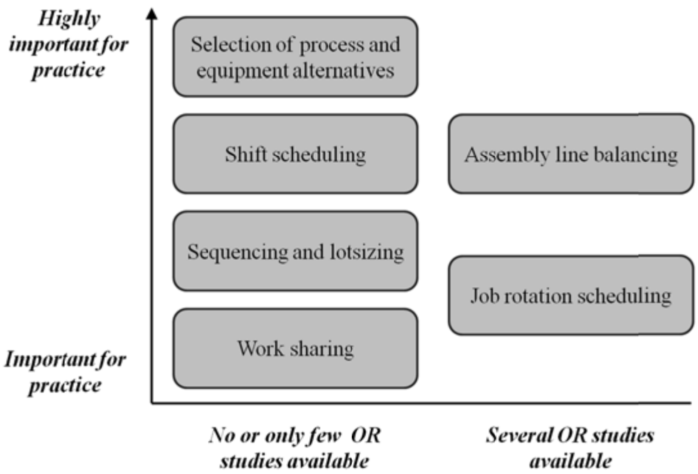

Figure 3. Directions for future research based on needs of planning in the automobile industry

Overall, there is a need for further OR analysis, especially for planning decision problems in industries with a high level of ergonomic risks, such as construction industry, healthcare, logistics (warehouses) and assembly lines (Schneider and Irastorza, 2010).

Physical ergonomics, examined in this paper, is only one aspect of ergonomics that influences the profitability of the production system. Organizational and cognitive ergonomic factors are of a high importance as well or are even more important (Boudreau *et al.*, 2003; Bidanda *et al.* 2005; Lodree *et al.*, 2009). Examples of the existing research include the study of Biskup (1999), who examined a single machine scheduling problem with *learning effects*. Powell and Schultz (2004) investigated the impact of *state-dependent behavior* of workers, who adjust their work pace, e.g., depending on the size and the fill level of the buffer, on the throughput of a serial line. Murray and Park (2012) embedded the constraints on the level of the *mental workload* in their model for scheduling the operators of the unmanned aerial vehicles.

Bringing together ergonomics and OR is an ongoing and a promising direction of research. This paper contributes to paving the way for it.

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