DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

Flexible job-shop scheduling considering human performance fluctuations

Henrik Prinzhorn
Christian Böning
Malte Stonis

IPH – Institut für Integrierte Produktion Hannover gGmbh

In production, product-related error costs can be reduced by focusing on human production factors, such as considering human performance fluctuations during the day, when production planning with respect to job-shop scheduling. In this article, the flexible job-shop scheduling problem is extended by considering product-related error costs and logistic costs. Product-related error costs are increased by over stressing the operative workers. Logistic costs are based on work in process and throughput time. This cost-based definition enables a production plan to be simultaneously optimized in respect of both error and logistic costs. The product-related error costs and flexible job-shop scheduling problem are described mathematically and a memetic algorithm is also presented as an approach. Within the memetic algorithm, the evolutionary process is supplemented with a local search procedure to improve the ability of solutions and repair procedures to rectify infeasible solutions. The influence of product-related error costs on the total costs of a production plan, throughput and job waiting times within job-shop scheduling is presented.

[flexible job shop scheduling, memetic algorithm, human performance fluctuation, error costs]

1 INTRODUCTION

To secure the company's success, manufacturing companies have to retain existing customers and win new ones. This is a major challenge in times of globalized competition and constant change through shorter product life cycles [1]. Many European companies focus on a high product quality to strengthen their competitive position [2]. Therefore, the quality of products has a high importance for companies [3] and ensures long-term success against competitors [4]. Product-related error costs occur if a company cannot meet the required quality requirements. Examples of product-related error costs are rework, spoilage, problem assessments or impairments [5]. According to ROTHLAUF, quality deficiencies lead to product-related error costs of 8% to 30% of the annual revenue [6].

To improve product quality, quality management methods (e.g. Total Quality Management (TQM), Total Productive Maintenance (TPM), Continuous Improvement (CI) and KAIZEN), are often used to reduce product-related error costs [7]. These methods are applied in construction (e.g. Poka Yoke), quality management and production process planning (e.g. FMEA), as well as the optimization of machines and processes [8]. However, the optimal use of the human production factor is still at the beginning, although an operative worker has a direct influence on the product quality in production [9] [10]. Considering this, the basis for this article are fluctuations in the performance of operative workers during the day. Thus, in times when the operative worker's performance slumps, the probability of the faulty execution of an operation increases, resulting in higher error costs. In contrast, when performance is at its peak, the probability of faulty execution decreases.

In manufacturing industry, one task in production planning is the allocation and execution of production jobs or operations ("job-shop scheduling"). Scheduling planning has a high potential for reducing product-related error costs (e.g. costs for rework, spoilage, repeatability tests and impairments) or of increasing product quality by considering human performance fluctuations [9]. The job-shop scheduling problem (JSP) is one of the most complex combinatorial optimization problems in production planning. Within the JSP i jobs and k machines are considered. Each job consists of j operations, which have to be performed in a specified sequence. Each operation is assigned to a technologically suitable machine [11]. The aim of JSP is to find a suitable sequence of machine operations, which typically optimizes an objective function. The flexible job-shop scheduling problem (FJSP) is an extension of the JSP. Within FJSP, operations can be freely assigned to the available machines [12]. JSP and FJSP belong to the class of NP-hard problems [11]. Therefore, for practical problems, it is difficult to find an optimal solution within a reasonable computation time [11]. For this reason, the focus has moved to the development of high-performance heuristics. Heuristics do not guarantee finding of optimal solutions, but they are suitable for solving most planning problems and they need less computing time.

Minimizing product-related error costs has to be done parallel to optimizing logistic objectives within production planning. According to NYHUIS and WIENDAHL, the fundamental objective of production logistics is the achievement of a maximum delivery capability and reliability with the lowest possible logistic and production costs [13]. Therefore, four logistic objectives (throughput time, delivery reliability, utilization and work in process (WIP)) must be considered [13] [14]. The throughput time of an operation within a job consists of processing time, set up time and waiting time. The throughput time can be divided into post-process waiting time, transport time and pre-process waiting time. Note that short throughput times will lead to smaller deviations between completion times and due dates, and therefore to high delivery reliability. The delivery reliability can be measured by the output lateness. To achieve low logistic and production costs, it is necessary to achieve a maximal utilization of the available capacities, as well as low storage and WIP levels to minimize the costs of tied-up capital [13] [14]. The conflict between the logistic objectives is called the "dilemma of scheduling" [14] [15]. To ensure a high level of capacity utilization, a high WIP level is required. However, a high WIP level leads to extended and different throughput times and therefore to lower delivery reliability. To avoid unbalanced optimization, a multi-objective function is necessary or the objectives, which have to be considered, must be aggregated.

The structure of this article is as follows: Section 2 provides an overview of existing research methods on the subject of this paper. Section 3 presents a description of a problem statement and section 4 includes the corresponding combinatorial optimization model. The heuristic approach, which has been developed to solve the optimization model, is presented in section 5. Section 6 presents the computational results and a validation of the developed approach. The article ends with a summary in section 7.

2 LITERATURE REVIEW

There are many approaches for solving the FJSP in literature. During the last decades, many new procedures for generating better solutions were developed. BRUCKNER and SCHLIE first described the FJSP and developed a polynomial algorithm which provides an optimal solution for a small instance (two jobs) [16]. After that, many heuristic approaches were developed for solving examples of a practical size. Some of these heuristics are Tabu Search (TS), Simulated Annealing (SA) and evolutionary procedures such as Genetic Algorithms (GA), Ant Colony Optimization (ACO) and Artificial Bee Colony (ABC) algorithms, or Particle Swarm Optimization (PSO). These heuristics can be classified into hierarchical and integrated approaches [12]. The aim of hierarchical approaches is to reduce the complexity of the FJSP by subdividing the problem into sub-problems. In the next step, the sub-problems are solved sequentially [17]. Among the heuristics, GAs have proved to be very effective for solving FJSP. Generally, GAs differ in their coding and decoding scheme, the generation of the initial population and the offspring strategy [18] [19]. In the recent past, memetic algorithms (MA), in which a GA is combined with a local Search (LS) procedure, became popular to provide a better solution quality [20] [21].

Human performance fluctuates during the day [22] [23].The function of organs in the human body (e.g. body temperature or blood pressure), are subject to recurring patterns, which are roughly equivalent to the duration of a day [24].The concept of circadian rhythm is also used for such patterns [25]. The influence of circadian rhythms on human performance has been analyzed in a study comparing time-of-day dependent mouth temperatures, by MONK and EMBREY[24]. Statements on time dependent fluctuations of human performance are based on an analysis carried out by BJERNER [26] and the physiological performance curve developed by GRAF [23]. According to POTTHAST [27], however, the physiological performance curve does not consider any central physical activity. Therefore, it is only possible to conclude a diminished psychological readiness in the human being. Circadian performance fluctuations in the operating performance of worker´s in industrial production, were first demonstrated by POTTHAST [27].

From the 1970s to the 1990s, there are no reported filed studies about human planners and schedulers in manufacturing industry. This is due to the development of computers and IT developments for solving complex industrial planning and scheduling problems [28]. SANDERSON was the first who focused on planning and scheduling from an explicitly human factor perspective [29]. On the premise of improving quality assurance, RAUCH-GEBBENSLEBEN developed a simulation model by creating input data for data mining methods [30]. In the simulation model, the tool wear and the performance of the operative worker are used as parameters for determining their influence on product-related errors. The probability of a product-related error by the operative worker can be estimated by using the simulation model. However, job-shop scheduling is not done. BUARQUE DE MADECO GUIMARAES has developed a method for taking into account circadian performance fluctuations in scheduling [31]. Its application is the scheduling of electricians for the maintenance and replacement of high-voltage power lines. In this case, operations are allocated according to their stress levels. Therefore, particularly stressful operations are performed when performance is at its peak. However, no performance curves specific to electrical work were used and product-related error costs were also not considered. GLONEGGER has dealt with the consideration of human performance fluctuations in the design of assembly flow systems [32]. The focus is on the influence of the diversity of product variations on the human performance of assembly flow systems, rather than on job-shop scheduling.

Based on the literature review, it can be concluded, that circadian performance fluctuation has been considered in industrial production. At the present time, however, there is no method for job-shop scheduling which considers human performance fluctuations to reduce product-related error costs. Therefore, in this article, the FJSP is extended to take into account product-related error costs and logistic objectives such as WIP, utilization and throughput time. The main goal is the development of a simple method, with practical application, for helping especially small and medium-sized enterprises (SME) to consider product-related error costs in their production planning. Both the consequences of not considering product-related error costs and the cost saving potential of doing so are presented in this article. Thus, the costs arising from a production plan have to be identified. For this purpose, the individual objectives are weighted with costs. To solve the extended FJSP for practical problem sizes, a heuristic approach is proposed as an MA. Note that the MA's performance in producing solutions to a practical problem has a higher priority than finding the optimal solution. Within the evolutionary process, a LS is implemented, similar to the approach used by RAEESI and KOBTI [33]. In addition, repair procedures are used to rectify infeasible solutions during the evolutionary process. Furthermore, an aggregated objective function is used to minimize the costs arising from a production plan [34].

3 PROBLEM DESCRIPTION

The product-related error costs flexible job-scheduling problem (pec-FJSP) consists of $i = 1, \dots, I$ jobs. Each job, I, consists of $j = 1, \dots, J$ operations. Each operation, j, must be run on one of the $k = 1, \dots, K$ machines within the planning horizon of $t = 1, \dots, T$ periods. POTTHAST'S human performance curve is standardized and assumed for consideration of human performance fluctuations per day [27]. POTTHAST defined the performance of workers in production as the deviation of the actual processing times to the present times. Here, the performance curve additionally includes time for rework. Moreover, no distinction is made between morning and evening types. Thus, it is a "quality-based" performance curve [35]. The amplitude of the performance curve depends on the complexity of a job (e.g. size of frame, number of components, production rate) and is estimated relative to the jobs considered. The reason for this is that the operational worker's performance (actual processing times) in a complex job is more variable than in a less complex job. For the jobs being considered, the maximum complexity of a job is 1, equivalent to an amplifier a_i of 1. The minimum complexity of a job is 0. In this case, the performance curve corresponds to a constant. Figure 1 shows the concept of a qualitative performance curve for a worker during the day, which considers the complexity of the jobs. According to PRINZHORN, each job can be characterized according to a required performance level (see [35]). For this purpose, each operation is evaluated relative to each other, according to five features (manual activities of an operation, error costs, degree of standardization, significance and errors occurred) to answer the question, how high is the required attention level during execution? In addition the performance curve is differentiated into ranges (e.g. different levels of concentration and attentiveness) between the global turning points (minimum, maximum). Thus, for each operation, time periods can be identified during which the required attentiveness level corresponds to the available attentiveness level (see figure 2). In doing this, time period dependent correction factors γ_{ijt} can be determined for an operation. The correction factor is equal to 1, if the required attentiveness level for an operation equals the available attentiveness for a time period. The correction factor is less than 1, if the available attentiveness level of a time period is less than the required attentiveness level. Accordingly, the over- or under-stressing of a worker is expressed by the correction factor. This quality-based evaluation is the basis of the proposed flexible job-shop scheduling to reduce product-related error costs. In the pec-FJSP aggregate-objective function, the logistic objectives, output lateness, WIP and throughput time, are optimized together with the product-related error costs. The resulting production plan can be shown in the form of a GANTT diagram (see figure 3). A GANTT diagram shows the chronological sequence of the respective job operations of the resources (machine, worker and so on). Considering figure 3, the objective conflict in the considered problem is as follows: Use the performance level in comparison to a logistic-optimal scheduling. On the assumption that the operation $O_{2,2}$ requires a high level of attention, it sensible to carry it out when the corresponding worker is at peak performance. From the view point of logistic costs, this may not be optimal.

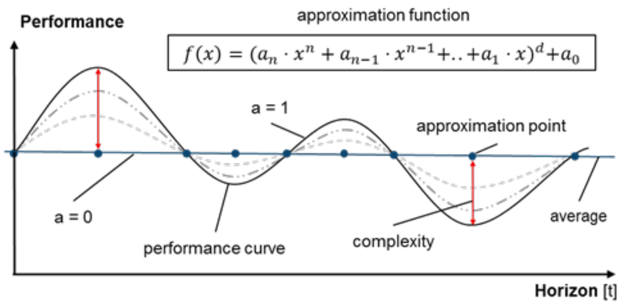

Figure 1: *Performance curve*

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

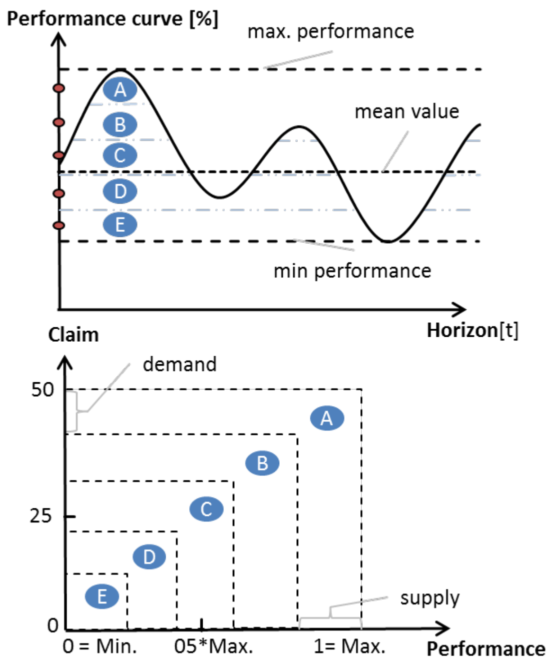

Figure 2: *Matching of performance curve and performance characterization of jobs/operations*

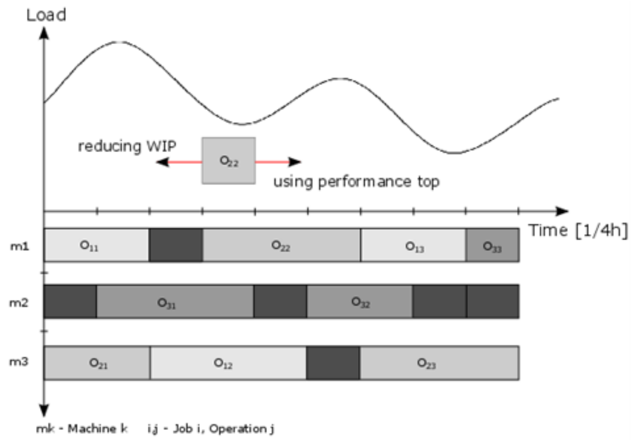

Figure 3*: Load and production plan*

The logistic objectives can be derived from a GANTT diagram (see figure 4). Output lateness is determined by comparing the time when a job is completed with the planned completion deadline (which is assumed to be equal with the delivery deadline). This involves distinguishing between completion which is too early (negative deviation) on the one hand, and too late (positive deviation) on the other hand. WIP is calculated as the total of job waiting times. Further sub-divisions of WIP are: (1) waiting times in stock before the processing of a job begins; (2) waiting times of precedent operations of a job (3) and waiting times in stock of finished products (see figure 3). Therefore, the throughput time of a job corresponds to the cumulative waiting times and the processing times (including set-up times). The quality-based evaluation is calculated for each operation. Minimizing the waiting times leads to the minimization of WIP and throughput times, as well as reducing negative output lateness of jobs. Minimizing over- and under-stressing is achieved by leveling out over the planning horizon concerned. Positive output lateness of jobs is prevented with a constraint, rather than being achieved via the objective function. This means that a suitable production plan can only be generated if the completion deadlines of all the jobs are satisfied. Capacity utilization is not considered in the pec-FJSP objective function as an objective. The machines' capacity utilization depends on the workload due to the jobs and operations considered. The number of jobs is predetermined before starting scheduling and therefore fixed during the optimization. However, the capacity utilization can be varied in the generation of instances. Nevertheless, the costs of unused capacity, which results from a low capacity utilization, must be considered to identify the real costs arising from a production plan. The costs of a machine's unused capacity consist of the machine costs per period. Total costs of unused capacity can be minimized if machines with higher machine costs per period are utilized more than machines with lower machine costs per period.

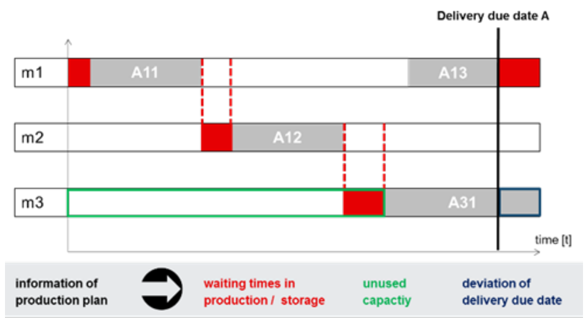

Figure 4: *Basis of the logistic objectives*

To estimate the costs arising from a production plan, costs for the considered objectives have to be estimated. The cost-based evaluation of the waiting times is undertaken based on the costs of tied-up capital, which are incurred during each period [10]. These costs must be identified after each operation within a job. The costs of tied-up capital consist of the interest on the actual manufacturing costs incurred for the job up to and including the current operation. The manufacturing costs consist of the total material costs (as per the parts list), machine costs (machine costs per hour), and labor costs (labor costs rates). Before the processing of a job begins, the manufacturing costs consequently only consist of the costs of materials. As the number of operations that have been completed within a job increase, the incurred costs of tied-up capital increase as well. As the overrunning of the completion deadline is not permitted, the evaluation of positive output lateness of jobs is not required (see figure 4). The over- and under-stressing of an operator is multiplied by an error cost price to obtain the error costs of a production plan. The over- and under-stressing of an operator can be expressed by a correction factor. The correction factor can be derived from the performance curve (see figure 2). For example, if the required attentiveness level for an operation is C, and the

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

operation is scheduled in a period where the performance level equals this attentiveness level, the correction factor is 1. On the other hand, the correction factor is higher than 1, if the attentiveness level required for an operation is less than the performance level for the corresponding period. Consequently, the correction factor is lower than 1, if the attentiveness level required for an operation is higher than the performance level for the corresponding period. It follows that the values of the correction factors for over- and under-stressing significantly influence the resulting product-related error costs of a production plan. Therefore, the definition of the values of the correction factors should be mapped as a whole. An error cost price can be determined by using the additional material ("spoilage") and time ("rework") requirements per year, related to a time period. The total costs of a production plan are calculated based on the logistics costs and the error costs. The identified cost parameters are incorporated into the objective function. The following assumptions are made for the pec-FJSP:

- All jobs, with their associated operations, must be processed within the planning horizon
- The processing of an operation cannot be interrupted
- The capacity that is utilized by the jobs must not exceed the available capacity of all the machines/ working places within the planning horizon
- The processing sequence for the operations within each job, must be adhered to
- Multiple operations within a manufacturing order must not be run in parallel on different machines/ working places
- Processing of an operation may only be carried out on a permitted machine/ working place
- At least one technologically suitable machine must be available for each operation
- Within a single period, only one operation can be processed on each machine/ working place
- Each machine is available in every period within the planning horizon
- The processing time of an operation is identical for each permitted machine
- The correction factor of an operation is known for each time period

4 OPTIMIZATION MODEL

For an optimization model, all logical restrictions must be identified and satisfied, for the given problem. To model a flexible job-shop scheduling problem which takes into consideration human performance fluctuations, we introduce the following decision variable: the binary decision variable x_{ijkt} equals 1, if operation j of product i is scheduled in period t on machine k, and 0 otherwise. Now we can formulate the optimization model with respect to indices and sets (see table 1), parameters (see table 2) and variables (see table 3):

Table 1: Indices and sets

i	identifier for a product $i \in \{1,2,\dots,I\}$
j	identifier for an operation $j \in \{1,2,\dots,J\}$
k	identifier for a machine, work place $k \in \{1,2,\dots,K\}$
t	identifier for a period $t \in \{1,2,\dots,T\}$
PA_i	set of operations of product i
Suc_{ij}	successor of operation j of product i

Table 2: Parameters

d_i	due date of job	period
pFK_{ij}	product-related error cost	€ / period
γ_{ijt}	correction factor of operation	
cD_{ij}	Cost rate delivery deviation	€ / period
cI_{ij}	cost rate of storage (inventory)	€ / period
cMS_{ij}	cost rate of working capital	€ / period
cWL_k	cost rate workload	€ / period
kap_k	usable capacity of machine k	
m_{ijk}	suitable machine k for operation j of job i	
p_{ij}	processing time	period
tt^*_{ij}	transition time	period

Table 3: Variables

ts_{ij}	starting time of an operation j of job i
te_{ij}	ending time of an operation j of job i
x_{ijkt}	$= \begin{cases} 1 & \text{if an operation j of job i is scheduled in period t on machine k} \\ 0 & \text{otherwise} \end{cases}$
Ys_{ijkt}	$= \begin{cases} 1 & \text{initial state of an operation j of job i on machine k in period t} \\ 0 & \text{otherwise} \end{cases}$
Ye_{ijkt}	$= \begin{cases} 1 & \text{final state of an operation j of job i on machine k in period t} \\ 0 & \text{otherwise} \end{cases}$
Z	Objective function (minimizing logistic and product-related error costs)

The formulation of the optimization model is as follows:

Objective function minimizing Z (1)

$$= \sum_{i=1}^{I}\sum_{j=1}^{J}(ts_{ij} - 1) \cdot cI_{ij} \tag{1.1}$$

$$+ \sum_{i=1}^{I}\sum_{j=1}^{J-1}(ts_{ij+1} - te_{ij}) \cdot cM_{ij} \tag{1.2}$$

$$+ \sum_{i=1}^{I}\sum_{j=J}^{J}(d_i - te_{ij}) \cdot kb_{ij} \tag{1.3}$$

$$+ \sum_{k=1}^{K}((kap_k - \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ijkt}) \cdot mks_k) \tag{1.4}$$

$$+ \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{ijkt} \cdot \frac{pFK_{ij}}{\gamma_{ijt}} \tag{1.5}$$

Constraints

$$x_{ijkt} - x_{ijkt-1} \le Ys_{ijkt} \quad \forall i,j \in PA_i,k,t \tag{2}$$

$$x_{ijkt} - x_{ijkt+1} \le Ye_{ijkt} \quad \forall i,j \in PA_i,k,t \tag{3}$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T} Ys_{ijkt} = 1 \quad \forall i,j \in PA_i \tag{4}$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T} Ye_{ijkt} = 1 \quad \forall i,j \in PA_i \tag{5}$$

$$ts_{ij} = \sum_{k=1}^{K}\sum_{t=1}^{T} Ys_{ijkt} \cdot t \quad \forall i,j \in PA_i \tag{6}$$

$$te_{ij} = \sum_{k=1}^{K}\sum_{t=1}^{T} Ye_{ijkt} \cdot t \quad \forall i,j \in PA_i \tag{7}$$

$$(ts_{ij} + p_{ij}) + tt^*_{ij} - 1 \le ts_{ij+1} \quad \forall i,j \in PA_i, s \in Suc_{ij} \tag{8}$$

$$te_{ij} - ts_{ij} + 1 = p_{ij} \quad \forall i,j \in PA_i \tag{9}$$

$$x_{ijkt} \le m_{ijk} \quad \forall i,j \in PA_i,k,t \tag{10}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ijkt} \le 1 \quad \forall k,t \tag{11}$$

The objective function (1) requires the minimization of error and logistic costs. In the first three lines, the costs of waiting times before the start of (1.1), between (1.2) and after the end of (1.3) the processing of operations of a job are minimized. In (1.4) the costs of unused capacity are minimized. Equation (1.5) guarantees minimizing error costs. Constraints (2) to (11) ensure the correct scheduling of the operations. Note, if an operation *j* of job *i* is scheduled in period *t*, the binary variable $x_{ijkt} = 1$. Thus, if this operation is not scheduled in period *t-1*, the initial state of operation *j* is period *t*. Therefore, (2) determines the initial state and (3) the final state of an operation. Equation (4) guarantees that an operation within the planning horizon is started only once. Therefore, equation (5) guarantees that an operation only ends once within the planning horizon. The starting time of an operation is determined by equation (6). Thus, equation (7) determines the ending time of an operation. Following the process sequence of the operations in a job is ensured by equation (8), and it prevents any overlaps in the scheduling. Equation (9) ensures that the interval between the start and end time of an operation comprises as many periods as are required to process that operation. Equation (10) ensures the selection of a suitable machine for an operation. Equation (11) ensures that in each period, only one operation for a job can be processed on each machine. This prevents any double allocations.

5 PROPOSED ALGORITHM

The pec-FJSP is an extension of the FJSP. Therefore, the pec-FJSP also belongs to the class of NP-hard problems. Thus, a heuristic approach is required for solving large problems. Here, a memetic algorithm (GA + LS) is developed and used for solving the pec-FJSP. The GA attempts to mimic the natural evolutionary process. Starting with an initial population, the algorithm executes genetic operators to hopefully produce offspring with a higher fitness level. The structure of the MA is as follows and will be explained in more detail:

1. **Coding**: A solution (production plan) of the pec-FJSP is coded as a GANTT diagram. A chromosome contains the production plan information in coded form. Each chromosome contains a solution of the pec-FJSP.
2. **Initial population**: The generation of the initial population takes place based on the latest starting time rule and a random component. Note that only suitable solutions are generated.
3. **Fitness evaluation**: The pec-FJSP objective function is used as the fitness function.
4. **Selection**: The n-size tournament selection is used for reproduction.
5. **Crossover**: The exchange of genetic information of m-chromosome creates new chromosomes. Infeasible solutions are repaired with repair procedures.
6. **Mutation**: The chromosomes undergo further change due to random mutation. The mutation takes place due to movement of an operation to another machine. This happens separately for each chromosome.
7. **Local search**: A local search is used for further improvement. This involves the fitness function specifically searching for operations which cause high costs and attempting to reduce these costs by changing the schedule.
8. **Reinsertion scheme**: At the end of the evolutionary process, the reinsertion scheme is used to decide which chromosomes will be removed from the current population and which will be incorporated into the population. In this, MA elitist reinsertion is used.

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

9. **Stopping criterion**: Step 3 to 8 describes the evolutionary process. A run of the evolutionary process is called a generation. The evolutionary process is repeated until the stopping criterion is reached. Here, it is a maximum computing time.

5.1 CODING

A chromosome consists of two strings: the operation and the machine string. A permutation with repetition is used to encode a chromosome, a solution of the pec-FJSP [35]. This is particularly suitable for sequencing problems, such as the JSP [36]. The machine string includes the machines allocated to the operations. A gene in the machine string describes on which machine an operation is scheduled. The operation string contains the sequence of operations j, within all jobs I (O_{ij}). Only the job index is integrated into the operation string. The job index is repeated according to the number of operations within the job. This ensures that any permutation of job indices can be interpreted as a feasible sequence of operations [37]. In decoding a chromosome, a solution, i.e. a production plan, is always feasible in respect of the processing sequence of the operations within a job.

For example, job 2 consists of two operations (see figure 3). Therefore, the job index 2 occurs two times within the operation string. The occurrence of the job index provides information about the operation. Job index 1 appears for the second time in the fifth gene of the operation string. Consequently, this is the second operation of job 1 (O_{12}). Unallocated time domains are depicted by idle time phases ($b_i = 1, \dots, B$). All idle time phases have job index 0 and a processing time of one period.

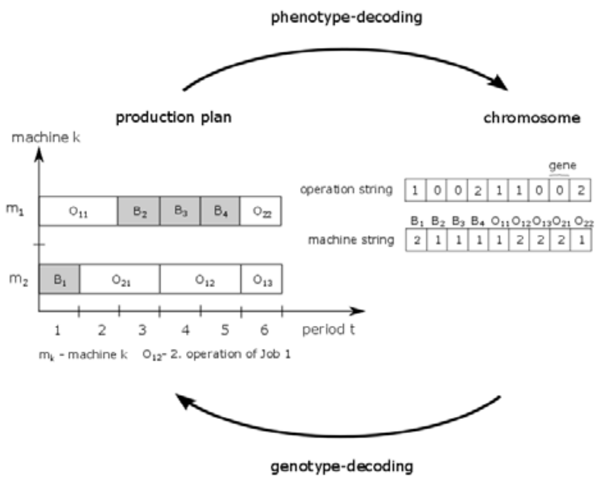

***Figure 5:** Phenotype and genotype decoding*

For decoding a chromosome in a production plan, the gene values in the operation string are considered from left to right and the corresponding operation or idle time phase, is allocated in the production plan for the machine, specified in the machine string. An operation or idle time phase, is always allocated at the earliest possible available period.

In Fig. 4 the first gene value in the operation string is job index 1. This is the first time that job index 1 occurs in the operation string. Hence, the corresponding operation is O_{11}, which has to be carried out on machine 1. Operation O_{11} is now allocated at the earliest possible available period for machine 1 (period 1). The next gene value in the operation string is job index 0 and represents the first idle time phase B_1. B_1 is allocated to machine 2 at the earliest possible available period (period 1). The idle time phases are necessary to determine a definite start and end period for the operations in the production plan. Without idle time phases, the decoding procedure could lead to several possible and infeasible production plans.

5.2 INITIAL POPULATION

An algorithm was developed for the generation of the initial population. The initial population contains only feasible chromosomes. The generation of a feasible chromosome is divided into two phases. First, the operations are scheduled on the machines. For this purpose, the latest starting times ($slate_i$) for each operation is determined based on the due date information for the corresponding job. Second, the subsequent steps are repeated until all the operations are scheduled. The operation with the smallest latest possible start time value is selected. Then the earliest possible start time ($searly_i$) for job i, relative to the selected operation, is determined. After that, a suitable machine for the particular operation is selected randomly – note that the unused machine's capacity must be equal to or greater than the capacity requirements for the specific operation. Now, all the potential start times for the selected machine between $slate_i$ and $searly_i$, are determined. If there are several possible start times, a selection is made randomly. If no potential start time can be found, all other permissible machines are considered in turn. If this also fails, the initialization is stopped, the production plan is deleted, and the initialization is restarted. After scheduling all operations, idle-time phases are assigned for the individual machines which have not yet been scheduled. The initialization is repeated until a specified population size μ is achieved. However, a chromosome can only occur once in the population. That means that each chromosome must have a different fitness level.

5.3 FITNESS EVALUATION

The fitness function calculates the respective fitness level of each chromosome in the population. The pec-FJSP objective function is used as the fitness function. To minimize error and logistics costs, the MA searches for solutions with a low fitness value. A low fitness value equates to a high fitness level. Within the evolutionary process infeasible solutions may arise (see Crossover) and are penalized by a "big M" (a very high value of 1,000,000,000).

5.4 SELECTION

Some chromosomes must be selected for the evolutionary process. Chromosomes are first randomly selected for the mating pool by tournament selection. This involves ξ chromosomes in the tournament and the chromosome with the best fitness being copied to the mating pool. This process is carried out μ-times. Chromosomes can occur several times in the mating pool. After that, two chromosomes are randomly selected from the mating pool for the evolutionary process.

5.5 CROSSOVER

To produce offspring, the selected chromosomes are crossed with each other. For this purpose, the precedence preserving order-based crossover (POX) procedure is used for the operation string, and the one-point crossover procedure is used for the machine string. The POX procedure guarantees with the encoding scheme used, the correct number of operations in the operation string of the offspring. The crossover may nevertheless produce infeasible solutions. The following impermissibility's may arise:

- Breaching the machine capacity (the total of the processing times and idle time phases on the machine is greater or less than T)
- Over running the completion deadline
- Deviation from the sequence in which the operations should be processed

If an infeasible solution is generated, two repair procedures are used to repair the chromosomes. The repair procedures are carried out one after the other. If a chromosome cannot be fully repaired, the described crossover procedures are carried out again. If no permissible chromosomes could be produced after running a specified number of crossover procedures (Limit_CO), the evolutionary process is continued using an impermissible chromosome. The aim of the first repair procedure is to rectify any breach of machine capacity. To do this, operations are moved from the most heavily over-loaded machine to the most lightly loaded machine. Changes are made to the specific genes which have caused the impermissibility. The aim of the second repair procedure is to rectify the other two impermissibilities. To do this, the machine assignment is fixed and an attempt is made to interchange the sequence of operations and idle time phases within the operation string in such a way that suitable chromosomes are produced. Both repair procedures include a fixed number of repair attempts (Limit_shiftingKap and Limit_repair). If the number of repair attempts is exceeded, the crossover procedures recommence.

5.6 MUTATION

Chromosomes undergo a further change due to random mutation within the evolutionary process. The mutation rate (Mutate_rate) decides whether a chromosome mutates. The mutation is based on the random movement of an operation to another machine. Therefore, during mutation, a machine is selected first. After that, the largest suitable continuous range of idle time phases on this machine is identified. Then another machine is specified, from which an operation can be moved. One operation is selected at random from all the operations which are assigned to this machine. If these preconditions are not fulfilled, another suitable machine is considered, or once all the suitable machines have been considered, another operation which has to be moved is selected. An operation may only be moved once. A mutation counter counts the attempts and stops the mutation after a randomly generated number of attempts.

5.7 LOCAL SEARCH

The local search procedure improves the fitness of the generated chromosomes. The basis of the local search procedure is the determination of the largest cause of costs within a chromosome, in the form of a critical operation pair. The critical operation pair can be determined in the decoded solution, by the corresponding start and end times and the cost rates. The highest costs may be caused by the costs of tied-up capital, due to long waiting times between the critical operation pair or, between the completion deadline and the last operation within a job. Furthermore, penalty costs for impermissibilities (see Crossover) may also cause the highest level of costs. If the critical operation pair is detected, the corresponding time domain in which the critical operation pair is scheduled, is completely removed from the production plan. An attempt is made to reschedule the operations removed so that the highest costs no longer arise and the chromosome's fitness is consequently improved. The local search procedure neighborhood is therefore defined as the number of all permissible allocations of the removed operations in the considered time domain. If no improvement can be achieved after a specified number of attempts (Limit_noAssign), the local search is continued with the critical operation pair responsible for the next highest level of costs. Furthermore, there is a limit on the number of attempts made which do not produce any improvement (Limit_noimprove), before the next chromosome is considered. The local search ends once a specified number of neighbors or chromosomes have been reached (Limit_searchCounter).

6 VALIDATION

The goal of the following evaluation is to validate the pec-FJSP. To do this, the influence of product-related error on the total costs of a production plan is tested. First, the performance of the developed MA is evaluated. Since the MA's practical applicability has a higher priority than its performance in computing the best possible solution, a short computing time is necessary. The MA should be able

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

to solve practical problem sizes with an adequate performance. Thus, it is not the purpose to reach or exceed the performance of existing state-of-the-art heuristic approaches for solving the conventional FJSP.

6.1 Experimental Set Up

The literature only includes examples from conventional FJSP. These are not applicable to the pec-FJSP. Therefore, it is necessary to generate examples for the pec-FJSP. Six examples are generated for validating the pec-FJSP and the MA. The set-up of the test examples *TI* is shown in table 4.

Table 4: Set-up of generated instances

Name	# of jobs	# of machines	# of operations	# of periods	Utilization (%)
TI01	2	3	3	32	26.0
TI02	4	3	3	32	52.1
TI03	6	6	3	32	38.5
TI04	8	6	3	32	49.4
TI05	10	6	3	32	60.4
TI06	12	6	3	32	72.3

The examples are based on the assumptions of job-shop production, in which the jobs must undergo three different process steps on three different types of machines. This produces a constant number of three operations for all instances. The situations differ in terms of the number of jobs, the number of machines that are available and the capacity utilization. The capacity utilization U in each instance is determined by the equation (12).

$$U = \frac{\sum_i \sum_j p_{ij}}{T \cdot K} \tag{12}$$

The machines are assigned to one of three machine types; each of them are able to process one specific operation. Table 5 shows the assignment of the machines to the machine types and the operations.

Table 5: Assignment of machines k to machine types and operations

	Machine type 1	Machine type 2	Machine type 3
Operation 1	$k_1; k_2$		
Operation 2		$k_3; k_4$	
Operation 3			$k_5; k_6$

Table 6 shows the assignment of the amplifier factor to the jobs, considering performance curve and attentiveness levels required for the operations. To characterize the attentiveness level required by the operations, three levels (*A*, *B*, *C*) were adopted. Attentiveness level *A* needs the highest attention, compared to the lowest attention by level *C*. Note if an instance exists of more than one job, the selected jobs follow from one to twelve, until the number of jobs considered in the instance is reached.

Table 6: Assignment of amplifier factors to jobs and attentiveness characterization of operations

	amplifier	attentiveness level operation 1	operation 2	operation 3
Job 1	1.00	A	B	C
Job 2	1.00	A	B	C
Job 3	0.90	A	C	B
Job 4	0.90	A	C	B
Job 5	0.80	B	A	C
Job 6	0.80	B	A	C
Job 7	0.70	B	C	A
Job 8	0.70	B	C	A
Job 9	0.60	C	A	B
Job 10	0.60	C	A	B
Job11	0.50	C	B	A
Job12	0.50	C	B	A

The performance curve used is shaped according to Potthast [27]. However, no distinction is made between morning and evening types. The performance curve is standardized relative to job 1 to job 12. The corresponding attentiveness levels, in relation to the time periods, are shown in table 7. This information can be used to derive the time period-related correction factors for the operations.

Table 7: Period-related attentiveness levels

Attentiveness level	Periods			
A	3-8	22-25		
B	1-2	9-10	18-21	26-29
C	11-17	30-32		

The planning horizon is based on a single-shift model, using a period length of 15 minutes and a shift length of eight hours (one operational calendar day with 32 periods). The job processing times (see table 8) and logistic costs, are based on a normal distribution of random numbers. The mean values were used for generating the normal distribution of random numbers and are based on empirically ascertained values in the mechanical engineering sector. The following assumptions were used for the determination of mean product-related error costs: the company studied can produce 400 different products, has annual revenue of 35 Mio. € and incurs product-related error costs of 15% of the annual revenue. The average processing time of an operation is one hour (4 periods). All jobs must be completed by period 32.

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

Table 8: Processing times of operations

	Operation 1	Operation 2	Operation 3
Job 1	5	5	4
Job 2	3	3	5
Job 3	3	3	5
Job 4	5	4	5
Job 5	4	3	3
Job 6	6	4	4
Job 7	3	4	4
Job 8	5	2	3
Job 9	2	5	3
Job 10	3	5	3
Job11	4	4	2
Job12	4	4	5

Table 9 includes the MA parameters, which were used. The parameters were applied and statistically analyzed, so that the combination of values produced the best results.

Table 9: Used MA parameters

Parameters	Description	Value
TimeDuration	Time duration in minutes	15
PopSize (μ)	Population size	50
mue (ξ)	Number of randomly chosen chromosomes for the mating pool (ξ)	2
Limit_CO	Number of Crossover tests	10
Limit_shiftingKap	Number of Repair tests (procedure 1)	20
Limit_repair	Number of Repair tests (procedure 2)	20
Mutate_rate	Mutation probability	0.6
Limit_tabuCounter	Number of considered chromosomes at LS	2
Limit_noAssign	Number of allocation attempts for critical operation pair at LS	10
Limit_noImprove	Number of improving attempts per chromosome at LS	2

6.2 Computational Results & Comparison

All instances were carried out on a computer with an Intel Core i5 2.5 GHz processor and 4 GB RAM. Note that the problem considered has not been addressed in literature. Therefore, no approach exists for solving the pec-FJSP and the MA developed could not be validated. Thus, all the instances were first solved using a commercial solver which can produce optimal solutions (reference solutions). This modelled the pec-FJSP in the GAMS modeling language and solved it using the CPLEX version 12.6 solver.

Each instance is solved once using the CPLEX solver. Solving is stopped after reaching a maximum computing time of 1 hour. In table 10, column CP shows the best solutions found by CPLEX for all the instances. Column CP time, shows the computing time required to find the best solution. During the remaining computing time, CPLEX did not find a better solution. CPLEX found the optimal solution for all instances. Thus, the solution is marked with an asterisk (see table 10). Column dev LB, shows the percentage deviation from the lower boundary found by CPLEX.

The MA is implemented in JAVA. Ten runs with a computing time of 5 minutes were executed for each instance. The MA best, column in table 10 shows the best solution found by ten runs. Column MA avg, shows the average solution which is calculated from the best solution found in each of the ten runs. Columns LB_dev shows the percentage deviation between the best solution generated by the MA and the best solution found by CPLEX, or between the average MA solution and the solution produced by CPLEX.

For all instances, the MA did not find the optimal solution. Therefore, the MA is unable to find the optimal solution. Across all instances, the average deviation is 6.08%. Thus, the MA is capable of solving the pec-FJSP with an adequate solution quality, within a short computing time, for a practical application.

Table 10: Comparison of CPLEX and MA

Name	CP	CP time (sec.)	LB dev. (%)	MA best	CP dev. (%)	MA avg.	CP dev. (%)
TI01	5281*	1	0.00	5314	0.73	5367	2.61
TI02	11697*	2	0.00	11781	0.82	11869	2.45
TI03	12491*	10	0.00	12937	3.45	13116	4.77
TI04	20463*	32	0.00	21122	3.22	21825	6.25
TI05	29221*	373	0.00	30723	4.89	31780	8.06
TI06	39069*	811	0.00	40762	4.16	42262	7.56
						avg.	6.08

Figure 6 shows the convergence curve for the best and the average solution generated by the MA based on instance TI04.

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

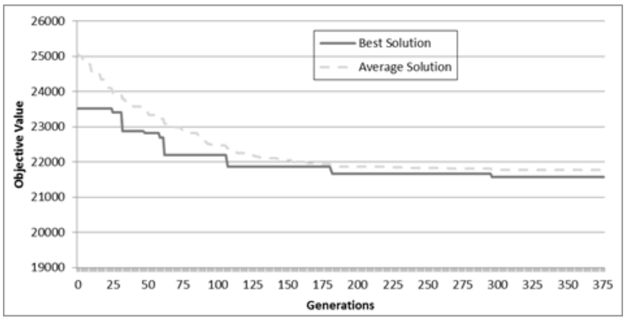

Figure 6: MA convergence curve Run 4 of TI04

Considering figure 5, the objective function value decreases very sharply within the first 50 generations. Within the next generations, the objective function value decreases only slightly. Only the first 375 generations are shown, because the subsequent generations produced no change in the objective function value. The computing time for the first 375 generation was 350 seconds. It should be noted that the MA can generate good solutions within a small number of generations.

6.3 Further analysis

To validate the influence of considering product-related error costs in production planning, instance TI04 was solved a further ten times, only taking account of logistic costs as an objective function. The under- and over stressing profile that was produced was recorded separately, to determine machine-related quality factors (see table 11 ff.). A machine-related quality factor describes the average correction factor used for those operations, which are scheduled on an individual machine. Note that the correction factor depends on the time period in which an operation is scheduled. Therefore, the machine-related quality factor is higher when the operational worker is less overloaded (underloaded) – overloading leads to higher product-related error costs. The results of both solutions for example TI04 (with and without consideration of the product-related error costs) are shown in table 12.

Table 11: Results of instance TI04 with and without consideration of product-related error costs – objective value

	without product-related error-costs			with product-related error-costs		
Run	Error costs	Logistic costs	Total costs	Error costs	Logistic costs	Total costs
1	115	21139	21254	112	21857	21969
2	114	21229	21343	112	21446	21558
3	113	20531	20645	110	21405	21515
4	112	20887	20999	110	21459	21569
5	112	20446	20558	112	21168	21280
6	114	21295	21409	112	21857	21969
7	113	21855	21968	109	21574	21683
8	113	21737	21850	110	21986	22096
9	114	20749	20863	109	21013	21122
10	114	22028	22142	113	21588	21701
avg.	113,4	21189	21144	110,9	21535	21646
dev. (%)	2,25	-1,61	-2,32			

The consideration of product-related error costs within the objective function leads to higher logistic and total costs. While the product-related error costs decrease by 2.25%, on the other hand, the logistic costs increase by 1.61%. However, the absolute value is deflected. Furthermore, the achievable cost-saving potential depends on the product-related error costs and logistic cost rates, which are used. Specifically, it depends on the relative cost ratio of product-related error costs to logistic costs. Each cost rate must be individually determined for each specific application. As stated above, an attempt has been made to make the costs used in the validation as realistic as possible. The correction factor assumed can also be adjusted. Finally, the pec-FJSP can lead to a reduction in the costs which arise in relation to a production plan.

Table 12: Results of instance TI04 with and without consideration of product-related error costs – quality factor

quality factor – with product-related error-costs							
Run	k1	k2	k3	k4	k5	k6	avg.
1	0.98	0.99	1.02	1.04	1.02	1.02	1.01
2	0.98	0.97	1.01	1.05	1.02	1.01	1.01
3	0.97	0.96	1.01	1.00	1.04	1.02	1.00
4	0.95	0.99	1.00	1.03	1.06	1.00	1.00
5	1.01	0.91	1.01	1.01	1.04	1.05	1.00
6	0.97	0.96	1.01	1.01	1.00	1.04	0.99
7	0.94	0.99	1.05	1.03	1.01	1.04	1.01
8	0.95	0.96	0.97	1.04	1.06	1.04	1.00
9	1.00	0.97	0.97	1.04	1.05	1.03	1.01
10	0.96	0.97	1.07	1.02	1.00	1.06	1.01
quality factor – without product-related error costs							
1	0.90	0.98	1.02	1.01	1.01	1.01	0.98
2	0.94	1.01	1.06	0.97	1.07	1.00	1.00
3	0.96	0.99	1.03	1.01	1.02	1.00	1.00
4	1.00	0.96	1.04	1.01	1.05	0.99	1.00
5	0.95	0.99	1.00	1.01	1.00	1.06	1.00
6	0.97	0.95	0.97	1.07	1.00	1.01	0.99
7	0.95	0.95	1.02	0.99	1.03	1.02	0.99
8	1.09	0.96	1.00	1.04	1.01	1.04	1.02
9	0.96	0.97	1.00	1.03	1.02	1.04	1.00
10	0.99	0.95	1.03	1.00	1.02	1.03	1.00

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

Comparing the machine-related quality optimization factors, with and without the consideration of product-related error costs, it can be stated that the average quality factor over all runs is higher if product-related error-costs are included in the objective function – the higher the value of the quality factor, the lower the overload of the worker (see table 13). Accordingly, the MA schedules complex operations in periods in which the worker is at peak performance.

Table 13: Comparison of the waiting times and throughput time

	without product-related error-costs (Run 8 of TI04)		with product-related error-costs (Run 8 of TI04)	
Job	waiting time	throughput time	waiting time	throughput time
1	6	20	0	14
2	0	11	7	18
3	8	19	2	13
4	5	21	4	18
5	7	17	14	24
6	3	17	9	23
7	3	14	3	14
8	6	16	3	13
total	38	135	42	137
dev. (%)			10..52	1..49

As shown in Table 13, the consideration of product-related error costs leads to an increase in the waiting times between the operations, and consequently also to an increase in the throughput time of the jobs. A comparison of the scenarios shows that the throughput times increase by 2 periods, when product-related error costs are considered. The reason is the fitting of the production plan to the assumed shape of the performance curve. Therefore, the assumed shape of the performance curve is significant.

7 Summary and Conclusion

In this article, the FJSP is extended by considering product-related error costs (pec-FJSP) due to over stressing of operational workers. The objective of the extended FJSP is to minimize error and logistic costs simultaneously. Logistic costs are based on the logistical objectives; work in process and throughput time. A memetic algorithm is used to solve the pec-FJSP. The evolutionary process is supplemented with a local search procedure and repair mechanisms. The MA is validated with instances which had been generated against those generated by a commercial branch-and-cut solver.

The MA achieved good results while using less computing time. Thus, the MA could be a suitable heuristic for applying the pec-FJSP in practice. The MA developed provides an inexpensive means for even small and medium-sized companies to exploit the existing cost-saving potential.

In further research, the analysis of the pec-FJSP should focus on the general influence factors of the problem stated above. Expressed differently: What are the cost drivers in FJSP considering product-related error costs? First steps are the relative cost rates of product-related error costs and logistic costs, the form of the performance curve, the standard deviation of the complexity of the products which must be produced and utilization.

Promotion notice

This article is produced within the research project “quality-based job-shop scheduling”. The IGF project 18312 N of the FQS – Forschungsgemeinschaft Qualität e.V. is funded by the AiF within the program for the promotion of industrial joint research (IGF) by the Federal Ministry of Economics and Energy based on a decision of the German Bundestag.

References

[1] H.-P. Wiendahl, Betriebsorganisation für Ingenieure, München und Wien: Carl Hanser Verlag, 2010.

[2] H. D. Seghezzi und J. R. Hansen, Qualitätsstrategien - Anforderungen an das Management der Zukunft, München und Wien: Carl Hanser Verlag, 1993.

[3] Deutsche Gesellschaft für Qualität e.V., Leitthesen für Qualität in Deutschland, München: Carl-Hanser-Verlag, 2012.

[4] G. F. Kaminske und J.-P. Brauer, Qualitätsmanagement von A bis Z: Erläuterung moderner Begriffe des Qualitätsmanagements, München und Wien: Carl Hanser Verlag, 2008.

[5] W. Geiger und K. W., Handbuch Qualität: Grundlagen und Elemente des Qualitätsmanagements - Systeme und Perspektiven, Wiesbaden: Vieweg Verlag, 2008.

[6] J. Rothlauf, Total Quality Management in Theorie und Praxis: Zum ganzheitlichen Unternehmensverständnis, München: Oldenburg Wissenschaftsverlag, 2010.

[7] T. Pfeiffer, Qualitätsmanagement Strategien, Methoden und Techniken, München und Wien: Carl Hanser Verlag, 2001.

[8] E. H. Hartmann, TPM - Effiziente Instandhaltung und Maschinenmanagement, München: mi-Fachverlag, 2007.

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

[9] P. Rochow, C. Böning und H. Prinzhorn, „Qualitätsorientierte Belegungsplanung,“ *Zeitung für wirtschaftlichen Fabrikbetrieb,* Nr. 10, pp. 599-602, 2015.

[10] E. Hering, J. Triemel und H.-P. Blank, Qualitätsmanagement für Ingenieure, Berlin u. a.: Springer Verlag, 2003.

[11] M. Pinedo, Scheduling: Theory, Algorithms and Systems, New York, Heidelberg, London: Springer, 2012.

[12] M. Yazdani, M. Amirir und M. Zandieh, „Flexible Job-Shop Scheduling wirh Parallel Variable Neighboorhood Search Algorithm,“ *Expert System Applications,* Nr. 37, pp. 678-687, 2010.

[13] P. Nyhuis und H.-P. Wiendahl, Fundamentals of Production Logistics, Berlin, Heidelberg: Springer, 2009.

[14] H.-P. Wiendahl, Load-Orientated Manufacturing Control, Berlin, Heidelberg New York: Springer, 1995.

[15] E. Gutenberg, Grundlagen der Betriebswirtschaftslehre - Die Produktion, Berlin, Heidelberg: Springer, 1951.

[16] P. Brucker und R. Schlie, „Job shop scheduling with multi-purpose machines,“ *Computin,* Bd. 45, pp. 369-375, 1990.

[17] Y. X. H. Yuan und J. Yang, „A hybrid harmony search algorithm for the flexible job shop scheduling problem,“ *Application Soft Computing,* Bd. 13, pp. 3259-3272, 2013.

[18] H. Chen, J. Ihlow und C. Lehmann, „Agenetic algorithm for flexible job shop scheduling,“ *International conference of robotic,* pp. 1120-1125, 1999.

[19] I. Kecem, S. Hammadi und P. Borne, „Approach by localization and multiobjective evolutionary optimization for flexible job shop scheduling problems,“ *System Manufacturing,* Bd. 32, pp. 1-13, 2002.

[20] J. Gao, L. Sun und M. Gen, „A hybrid genetiv and variable neighborhood descent algorithm for flexible job shop scheduling problems,“ *Computing in Operations Research,* Bd. 35, pp. 2892-2907, 2008.

[21] N. Al-Hinai und T. El-Mekkawy, „An Efficient Hybridized Genetic Algorithm Architecture for the Flexible Job Shop Scheduling Problem,“ *Flexible Services and Manucturing Journal,* Bd. 23, pp. 64-85, 2011.

[22] H. O. Günther und H. Tempelmeier, Supply Chain und Operationsmanagement, Norderstedt, 2014.

[23] O. Graf, Arbeitsablauf und Arbeitsrythmus - Handbuch der gesamten Arbeitsmedizin, Bd. 1, Berlin, München und Wien: Verlag Urban & Schwarzenberg, 1961.

[24] T. H. Monk und D. E. Embrey, A field study of circadian rythms in actual and interpolated taks performance, Oxford: Pergamon Press, 1981.

[25] J. Gärtner, Handburch Schichtpläne - Planungstechnik, Entwicklung, Ergonomie und Umfeld, Zürich: vdf Hochschulverlag, 1998.

[26] B. Bjerner, A. Holm und A. Swensson, „Diurnal Variation in Mental Performance,“ *British Journal of Industrial Medicine,* Bd. 12, p. S. 103 ff, 1955.

[27] J.-M. Potthast, Nachweis zirkadianer Leistungsschwankungen bei manuellen Montagetätigkeiten, Hannover: Dissertation, Universität Hannover, 2013.

[28] B. Mac Carthy, J. Wilson und S. Crawford, „Human Performance in Industrial Scheduling,“ *Human Factors and Ergonomics in Manufacturing,* Bd. 11, Nr. 4, pp. 299-320, 2001.

[29] „The human planning and scheduling role in advanced manufacturing systems,“ *Human Factors,* Bd. 31, pp. 635-666, 1989.

[30] B. Rauch-Gebbensleben, F. Kähne, G. Horton, N. Schlitter, S. Schilz und M. Neike, „Ein Simulationsmodell zur Nachbildung von unternehmensübergreifenden Produktionsfehlern,“ *Advances in simulation for production and logistics applications,* pp. 309-318, 2008.

[31] L. Guimaraes, J. Ribeiro, T. Saurin und P. Homem de Bittencourt, „Circadian rhythms as a basis of work organization. A study with live line electricians,“ *The Journal of Human Factors and Ergonomics Society,* Bd. 55, Nr. 1, pp. 204-217, 2013.

DOI: 10.2195/lj_NotRev_prinzhorn_en_201710_01
URN: urn:nbn:de:0009-14-46119

[32] M. Glonegger, Berücksichtigung menschlicher Leistungsschwankungen bei der Planung von Variantenfließmontagesystemen, München : Technische Universität München, Dissertation, 2014.

[33] M. Raessi und Z. Kobti, „A memetic algorithm for job shop scheduling using a critical path based local search heuristic,“ *Memetic Computing,* Bd. 4, pp. 231-245, 2012.

[34] J. Jiang, M. Wen, K. Ma., X. Long und J. Li, „Hybrif Genetic Algorithm for Flexible Job Shop Scheduling with Multi-Objective,“ *Journal of Information & Computational Science,* Bd. 8, pp. 2197-2205, 2011.

[35] H. Prinzhorn, P. Rochow und P. Nyhuis, „Grundlagen einer Methode für eine qualitätsorientierte Belegungsplanung,“ Logistics Journal, 2017.

[36] C. Bierwirth, „A generalized permutation approach to job shop scheduling with genetic algorithms,“ *OR Spektrum,* Bd. 17, Nr. 87, pp. 87-92, 1995.

[37] A.-E. Eiben und J. Smith, Introduction to Evolutionary Computin, Berlin, Heidelberg: Springer, 2003.

[38] G. Zäpfel, R. Braune und M. Bögl, Metaheuristic Search Concepts, Berlin, Heidelberg: Springer, 2010.

[39] H.-O. Günter und H. Tempelmeier, Produktion und Logistik, Berlin und Heidelberg: Springer Verlag, 2012.

[40] W. H. Spriggs, Essentials of Polysomnography, London: Jones & Bartleft Publishers, 2009.

[41] C. Schlick, R. Bruder und H. Luczak, Arbeitswissenschaften, Heidelberg u. a.: Springer Verlag, 2010.

[42] H.-V. Ulmer, „Graf-concept of circadian rhythms of working capacity - paradigmatical error by wrong generalization,“ *Pflügers Archiv - European Journal of Physiolgy,* Nr. 447, p. 153, 2004.

[43] G. Reinhart, M. Glonegger, J. Egbers, J. SChilp, A. Göritz und J. Weikamp, „Taktzeitadaption unter Berücksichtigung der zirkadianen Rhythmik,“ *wt Werkstattechnik online,* Nr. 9, pp. 595-599, 2011.

[44] Betriebsorganisation, Verband für Arbeitsstudien und, Arbeitsgestaltung in der Produktion, München: Hanser Verlag, 1991.