Optimizing the Troops-to-Tasks Problem in Military Operations Planning

Maria Fleischer Fauske

Norwegian Defence Research Establishment (FFI)
maria.fauske@ffi.no

ABSTRACT

In the planning of military operations, deciding who should do what, where, and when is crucial for the success of the operation. This troops-to-tasks analysis is a project scheduling problem closely related to the well-established resource-constrained project scheduling problem, with many additional characteristics and constraints. The standard resource-constrained project scheduling problem is NP hard. When it comes to the troops-to-tasks analysis, it will vary from case to case whether the problem is solvable mathematically within a practical time frame, and within the memory limits on today's computers. In this paper we outline the scope of the troops-to-tasks analysis. We present this problem setting, and emphasize its complexity compared to known problems from the literature. We formulate a mathematical model for optimizing the troops-to-tasks analysis in a high intensity land operation on brigade level with supporting resources from the Air Force. This is a small to medium sized operation where the troops-to-tasks problem is solvable mathematically. The model we present in this paper gives us the opportunity to study the characteristics of the problem, and it can serve as a tool in future research, when testing the performance of heuristic solution methods.

INTRODUCTION

Military operations often involve a large set of tasks that have to be performed with limited resources. An important part of planning an operation is deciding who does what, where, and when. In operational planning, this is called the troops-to-tasks analysis. This analysis is conducted by the operational planning staff, under the guidance of the commander.

The Norwegian Defence Research Establishment (FFI) "has the primary responsibility for defence-related research in Norway. FFI is the chief adviser on defence-related science and technology to the Ministry of Defence and the Norwegian Armed Forces" (http://www.ffi.no/en/Sider/default.aspx). Analysts from FFI frequently participate in exercises with the Norwegian Armed Forces, and they were deployed with the Norwegian Armed Forces in Afghanistan in the period 2008–2013. Through this, we have identified the potential of optimizing the troops-to-tasks analysis. Such an optimization has several purposes. One is to find out who should do what in the operation. Another could be to check the feasibility of a given plan, for example, when it comes to the desired timelines and resource usage. In addition, an optimization model would be a tool for testing different alternatives by varying input data and conditions to see how such variations affect the operational plan.

The troops-to-tasks analysis is also a part of long-term defense planning (LTP). At FFI, much effort is put into the study of the future development of the Norwegian force structure (Hennum and Glærum, 2008, 2010). Similar to the case in NATO, we use a scenario-based approach to long-term planning. In principle, the scenarios represent high- or low-intensity operations. By identifying the necessary resources for handling the different scenarios, analysts develop effective alternatives for future force structures.

A military operation can be viewed as a project in which activities must be performed by a set of resources. There have been many efforts to incorporate methods from project scheduling and general planning into military operational planning (Abbas et al., 2006; Bui et al., 2009; Li and Womer, 2009a; Popken and Cox, 2004; Schlabach et al., 1999; Wilkins and Desimone, 1994; Willick et al., 2010). The difference between a troops-to-tasks problem and other closely related problems from the literature is the complexity introduced by including aspects of the problem such as resource hierarchy, locations, and resources skills and capacities, as we describe later.

The troops-to-tasks problems fall into the category of resource-constrained project scheduling problems (RCPSP) (Brucker et al., 1999; Hartmann and Briskorn, 2010; Icmeli et al., 1993; Özdamar and Ulusoy, 1995). The RCPSP considers a project with J activities, where each activity j has a processing time p_j. There may be precedence relations between some of the activities. This means that an activity j cannot be processed before its predecessors are completed. There are $\mathcal{K}$ renewable resources, and each activity requires r_{jk} units of resource k in each period that the activity is in process.

APPLICATION AREAS:
Planning of military operations
OR METHODOLOGY:
Optimization

The activities are scheduled with starting times S_j. The model allocates resources and starting times to each activity and the objective is to minimize the makespan.

RCPSPs are proven to be NP hard, which means that problems other than very small ones cannot be solved exactly within reasonable time (Blazewics et al., 1983). The RCPSP and related problems are usually solved with heuristic algorithms, like the tabu search algorithm and genetic algorithms. We find many references to different algorithms in the literature. Kolisch and Hartmann (2006) give an overview of many of them. Bui et al. (2009) formulates a multiobjective risk-based framework for mission capability planning, formulating the military planning problem as a basic, though stochastic, RCPSP. Li and Womer (2009a) study the planning of shipboard manpower with a case study from the US Navy.

The multiskill project scheduling problem (MSPSP) is an extension of the RCPSP proposed by Bellenguez and Néron (2004). Here, the resources are, e.g., staff members who are able to perform more than one kind of activity. That is, they possess more than one skill. The activities have different skill requirements, instead of specific resource requirements. Many skills may be necessary to process one activity. Staff members can only process one activity at a time. The troops-to-tasks problem is an MSPSP with many additional constraints and possible objectives. The troops are like staff members with different skills. Li and Womer (2006) also study problems with multiskilled personnel, or multipurpose resources. They study both minimization of the total number of resources (Li and Womer, 2009a) and minimization of project costs (Li and Womer, 2009b).

The MSPSP can be viewed as a variant of the well-established multimode resource-constrained project-scheduling problem (Alcaraz et al., 2003; Hartmann and Briskorn, 2010), as explained by Bellenguez-Mourineau and Néron (2008). In that case, resource requirements for each processing mode of each activity correspond to a given subset of resources that may process that activity. This, however, may lead to a very large set of modes, given the many skills that each resource may possess and the number of resources that may be necessary to process an activity (Bellenguez-Morineau and Néron, 2008).

The MSPSP is also NP hard, which leads us to suspect that troops-to-tasks problems will also often be difficult or impossible to solve mathematically. However, because of the constraints and the characteristics of some troops-to-tasks problems, there will be problem instances that are solvable within a timeframe that is acceptable in practice. In this paper, we show an example of such a problem instance. We also discuss how the characteristics of a troops-to-tasks problem will influence its solvability, and how we can model it in a manner that increases the chance of solvability.

Optimizing the troops-to-tasks analysis will be useful in many sorts of operations in the whole spectrum of conflict, from low-intensity peace operations to high-intensity operations. In this paper, we look at the high-intensity case. In peace operations the models might have different constraints and objectives, but we will not study these in this paper. The purpose of this paper is threefold. First, we want to outline the scope of the troops-to-tasks analysis for high-intensity operations. We present this problem setting, and emphasize its complexity compared to known problems from the literature. Some parts of the troops-to-tasks problem setting have been previously addressed. Second, we formulate a mathematical model for optimizing the troops-to-tasks analysis in high-intensity operations. We present a case that represents an operation where the troops-to-tasks optimization is solvable using our mathematical model. We study the structure of this problem instance, and how this affects the solvability of the problem. Third, we regard our work as groundwork for developing heuristic solution methods for solving troops-to-tasks problems of all sizes. Our model is an essential benchmarking tool when it comes to the development of heuristic algorithms.

The model we present is based on NATO's operational planning process, and how the operational planning staff evaluates the resource requirements in this process. Operational planning in NATO follows a strict procedure, which is described in the Comprehensive Operations Planning Directive (COPD) (SHAPE, 2010). In this process, the staff develops several tentative courses of action (COAs), which are options that ''will accomplish or contribute to the accomplishment of a mission or task, and from which a detailed plan is developed'' (SHAPE, 2010, 7-2). Considering as many COAs as possible provides flexibility on how forces may be employed. A part of analyzing each COA is conducting a troops-to-tasks analysis. This analysis ''seeks to determine the military capabilities and capacities required to implement the COA'' (SHAPE, 2010, 4-58). The goal is to ''optimize the joint force employment and preclude duplication of effort'' (SHAPE, 2010, 4-59).

Even when following this strict procedure, the COPD states that ''throughout the planning and execution process, there must be a continual review process to update the design, plan and execution of an operation'' (SHAPE, 2010, 1-3). In this context, an easy-to-update scheduling tool would be useful for the staff supporting the commander. The tool that NATO uses for operational planning (TOPFAS) includes the troops-to-tasks analysis, but there is no optimization process included in TOPFAS yet, instead relying on military judgement.

MODELING CONSIDERATIONS

The model we describe in this paper is aimed at a high-intensity land operation with supporting resources from the Air Force or the Navy. In the Army resources are hierarchical, as a person is a part of a squad is a part of a platoon, etc., and the personnel are regarded as resources in the troops-to-tasks analysis. However, in the Navy and in the Air Force the platforms are often regarded as the resources in a planning context. So a vessel or an aircraft including its personnel is assigned to a task, not the personnel itself. This means that for planners some resources may be part of a strict hierarchy and others may not.

Even though the military hierarchy consists of many levels, an order will only go one level down. In planning, however, it is essential to look further than that. A brigade commander, for example, will make his plan in cooperation with all of the commanders of the underlying battalions, who are coordinating their companies, and so on. The hierarchy puts restrictions on where the different resources may be at a certain time. In our model, the units that are a part of the hierarchy must operate as a whole, requiring that all underlying troops are situated in (approximately) the same location. We model this with super-resources and sub-resources. Units that can operate freely are modeled with a one-to-one relation between a dummy super-resource and the sub-resource (the resource itself).

Resources may possess many skills. The resources can use several skills at the same time. In many operations, the resources' skills may be of different levels. Such hierarchical levels of skills have been studied by Bellenguez and Néron (2005). However, in a high-intensity operation we assume that every resource will only be assigned activities that they are highly qualified to perform, therefore we do not consider levels of skills.

Resources can process more than one activity at a time if those activities can be processed in the same location, and if none of these activities require the full attention of the resource. We model this as exclusive and non-exclusive activities. If an activity is exclusive, the resources processing it can *only* process this activity at a certain point in time. In a high intensity operation, many of the activities will be exclusive.

Resources also have a capacity for each skill. Two resources possessing the same skill might have different capacities for that skill. For example, one type of aircraft may be able to solve a task using one aircraft, while another type may need two aircraft to process the same task. A surveillance activity may, for example, require a capacity of 0.8 of a specific surveillance skill. That means that this activity can be processed equivalently by two resources that each has a capacity of 0.4 of this skill or by one resource that has a capacity of 1 of this skill. If a resource's capacity is larger than what is required, that does not mean that it has ''left over'' capacity to use on another task at the same time. It is the exclusiveness of the activities that decides whether a resource can do more than one task at a time.

A resource is situated in a location and it takes time to move between locations. Location problems have been studied in several papers (Krüger and Scholl, 2010; Mika et al., 2006), but then mostly without the resources travelling between the locations where they are situated. Travelling time between locations may be modeled as a sort of set-up time, or by saying that an activity cannot be started before all resources that shall process it have had the time to travel to the activity's location. Set-up times are studied in, e.g., Mika et al. (2006, 2008), Neumann et al. (2002), and Schwindt (2005).

Activities may or may not have to be processed at a specific time. Several papers consider release dates (first allowed starting time) and deadlines (last allowed starting time) (Drezet and Billaut, 2008; Kis, 2005, 2006; Klein, 2000; Klein and Scholl, 2000). Similarly, activities may have to be performed within certain phases of the operation. In high-intensity operations, there are usually different phases, and the transition to a new phase is often marked by the successful completion of certain tasks. We model this using precedence relations between activities.

Some tasks might have to be processed in parallel. We say that such parallel activities must start at the same time, which means that they could end at different times, depending on the duration of each activity.

MATHEMATICAL FORMULATION

In this section we show the mathematical formulation of the troops-to-tasks analysis in a high-intensity land operation with supporting resources from the Navy and the Air Force.

Input data

- T: end time in the model
- $\mathcal{J}$: set of activities
- $\mathcal{J}^{exc}$: set of exclusive activities
- $\mathcal{J}_j^{pre}$: set of predecessor activities of activity j
- $\mathcal{J}_j^{par}$: set of parallel activities of activity j
- $\mathcal{K}$: set of resources
- $\mathcal{K}^{sup}$: set of super-resources
- $\mathcal{K}_k^{sub}$: set of subresources of resource k
- $\mathcal{S}_k$: set of skills that resource k possesses
- $\mathcal{S}_j$: set of skills required for activity j
- L: set of locations
- L: number of locations
- J: number of activities
- c_{sk}: capacity of skill s for resource k
- ${k_k}^{sup}$: super-resource of resource k
- $d_{ll'k}$: travel time between locations l and l' for resource k
- d_j: duration of activity j
- ES_j: release date (earliest allowed starting time) of activity j
- LS_j: deadline (latest allowed starting time) of activity j
- ${c_{sj}}^{req}$: minimum capacity requirement of skill s from activity j
- M: big number

Decision Variables

$$w_{jt} = \begin{cases} 1, & \text{if activity } j \text{ is processed,} \\ & \quad \text{starting at time } t \\ 0, & \text{else} \end{cases}$$

$$x_{jtks} = \begin{cases} 1, & \text{if activity } j \text{ is started at time } t, \\ & \quad \text{processed by resource } k \\ & \quad \text{using skill } s \\ 0, & \text{else} \end{cases}$$

$$y_{lkt} = \begin{cases} 1, & \text{if resource } k \text{ is in location } l \text{ at time } t \\ 0, & \text{else} \end{cases}$$

Objective Function

The objective is to minimize the makespan of the project, i.e., the start-up time of dummy activity J.

$$\min \sum_{t=1}^{T} w_{Jt} t \tag{1}$$

Constraints

$$\sum_{t=1}^{T} (t + d_j - 1) w_{jt} \leq \sum_{t=1}^{T} w_{Jt} \quad j \in J \tag{2}$$

$$\sum_{k \in \mathcal{K}} \sum_{s \in S_k} x_{jtks} \geq w_{Jt} \quad j \in J, t = 1, \ldots, T \tag{3}$$

$$x_{jtks} \leq w_{jt} \; j \in J, t = 1, \ldots, T, k \in \mathcal{K}, s \in S_k \tag{4}$$

$$w_{jt} c_{sj}^{req} \leq \sum_{k \in \mathcal{K}} c_{sk} x_{jtks} \quad j \in J, t = 1, \ldots, T, s \in S_j \tag{5}$$

$$\sum_{t=1}^{T} w_{jt} t \geq \sum_{t=1}^{T} w_{jt} ES_j \quad j \in J \tag{6}$$

$$\sum_{t=1}^{T} w_{jt} t \leq \sum_{t=1}^{T} w_{jt} LS_j \quad j \in J \tag{7}$$

$$\left(1 - \sum_{t=1}^{T} w_{jt}\right) M + \sum_{t=1}^{T} w_{jt} t \geq \sum_{t=1}^{T} w_{j't} t + d_{j'} \qquad j \in J, j' \in J_j^{pre} \tag{8}$$

$$\sum_{t=1}^{T} w_{jt} \leq \sum_{t=1}^{T} w_{j't} \; j \in J, j' \in J_j^{pre} \tag{9}$$

$$\sum_{t=1}^{T} w_{jt} t = \sum_{t=1}^{T} w_{j't} t \; j \in J, j' \in J_j^{par} \tag{10}$$

$$\sum_{t=1}^{T} w_{jt} \geq 1 \; j \in J \tag{11}$$

$$\frac{1}{M} \sum_{s \in S_k} x_{jtks} + \sum_{\tau \in t}^{t+d_j-1} \left(\sum_{s \in S_k} x_{j'\tau ks} \right) \leq 1 \qquad t = 1, \ldots, T - d_j, k \in \mathcal{K}, j \in J, j' \in J^{exc}, j' \neq j \tag{12}$$

$$\sum_{s \in S_k} x_{jtks} + \frac{1}{M} \sum_{\tau \in t}^{t+d_j-1} \left(\sum_{s \in S_k} x_{j'\tau ks} \right) \leq 1 \qquad t = 1, \ldots, T - d_{j+1}, k \in \mathcal{K}, j' \in J, j \in J^{exc}, j' \neq j \tag{13}$$

$$\sum_{l \in L} y_{\ell kt} \leq 1 k \in \mathcal{K}, t = 1, \ldots, T \tag{14}$$

$$y_{ljkt'} \geq \sum_{k'' \in \mathcal{K}_{k'}^{sub}} \sum_{s \in S_{k''}} x_{jtk''s} \qquad k \in \mathcal{K}_{k'}^{sub}, k' = {}^{\sup}_{k}, j \in J, t = 1, \ldots, T - d_j + 1, \quad t' = t, \ldots, t + d_j - 1 \tag{15}$$

$$\sum_{j \in J} \sum_{t' = \max\{1, t - d_j + 1\}}^{t} \sum_{k'' \in \mathcal{K}_{k'}^{sub}} \sum_{s \in S_{k''}} x_{jt'k''s} \geq \sum_{l \in L} y_{\ell kt} \qquad k \in \mathcal{K}_{k'}^{sub}, k' = k_k^{\sup} t = 1, \ldots, T \tag{16}$$

$$(y_{lkt'} - 1) M \leq (t' - (t + d_{lljk} + 1)) y_{ljkt} \qquad k \in \mathcal{K}, j \in J, l \in L, t = 1, \ldots, T - 1, t' = t, \ldots, T \tag{17}$$

$$x_{jtks} = \{0, 1\} \; j \in J, t = 1, \ldots, T, k \in \mathcal{K}, s \in S_k \tag{18}$$

$$w_{jt} = \{0, 1\} \; j \in J, t = 1, \ldots, T \tag{19}$$

$$y_{lkt} = \{0, 1\} \; l \in L, k \in \mathcal{K}, t = 1, \ldots, T \tag{20}$$

Constraint (2) makes sure that the dummy sink activity marks the end of the project, by making it start after all other activities have finished. Constraints (3) and (4) make sure that $w_{jt} = 1$ if at least one resource processes an activity j. Capacity requirements are handled by constraint (5). Constraints (6) and (7) take care of release dates and deadlines. Precedence constraints are taken care of by (8) and (9), and parallel constraints are handled by (10). Constraint (11) makes sure that every activity is processed. If a resource is processing an activity, it cannot start processing an exclusive activity. This is taken care of by constraint (12). Similarly, in constraint (13), if a resource is processing an exclusive activity, it cannot start processing another activity. A resource cannot be in more than one location, as we see in constraint (14). Constraint (15) says that when a resource or at least one of its co-sub-resources is processing an activity, the resource must be in the location of that activity. Constraint (16) ensures that resources are not allocated to a location when not processing an activity or when its co-sub-resources are not processing an activity. This property is used in the model when calculating travel times between activities in constraint (17). Constraints (18–20) define the variables.

ANALYSIS

In this section, we illustrate the use of our model through an example. In this example we describe a high-intensity land operation on brigade level with supporting resources from the Air Force. Our brigade structure consists of four battalions, each with three underlying companies, in addition to different kinds of supporting units, such as logistics, medical, staff, Intelligence, Surveillance, Target Acquisition, and Reconnaissance (ISTAR), and Command and Control Information System (C2IS). These supporting units are, however, dedicated to tasks so they can be excluded from the optimization. From the Air Force, there are six aircraft of two different types available. Each army unit has five skills, and the type of skills they possess vary among the units. Each aircraft has two different skills. The operation takes place in three different areas, where there are tasks to be performed in different locations in each area. This is illustrated in Figure 1 where we can see the 12 different locations in the operation. Travel times for army units between the three areas are shown in the figure. As for the travel times between the locations in each area (solid lines), the short lines represent a travel time of 1 time unit, and the longer lines represent a travel time of 2 time units. One time unit corresponds to 6 hours. The air craft have negligible travel times.

There are several tasks to be performed in each location. In the locations with a thicker circle line, there are targets that will be taken out. There are a total of 25 tasks to be performed. With tasks 1–8 taking place in Area 1, tasks 9–18 taking place in Area 2, tasks 19–24 taking place in Area 3, and task 25 being an observation point to be held for a longer period of time in location 12. The task durations vary from 1 to 3 time units. Each task requires one to three skills. The tasks where targets are to be attacked require a capacity of 2 of some skills. For all other tasks, the capacity requirement is 1 for each skill. There are several precedence relations between tasks. These relations are shown in Figure 2. Tasks 8, 16, and 24 in the three target locations must be processed in parallel. Sixteen of the 24 tasks are exclusive. Four of the tasks have a deadline (latest allowed start-up time) in time step 1. The rest of the timing requirements are expressed through precedence relations.

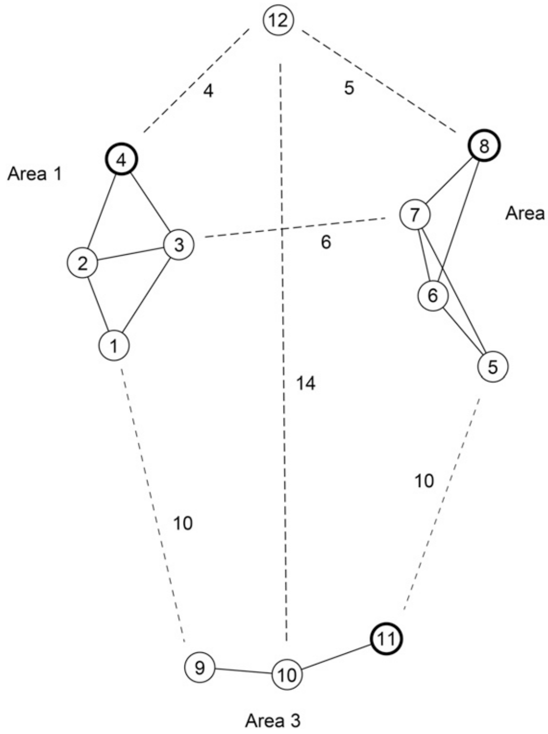

Figure 1. The operation takes place in three different areas. In these three areas, there are a total of 12 smaller locations where the tasks shall be performed. Travel times between the three areas are shown in the figure. In addition, the short, solid lines represent a travel time of 1 time unit, and the longer, solid lines represent a travel time of 2 time units.

We implemented the model in IBM ILOG CPLEX Optimization Studio on a computer with a 2:90 GHz Intel(R) Core(TM) i7-3520M CPU, running 64-bit Windows 7 operating system. The resulting operational plan is shown in Table 1. The runtime of this optimization was 2 minutes 17 seconds.

The solvability of troops-to-tasks problems will vary from case to case. There are many characteristics of the problems that influence the solvability. The size of the operation when it comes to the number of resources, tasks, locations, time steps, etc., is one. The solvability of the problem may be adjusted by:

- including or excluding supporting units such as logistics and medical units in the optimization,
- varying the number of tasks that are dedicated to specific resources in advance,
- adjusting the number of locations by making the locations cover smaller or larger areas,

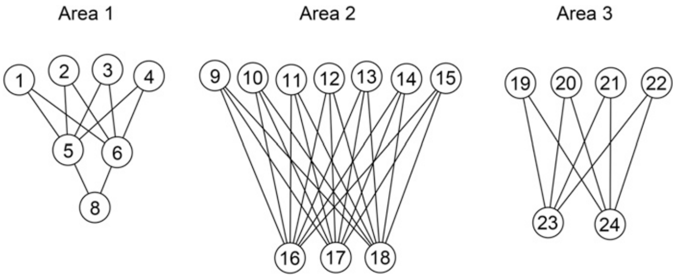

Figure 2. There are several precedence relations between the tasks in the operation.

- viewing the operation area as one large area or several smaller areas, doing one optimization for each area,
- adjusting the number of hours in each time step,
- dividing the operation into more or fewer phases, or
- being more or less strict on the release date and deadline requirements.

Obviously, decreasing the level of detail in the model might decrease the quality of the solution. A characteristic that influences the solvability, but is not possible to adjust in the same manner as the ones above, is the number of exclusive activities in the operation. In the example in this paper, the solution time when all activities are set to be exclusive is 9 minutes 10 seconds. It is hard to set a general acceptable runtime for the planning of operations, as this limit would vary from operation to operation. However, we assume that when the runtime gets higher than 15–20 minutes, it starts to become impractical to do many runs.

CONCLUSION

The troops-to-tasks problem setting is very complex compared to standard resource-constrained project scheduling problems. We believe that the value of an optimization model for the troops-to-tasks analysis will vary from planning situation to planning situation, but in

Table 1. The resulting plan from the troops-to-tasks analysis. The resources are grouped according to the hierarchy.

Resource/time	1	2	3	4	5	6	7	8	9	10
R1	A19		A22							
R2										
R3	A20									
R4	A9	A9								A18
R5	A9, A10	A9, A10		A11						A17
R6	A9	A9		A13	A12		A14	A14		
R7	A1, A2, A3	A1, A2	A1		A7					
R8	A2	A2					A5	A5		
R9	A1	A1	A1		A6					
R10										
R11	A25	A25	A25	A25	A25	A25	A25	A25	A25	A25
R12										
R13	A15									A16
R14	A4	A4								A8
R15	A10	A10								
R16				A23						A24
R17	A21				A12					
R18	A4	A4								

many cases it would be a useful tool for the analysts to contribute to the decision-making process. NATO wants to include an optimization model in their planning tool, TOPFAS, and there is an explicit desire from military personnel in the Norwegian Armed Forces for optimization of the troops-to-tasks analysis. It is, however, impossible to include all real-life aspects in an automatic troops-to-tasks analysis. A schedule provided by such a model will almost certainly need to be adjusted by the military staff. A useful way of applying models in military planning is to generate different solutions quickly, based on changes in inputs. Such experimentation adds valuable information about the situation at hand.

The mathematical model we presented in this paper is based on the resource-constrained project scheduling problem, which is NP hard. Larger instances of troops-to-tasks problems will have too high a memory consumption to be solvable, or runtimes that are impractically long. However, because of the many restrictions and characteristics of the troop-to-tasks problems, smaller or medium-sized problems might be solved mathematically. As we describe in this paper, the problems can be modelled in a manner that increases the probability of solvability. Decreasing the level of detail might, however, decrease the quality of the solution. To be sure to solve most kinds of troops-to-tasks problems, it is necessary to develop heuristic algorithms. These cannot guarantee optimal solutions, but the literature shows that such algorithms perform very well. The mathematical model presented in this paper will be important to use for benchmarking when developing heuristic solution methods.

REFERENCES

Abbas, H., Bender, A., Baker, S., and Sarker, R. 2006. Identifying the Fleet-Mix in a Military Setting, *Proceedings Second International Intelligent Logistics Systems Conference* (IILS2006). Springer-Verlag, 8.1–8.11.

Alcaraz, J., Maroto, C., and Ruiz, R. 2003. Solving the Multi-Mode Resource-Constrained Project Scheduling Problem with Genetic Algorithms, *Journal of the Operational Research Society*, Vol 54, June, 614–626.

Bellenguez, O. and Néron, E. 2004. Lower Bounds for the Multi-skill Project Scheduling Problem with Hierarchical Levels of Skills, *Proceedings of the 5th International Conference on Practice and Theory of Automated Timetabling.* LNCS 3616, Springer, 229–243.

Bellenguez-Morineau, O., and Néron, E. 2008. Multi-Mode and Multi-Skill Project Scheduling Problem, *Resource-Constrained Project Scheduling, Models, Algorithms, Extensions and Applications*, S. D. C. Artigues and E. Néron, eds. ISTE Ltd. and John Wiley & Sons, 149–160.

Blazewics, J., Lenstra, J. K., and Kan, A. H. G. R. 1983. Scheduling Subject to Resource Constraints: Classification and Complexity, *Discrete Applied Mathematics*, Vol 5, No 1, 11–24.

Brucker, P., Drexl, A., Möhring, R., Neumann, K., and Pesch, E. 1999. Resource-Constrained Project Scheduling: Notation, Classification, Models, and Methods, *European Journal of Operational Research*, Vol 112, No 1, 3–41.

Bui, L. T., Barlow, M., and Abbass, H. A. 2009. A Multi-Objective Risk-Based Framework for Mission Capability Planning, *New Mathematics and Natural Computation*, Vol 5, No 2, 459–485.

Drezet, L.-E., and Billaut, J.-C. 2008. A Project-Scheduling Problem with Labor Constraints and Time-Dependent Activities Requirements, *International Journal of Production Economics*, Vol 112, No 1, 217–225.

Hartmann, S., and Briskorn, D. 2010. A Survey of Variants and Extensions of the Resource-Constrained Project Scheduling Problem, *European Journal of Operational Research*, Vol 207, No 1, 1–14.

Hennum, A. C., and Glærum, S. 2008. Norwegian Long-Term Defence Planning. Technical Report, NATO RTO-TR-069-SAS-072.

Hennum, A. C., and Glærum, S. 2010. J-DARTS: An End-to-End Defence Planning Tool Set. Technical Report, NATO RTO-TR-069-SAS-081.

Icmeli, O., Erenguc, S. S., and Zappe, C. J. 1993. Project Scheduling Problems: A Survey, *International Journal of Operations and Production Management*, Vol 13, No 11, 80–91.

Kis, T. 2005. A Branch-and-Cut Algorithm for Scheduling of Projects with Variable Intensity Activities, *Mathematical Programming*, Vol 103, No 3, 515–539.

Kis, T. 2006. RCPS with Variable Intensity Activities and Feeding Precedence Constraints, *Perspectives in Modern Project Scheduling*, J. Józefowska and J. Weglarz, eds. Springer, 105–129.

Klein, R. 2000. Project Scheduling with Time-Varying Resource Constraints, *International Journal of Production Research*, Vol 38, No 16, 3937–3952.

Klein, R., and Scholl, A. 2000. Scattered Branch and Bound: An Adaptive Search Strategy Applied to Resource-Constrained Project Scheduling, *Central European Journal of Operations Research*, Vol 7, No 3, 177–201.

Kolisch, R., and Hartmann, S. 2006. Experimental Investigation of Heuristics for Resource-Constrained Project Scheduling: An Update, *European Journal of Operational Research*, Vol 174, No 1, 23–37.

Krüger, D., and Scholl, A. 2010. Managing and Modelling General Resource Transfer in (Multi) Project Scheduling, *OR Spektrum*, Vol 32, No 2, 369–394.

Li, H., and Womer, K. 2006. Project-Scheduling with Multi-Purpose Resources: A Combined MILP/CP Decomposition Approach, *International Journal of Operations and Quantitative Management*, Vol 12, No 4, 305–325.

Li, H., and Womer, K. 2009. A Decomposition Approach for Shipboard Manpower Scheduling, *Military Operations Research*, Vol 14, No 3, 1–24.

Li, H., and Womer, K. 2009. Scheduling Projects with Multi-Skilled Personnel by a Hybrid MILP/CP Benders Decomposition Algorithm, *Journal of Scheduling*, Vol 12, No 2, 281–298.

Mika, M., Waligóra, G., and Weglarz, J. 2006. Simulated Annealing and Tabu Search for Multi-Mode Resource-Constrained Project Scheduling with Positive Discounted Cash-flows and Different Payment Models, *Perspectives in Modern Project Scheduling*, J. Józefowska and J. Weglarz, eds. Springer, 131–165.

Mika, M., Waligóra, G., and Weglarz, J. 2008. Tabu Search for Multi-Mode Resource-Constrained Project Scheduling with Schedule Dependent Setup Times, *European Journal of Operational Research*, Vol 187, No 3, 1238–1250.

Neumann, K., Schwindt, C., and Zimmermann, J. 2002. *Project Scheduling with Time Windows and Scarce Resources.* Springer.

Özdamar, L., and Ulusoy, G. 1995. A Survey on the Resource-Constrained Project Scheduling Problem, *IIE Transactions*, Vol 27, No 5, 574–586.

Popken, D., and Cox, L. 2004. A Simulation-Optimization Approach to Air Warfare Planning, *Journal of Defence Modeling and Simulation*, Vol 1, No 3, 127–140.

Schlabach, J. L., Goldberg, D. E., and Hayes, C. C. 1999. FOX-GA: A Genetic Algorithm for Generating and Analyzing Battlefield Courses of Action, *Evolutionary Computation*, Vol 7, No 1, 45–68.

Schwindt, C. 2005. *Resource Allocation in Project Management.* Springer.

SHAPE. 2010. Allied Command Operations—Comprehensive Operations Planning Directive, Interim v1.0. Technical report. Strategic Headquarters Supreme Headquarters Allied Powers Europe.

Wilkins, D. E., and Desimone, R. V. 1994. Applying an AI Planner to Military Operations Planning, *Intelligent Scheduling*, M. Zeweben and M. Fox, eds. Morgan-Kaufmann, 685–708.

Willick, K., Wesolkowski, S., and Mazurek, M. 2010. Multiobjective Evolutionary Algorithm with Risk Minimization Applied to a Fleet Mix Problem, *Proceedings IEEE Congress on Evolutionary Computation* (CEC 2010). IEEE, 1–7.