Mobile Workforce Scheduling Problem With Multitask-Processes

Asvin Goel[1,2], Volker Gruhn[1], and Thomas Richter*[1]

[1] Chair of Applied Telematics / e-Business, University of Leipzig
Klostergasse 3, 04109 Leipzig, Germany
`{goel,gruhn,richter}@ebus.informatik.uni-leipzig.de`
[2] MIT-Zaragoza International Logistics Program, Zaragoza Logistics Center
Avda. Gómez Laguna 25, 1^{a} planta, 50009 Zaragoza, Spain
`asvin@mit.edu`

Abstract. In this work we introduce a new generalization of the Resource-Constrained Project Scheduling Problem – the Mobile Workforce Scheduling Problem with Multitask-Processes (MWSP-MP). This scheduling problem arises in mobile work scenarios and is characterized by tasks to be scheduled that are not independent from each other, but belong to structured business processes. These business processes are subject to timing and cost related properties and restrictions that have to be considered for the scheduling of resources. We fortify the relevance of the MWSP-MP by illustration with process examples from the utility industry and present an initial heuristic for the insertion of processes into solutions of the problem.

Key words: Workforce Scheduling, Mobile Business Processes, Workforce Management

1 Introduction

Mobile business processes can be seen as processes, of which at least one activity takes place outside the organization's physical bounds [1][2]. If we consider mobile processes in network based industries (e.g. utilities, telecommunications) we can state that indeed selected mobile processes can be seen as a combination of mobile activities, taking place at different locations. These processes consist of more than one mobile activity. The problem description in the following section introduces such a business process originating in the utility industry. The business processes in question are usually composed of different mobile activities taking place at different locations. Additionally time restrictions apply as e.g. down-times have to be minimized. In such mobile environments numerous business processes are executed in parallel by different workers / teams. Based on their respective qualifications and locations workers may perform not all but just a few activities of a process, possibly even alternatingly for two or more processes. Additionally complexity increases by the possibility of emergencies

---

* Corresponding author

(processes with high priorities) during operation which demand the immediate re-scheduling of closeby, adequately skilled workers.

The scheduling of workers in such environments is a challenging task. We introduce a new generalization of the Resource-Constrained Project Scheduling Problem, the Mobile Workforce Scheduling Problem with Multitask-Processes – MWSP-MP. This scheduling problem considers costs related to travel efforts, costs related to process execution by differently skilled workers, and process priority constraints. We formalize the problem and outline a method for inserting idle processes into an existing solution and an insertion heuristic for generating solutions from scratch.

The remainder of this article is organized as follows. Section 2 introduces the problem with an illustrating business process. Section 3 gives an overview of the related work. In section 4 we introduce the scheduling objectives and the resulting formulation of the problem. In section 5 we present an algorithm for inserting processes into the current solution. In the concluding section 6 we discuss further research.

2 Problem illustration

We will illustrate the problem based on a mobile business process. The process discussed here is among the knowledge gained from a consulting project with a German gas and power supply. The project aims for the performance evaluation of the whole network maintenance department, considering workers' scheduling, assignment of assets to different regional subsidiaries, qualification gaps of working units, and the like.

Consider for instance the damage handling of the network maintenance unit of a utility. The top part of Fig. 1 shows a typical situation after a power cable is damaged, e.g. due to construction work. The damage occurs at location L3 while the cable runs from a substation at location L1 to another substation at location L2.

For the repair of the damage security concerns demand that the stations at L1 and L2 have to be turned off before and turned on again after the damage is fixed. The bottom part of Fig. 1 shows the resulting process as UML Activity Diagram. As long as the stations are turned off no energy is sold to customers connected between L1 and L2 (such customers can still draw electricity from the line if the cable ist damaged at only one point and no shortcut occurred during the damage). Thus and due to legal regulations demanding a minimum yearly uptime it is desirable to minimise the downtime of the line.

If the whole process outlined in Fig. 1 is associated to a time window (i.e. an interval defining the earliest possible start and the latest possible end of the process) or a maximum duration (as for power outages), all five tasks are closely coupled in time, while possibly far apart in space. Thus different workers may have to perform the different tasks to match the harsh time restrictions. For our example this means that different workers may turn the stations on and off while a third team works at the site of the damage. It is thus necessary to

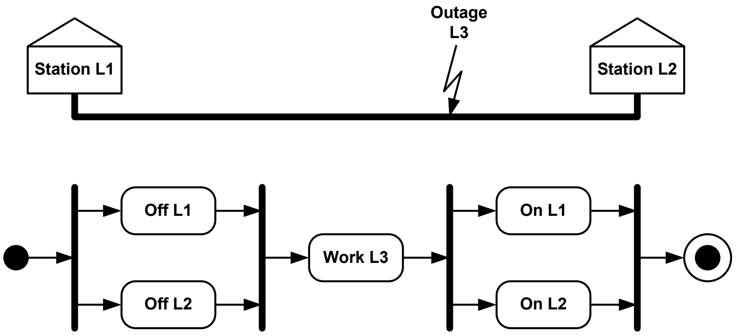

Fig. 1. Power line outage and maintenance process

create individual schedules (working plans) for the workers matching the time restrictions of the whole process. As a task performed by a mobile worker is part of a distinct *administrative* business process, processes with multiple mobile tasks to be performed at multiple locations by multiple workers add a new dimension by forming a cross sectional *functional* process.

If we consider the aim to reduce travel efforts while preserving the service quality of all processes (i.e. the priority-dependent accomplishment) in the system, it is obvious, that the workers have to perform tasks in both different administrative processes and different functional processes close to their respective locations (see Fig. 2; W1 – W3 denote workers). The resulting overlap of concerns of workers' schedules turns actually independent processes into interdependent processes, since both processes and traveling/working are subject to time restrictions. In this way delays that occur at a certain site may cause massive delays and thus increasing costs at completely different sites and processes.

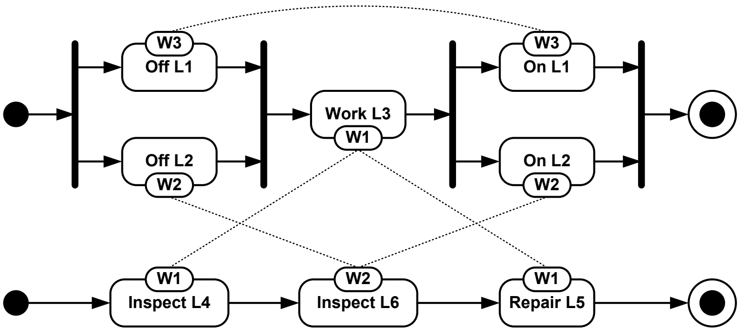

Fig. 2. Process interdependencies

For increasing numbers of processes and workers the generation of the worker's schedules becomes a challenging task. The problem of scheduling of mobile workers generalizes both the NP-hard Resource-Constrained Project

Scheduling Problem (RCPSP) [3], and the NP-hard Vehicle Routing Problem. The generalizations made in this paper are motivated by the real world problem of a German gas and power supplier, but can apply for several more industries in which one or more of the following statements are true:

1. Tasks take place at geographically distributed locations which resources have to travel to.
2. Processes composed from tasks are subject to time window constraints, priority constraints, and duration dependent costs.
3. The planning horizon is short term (one to five days) while numerous processes with a longer completion horizon (e.g. one year) exist in the system.

In this work we present a mathematical formulation of the Mobile Workforce Scheduling Problem with Multitask-Processes (MWSP-MP) by adapting the way the class of RCPSPs is usually formulated [4] and a first simple algorithm for the insertion of processes and the generation of an initial solution.

3 Related Work

Several problems are related to our work. In the case where each process consists of exactly one task, the problem can be interpreted as a variant of the Vehicle Routing Problem with Time Windows. Comprehensive surveys on the Vehicle Routing Problem (VRP) and the VRP with Time Windows are given by [5] and [6]. Different skills and qualifications of resources can be interpreted as order/vehicle compatibility constraints which are commonly used for the Heterogeneous Fleet VRP which recently was surveyed by [7]. There are several generalizations of the VRP in which each transportation request consists of more than one task. In the Pickup and Delivery Problem [8, 9] each transportation request consists of exactly one pickup task and one delivery task. In the General Pickup and Delivery Problem [10] and the General Vehicle Routing Problem [11] transportation requests may include multiple pickup and delivery tasks. These problems have in common, that all tasks belonging to one transportation request must be executed by the same vehicle. In the problem considered in this paper, however, tasks belonging to the same process may be executed by different resources.

If mobility is omitted from the problem domain the resulting can be interpreted as resource-scheduling and resource distribution in business process management. The foundations of resource scheduling research date back to the 1990ies [3, 4]. These contributions introduce resource scheduling from an Operations Research point-of-view originating from the abovementioned Vehicle Routing Problem research. Sprecher and Drexl [12] introduce a solution algorithm for projects with precedence constraints. In the realm of business process management such projects can be compared to processes. Ursu et al. [13] present a distributed solution for workforce allocation based on independent agents. The workforce allocation is achieved by negotiation between agents utilizing a specialized communication protocol. Russell et al. introduce a series of 43 Workflow resource patterns in [14]. A discussion of organizational aspects of resource management is given in [15]. Netjes et al. [16] introduce a Colored Petri Net [17] based model for the analysis of resource utilization and perform several examinations regarding the skill balancing and resource allocation order in banking processes. In-depth Petri net based modeling and analysis of work distribution mechanisms of the Workflow Management Systems Staffware, FileNet, and FLOWer is presented in [18]. Further research by Pesic and van der Aalst focuses on the development of a reference model for work distribution in Workflow Management Systems [19]. They focus on the general lifecycle of work items and introduce a CPN based approach for the distribution of work items to resources at runtime. Though most of the work depicted above had creative influence on our work none covers the properties of mobile process environments.

Resource allocation in mobile process environments has been in the focus of the following work. An automated resource management system (ARMS) for British Telecom is introduced in [20]. The system is intended for forecasting and analysis of resource demands and executes the dispatching of jobs to resources but does not handle precedence relations of chained tasks and process durations. Cowling et al. introduce a similar problem in [21]. They consider mobile processes with time window restrictions, skill demands, and precedence constraints applying to tasks. The determination of tasks to be performed is based on static priority values of the tasks with the objective to perform a maximum of highly prioritized tasks. Complex processes consisting of several tasks and implications of process durations are not considered. Our problem in opposition considers the process as a whole with related constraints.

4 The Mobile Workforce Scheduling Problem with Multitask-Processes (MWSP-MP)

In this section we will introduce the foundations and parameters of the MWSP-MP based on the properties of the processes it is suited for. We assume that numerous processes are well known in advance and have a long execution horizon (e. g. annual inspections have to be performed in the current year without further timing restrictions given). Such processes usually have a very low priority at the beginning of the year. Additionally higher prioritized processes show up dynamically and usually have a shorter execution horizon (same day to one month). An example is the repair of failed equipment. Since processes are subject to priorities we want to execute processes with higher priority first. Nonetheless, due to legal regulations all processes ultimately have to be performed during their respective execution horizon (up to one year). The planning horizon is too short (one day to one week) to plan all processes present. To avoid low processes being postponed over and over we consider to dynamically increase priorities of actually low priority processes gradually whenever the next planning horizon is due. This is subject to the preprocessing of the data before scheduling, not to the scheduling algorithm itself. For any process considered all or none tasks have to be performed.

Based on the nature of the processes in question process costs are determined by the duration of process execution. For the example in Fig. 1 this means, that the process is more expensive the longer the stations L1 and L2 and the according connected consumers are shut down. Further costs arise by the travel times and travel distances of the workforce. Accordingly we want the workforce to travel as sparse as possible.

Let us denote the set of all processes by $\mathcal{P}$. Each $p \in \mathcal{P}$ is associated with a priority value π_p. For each process $p \in \mathcal{P}$ let $\mathcal{T}_p$ denote the set of tasks belonging to process p. Each task $\tau \in \mathcal{T}_p$ may require some skills (qualifications) for performing the task. These skill requirements are represented by a vector $q^\tau := (q_1^\tau, \ldots, q_k^\tau)$, where k represents the number of different skills a resource may have. Let $\mathcal{C}_p \subset \mathcal{T}_p \times \mathcal{T}_p$ denote the set of precedence constraints associated to process p. These constraints require that for each pair of tasks $\tau, \tau' \in \mathcal{T}_p$ with $(\tau, \tau') \in \mathcal{C}_p$ task τ must be completed before task τ' may be started. For each pair $(\tau, \tau') \in \mathcal{T}_p \times \mathcal{T}_p$ let $c_{\tau,\tau'}$ denote the costs arising at each unit of time between the beginning of task τ and the completion of task τ'. In the example in Figure 1, these costs may represent the costs per unit of time during which stations L1 and L2 are shut down.

Let us denote the set of all resources (workers) by $\mathcal{R}$. Each worker $r \in \mathcal{R}$ has specific skills represented by a vector $q^r = (q_1^r, \ldots, q_k^r)$. For each resource $r \in \mathcal{R}$ let n_r denote the resource's depot. Let $\mathcal{D} := \{n_r \mid r \in \mathcal{R}\}$ denote the set of all depots. Note that for any two resources $r, r' \in \mathcal{R}$ we assume that $n_r \neq n_{r'}$, even if the depot of the two different resources is located at the same geographical position.

Let

$$\mathcal{N} := \mathcal{D} \cup \bigcup_{p \in \mathcal{P}} \mathcal{T}_p$$

and

$$\mathcal{A} := \mathcal{N} \times \mathcal{N} \setminus \{(n,n) \in \mathcal{N} \times \mathcal{N} \mid n \notin \mathcal{D}\}$$

For each resource $r \in \mathcal{R}$ and each arc $(n,m) \in \mathcal{A}$ let c_{nm}^r and d_{nm}^r denote the nonnegative costs and duration for traveling from n to m. For each resource $r \in \mathcal{R}$ and each task $\tau \in \bigcup_{p \in \mathcal{P}} \mathcal{T}_p$ let s_τ^r denote the service time resource r needs for performing task τ.

The Mobile Workforce Scheduling Problem with Multitask-Processes (MWSP-MP) is then modeled using the binary variables x_{nm}^r indicating whether resource r visits node m immediately after node n ($x_{nm}^r = 1$), or not ($x_{nm}^r = 0$), the binary variables y_n^r indicating whether resource r visits node n ($y_n^r = 1$), or not ($y_n^r = 0$), and the continuous variables t_n indicating the arrival time at node n.

The resulting (bi-objective) MWSP-MP is

minimize

$$\sum_{r \in \mathcal{R}} \sum_{(n,m) \in \mathcal{A}} x_{nm}^r c_{nm}^r +$$

$$\sum_{p \in \mathcal{P}} \sum_{(\tau,\tau') \in \mathcal{T}_p \times \mathcal{T}_p} \sum_{r \in \mathcal{R}} y_{\tau'}^r (t_{\tau'} + s_{\tau'}^r - t_\tau) c_{\tau,\tau'} \tag{1}$$

maximize

$$\sum_{p\in\mathcal{P}} \pi_p \frac{\sum_{\tau\in\mathcal{T}_p}\sum_{r\in\mathcal{R}} y^r_\tau}{|\mathcal{T}_p|} \tag{2}$$

subject to

$$\sum_{(n,m)\in\mathcal{A}} x^r_{nm} = \sum_{(m,n)\in\mathcal{A}} x^r_{mn} \text{ for all } r\in\mathcal{R}, n\in\mathcal{N} \tag{3}$$

$$\sum_{r\in\mathcal{R}}\sum_{(n,m)\in\mathcal{A}} x^r_{nm} = y^r_n \text{ for all } n\in\mathcal{N} \tag{4}$$

$$y^r_{n_r} = 1 \text{ for all } r\in\mathcal{R} \tag{5}$$

$$\sum_{r\in\mathcal{R}} y^r_n \le 1 \text{ for all } n\in\mathcal{N} \tag{6}$$

$$\sum_{\tau'\in\mathcal{T}_p}\sum_{r\in\mathcal{R}} y^r_{\tau'} = |\mathcal{T}_p| \sum_{r\in R} y^r_\tau \text{ for all } p\in\mathcal{P}, \tau\in\mathcal{T}_p \tag{7}$$

$$\begin{array}{c} x^r_{nm} = 1 \Rightarrow t_n + s^r_n + d^r_{nm} \le t_m \\ \text{for all } r\in\mathcal{R}, (n,m)\in\mathcal{A} \mid m\neq n_r \end{array} \tag{8}$$

$$\begin{array}{c} y^r_n = 1 \Rightarrow t^{min}_n \le t_n \le t^{max}_n - s^r_n \\ \text{for all } r\in\mathcal{R}, n\in\mathcal{N} \end{array} \tag{9}$$

$$y^r_n = 1 \Rightarrow q^n \le q^r \text{ for all } r\in\mathcal{R}, n\in\mathcal{N} \tag{10}$$

$$\begin{array}{c} x^r_{nm}\in\{0,1\} \text{ for all } r\in\mathcal{R}, (n,m)\in\mathcal{A} \\ y^r_n\in\{0,1\} \text{ for all } r\in\mathcal{R}, n\in\mathcal{N} \end{array} \tag{11}$$

Objective (1) is to minimize travel costs plus process execution costs. Note, that if resource r executes task τ', $(t_{\tau'} + s^r_{\tau'}) - t_\tau$ represents the time between the begin of task τ and the end of task τ', and that $y^r_{\tau'} = 1$ for at most one resource. Objective (2) is to maximize the sum of all priorities associated to processes performed. Equation (3) represents the flow conservation constraints forcing that each node $n \in \mathcal{N}$ will be left after being reached by a resource. (4) assures that the values of binary variables x^r_{nm} and y^r_n are well defined. (5) assures that each resource departs from its depot. (6) and (7) guarantee that each node is visited at most one and that either all tasks associated to a process are performed or none. Equations (8) and (9) represent time windows constraints. (10) represents skill constraints, imposing that only resources with appropriate qualifications can execute tasks. Note that the operator $\le$ is defined to compare vectors element-wise. Finally equation (11) imposes that the values of x^r_{nm} and y^r_n are binary.

5 Solution approach

This section describes a method for inserting idle processes into the current solution and outlines a solution algorithm for the MWSP-MP. For each process $p \in \mathcal{P}$ and each task $\tau \in \mathcal{T}_p$ let us define precedence indices i_τ in such a way that i_τ represents the length of the longest path from a task without predecessors to τ in the network defined by $\mathcal{T}_p$ and $\mathcal{C}_p$ (see Fig. 3). All arcs defined by $\mathcal{C}_p$ are assumed to have length 1.

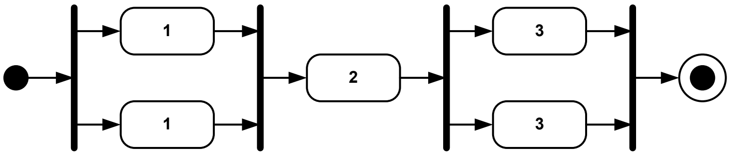

Fig. 3. Precedence of tasks

Given an initial solution s of the MWSP-MP let $\sigma_r^s = (\tau_1, \ldots, \tau_{\lambda_r^s})$ be the work plan of resource $r \in R$. A process $p \in P$ can be inserted into the solution using the algorithm outlined in Fig. 4.

In this algorithm $insert(s, r, \tau, j)$ inserts task τ between positions j and $j+1$ in the schedule of resource r. We assume that throughout this algorithm all time values are set to the first possible value complying with time window and precedence constraints. Under this assumption the verification whether the solution obtained by this operation is feasible is relatively easy. However, compliance with time window and precedence constraints must be carefully verified for all succeeding tasks. This algorithm either terminates with a set of feasible solutions S or with an empty set if no feasible insertion is possible. Depending on process execution costs, the start times of certain tasks may be shifted to later points in time to minimize total costs. Among all feasible solutions in S the one with lowest costs can be chosen.

Let us now outline an algorithm (see Fig. 5) for determining solutions from scratch using above method in an iterative way. The insertion heuristic iteratively choses the idle process with highest priority value and inserts it to the current solution using the algorithm for process insertion described above.

By this the heuristic simultaneously keeps an eye on maximizing priorities and minimizing costs. The solution obtained by this insertion heuristic can be further improved by meta-heuristic approaches such as Large Neighbourhood Search [22]. Further work will evaluate the effectiveness of the outlined insertion algorithm and different improvement methods.

6 Conclusion

We introduced a new generalization of the Resource-Constrained Project Scheduling Problem, the Mobile Workforce Scheduling Problem with Multitask-Processes

```
$S := \{s\}$
for $i = 1$ to $max\{i_\tau | \tau \in \mathcal{T}_p\}$ do
  for all $\tau \in \mathcal{T}_p$ with $i_\tau = i$ do
    $S^* = \emptyset$
    for all $r \in R$ with $q^\tau \leq q^r$ do
      for all $s \in S$ do
        for $j = 1$ to $\lambda_r^s - 1$ do
          $s^* = insert(s, r, \tau, j)$
          if $s^*$ is feasible then
            $S^* \leftarrow S^* \cup \{s^*\}$
          end if
        end for
      end for
    end for
    $S = S^*$
  end for
end for
```

Fig. 4. Algorithm for process insertion

```
$s$ = empty schedule
repeat
  1. chose (previously not selected) process $p \in P$ with highest priority $\pi_p$
  2. determine cheapest insertion possibility and insert $p$ to schedule $s$ (if possible)
until no further feasible insertion is possible
```

Fig. 5. Insertion heuristic

– MWSP-MP. We presented a formulation of the problem and outlined a method for inserting idle processes into an existing solution and an insertion heuristic for generating solutions from scratch. Nonetheless this is work in progress, and we are currently implementing the algorithms and evaluate them. For this purpose we obtained real world data in terms of the network structure from a German power and gas supply serving 500.000 customers and covering an area of 7000 km^2. Additionally the process environment in question has to deal with process interruption and the rollback of interrupted tasks. This may occur if highly prioritized processes require currently working resources to participate in the remedy of defects immediately. The according constraints will be introduced into the problem. Our research aims at a scheduling algorithm to be utilized in business process simulation [23] for the optimization of mobile process environments.

Acknowledgment

The Chair of Applied Telematics/e-Business at the University of Leipzig is endowed by Deutsche Telekom AG.

References

1. Gruhn, V., Köhler, A., Klawes, R.: Modeling and analysis of mobile business processes. Jounal of Enterprise Information Management **20**(6) (2007) 657
2. Luff, P., Heath, C.: Mobility in collaboration. In: Proceedings of the 1998 ACM Conference on Computer supported cooperative work, ACM Press, New York, USA (1998) 305–314
3. Kolisch, R.: Serial and parallel resource-constrained project scheduling methods revisited: Theory and computation. European Journal of Operational Research **90**(2) (1996) 320–333
4. Brucker, P., Drexl, A., Möhring, R., Neumann, K., Pesch, E.: Resource-constrained project scheduling: Notation, classification, models, and methods. European Journal of Operational Research **112**(1) (1999) 3–41
5. Laporte, G., Semet, F.: Classical heuristics for the capacitated vrp. In Toth, P., Vigo, D., eds.: The Vehicle Routing Problem. SIAM Monographs on Discrete Mathematics and Applications, Philadelphia (2002) 109–128
6. Cordeau, F.J., Desaulniers, G., Desrosiers, J., Solomon, M., Soumis, F.: Vrp with time windows. In Toth, P., Vigo, D., eds.: The Vehicle Routing Problem. SIAM Monographs on Discrete Mathematics and Applications, Philadelphia (2002) 157–193
7. Baldacci, R., Battarra, M., Vigo, D.: Routing a heterogeneous fleet of vehicles. In: The Vehicle Routing Problem: Latest Advances and New Challenges. Volume 43 of Operations Research/Computer Science Interfaces Series. Springer (2008) 3–27
8. Parragh, S., Doerner, K., Hartl, R.: A survey on pickup and delivery problems - part i: Transportation between customers and depot. Journal für Betriebswirtschaft **58**(1) (2008) 21–51
9. Parragh, S., Doerner, K., Hartl, R.: A survey on pickup and delivery problems - part ii: Transportation between pickup and delivery locations. Journal für Betriebswirtschaft **58**(2) (2008) 81–117
10. Savelsbergh, W.P.M., Sol, M.: The general pickup and delivery problem. Transportation Science **29**(1) (1995) 17–30
11. Goel, A., Gruhn, V.: A general vehicle routing problem. European Journal of Operational Research **191**(3) (2008) 650–660
12. Sprecher, A., Drexl, A.: Multi-mode resource-constrained project scheduling by a simple, general and powerful sequencing algorithm. European Journal of Operational Research **107**(2) (1998) 431–450
13. Ursu, F.M.: Distributed resource allocation via local choices: A case study of workforce allocation. International Journal of Knowledge-Based and Intelligent Engineering Systems **9**(4) (2005) 293–301
14. Russell, N., van der Aalst, M.P.W., ter Hofstede, H.M.A., Edmond, D.: Workflow resource patterns. In Pastor, O., Falcao e Cunha, J., eds.: Proceedings of the 17th Conference on Advanced Information Systems Engineering (CAiSE'05). Volume 3520 of Lecture Notes in Computer Science. Springer-Verlag, Berlin (2005) 216–232
15. Zur Muehlen, M.: Organizational management in workflow applications - issues and perspectives. Information Technology and Management **5**(3) (2004) 271–291
16. Netjes, M., van der Aalst, M.P.W., Reijers, A.H.: Analysis of resource-constrained processes with colored petri nets. In: Sixth Workshop and Tutorial on Practical Use of Coloured Petri Nets and the CPN Tools. (2005)

17. Jensen, K.: Coloured Petri nets (2nd ed.): basic concepts, analysis methods and practical use volume 1. Springer-Verlag, London, UK (1996)
18. Pesic, M., van der Aalst, M.P.W.: Modelling work distribution mechanisms using colored petri nets. International Journal on Software Tools for Technology Transfer (STTT) **9**(3) (2007) 327–352
19. Pesic, M., van der Aalst, M.P.W.: Towards a reference model for work distribution in workflow management systems. Business Process Reference Models
20. Voudouris, C., Owusu, K.G., Dorne, J.H.R., Ladde, C., Virginas, B.: Arms: An automated resource management system for british telecommunications plc. European Journal of Operational Research **171**(3) (2006) 951–961
21. Cowling, P., Colledge, N., Dahal, K., Remde, S.: The trade off between diversity and quality for multi-objective workforce scheduling. Lecture Notes In Computer Science **3906** (2006) 13
22. Shaw, P.: A new local search algorithm providing high quality solutions to vehicle routing problems. APES Group, Dept of Computer Science, University of Strathclyde, Glasgow, Scotland, UK (1997)
23. Gruhn, V., Richter, T.: A general model of mobile environments: Simulation support for strategic management decisions. In: Proceedings of the 2nd International Workshop on Personalization in Grid and Service Computing (PGSC'08). (2008)