Optimizing the daily manpower planning in a real transhipment container terminal

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1. Introduction

The hub-and-spoke topology of maritime networks results in a critical role for transhipment container terminals (TCTs) owing to the consolidation of flows among them. Unlike origin and destination ports, TCTs are under heavy competitive pressure, because shipping liners have the high bargaining power of re-designing maritime routes if they are not satisfied with TCTs. As a result, TCTs must provide high-performance and cost-effective services and plan accurately the management of their resources to satisfy the requests of shipping liners.

Since few ports adopt completely automated systems, manpower is a key resource for TCTs, particularly for those with high labour costs. Moreover, it represents one of the main cost items, which sometimes amount to more than 50% of the total annual operating cost (Serra, 2014). Therefore, manpower management is a crucial issue for TCTs.

The workload in TCTs is typically organized in personnel shifts 24/7. Due to union and work rules, personnel shifts must be planned a number of months before their implementation. However, when personnel shifts are built, there is little or any knowledge on the final manpower demand, because maritime logistics is affected by both uncertainty and vulnerability, due to natural causes (wind, etc.), equipment failures, labour disputes, as well as geopolitical factors. As a result, the relevant uncertainty in maritime logistics produces frequent priority changes for TCTs, who must adjust their internal processes to these external changes, in order to keep on being competitive in the shipping industry.

This paper investigates the case study of a TCT in which workload uncertainty is addressed by separating the manpower planning problem into two planning stages:

- Long-term plan, which consists of a sequence of workdays and days off, which spans a monthly horizon. The long-term plan denotes a worker as fixed in a shift if he must be on-
duty in that shift, whereas he is denoted as flexible in a day if he must be on-duty in that day, but his shift will be determined in the next planning stage, when there will be precise knowledge on the final workload. This imprecise information prevents deciding at this stage what each worker is required to do and results in the risk of personnel overmanning and undermanning.

- **Daily plan**, which is typically performed 24 hours before the day in question, when the workload is almost certain. It is required to inherit the separation between fixed and flexible operators from the long-term plan, determine the shifts of flexible workers and decide what each worker is required to do in the next workday. Moreover, at this stage the TCT must decide how many external workers can be hired and derive personnel undermanning or overmanning.

The most original attribute of the daily manpower planning problem in this case study is the organization of the terminal activities in shifts (hereafter called activity shifts). These shifts differ from the shifts of internal operators. In addition, although there is much literature on workforce management in several fields (De Bruecker e.a., 2015), little attention has been devoted so far to the specific context of container terminals (Stahlbock, Voss, 2008; Carlo, Vis, Roodbergen, 2014).

Kim e.a. (2004) investigated the scheduling of preselected operators to handling activities. Lim, Rodrigues, and Song (2004) studied the operator movement planning at the Singapore port, but the number of workers was taken for granted. The same assumption was made by Hartmann (2005), who presented a model for the scheduling of jobs and operators in container terminals. Legato and Monaco (2004) studied a manpower planning problem with overlapping shifts for personnel and activities. The same assumption was also made in Di Francesco e.a. (2015-a; 2015-b).

To conclude, the limited research on manpower planning has resulted in few tools to support decision-making processes, which are typically based on hunch and experience. In addition, no studies have analysed TCTs’ decision policies on the manpower planning and evaluated how good they are. In this paper, we illustrate the policy adopted in this case study and compare it to the solutions of an optimization model, which is proposed to minimize the assignment costs of workers to shifts, tasks and activities, while avoiding both overmanning and undermanning, if possible.

This paper is organized as follows. In Section 2 the main components and decisions of the daily manpower planning problem are described. The decision policy of a real TCT on this problem is presented in Section 3. An optimization model for the daily manpower problem is formulated in Section 4. In Section 5 we compare the terminal policy to the solutions of the optimization model. Finally, Section 6 presents a summary of conclusions and describes future research perspectives.
2. The daily manpower problem in a case study

The daily manpower problem inherits the long-term plan, which divides each workday of internal operators into 3 personnel shifts of 8 hours each. External workers can also be hired when the internal manpower is insufficient and their workdays are divided into 4 shifts of 6 hours each.

Since the number of internal and external operators is limited, workforce undermanning may occur. As the TCT cannot afford to pay penalties for delays produced on vessels, undermanning is mainly addressed by the overtime of internal operators, if they are in a day off according to the long-term plan. Personnel overmanning may also occur, because the long-term plan is built when the workload is not yet known. Overmanning must be detected, because the TCT cannot pay workers for doing nothing and is faced by changes in the long-term plan: unused workers are shifted in other workdays when higher workload demands are expected to occur.

Operators perform two types of activity in the TCT: vessel activities and housekeeping ones. A vessel activity is a sequence of handling operations, in which containers are loaded onto and discharged from a vessel. A housekeeping activity is a sequence of container transfers along the yard, occurring when the areas of the incoming and outgoing vessel activities differ. Generally speaking, vessel activities have higher priority, because shipping liners request them, whereas housekeeping must be unavoidably performed to be in the position of performing future vessel operations. In this case study, daily activity shifts are organized in four intervals of 6 hours and overlap exactly with the shifts of external operators, but their differ from the shifts of internal operators.

Each activity is performed by a gang of workers, each of which is charge of one task. Tasks have a hierarchy and each internal operator is paid according to the top task he can do. He can also be employed in lower-level tasks, but he can never be assigned to upper lever tasks. Although many tasks are performed in the terminal, only the most important ones are considered in this study: the Quay Cranes (QC) driver, who moves containers between vessels and terminal berths, the Rubber Typed Gantry crane (RTG) driver, who stores containers in the yard and the driver of Internal Transfer Vehicles (ITV), which are low-cost tractors providing horizontal transport. The QC is the top-level task, in fact QC operators can also perform any other task, whereas RTG operators can also be employed as ITV ones and ITV operators can perform this task only. External workers can carry out the ITV task only.

The typical housekeeping gang is made up with 5 operators: 2 of them are deployed in the RTG task and the remaining 3 in the ITV one. The standard vessel gang is made up of 6 operators: 1 deployed in the QC task, 2 in the RTG one and 3 in the ITV one. However, 2 operators in each vessel gang must be able to perform the QC task: due to the physiological impossibility of keeping...
high handling rates for 8 hours in this crucial task, QC operators are deployed for 4 hours each in this task, which is swapped after in the mid-term of the personnel shift. The objective of the daily manpower plan is to assign internal and external workers to shifts, tasks and activities at the lowest operating cost, as well as to minimize personnel undermanning and overmanning. The plan is required to provide the workload demand, which can be described as number of workers requested to perform each task in each activity and personnel shift. Generally speaking, it is recommended to assign the most skilled operators to the most important activities. Therefore, internal operator costs should reflect the individual ability of each worker to perform tasks and activities during shifts. Unlike internal operators, the costs of external workers do not have individual attributes, because the TCT does not know a priori which external person will be employed. Nevertheless, they must be paid according to shifts, tasks and activities. According to work contracts, overtime costs are the highest ones and, hence, they should be used only if it is necessary.

3. The terminal policy on the daily manpower problem

The policy of the TCT on the daily manpower problem is organized as follows. First, the TCT assigns all operators in fixed shifts to tasks and activities, which are ranked and served according to a priority list. This assignment starts from the operators able to do the QC task, goes on with those able to do the RTG task and, next, with those able to do the ITV task. In case of overmanning for a specific task, operators in surplus will be later selected for employment in a lower-level task and, if this is not possible, they are set to have a day-off and a future rest day in the long-term plan is changed into a workday. In the case of undermanning for a specific task, shortages will be addressed by the following assignment of operators in flexible shifts.

Next, the TCT focuses on flexible operators and determines their shifts, in order to have the same number of workers in each personnel shift. This choice is motivated by its simplicity and the current lack of decision tools able to evaluate different manpower configurations. However, the uniform manpower supply may show to be ineffective whenever the manpower demand is not uniform in the daily planning horizon.

Finally, the terminal policy determines the tasks and activities of operators in flexible shifts. The procedure starts from the QC task, goes on with the RTG one and ends with the ITV one. In the last case, undermanning is addressed first by external operators and, if they are again insufficient, by the overtime of operators, who were set to be off-duty in that day. In case of overmanning, operators are set to have a day off and a future rest day in the long-term plan is changed into a workday.
4. Optimization model

In this paragraph we propose a mathematical programming model for the daily manpower problem arising in the presented case study.

Let $I$ be the set of internal operators. They can be employed on a set $J$ of periods, which typically span over a daily planning horizon. Each period $j \in J$ represents a time interval equal to the greatest common divisor between the shift duration of internal operators, that of external operators and that of activities. As shown in Table 1, in this case study each period $j \in J$ represents intervals of 2 hours, as the shift of internal operator takes 8 hours, that of external operators take 6 hours and an activity shift is 6 hours long.

<table>
<thead>
<tr>
<th>FIRST SHIFT OF INTERNAL OPERATORS</th>
<th>SECOND SHIFT OF INTERNAL OPERATORS</th>
<th>THIRD SHIFT OF INTERNAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8h$</td>
<td>$8h$</td>
<td>$8h$</td>
</tr>
<tr>
<td>FIRST SHIFT OF EXTERNAL OPERATORS</td>
<td>SECOND SHIFT OF EXTERNAL OPERATORS</td>
<td>THIRD SHIFT OF EXTERNAL OPERATORS</td>
</tr>
<tr>
<td>$6h$</td>
<td>$6h$</td>
<td>$6h$</td>
</tr>
<tr>
<td>FIRST ACTIVITY SHIFT</td>
<td>SECOND ACTIVITY SHIFT</td>
<td>THIRD ACTIVITY SHIFT</td>
</tr>
<tr>
<td>$6h$</td>
<td>$6h$</td>
<td>$6h$</td>
</tr>
<tr>
<td>$\begin{array}{llll} j=1 &amp; j=2 &amp; j=3 &amp; j=4 \ 2h &amp; 2h &amp; 2h &amp; 2h \end{array}$</td>
<td>$\begin{array}{llll} j=5 &amp; j=6 &amp; j=7 &amp; j=8 \ 2h &amp; 2h &amp; 2h &amp; 2h \end{array}$</td>
<td>$\begin{array}{llll} j=9 &amp; j=10 &amp; j=11 &amp; j=12 \ 2h &amp; 2h &amp; 2h &amp; 2h \end{array}$</td>
</tr>
</tbody>
</table>

Table 1. Discretization of the daily planning horizon

Let also $d$ be the number of periods in a day (i.e. $d = 12$), $s$ the number of periods in a shift of internal operators (i.e. $s = 4$), $e$ the number of periods in a shift of external operators (i.e. $e = 3$) and $\rho$ the number of shifts internal operators in a day (i.e. $\rho = 3$), each of which denoted by the index $p$.

Let $Z_j$ be the set of activities to be performed in period $j \in J$. Since several tasks are requested to perform any activity $z \in Z_j$ in period $j \in J$, let $K_z$ be the set of tasks requested for activity $z \in Z_j$ in period $j \in J$ and $K_z \subseteq K_z$ the set of tasks that can be outsourced for activity $z \in Z_j$ in period $j \in J$.

The elements of set $K_z$ are $\{QC, RTG, ITV\}$ for activities and $\{RTG, ITV\}$ for housekeeping ones.

Moreover, let $I_k \subseteq I$ be the set of operators able to perform task $k \in K_z$ for operation $z \in Z_j$ in period $j \in J$. Let also $I_j \subseteq I$ be the set of fixed workers in period $j \in J$, $F \subseteq I$ the set of flexible workers in the considered day and $R \subseteq I$ the set of internal workers having a day off in the considered day. In addition, let $n_{kzj}$ be the number of internal operators requested to perform task $K \in K_z$ for activity $z \in Z_j$ at shift $j \in J$.

Five types of variables are defined:
• $x_{ikzj}$ is the operator selection variable, which takes value 1 if worker $i \in F \cap I_k$ is employed as a flexible worker to perform task $k \in K_z$ on activity $z \in Z_j$ in period $j \in J$, 0 otherwise. Let $c_{ikzj} \geq 0$ be the related unitary cost.

• $y_{ikzj}$ is the operator selection variable, which takes value 1 if worker $i \in I_j \cap I_k$ is employed as a fixed worker to perform task $k \in K_z$ on activity $z \in Z_j$ in period $j \in J$, 0 otherwise. Let $c_{ikzj} \geq 0$ be the related unitary cost.

• $v_{kzj}$ is an integer non-negative variable representing the number of external workers hired to perform task $k \in K_z$ on operation $z \in Z_j$ in period $j \in J$. Let also $w_j$ be the maximum number of external workers employable at period $j \in J$ and $d_{kzj}$ the related unitary cost.

• $u^+_{kzj}$ is an integer non-negative variable representing number of workers in surplus in task $k \in K_z$ for activity $z \in Z_j$ in period $j \in J$. Let $f^+_{kzj}$ be the related unitary cost.

• $u^-_{kzj}$ is an integer non-negative variable representing number of workers in shortage in task $k \in K_z$ for activity $z \in Z_j$ in period $j \in J$. Let $f^-_{kzj}$ be the related unitary cost.

The problem can be formulated as follows:

$$\min \sum_{i \in I_j} \sum_{k \in K_z} \sum_{z \in Z_j} \sum_{j \in J} c_{ikzj} (x_{ikzj} + y_{ikzj}) + \sum_{k \in K_z} \sum_{z \in Z_j} \sum_{j \in J} d_{kzj} v_{kzj} + \sum_{k \in K_z} \sum_{z \in Z_j} \sum_{j \in J} f^+_{kzj} u^+_{kzj} +$$

$$+ \sum_{k \in K_z} \sum_{z \in Z_j} \sum_{j \in J} f^-_{kzj} u^-_{kzj}$$

(subject to)

1. $\sum_{i \in I_k \cap F} x_{ikzj} + \sum_{i \in I_k \cap I_j} y_{ikzj} + v_{kzj} - u^+_{kzj} + u^-_{kzj} = n_{kzj}$ for all $j \in J$, for all $z \in Z_j$, for all $k \in K_z$ (2.a)

2. $\sum_{i \in I_k \cap F} x_{ikzj} + \sum_{i \in I_k \cap I_j} y_{ikzj} - u^+_{kzj} + u^-_{kzj} = n_{kzj}$ for all $j \in J$, for all $z \in Z_j$, for all $k \in K_z \setminus \overline{K}_z$ (2.b)

3. $\sum_{k \in K_z} \sum_{z \in Z_j} x_{ikzj} = 1$ for all $i \in F$ (3)

4. $\sum_{k \in K_z} \sum_{z \in Z_j} x_{ikzj} = \sum_{k \in K_z} \sum_{z \in Z_j} x_{ikz(j+1)}$ for all $i \in F$, for all $j \mod s \neq 0$ (4)

5. $\sum_{k \in K_z} \sum_{z \in Z_j} y_{ikzj} = 1$ for all $i \in I_j$, for all $j = 1 + (p - 1)s$, for all $p = 1, \ldots, \rho$ (5)

6. $\sum_{k \in K_z} \sum_{z \in Z_j} y_{ikzj} = \sum_{k \in K_z} \sum_{z \in Z_j} y_{ikz(j+1)}$ for all $i \in I_j$, for all $j \mod s \neq 0$ (6)
\begin{align*}
\sum_{k \in K_z} \sum_{z \in Z_j} v_{kjz} & \leq w_j & j \in J \ (7) \\
\sum_{k \in K_z} \sum_{z \in Z_j} v_{kjz} = \sum_{k \in K_z} \sum_{z \in Z_j} v_{kjz(j+1)} & \forall j \mod e \neq 0 \ (8) \\
x_{ikzj} = x_{ikz(j+1)} & j = 1,5,7,11, \forall z \in Z_j, k \in K_z = \{qc\}, \forall i \in F \cap I_k \ (9) \\
\sum_{z \in Z_j} (x_{ikzj} + x_{ikz(j+1)}) & \leq 1 j = 2,6,10, k \in K_z = \{qc\}, \forall i \in I_j \cap I_k \ (10) \\
y_{ikzj} = y_{ikz(j+1)} & j = 1,5,7,11, \forall z \in Z_j, k \in K_z = \{qc\}, \forall i \in I_j \cap I_k \ (11) \\
\sum_{z \in Z_j} (y_{ikzj} + y_{ikz(j+1)}) & \leq 1 j = 2,6,10, k \in K_z = \{qc\}, \forall i \in I_j \cap I_k \ (12) \\
x_{ikzj} \in \{0,1\} & \forall j \in J, \forall z \in Z_j, k \in K_z, \forall i \in F \cap I_k \ (13) \\
y_{ikzj} \in \{0,1\} & \forall j \in J, \forall z \in Z_j, k \in K_z, \forall i \in I_j \cap I_k \ (14) \\
v_{kjz} \in Z^+ \cup \{0\} & \forall j \in J, \forall z \in Z_j, k \in K_z \ (15) \\
u_{kjz}^+ \in Z^+ \cup \{0\} & \forall j \in J, \forall z \in Z_j, k \in K_z \ (16) \\
u_{kjz}^- \in Z^+ \cup \{0\} & \forall j \in J, \forall z \in Z_j, k \in K_z \ (17)
\end{align*}

The objective function (1) minimizes the assignment costs of internal and external operators, as well as those of personnel undermanning and overmanning. The fulfillment of workload demand is enforced by constraints (2.a) for the tasks that can be outsourced and (2.b) in the other case. Constraints (3) guarantee that each flexible operator starts his shift in period 1, 5 or 9. According to constraints (4), if he starts working in period 1, he continues his shift in periods 2, 3, and 4; if he starts working in period 5, he continues his shift in periods 6, 7, and 8; if he starts working in period 9, he continues his shift in periods 10, 11, and 12. Constraints (5) enforce that each fixed operator starts his shift in period 1, 5 or 9, as determined in the long-term plan. According to constraints (6), if he starts working in period 1, he continues his shift in periods 2, 3, and 4; if he starts working in period 5, he continues his shift in periods 6, 7, and 8; if he starts working in period 9, he continues his shift in periods 10, 11, and 12. Constraints (7) enforce that the number of external workers in each period is limited. According to constraints (8), if he starts working in period 1, he continues his shift in periods 2 and 3; if he starts working in period 4, he continues his shift in periods 5 and 6; if he starts working in period 7, he continues his shift in periods 8 and 9; if he starts working in
period 10, he continues his shift in periods 11 and 12. Constraints (9) and (10) guarantee that each operator in fixed shifts is employed as a quay crane driver for 4 consecutive hours at most. Constraints (11) and (12) enforce the same restrictions to QC operators in fixed shifts. Constraints (13), (14), (15), (16) and (17) report the domain of decision variables.

5. Experimentation
The terminal policy and the solutions of the optimization model are compared using a set of realistic problem instances. The model is implemented using the PuLP library, which is an open source package that allows mathematical programs to be described in the Python computer programming language. In this paper, PuLP is set to call the freeware solver GLPK 4.46 running on a PC with a 2.3 Ghz processor and 8 Gb of memory. All instances are optimally solved in a few minutes.

In each instance, the internal manpower is inherited from the long-term plan of a randomly selected day in which 45 operators are on duty and 38 operators are in a day off. The 45 available operators are divided as follows: 30 in fixed shifts and 15 in flexible shifts. All operators in fixed shifts are able to do all tasks (QC, RTG and ITV), whereas 5 operators in flexible shifts can do all tasks and the 10 remaining operators are able to do both the RTG task and the ITV one.

The instances are reported in the lines of Tables 1, 2 and 3. All instances are described by the manpower demand, which is described in terms of number of vessel gangs in each activity shift (i.e. housekeeping is not considered, but the experimentation can be carried out with any number of vessel and housekeeping gangs). For example, the fourth instance in Table 2 is denoted by $P_7_6_3_4$, which means 7 vessel gangs requested in the first activity shift, 6 in the second, 3 in the third and 4 in the fourth. Instances in Table 1 present a low variance and a high uniformity in the daily manpower demand, those in Table 2 a medium variance and uniformity and those in Table 3 a high variance and a low uniformity. Terminal policy and model solutions are respectively denoted by $T$ and $M$ in the columns of Tables 1, 2 and 3. Moreover, the following notation is adopted:

- $QC$ is the number of operators used in the QC task in each period;
- $RTG$ is the number of operators used in the RTG task (even if their top task may be QC) in each period;
- $ITV$ is the number of internal operators used in the ITV task (even if their top task may be QC or RTG) in each period;
- $EXT$ is the number of external operators (hired in the ITV task only) in each period;
- $U^+$ number of internal operators in surplus in each period;
- $QC^-$ is the number of QC operators in shortage in each period;
• RTG is the number of RTG operators in shortage in each period;
• ITV is the number of internal ITV operators in shortage in each period.

The last line of each Table reports the sum of the results over all problem instances.

<table>
<thead>
<tr>
<th>QC</th>
<th>RTG</th>
<th>ITV</th>
<th>EXT</th>
<th>U+</th>
<th>QC</th>
<th>RTG</th>
<th>ITV</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>M</td>
<td>T</td>
<td>M</td>
<td>T</td>
<td>M</td>
<td>T</td>
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<tr>
<td>P_2_2_2_3</td>
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<td>66</td>
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<td>P_2_2_1_1</td>
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<td>P_4_4_5_5</td>
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<td>P_3_5_3_3</td>
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<td>288</td>
<td>288</td>
<td>693</td>
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</table>

Table 2. Instances with low variance and high uniformity in manpower demand

Table 2 shows in the case of low variance and high uniformity the terminal policy returns identical results with respect to the optimization model. Therefore, the policy certifies its effectiveness, because no optimization room is proved to exist.

<table>
<thead>
<tr>
<th>QC</th>
<th>RTG</th>
<th>ITV</th>
<th>EXT</th>
<th>U+</th>
<th>QC</th>
<th>RTG</th>
<th>ITV</th>
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<td>M</td>
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<td>M</td>
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</tr>
<tr>
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<td>114</td>
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<td>144</td>
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<td>P_3_6_3_6</td>
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<td>P_10_2_2_3</td>
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<td>384</td>
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<td>588</td>
<td>681</td>
<td>207</td>
<td>90</td>
<td>945</td>
</tr>
</tbody>
</table>

Table 3. Instances with medium variance and medium uniformity in manpower demand

Table 3 shows that, in case of medium manpower variance and medium uniformity, the model is much more able to reduce shortages in the RTG task. No shortage problem is observed on QCs and ITVs, owing to the high manpower supply in the QC task and external operators hired in the ITV task, respectively. However, the model makes use of a larger number of external operators to perform the ITV task and returns a larger number of internal operators in surplus.
Table 4. Instances with high variance and low uniformity in manpower demand

Table 4 shows that, in the case of high variance and low uniformity, the model is more efficient in reducing undermanning and overmanning, while hiring a similar number of external operators. The higher quality of model solutions depends on the possibility of employing flexible operators in peak periods of the manpower demand, whereas this not possible according to the terminal policy.

6. Conclusion

Manpower planning is a crucial problem for TCTs, which must decide shifts, tasks and activities of operators, while avoiding both personnel undermanning and overmanning. This paper has investigated a case study of the daily manpower planning problem in which personnel and activity shifts do not overlap. It has been modelled by an integer linear programming model, which was optimally solved by a freeware solver in a few minutes.

The optimal solutions of the model have been compared to the decision policy of a real TCT, which ranks activities in a priority list and assigns operators to activities starting from the topmost task. A key criticality in this policy is the unexploited option of flexible operators, who are assigned to shifts in such a way to provide a uniform manpower supply in the daily planning horizon. The
motivation for this choice is just the simplicity of implementation for the TCT, which has no planning tools to evaluate other manpower configurations rapidly.

The experimentation has shown that the terminal policy is optimal in case of low variance and high uniformity in the daily manpower demand, as they return the same solution of the optimization model. In case of medium and high variance, the model outperforms significantly the terminal policies, because it is able to increase the manpower in the peak periods of the manpower demand. Research in the field is in progress to model activities spanning over several days. In addition, future formulations are required to account for possible sources of randomness. Finally, the model generality may be of interest for other application areas (e.g. the healthcare).

References


