Proceedings of the 2018 Winter Simulation Conference
M. Rabe, A.A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, eds.

ACTOR-ORIENTED OPTIMIZATION MODEL FOR MAINTENANCE TASKS

Sven Tackenberg

Department of Production Planning
in Industrial Engineering
OWL University of Applied Sciences
Liebigstraße 87
32657 Lemgo, GERMANY

Sönke Duckwitz

Institute of Industrial Engineering
and Ergonomics
RWTH Aachen University
Bergdriesch 27
52062 Aachen, GERMANY

ABSTRACT

This paper introduces an extension of the well-established Resource-Constrained Project Scheduling Problem (RCPSP) to apply it to maintenance problems of highly frequented infrastructure. A major complication of the observed scheduling problem is that the infrastructure is only temporarily available for maintenance and repair work during the shift of the workforce. A multi-criteria evolutionary algorithm with a novel problem representation is introduced which is capable of revising technician-task allocations whereas the duration of the task may be stochastic. The main objective is to develop shift plans which maximize the utilization rate of technicians due to a minimization of waiting times caused by the use of the infrastructure through other actors. The results of the already implemented core algorithm for an actor-oriented model illustrate a fast convergence towards an optimal work allocation within a team as well as an efficient sequence of tasks.

1 INTRODUCTION

Maintenance problems of highly frequented infrastructure such as the railway infrastructure, motorway or power networks are examples of operations that can be processed only at specific times and which are susceptible to disruption. Therefore, scheduling of these operations responding to the limited access to the installation as well as the restricted capacity of technicians is a difficult task. Human dispatchers who are responsible for the compilation of teams and the assignment of tasks to teams base their decisions on their individual experience and domain knowledge. Accordingly, three elements are crucial for the quality of plans: The amount and precision of available information regarding the accessibility to the component of infrastructure to be maintained as well as the ability of technicians and the probable processing time.

The scheduling problem is described by a given set of tasks and a group of technicians. In each work shift, teams of technicians are supposed to process tasks that have merely precedence constraints. The team members must stay together during a work shift but they can work on different tasks at the same location. Therefore, tasks may be performed with overlapping, an interruption of tasks is allowed and if a task is started it has to be finished in the same shift. Any travel and setup time between tasks is considered in the parameters of a task. The objective of the scheduling problem is to utilize the capacity of the teams, to maximize the number of tasks finished on time as well as to use the possible maintenance periods of the infrastructure as comprehensive as possible.

The paper is organized as follows. In section 2 the maintenance problem is introduced and in section 3 a formal problem description is given. Based on the characteristics of the scheduling problem a short literature review is presented in section 4. In the following section 5 the current state of the algorithm is explained and in section 6 the computational results of our algorithm are reported.

2 THE MAINTENANCE PROCESS

In the domain of infrastructure management the scheduling of maintenance tasks for e.g. the railway infrastructure, a motorway or a power networks is very demanding. The challenges arise from dependencies between many different players, a limited capacity of the infrastructure and external factors such as weather conditions or regulations on working hours. High costs of maintenance associated with a low utilization rate of technicians as well as a poor accessibility to the components of the infrastructure have led to particular interest in scheduling maintenance teams (Maletič et al. 2012).

Inefficient team constellations and withdrawal periods due to a low accessibility to the components of the infrastructure for maintenance purposes are major sources of high maintenance and repair costs. Combining all activities related to the maintenance of the infrastructure, maintenance can be regarded as the process of inspecting and if necessary repairing the components of the infrastructure. Thereby, the field of maintenance is characterized by tasks which require a heterogeneous skilled workforce.

With a focus on the maintenance core processes for a railway infrastructure, the work can be described as follows. The members of a maintenance team start their shift together at a defined maintenance base. After preparing and loading tools and material the team members drive together to the location of the operation site. At the site a member of the team has to register the operation and to lock the area of the infrastructure which is influenced by the maintenance work. Due to train traffic and safety regulations a locking of parts of the infrastructure is only admissible under given circumstances and is carried out by an operator who is not a member of the maintenance team. If an area or a component is locked, the track section is closed to train traffic. During the locking period the technicians are allowed to work on the infrastructure and to process maintenance tasks. When the maintenance operations are finished and the safety of the installation is approved, trains are able to enter the track section again.

Let us consider a typical scheduling problem of a dispatcher. We assume that the minimum shift of the technicians is at least 6 hours due to a work agreement. The available daily shutdown period of the infrastructure is for example from 1 a.m. to 4 a.m. During this period an unrestricted access to the infrastructure for maintenance purposes is given. Outside this period, train traffic is possible and has priority over maintenance. As a result, the probability of process related waiting times for the technicians increases. Figure 1 a) illustrates an exemplary instance of scheduled inspection and maintenance tasks on a day shift. During a night shift repair work is mainly carried out to upgrade or replace defective components. This process is illustrated in Figures 1 b). The arrow represents the shutdown period of the infrastructure. Note that these processes describe only those forms of maintenance processes that were inspired by the observations of the authors. Thereby, we decided to focus on the scheduling problem of a day and a night shift as they illustrate the shortcomings of current RCPSP approaches.

3 PROBLEM DESCRIPTION AND NOTATION

The problem we introduce in this paper is based on the work of Firat and Hurkens (2011) as well as Li and Womer (2009). In the following sections we describe the scheduling problem in our notation.

3.1 Technicians

To perform the maintenance tasks, a set of technicians $W = \{1, ..., m\}$ is given. All of them have a priori defined working hours for each calendar day. The variable t_{day} defines the simulation time t at midnight of the current day. Individual working hours of $w \in W$ are expressed by the period between start $\tau_{w,AA}$ and lunchtime $\tau_{w,PA}$ as well as between end of break $\tau_{w,PE}$ and end of work $\tau_{w,AE}$. $\varsigma_{w,t} = 1$ denotes the availability of technician w at the time of t and zero otherwise.

In order to characterize the individuality of each technician we use the terms qualification to describe the formal basic qualifications (e.g. track layers, signal engineer) (1) and competence to express the individual expertise for processing a task in a specific domain. The set of qualifications is denoted by $q \in Q$. Each technician w has at least one qualification $q \in Q$ (2) and one competence $k \in K$ (5). The qualifications of W are described by the qualification matrix $QM^{(w,q)}$ (2)

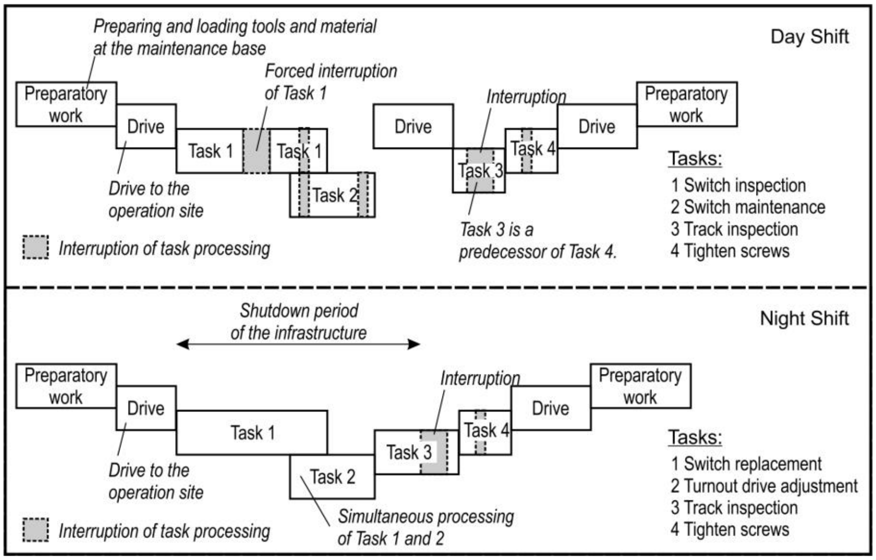

Figure 1: Simplified description of the maintenance process.

$$\xi_{w,q} := \begin{cases} 1, & if: \quad employee\ w \in W\ has\ the\ qualification\ q \in Q \\ 0, & else \end{cases}, \tag{1}$$

$$QM^{(w,q)} := \begin{Bmatrix} \xi_{11} & \cdots & \xi_{1Q} \\ \vdots & \vdots & \vdots \\ \xi_{W1} & \cdots & \xi_{WQ} \end{Bmatrix}, \quad \xi_{w,q} \in \{0,1\}, \sum_{q \in Q} \xi_{w,q} \geq 1, \ \forall\, w \in W, q \in Q. \tag{2}$$

For each competence k of a technician w the acquired level l is expressed by a competence vector $KV_w^{(1.k)}$(3). Due to the fact that gaining expertise often takes place in steps described by levels $l \in L$, the model defines hierarchical relations between these levels (4). Therefore, the levels of w for all competences can be expressed by a matrix $(l, k) \in L \times K$ (5). The level l of expertise of technician w in the domain of competence k is defined by max $\{\{0\}, \{k \in L |\, KM_w(l,k) = 1\}\}$ (Firat and Hurkens 2011)

$$KV_w^{(1,k)} \in \{0, 1, \dots, |L|\}, \ \forall\, w \in W, \tag{3}$$

$$KM_w^{(l,k)} := \begin{cases} 1, & if: \quad l \leq KV_w^{(1,k)} \\ 0, & else \end{cases}, \ \forall\, k \in K, l \in L, w \in W, \tag{4}$$

$$KM_w^{(l,k)} := \begin{Bmatrix} \nu_{11} & \cdots & \nu_{1k} \\ \vdots & \vdots & \vdots \\ \nu_{l1} & \cdots & \nu_{lk} \end{Bmatrix}, \ \nu_{l,k} \in \{0,1\}, \sum_{l \in L} \sum_{k \in K} \nu_{l,k} \geq 1, \forall\, k \in K, l \in L, w \in W. \tag{5}$$

QM, *KV* and *KM* of a technician in the problem instance with |L| = |K| = 3 may be

$$QM = \begin{pmatrix} \mathbf{1} & \mathbf{1} & \mathbf{0} \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix}, \quad KV_1 \in (3 \quad 1 \quad 0), \quad KM_1 = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}. \tag{6}$$

Both matrices and the vector indicate that technician $w = 1$ is a track layer (qualification 1) and has an expertise of level 3 with respect to ultrasound analysis ($k = 1$). Further w has the qualification of a track switch technician (qualification 2) and has basic competences for fixing standard turnout drives ($k = 2$, $l = 1$), but w has no skills as a signal engineer (qualification 3) and no competences for fixing signals ($k = 3$, $l = 0$).

If precedence relations between tasks are not defined, technicians decide independently and according to their own judgement which task should be processed next. But, a technician does not always make rational decisions during a maintenance process. Empirical studies indicate that humans are prone to seeing short-term tasks as more important than long-term ones due to the operational day-to-day business in an organization. In the case of maintenance, a task is often preferably selected if the desired result can be reached with low workload, the task is perceived as an interesting challenge or the time frame until the required completion date greatly decreases. In the literature this behaviour is referred to as bounded rational behaviour (Kahneman 2003). Steel and König (2006) include the time factor in a prioritization rule to describe the forms of decisions and actions taken, referred to as Temporal Motivational Theory.

Organizing the executable tasks by a human is based on evaluating the positive and negative aspects of processing task j at time t (7). Supporting aspects of selecting a specific task j are the importance I_j and the urgency of j. The criterion of urgency is expressed by the period between the desired deadline t_{j_dead} of j, the present time t as well as the attained degree of processing δ_j, in relation to the planned time exposure $a_{j,m}$. Negative aspects are described by the familiarization of the technician with the task δ_{STpj} and the preparation time a_{STj} if a task is initially processed or being resumed after an interruption. The influence of the individual character on decision making is taken into consideration by the factors F_w and F_{STw} and Γ^+. The priority of a task is expressed as (Duckwitz et al. 2011)

$$\text{Priority}_j\,(t) = \frac{I_j \cdot F_w}{1 + \Gamma^+ \left(\frac{t_{j\,dead} - \mathrm{t}}{a_{j,m}\,(1 - \delta_i)} \right)} - \left((1 - \delta_{STj})\, a_{STj}\, F_{STw} \right). \tag{7}$$

3.2 Team of Technicians

A team g consists of at least one technician w, subset of the total set of technicians $g \subseteq W$. The number of assigned technicians to a team g is denoted by: $W_g = \{1, \ldots, W\}$. Thereby, a team has a defined start and end of work. Within that period all team members need to be available. The number of each type of qualification of team g are found by summing up the individual qualifications QV_w within g, so we get the qualification vector QV_g (8)

$$QV_w^{(1,q)} \in \{0,1\}\ \forall\, w \in W, \qquad QV_g^{(1,q)} = \textstyle\sum_{w \in g} QV_w^{(1,q)}. \tag{8}$$

The level of a competence k of team g is determined by the maximum level of its team members. For processing a task it is assumed that it is sufficient if at least one technician of the team has an adequate level of competence. Furthermore, the competences are cumulative in the sense that a higher level covers the competencies of lower levels in the same domain

$$KV_{g,k} = max \left\{ KV_w^{(1,k)} | w \in W, \forall k \in K \right\}. \tag{9}$$

3.3 Task

A task j of the set of maintenance tasks $J = \{1, ..., |J|\}$ is executable in one of its $m = \{1, ..., |M_j|\}$ modes. The mode m determines the workload $a_{j,m}$, to perform task j and the required number of technicians with a specific qualification. The assignment of a task $j \in J$ to a technician $w \in W$ and the mode m is expressed by the value "1" of the binary variable $\alpha_{j,m,w}$, otherwise "0".

The qualification requirements of task $j \in J$ are expressed by the matrix $AQ^{(m,q)}$ which provides the information of the desired number of technicians by reference to any qualification $q \in Q$ and the mode of execution $m \in M$ (10). The requirements in $AQ^{(m,q)}$ are cumulative in the meaning that one technician can meet several qualification requirements of a task. Consequently, the team g must satisfy (11)

$$AQ_j^{(m,q)} = \begin{Bmatrix} ap_{1,1} & \cdots & ap_{1,q} \\ \vdots & \vdots & \vdots \\ ap_{m,1} & \cdots & ap_{m,q} \end{Bmatrix}, \; ap_{m,q} \in \{0,1,\dots,|W|\}, \; \forall\, j \in J,\; m \in M_j,\;\; q \in Q, \tag{10}$$

$$QV_g^{(1,q)} = \sum_{w \in W_g} QV^{(w,q)} \alpha_{j,m,w} \geq AQ_j^{(m,q)}, \; \forall\, j \in J,\; m \in M_i, q \in Q. \tag{11}$$

The required level of competence for performing task $j \in J$ in mode m is defined by the matrix $AK^{(l,k)}{}_{j,m}$ (12). Similar to the model of Firat and Hurkens (2011), the requirements are cumulative. Any requirement at a level is carried to lower ones in the same domain: $AK^{(l,k)}{}_{j,m} \geq AK^{(l',k)}{}_{j,m}$, for all $l' \leq l$

$$AK_{j,m}^{(l,k)} = \begin{Bmatrix} ak_{1,1} & \cdots & ak_{1,k} \\ \vdots & \vdots & \vdots \\ ak_{l,1} & \cdots & ak_{l,k} \end{Bmatrix}, \; ak_{l,k} \in \{0,1\}, \; \forall\, j \in J,\; m \in M_i,\;\; l \in L,\; k \in K. \tag{12}$$

An example of competence requirement matrix ($l = 3$, $k = 3$) for task j and mode $m = 1$ may be

$$AK_{j,1} = \begin{Bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 1 \end{Bmatrix}, \tag{13}$$

$$KM_g^{(l,k)} \geq AK_{j,\mathrm{m}}^{(l,k)}, \; \forall\, (l \in L, k \in K),\; j \in J,\; m \in M_j. \tag{14}$$

According to the example (13), in a team processing task j in mode 1, there must be at least technicians with the competence 1, level 2 and competence 3, level 3. Therefore, the constraint (14) ensures that the team g satisfies the competence requirements.

The duration $d_{\mathrm{j,m}}$ describes the execution time of task j in mode m. Due to the fact that tasks may or may not be preemptive, the individual periods of processing $d_{j,m}(1),\dots, d_{j,m}(N)$ have to be considered as well as the total duration of a task. The latter is calculated as the period between initial and complete processing. The amount of work $a_{j,m}$ of a task j is fixed and does not necessarily represent the duration of a task. During task processing the degree of processing increases and the level of remaining amount of work decreases. Thereby the extent of decline per time unit of task j varies with the number of technicians assigned. Due to a time-dependent accessibility to the components of the infrastructure, performing a task maybe interrupted. The occurrence as well as the duration of such a process-related waiting period is stochastic and is described by a probability distribution. It can thus be seen as a Stochastic Resource-Constrained Project Scheduling Problem (*SRCPSP*): $d_{j,m} + p_j$, whereas $d_{j,m}$ is the duration for processing the work content $a_{j,m}$ and p_j is the stochastic duration of the process related waiting period. Due to the fact that there is always the risk of not being able to release the infrastructure after the granted work period, p_j can work here as a time buffer.

Precedence relations of tasks describe the functional and/or chronological relation between them. To each task $j \in J$ a set of precedence relations $Pred(j)$ is assigned, with the exception of the initial task of the scheduling problem $j = 0$, $Pred(j) = \emptyset$. All tasks in $Pred(j)$ must be sufficiently completed before task j can be initially processed. Pre-emption of tasks is allowed, therefore the degree of processing δ_i of tasks in $Pred(j)$ has to be considered instead of start times and durations of $Pred(j)$.

To each task a priority can be assigned. The priority of a task is described by the domains urgency and importance. Urgency arises from the formal maintenance rules and describes the latest possible appointment $t_{j,dead}$ for task completion. Importance of a task is derived from the significance of the system to be maintained and the work content.

3.4 Schedules and Objectives

The period under review T is portioned into successive intervals of workdays τ_{day}. For each workday, teams of technicians are defined to process the assigned tasks. Let g be a team on a certain workday τ_{day}. $W_g \subseteq W$ denotes its technicians, $J_g \subseteq J$ denotes the scheduled tasks of the team, and $\tau_{day,g} \in \{\tau_{g,AA}, \ldots, \tau_{g,AE}\}$ denotes the working period of g.

The objective is to minimize the total duration and the delay of all tasks J (15). The span of delay for a task is the length between scheduled time of completion $t_{j,comp} = \min\{t \cdot \delta_j \mid \delta_j = 1\}$, $\forall\, t \in T$ and latest valid completion $t_{j,dead}$. The value measures the robustness of task implementation and considers only delays

$$R = \sum_{j \in J} \left(t_{j,comp} - t_{j,dead}\right), \quad \forall\, t_{j,comp} - t_{j,dead} < 0. \tag{15}$$

Another objective of our problem is to minimize the weighted average maintenance costs for a given set of tasks J (16). The value is calculated by the sum of working hours $\varsigma_{w,t}$ of team g, whereas c_w denotes the individual hourly wage of the team members

$$C = \frac{1}{J} \sum_{g \in G} \sum_{w \in W_g} \sum_{t \in T} \frac{\varsigma_{w,t}}{60} \cdot c_w. \tag{16}$$

4 LITERATURE REVIEW

The scheduling problem considered in this paper is a modification of the RCPSP which became a standard for planning problems with sequence relationships and boundary conditions. An extensive review of the heterogeneous variants of the RCPSP is provided by Hartmann and Briskorn (2010). The original RCPSP describes a scheduling problem of a project which consists of a set of tasks $i = \{1, \ldots, N+1\}$. Each task has to be scheduled and the duration of i is denoted by p_i. The precedence relations are defined by the set of immediate predecessors of a task $j \in P_i$. Only if all predecessors P_i of task i are processed completely, i can be initially executed. Each task i requires $r_{i,k}$ units of the renewable resources k during each period of processing. The availability of k in each period is R_k units, $k = 1, \ldots, K$ (Artigues et al. 2008). The result for a RCPSP is a schedule S which consists of a set of starting times ($S_1, S_2, \ldots, S_{N+1}$). A plan S is the optimal solution for the respective problem if the schedule length $T(S) = S_{N+1}$ is the global minimum and all precedence and resource-constraints are satisfied. Two categories of heuristic algorithms for solving the RCPSP are distinguished in literature: the priority-based heuristics and metaheuristic approaches, such as simulated annealing, genetic algorithms and tabu search algorithms (Hartmann and Briskorn 2010).

The RCPSP approaches are of interest, because they make a substantial contribution to the pre-defined predecessor/successor relationships of maintenance processes. This ensures that the chronological order corresponds to the function-logic requirements of maintenance tasks. But the elemental RCPSP does not consider the abilities and temporal availability of technicians as well as heterogeneous valid processing types for performing a task. To overcome this gap the Multi-Mode RCPSP (MM-RCPSP) and the Multi-Skill Project Scheduling Problem (MSPSP) were introduced. The MM-RCPSP permits that a task *i* can be processed in different ways. Each valid type of processing task *i* is represented by a mode $m_i = 1, \ldots, M_i$ (Kolisch and Drexl 1997). In the MSPSP the resources are workers with heterogeneous skills. The requirements of a task are matched with the abilities and capabilities of workers. Therefore all subsets of workers have to be identified that are capable of carrying out an activity with regard to the required skill levels (Bellenguez and Néron 2008; Li and Womer 2009). Due to the depiction of matching between task requirements and hierarchical skill levels of workers the problem introduced by Bellenguez and Néron (2008) has a significant similarity to scheduling maintenance tasks. But, they assume that each worker can satisfy only one of the required skills of a task and therefore it is contrary to the real-world maintenance process. We focus on the work of Firat and Hurkens (2011) because they developed a variant considering simultaneous skill use. In the literature several objectives are taken into account for the MM-RCPSP and the MSPSP. Li and Womer (2009) are focusing on minimizing the cost of the workforce. Bellenguez and Neron (2008) are minimizing the project duration and Firat and Hurkens (2011) are interested in identifying efficient outsourcing. If several objectives have to be considered simultaneously and a weighting of objectives is not suitable, the concept of Pareto-optimal solutions is often used (Hartmann and Briskorn 2010; Targiel et al. 2018).

5 EVOLUTIONARY ALGORITHM

A Multi-objective Evolutionary Algorithm (MOEA) uses techniques and procedures inspired by evolutionary biology and serves here as a heuristic meta strategy to solve complex optimization problems. To evaluate the quality of the developed plans we use the Strength Pareto Evolutionary Algorithm (SPEA2) of Zitzler et al. (2001).

The MOEA starts by computing an initial population (POP) of individuals. Each individual represents a plan for performing the maintenance tasks $j \in J$ and is evaluated according to the objectives of the scheduling problem. We use the Pareto concept as a fitness value for dominance relations between individuals of POP as well as a classification regarding their unique characteristic. The latter is based on density relations between the identified solutions and is a control parameter to distribute efficient individuals uniformly within the search space. As long as the fitness of the individuals is insufficient, the genetic operations recombination and mutation modify the individuals of POP.

5.1 Definition of Individuals

The genetic representation has to reflect the scheduling problem as well as the mode assignment problem. To solve the scheduling problem, tasks have to be assigned to technicians and starting times must be defined. We use a random key list which consists of vectors λ_j for all tasks $j \in J$ (17). The random list represents a genotype $I = \lambda_j$ (individual of the population, $j \in J$) and is transferred during the optimization process to a detailed schedule. Each task *j* is characterized by random variables which are part of the vector λ_j:

$$\lambda_j = \left(s_j, e_j, n_j, w_j, m_j, \mathcal{J}_j, c_j\right), \forall j \in J. \tag{17}$$

- Relative starting time s_j: The variable defines the earliest possible starting time at which task j can be initially processed. Each value of s_j refers to the required degree of completion of Pred(j).
- Duration e_j: The variable e_j is used to calculate the process-related waiting period during performing task j. The variable references to a random number of a probability distribution.
- Number of technicians n_j: The variable n_j refers to the number of technicians w, assigned to j.
- Mode m_j: The variable describes the selected execution type to perform task j (e.g. use of specific machines and technical procedures) and refers to a concrete amount of work $a_{j,m}$.

- Technicians wj: wj is determined by nj and refers to one or several technicians who fulfill the qualification and competence requirements of j. Therefore, wj is a subset of all valid combinations of technicians for nj.
- Importance of task $\mathcal{I}$j: The variable represents the importance of j.
- Demanded date of completion dj: The value of dj determines the planned deviation from the demanded date of completion of j.

5.2 Algorithm

The algorithm consists of three phases, initial definition of λ_j, schedule construction phase and modification of λ_j. Figure 2 shows the flowchart of our algorithm. The initial definition of λ_j includes the identification of the requirements of $j \in J$ for task performing. Furthermore, the initial values of the variables λ_j of an individual and for all individuals of POP are determined. Thus, specific technicians are assigned to a task, the priority of j is determined and the amount of work as well as the duration for process-related waiting times are calculated.

In the schedule construction phase, detailed schedules are developed based on the values of λ_j. The calculated priorities of the tasks are used to simulate the behavior of technicians and to define the sequence of tasks as well as the time when j is processed. Hence, for every schedule, a certain combination of λ_j is fixed in advance. Starting with one of the tasks which have no precedence relations the schedule is initialized and the length of the schedule is increased by adding tasks iteratively. In each iteration the algorithm tries to add another task to an existing team based on the values of λ_j. If a conflict occurs, the algorithm modifies the task technician assignment of λ_j (local repair) to give priority to the assignment of j to an existing team. Alternative, a new team is set up. Different schedules are given by the specified permutation of the priority values of tasks under consideration of precedence relations as well as the assignment of technicians to tasks and teams. The algorithm builds workday schedules for several teams successively. Constructing a work day schedule starts with the assignment of the first task. If the remaining time of a work day is insufficient for placing the task in the schedule of g, the task is shifted to the next day.

Having constructed a complete schedule, its fitness is evaluated based on the SPEA2 approach of Zitzler et al. (2001). If the identified solution is non-dominated, then the archive is updated. For the creation of new schedules in the modification phase, two individuals are combined using a simulated binary crossover operator (Tackenberg et al. 2017). While the crossover operator combines the information of two existing individuals, the mutation operator is applied to compute newly generated individuals. The polynominal mutation method selects tasks and variables of λ_j, $j \in J$ according to their contribution to the fitness value and initiates a purposeful change of λ_j (Tackenberg et al. 2017).

6 COMPUTATIONAL EXPERIMENTS

To the best of our knowledge, no public benchmark data exist for an actor-oriented model of performing a maintenance service. Therefore, we decided to investigate problem instances taken out of Néron (2002), Li and Womer (2009), Duckwitz et al. (2011) and Tackenberg (2016). In this paper our algorithm is parameterized according to Tackenberg et al. (2017) to evaluate the main aspects of the introduced maintenance problem.

We use the problem instance of Néron (2002) to evaluate the quality of developed task sequences and the assignment of technicians to tasks. For the MSPSP instance with four tasks and four workers our algorithm identifies the minimal project duration of 8 hours within 3 seconds. In contrast to the literature two optimal and feasible solutions regarding the assignment of workers to tasks are identified.

The problem instance of Li and Womer (2009) is used to evaluate the development of a schedule based on the bounded rational behaviour of technicians (7). Thereby, each technician satisfies only one of the required skills of a task and due to the simulated behaviour of task selection and task performing the schedule is generated. It was observed that our algorithm identifies the published plan of Li and Womer (2009) with a duration of 26 weeks. Due to time buffer contained in this plan our algorithm gets a minimal duration of 21 weeks which also satisfies all temporal constraints. The multicriteria optimization (duration, number of workers) leads to three efficient, non-dominated schedules: (21,6); (25,5) and (27,4).

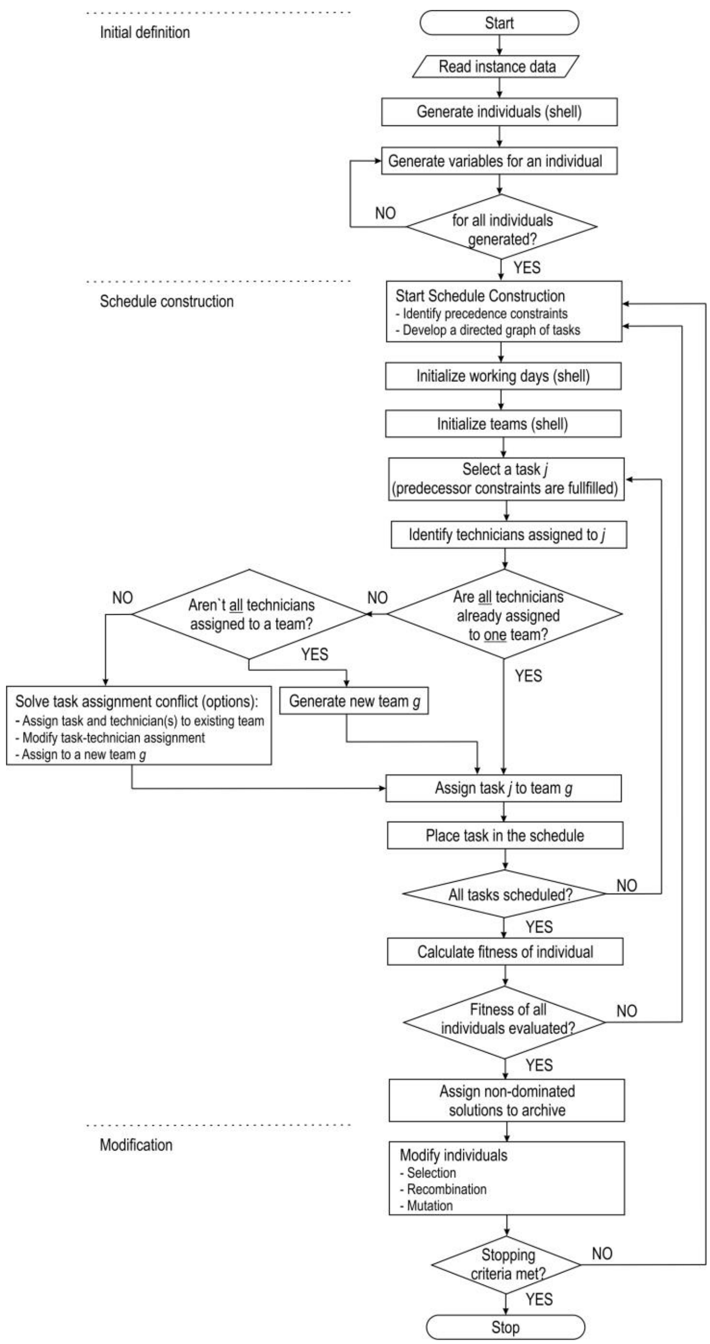

Figure 2: Flowchart of the algorithm.

In order to evaluate the simulated behavior of technicians within a team, we decided to use the scheduling problem of Duckwitz et al. (2011). The problem consists of ten tasks and the assignment of tasks to the three workers of a team is fixed. An overlapping of tasks with precedence relations is allowed and a joint performing of tasks is required. During optimization the algorithm modifies the importance and the time of completion of each task. Figure 3 illustrates the decision making of the three technicians based on the values of an individual. A detailed analysis verifies the simulated task performing at the respective dates. The task A_1 is processed first due to predecessor constraints. Performing A_2 and A_3 by technician 1 occurs profoundly parallel since the algorithm has assigned an identical priority to these tasks. Performing A_4 is initially preferred over A_5 due to the influence of technicians 2 competence level. A_7 begins once the demanded degree of completion of A_4 and A_5 has been nearly reached. The simulated progression of the tasks were compared to a priori observed work behavior of three persons and it was shown that an interruption of task performing and task switching is sufficiently represented.

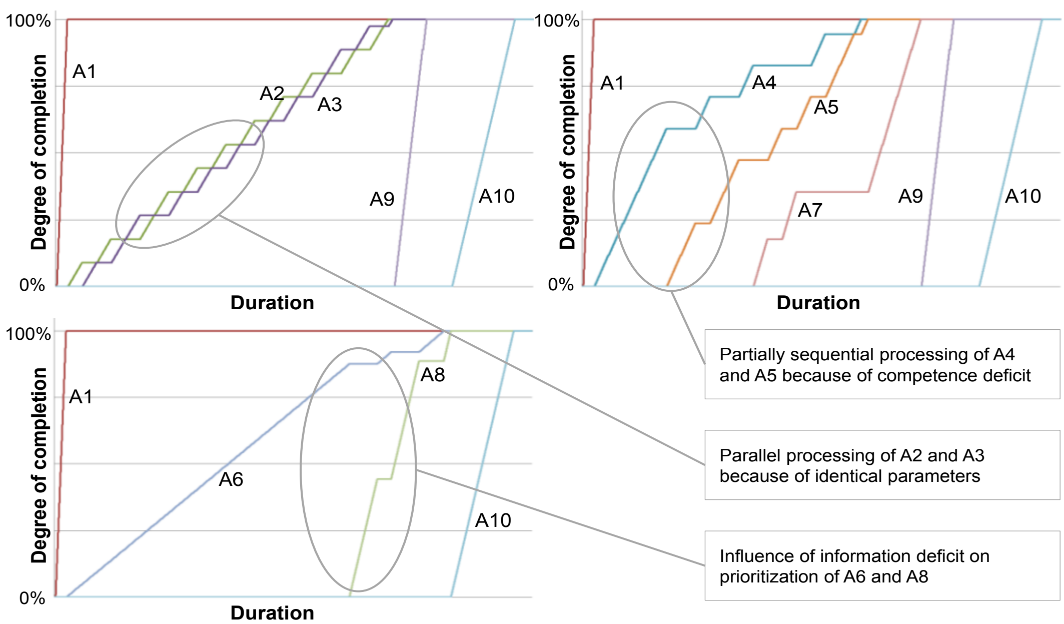

Figure 3: Simulated behavior of technicians.

The Stochastic Multi-skill project scheduling problem to evaluate the robustness of a schedule is derived from Tackenberg (2016). The scheduling problem comprises 15 tasks which are performed by one team. The duration of a task is calculated based on the fixed amount of work (calculated with REFA methods), the number of technicians assigned and the intended time buffer for a process-related waiting time. The process-related waiting times are characterized by triangular distributions and a specific value for each task is based on a random number of a Monte Carlo draw. Each point illustrated in Figure 4 represents a valid schedule. The following findings can be derived based on an analysis of the Pareto-front and the distribution of the solutions in the range of results:

- The precedence constraints between tasks and the availability of technicians limit the range of results.
- The assignment of tasks to technicians with heterogeneous competence levels has a considerable impact on the duration and the cost. A high level of competence leads to a shorter duration of a task but due to higher wages the cost increases.
- An increase of the duration due to included time buffer correlates with a higher probability of implementation.
- The algorithm calculates a Pareto front of efficient schedules for each level of robustness. Therefore, dispatchers have the opportunity to select a plan according to their preferences.

7 SUMMARY AND CONCLUSION

This paper proposes a comprehensive approach to modeling and solving relevant aspects of maintenance problems. The opportunity to describe the behavior of technicians and the stochastic process related waiting times due to a restricted accessibility to the components of the infrastructure are aspects of our problem that distinguish it from the RCPSP. We subsequently introduce the concept of a stochastic interruption of task processing and describe an actor-oriented model. Moreover, we propose a multi-criteria algorithm to develop efficient plans. The computational experiments demonstrate that the algorithm converges on the Pareto-Front within only a few generations. This behavior of convergence indicates that the presented approach is suitable for scheduling the maintenance workforce of a company. The current approach will support infrastructure managers of railway undertaking and energy suppliers to improve the handling and scheduling of orders. Only with the proposed multi-criteria optimization algorithm which simultaneously consider a variety of restrictions (e.g. the time-limited accessibility to the component of infrastructure), a workable timetable is achieved. We are recently working on the integration of a realistic calculation of the travel time depending on the sequence of tasks and the operation site. Finally, a set of test cases for maintenance scheduling problems is provided in near future.

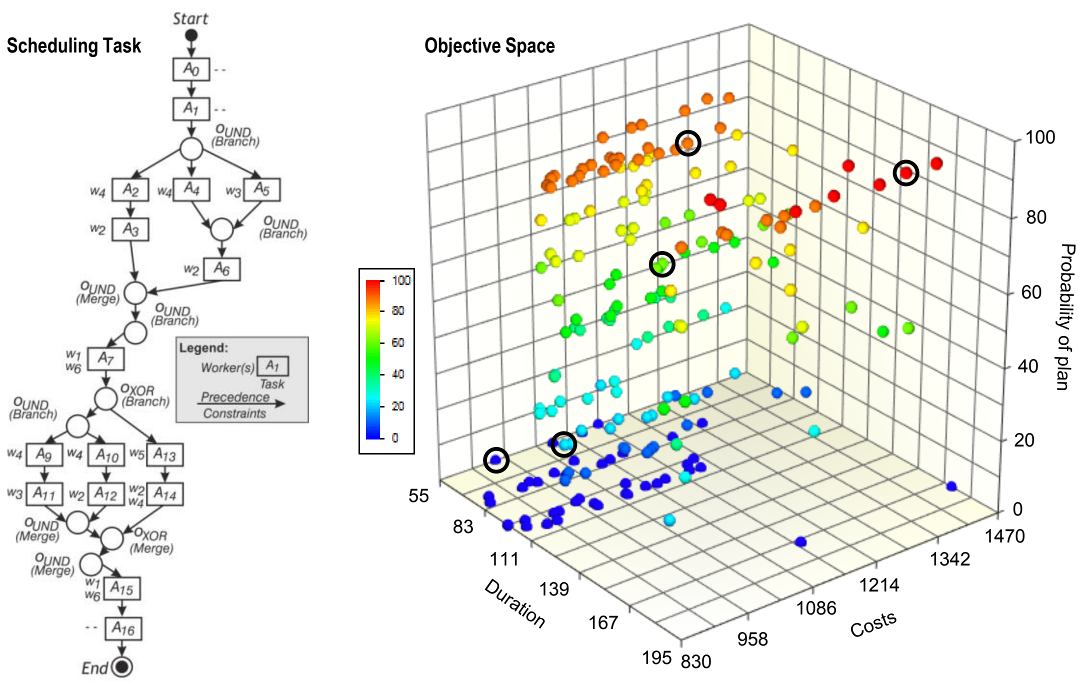

Figure 4: Objective space of the investigated stochastic scheduling problem.

REFERENCES

Artigues, C., S. Demassey, and E. Néron. 2008. *Resource-Constrained Project Scheduling. Models, Algorithms, Extensions And Applications*. 1st Ed. Hoboken, NJ: Wiley.

Bellenguez-Morineau, O., and E. Néron. 2008. "Multi-Mode And Multi-Skill Project Scheduling Problem". In *Resource-Constrained Project Scheduling. Models, Algorithms, Extensions And Applications*, edited by C. Artigues et al., 149-160. Hoboken, NJ: Wiley.

Duckwitz, S., S. Tackenberg, and C. M. Schlick 2011: "Simulation Of Human Behavior In Knowledge-Intensive Services". In *Proceedings Of The RESER 2011 Productivity Of Service Nextgen –Beyond Output / Input*, edited by W. Ganz et al., 1-20, Stuttgart: Fraunhofer Verlag.

Fırat, M., and C. Hurkens. 2011. "An Improved MIP-Based Approach For A Multi-Skill Workforce Scheduling Problem". *Journal Of Scheduling* 15(3):1-18.
Hartmann, S., and D. Briskorn. 2010. "A Survey Of Variants And Extensions Of The Resource-Constrained Project Scheduling Problem". *European Journal Of Operational Research* 207(1):1-14.
Kahneman, D. 2003. "Maps Of Bounded Rationality: A Perspective On Intuitive Judgment And Choice". In: *Prize Lecture, Les Prix Nobel, The Nobel Prizes 2002*, edited by T. Frängsmyr, Stockholm, Nobel Foundation.
Kolisch, R., and A. Drexl. 1997. "Local Search For Nonpreemptive Multi-Mode Resource-Constrained Project Scheduling". *IIE Transactions* 29:987-999.
Li, H., and K. Womer. 2009. "Scheduling Projects With Multi-Skilled Personnel By A Hybrid MILP/CP Benders Decomposition Algorithm". *Journal Of Scheduling* 12:281-298.
Maletič, D., M. Maletič, And B. Gomišček. 2012. "The Relationship Between Continuous Improvement And Maintenance Performance". *Journal Of Quality In Maintenance Engineering* 18(1):30-41.
Néron, E. 2002. "Lower Bounds For The Multi-Skill Project Scheduling Problem". In *Proceedings Of The 8th International Workshop On Project*, Valencia, Spain, 274-277.
Steel, P., and C. J. Koenig. 2006. "Integrating Theories Of Motivation". *The Academy Of Management Review* 31(4):889-913.
Tackenberg, S. 2016. *Konzeption Und Entwicklung Einer Mehrkriteriellen Evolutionären Metaheuristik Zur Planung Wissensintensiver Dienstleistungen*. 1st Ed. Aachen: Shaker Verlag.
Tackenberg, S., S. Duckwitz, C. Schmalz, and C. M. Schlick. 2017. "Resource-Constrained Project Scheduling Problem: Investigation Of The Quality Of Project Plans". In *Advances In Ergonomic Design Of Systems, Products And Processes*, edited by C. M. Schlick et al., 31-59, Berlin: Springer.
Targiel, K.S., M. Nowak, and T. Trzaskalik. 2018. "Scheduling Non-Critical Activities Using Multicriteria Approach". *Central European Journal Of Operations Research* 13(51): 1-14.
Zitzler, E., M. Laumanns, and L. Thiele. 2001. SPEA2: *Improving The Strength Pareto Evolutionary Algorithm*. No. 103, Zürich: Swiss Federal Institute Of Technology (ETH).

AUTHOR BIOGRAPHIES

SVEN TACKENBEG is full professor for Production Planning in the field of Industrial Engineering at the OWL University of Applied Sciences. He holds a PhD in Industrial Engineering of RWTH Aachen University. Until 2017 he worked for a German railway company in the field of maintenance management. His e-mail address is sven.tackenberg@hs-owl.de.

SÖNKE DUCKWITZ is working in the field of developing IT solutions for maintenance management. Until 2016 he was head of the work organization group at the institute of Industrial Engineering (IAW) of RWTH Aachen University. His e-mail address is sduckwitz@gmail.com.