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Editors

Mueller
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MINING GOES DIGITAL

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Proceedings in Earth and geosciences
Volume 3

APCOM

MINING GOES DIGITAL

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Mining Goes Digital

Editors

Christoph Mueller
MT-Silesia Sp. z o.o. Wroclaw, Poland

Winfred Assibey-Bonsu
Gold Fields Ltd., Perth, Australia

Ernest Baafi
University of Wollongong, Australia

Christoph Dauber
Technische Hochschule Georg Agricola, Bochum, Germany

Chris Doran
Mitacom Pty Ltd., Brisbane, Australia

Marek Jerzy Jaszczuk
Silesian University of Technology, Gliwice, Poland

Oleg Nagovitsyn
Kola Research Institute, Russian Federation

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Preface

The abbreviation "APCOM" stands for "*Applications for Computers and Operations Research in the Minerals Industry*". When the conference started in 1964, it was an informal meeting of scientists from different universities in the USA together with the "Society of Mining Engineers" (SME) of the United States. During the years the APCOM conference was performed in a mostly bi-annual rhythm. Up to today APCOM maintained its original logo formed around a punch card clearly remembering the historic origin of the conference from the times prior to the revolution caused by the era of semiconductors.

In the beginning, APCOM focused on the optimization of geostatistics and resource estimation and a number of methods used in these fields were initially presented and discussed on APCOM conferences. This field still today is an important part of any APCOM.

During the years, information technology has dramatically developed, new algorithmic methods evolved and the entire fields of electronic communication, machine automation, autonomous machines and process optimization developed. Consequently, today, APCOM is much more than a meeting of specialists in geostatistics and resource estimation: The APCOM has expanded to a conference covering all kinds of Information and Communication Technology in the mineral industry: Already in 2005 on the conference in Tuscon/AZ, the term "Mining Process Optimization" was presented as the next paradigm shift in mining after mechanization and automation, which marked another example of the continued innovative impact of the APCOM. Well ahead of the current discussions about "Digital Transformation".

In this tradition the 39th APCOM 2019 is performed in Wroclaw (Poland), a town with innovative tradition from the early times of industrialization when the town was German Breslau. A few examples can only give a glimpse of the importance of the town's historic industrial and academic achievements:

- 10 Nobel prize winners (out of 102 Germans) were born or working in Breslau.
- The first publicly owned electric power station in Germany went in operation in 1882.
- Electric public trams were introduced 1892.
- The world's biggest free span concrete hall ("Jahrhunderthalle" – "Hala Stulecia") was built in 1912 (it is an Unesco world cultural heritage site today).
- Diesel electric fast trains "Flying Silesian" featuring a top speed of 205 km/h were developed 1935 at Linke-Hoffmann Werke in Breslau, running abt. 500 km Berlin-Bytom (Beuthen) in 4 hrs 17 min!

Today Wroclaw again is a leading innovation hub in Middle-Eastern Europe hosting the internationally highly acknowledged Wroclaw University of Technology. A large number of big and small innovative companies are active not only in the area of Information and Communication Technology, but also in Chemistry, Biotechnology and Engineering. World known names like Google, Nokia, IBM, Bombardier or Volvo Buses are just few examples. Also KGHM as a world leading copper producer operates a research center in the city.

In this tradition the 39th APCOM conference titled "Mining Goes Digital" presents innovative IT related papers from Resource estimation and geostatistics, Mine Planning, Robotics, equipment automation, autonomous guidance and many other integrative aspects of digital transformation in the minerals industry. A few papers also provide inputs from other industries into the mining community to create potential synergies. This evolution of the APCOM from its origins in resource estimation to a general mining IT related conference also emphasizes the importance of a holistic view on the optimization of the overall mining operations from the resource to the preparation plant in the era of digital transformation.

In this view, the APCOM conference in Wroclaw also marks a change in the appearance of the conference logo: The original APCOM logo was changed slightly: The attentive reader may have observed that the original punchcard was exchanged by a more up-to-date symbolic PCB layout and an upgraded font set. So the APCOM can be recognized as "the" leading international event for Information Technology in mining for many years to come.

Dr. Christoph Mueller
Chairman of the 39th APCOM 2019

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Editors

Dr. Christoph Mueller

Dr. Christoph Mueller, born 1963, after his engineering studies and an additional education in technical software engineering at Siemens got his PhD in Electronics and Telecommunications.

Since 1992 Christoph Mueller works mainly with automation projects for mobile machinery in the raw material industries. From 1997 he is operating his own companies specialized on successfully turning innovations into operational benefits in major mining process optimization and machine automation projects. Currently, these companies in Germany and Poland are working mainly with functional safe machine automation, driver assistance systems and autonomous operation in areas as mining and tunneling, agriculture or airport equipment.

Dr. Winfred Assibey-Bonsu BSc(Mining); PhD(Eng) Wits Univ.; EDP, Wits Business School, FSAIMM, MSACNASP

Current Position: Group Geostatistician and Evaluator, Gold Fields Ltd, Corporate Technical Services, Perth, Australia.

Employment post PhD studies; Gold Fields of South Africa, 1991 to 1994; Gencor Limited, 1994 to 1998; Gold Fields Limited, 1998 to date.

Winfred's experience includes mineral resource assets assessment for mining companies as well as new business associated work including prospects in South Africa, Australia, South America, Zaire, Ghana, Ivory Coast, Philippines, Ethiopia, Tanzania, Cuba, Dominican Republic, Russia, Finland, Romania, Papua New Guinea.

Winfred is a dedicated family man with wife and four children. He enjoys reading and soccer.

Dr. Ernest Baafi

Ernest Yaw Baafi holds PhD in Mining Engineering from University of Arizona, MS in Mining Engineering from Penn State University, US and BE, ACSM from Camborne School of Mines, Cornwall, UK. He is Associate Professor in Mining at University of Wollongong, Australia where he is currently the Academic Program Director in Mining Engineering. His primary field of research is the application of computers and operations research methodologies to system evaluation and design. His current research activities include geostatistical ore reserve estimation, mine system simulation, logistics and optimisation. He is the current Chair of the International Council of Application of Computers and Operations Research in the Minerals Industry (APCOM), representing the Australasian Institute of Mining and Metallurgy (AusIMM) on the Council.

Prof. Dr. Christoph Dauber

Born in 1954, Prof. Dauber has studied Mining Engineering at the RWTH Aachen, where he obtained his Ph.D. about refrigeration techniques for deep hard coal mines. 1982 he joined RAG, the biggest hard coal mining company in Germany, and started as a deputy and undermanager. An exchange of engineers gave him the opportunity to work for six month in two Australian coal mines. Seven years he acted as the production manager of the hard coal mines Ewald and Walsum, before he joined the central technical department. Being the responsible manager for central technical support and supply he initiated and accompanied a couple of operational innovations. 2008 he become a professor at the THGA in the field of mining technology. Additionally he held the position of a Vice President responsible for research and development. Since 2015 he works as a part-time professor for the THGA.

Dr. Chris Doran

Dr. Chris Doran is a Mining Technology Consultant at Mitacom, a company specialising in technology services related to mobile equipment safety and automation for minerals and resource industry clients in Australia, Southern Africa and South America, including development of requirements for collision avoidance and introduction of advanced technologies and automation systems into mining operations. Dr. Doran is a key participant in several industry programs to improve mobile equipment safety, promote interoperability, a driving innovation between mining houses, mobile equipment manufacturers (OEMs) and technology providers. He is also an active contributor to the development of national and international standards for safety and interoperability in the field of earthmoving and mining.

Prof. Dr. Marek Jerzy Jaszczuk

Professor Marek Jaszczuk PhD, DSc is employed at the Department of Mining Mechanization and Robotics of the Faculty of Mining and Geology of the Silesian University of Technology in Gliwice, Poland. His subject covers issues related to the identification of external and internal loads of mining machinery, especially shearer-loaders, armored face conveyors and hydraulic roof supports, as well as the interaction of mining machines with their natural environment. He is the author and co-author of original mathematical models and software for computer-aided design of cutting drums for longwall shearers and multi-criteria optimization of design features of the hydraulic roof supports. For the solutions resulting from the research he and his team won the Team Award of the Prime Minister for the outstanding national scientific and technical achievement and the 1st degree Award of the Minister of Labour and Social Policy. They have also been awarded medals of prestigious innovation exhibitions at home and abroad, including: Warsaw, Brussels, Nuremberg, Seoul, Kuala Lumpur and SuZhou.

He is the author and co-author of 4 academic textbooks, 5 monographs, over 90 articles in domestic and foreign journals, over 50 papers delivered at national and international conferences and the scientific editor of 5 monographs. He gained 15 patents for innovative solutions.

Oleg Nagovitsyn, Dr. Eng.

Oleg Nagovitsyn, Dr. Eng. is Deputy Director of the Mining institute of the Kola Science Centre of the Russian Academy of Sciences.

Oleg Nagovitsyn's scientific activity is connected with the studies aimed at development of the software which realizes the functions of a mining-and-geological information system for the mining and mineral processing. The geo-information system is based on the application of subject-oriented databases, visualization and integration; spatially related geological, technological, geophysical, geomechanical and monitoring data which form a single geo-information space of the mining and processing enterprise. The practical significance of the studies lies in the fact that the developed software, educational and methodological materials realize the computer technology of geological modeling, design and planning of mining operations.

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Prof. Dr hab. Wojciech Moczulski, *Silesian University of Technology, Gliwice, Poland*

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Optimization model for rostering and crew assignment for train transportation

J. Amaya & E. Molina
Department of Mathematical Engineering and Center for Mathematical Modeling, University of Chile, Santiago, Chile

N. Morales
Delphos Lab., Advanced Mining Technology Center, University of Chile, Santiago, Chile

P. Uribe
Center for Mathematical Modeling, University of Chile, Santiago, Chile

ABSTRACT: This work introduces a model and software for the rostering and crew scheduling problems, for train operation in the mining industry in Chile. The transportation rail network covers most of locations of the industry in the North of the country, including mines, plants and ports. The model possesses particular features due to specific regulations with which train operators in mine material transportation are required to comply. The model and algorithm have been implemented with a user interface suitable for the remote execution of real instances on a High Performance Computing platform. The transportation company regularly uses this computerized tool for planning crew schedules and generating efficient assignments for changing operational conditions. The problem has been partitioned in two steps. Firstly, through a linear mixed integer optimization model, every trip is divided in elemental segments to be served by the crews. Secondly, another optimization model produces the crew assignment to fulfil all the trips demand. The optimization instances are solved by using Gurobi, coded in AMPL and it permits an efficient management of the human resources (drivers), equilibrating the workloads between them.

1 INTRODUCTION

This work introduces two mathematical models that are used together for the rostering and crew scheduling problem, for the operation of trains in the mining industry in a large geographic area located in Chile. The transportation rail network covers most of locations of the industry in the very North of the country, including mines, plants and ports and others.

The problem we are interested on has to deal with two main aspects. Firstly, train trips can be very long, meaning that the same train may have different crew operating it over a the train travel. Therefore, train-stops must be defined at which crew members can be replaced. The location of these stops is limited by several reasons, like nearby location of urban towns, and also they cannot be too far away from each other: in order to allow the crew replacement, a maximum of 10.5 hours limitation, nor they can be too close to each other because that would produce delays and make the transportation company unable to comply with demand. Secondly, the transportation company needs to deal with all the logistics related to the crews: at each train stop, a *fresh* crew takes over the train, so this crew had to be transported from a base or camp; and conversely, another crew leaves for resting and needs to be taken back to base. These crew transportation (from base to train and otherwise) are done using company cars.

The problem described above needs to be solved over the a long time-span that consider in-between resting time of the crew members and overall labor regulations. This gives rise to a very complex instance that involves the partitioning of trips in elemental segments and efficient assignments of crews, to comply with train trips and labor regulations.

In order to tackle this problem, we used mathematical programming to address the two main elements of the problem. For this, the problem has been partitioned in two steps. Firstly, through a linear mixed integer optimization model, every trip is divided in elemental segments to be served by different crews. Secondly, another optimization model produces the crew assignment to fulfil all the trips demand. The drivers must have rest periods (in certain specific camps, whose locations are also decided by the second model.

Figure 1 briefly represents these two problems. The figure illustrates two train trips: Trip 1 goes from West to East and has 9 possible train stops (model selected 3, in black). Trip 2 goes from East to West, has 8 potential stops, but 3 only have been selected. Selected train-stops are points where crew exchanges take place. The figure also represents the schedule of one crew (for simplicity). This crew starts services at Base A (after resting), then it is transported to the first stop or Trip 1 and drives that train to its second stop where it is replaced (by other crew, not depicted in the figure) and transported to Base B. After that it starts its resting time and then starts to work again at Base C, from where it is taken to the first stop of Trip 2, driving that train up its second stop. At that point, the crew is replaced (again by a crew not depicted) and taken to Base A to start a resting period.

It is worth noting that the models and algorithms that we describe have been implemented with a user interface suitable for the remote execution of real instances on a High Performance Computing platform, on an Intel Xeon E5-2660 v2 processor with 10 cores and 48 Gb of RAM. The transportation company regularly uses this computerized tool for planning crew schedules and generating efficient assignments for emerging and changing operational conditions. The optimization models are solved by using Gurobi, coded in AMPL. Many different real scenarios can be tackled by the user, permitting an efficient management of the human resources (drivers) and equilibrate workloads between them.

A similar two-steps approach has been proposed by Drexl et al (2013), but unlike to that paper which focused in an heuristic solution, we focus on integer programming models. A general introduction to this kind of rostering, vehicle and crew assignment models can be found in Ceder (2007), and a practical scheduling model for a crew rotation scheme is solved by Amaya et al (2018), by using a local search optimization strategy. Şahin et al (2011) address the problem of finding a minimal number of crews to carry out a given set of duties (trips), based on a sequential algorithmic procedure. The crew capacity planning problem, to minimize the crew size in railways, is also studied by Suyabatmaz et al (2015).

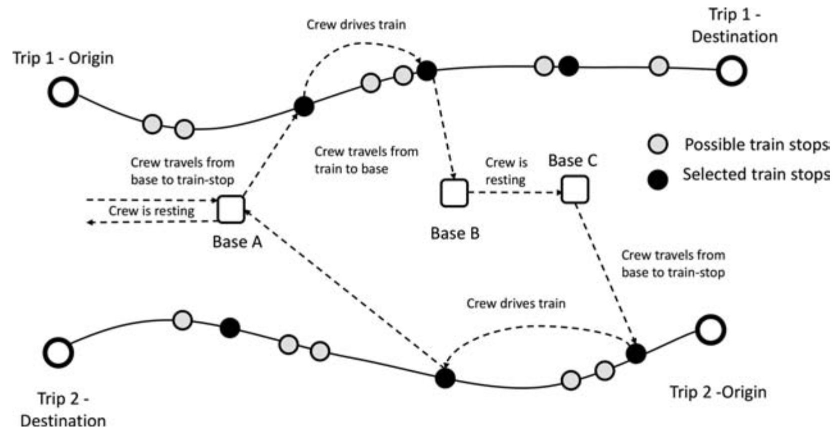

Figure 1. Schematic representation of two train trips and one crew schedule. Train trips and stops are in solid black. Crew schedule is represented by segmented lines.

2 PARTITIONING THE TRAIN TRIP IN ELEMENTAL SEGMENTS

The idea is to divide each trip in elemental sub-trips, in order to generate a list of possible points or locations where the crew replacement can be made. This partition will be used for the crew assignment to the elemental sub-trips, in a second model. Let L be the set of possible locations of change points where the crews can be replaced and $K_t \subseteq L$ all the existing locations along the trajectory of the train t. Each train has a well defined itinerary, that is to say, we know exactly the time of each train at a given location. Furthermore, trains are classified in two types: rotative, whose initial and final point on the trajectory are the same, i.e., as a cycle, and no rotative, whose initial and final point on the trajectory are different. The set of rotative trains is denote by T_c and the no rotative trains T_{nc}, thus, $T = T_c \bigcup T_{nc}$. Moreover we know the following set of parameters:

$k_{t,l}$: Time of train (trip) t at location $l \in K_t$
d^t: Total duration of train t
$d^t_{l,ll}$: Travel time of train t, from location l to ll
$tr_{l,b}$: Travel time for driving a crew from from location l to camb b
d_{bl}: Travel time to drive a crew from location l to the nearest camp

The itinerary of a train induces an order in the set of locations, so we say $l <_t ll$ if $k_{t,l} < k_{t,ll}$. For rotative trains this order doesn't give much information, but for no rotative is really important define it to write its constraints. The binary decision variables are defined below:

$$z_{t,l} = \begin{cases} 1 & \text{if train } t \text{ make a crew replacement at location } l \in K_t \\ 0 & \text{if not} \end{cases}$$

$$v^t_{l,ll} = \begin{cases} 1 & \text{if locations } l, ll \in K_t \text{ are consecutive replacement points for the train } t \\ 0 & \text{if not} \end{cases}$$

In this first model we look for locations that are comparatively near to all bases, in order to minimize the total travel time in cars. The set of constraints to be considered for this problem is described below.

To force a no rotative train to start in a given location $l^t_o = initial(K_t) \in L$, ending at location $l^t_d = final(K_t) \in L$ we impose:

$$\sum_{l \in K_t : l^t_o < l} v^t_{l^t_o,l} = 1, \quad \forall t \in T_{nc} \tag{1}$$

$$\sum_{l \in K_t : l < l^t_d} v^t_{l,l^t_d} = 1, \quad \forall t \in T_{nc} \tag{2}$$

And to connect variables v and z we impose, which means that if train t stops at location l then the train arrives to and leaves that location:

$$\sum_{ll \in K_t : l < ll} v^t_{l,ll} = z_{t,l}, \forall t \in T, \quad \forall l \in K_t \setminus \{l^t_d\} \tag{3}$$

$$\sum_{ll \in K_t : ll < l} v^t_{ll,l} = z_{t,l}, \forall t \in T, \quad \forall l \in K_t \setminus \{l^t_o\} \tag{4}$$

For a rotative train, past constrains turn in:

$$\sum_{ll \in K_t : l \neq ll} v^t_{l,ll} = z_{t,l} = \sum_{ll \in K_t : ll \neq l} v^t_{ll,l}, \quad \forall t \in T_c, \quad \forall l \in K_t \tag{5}$$

The number of daily work hours for crews limited by a given parameter JE_t:

$$v^t_{l,ll} d^t_{l,ll} \leq JE_t, \forall t \in T, \forall l, ll \in K_t, l < ll \tag{6}$$

In order to control the number of sub-trips for each train, we include the next constraint in case of no rotative trains:

$$\sum_{l\in K_t} z_{t,l} \le \left[\frac{d^t}{JE_t} \right] + k, \quad \forall t \in T_{nc} \tag{7}$$

and in case of rotative trains:

$$\frac{d^t}{JE_t} \le \sum_{l\in K_t} z_{t,l} \le \left[\frac{d^t}{JE_t} \right] + k, \quad \forall t \in T_c \tag{8}$$

where $k \ge 1$ because the value $\left[\frac{d^t}{JE_t} \right] + 1$ represents the minimal number of sub-trips that fulfill the precedent constraints. This is necessary because the problem may have multiple solutions and we want to keep the one that has a minimal points of crew replacements. In principle, the value $k = 1$ is good if we only consider past constraints, but if we add some additional, as we will show below, the value $k = 1$ could generate infeasibility.

For operational reasons, we need to impose an additional constraint, saying that some changes of crews must be made at a certain prefixed zones (subset of locations). Let $Zc_i \subseteq L, i = 1,..,nz$ the zones where a crew replacement is mandatory. Then,

$$\sum_{l\in K_t \bigcap Zc_i} z_{t,l} \ge 1, \quad \forall t \in T, i = 1,..,n, K_t \bigcap Zc_i \ne \emptyset \tag{9}$$

In the context of our specific application, those zones are determined by the capability of the operators (crews) to drive in each geographic; in other words, not all the drivers are authorized to drive train in every zones. The zones (actually, there are three, but this is a parameter of the model) have well defined intersections to ensure feasibility, because changes of crews can be done in the intersections to allow train crossing from a zone to another. The zones are represented by the sets Zc in the model.

Concerning the choice of the objective function, we firstly propose to minimize the total distance between the change points and all rest camp for crews:

$$\min \sum_{t\in T} \sum_{l\in K_t} \sum_{b\in B} tr_{l,b} z_{t,l} \tag{10}$$

Another option is to choose locations at minimal distance to nearest camp:

$$\min \sum_{t\in T} \sum_{l\in K_t} db_l z_{t,l} \tag{11}$$

The result of this model generate an efficient choice of locations for crews changes, as near as possible to the rest camps for crews. In the next section we will introduce a model to generate an optimal crew assignment for the whole set of trains along one week period.

3 THE CREW ASSIGNMENT MODEL

Let us consider a set of M crews (in our specific application, each crew is composed by two operators) and the set V containing all the sub-trips to be fulfilled, defined by the previous model. All those sub-trips have as starting and final stop, two consecutive locations for crew change (in fact, these are points of the timetable for each train). Each one is determined by the variables $v^t_{l,ll}$ having value 1. We also denote D_v the set of days in which the trip v runs (typically $D_v = \{1, \ldots, 7\}$).

The idea of this model is to connect a sequence of compatible elemental trips to be fulfilled by each specific crew. For this, we need to add two artificial trips v_0 and v_f, to connect with the initial and final locations of the train, we then define $V_e := V \bigcup \{v_0, v_f\}$. These two trips will be assigned to fictitious days 0 and 8 respectively. To define compatibility, we use a new variable $d_{v,vv,b}$, corresponding to the duration of the travel from the final location of v to the camp b and then to the origin of trip vv. We also define $h^0_{v,k}$ and $h^f_{v,k}$ as the initial and final times of trip v at day k. The parameter TE denotes the legal maximal duration for the transportation of the crew, from the location to the base camp.

Finally, we define the compatibility parameter $comp_{v,k,vv,kk,b}$ related to two trips. This parameter takes value 1 if the trip v at day k is compatible with trip vv at day kk, having rest camp in base b. In other words, the crew ends trip v at day k, then is transported to camp b and after the rest period the crew is transported to take service at trip vv, day kk.

- A trip can only be compatible with trips in next days, that is to say, if $kk < k$ then $comp_{v,k,vv,kk,b} = 0$.
- All trips are compatible with the fictitious trips v_0 y v_f, that is $comp_{v_0,0,v,k,b} = 1$ and $comp_{v,k,vf,8,b} = 1$.
- Due to the minimum rest time in base camp (10 hours and 20 minutes), we set $comp_{v,k,vv,kk,b} = 1$ if $k < kk$ and $d_{v,vv,b} + 10 + \frac{1}{3} \leq h^0_{vv,kk} - h^f_{k,v}$.
- In other cases $comp_{v,k,vv,kk,b} = 0$.

Finally, we define the main variables for the crew assignment model:

$$w_{v,k,vv,kk,b} = \begin{cases} 1 & \text{if trip } v \text{ day } k \text{ connect with trip } vv \text{ day } kk\text{, resting time in } b \\ 0 & \text{if not} \end{cases}$$

This variable is set to zero if the two trips are not compatibles. The objective function of this problem corresponds to minimize the total transportation time of crews from trains to base camps and viceversa:

$$\min \sum_{v \in V} \sum_{k \in D_v} \sum_{vv \in V} \sum_{kk \in D_{vv}} \sum_{b \in B} d_{v,vv,b} w_{v,k,vv,kk,b} \tag{12}$$

The constraints correspond to the flows of value 1, from v_0 to v_f. The first two constraints say that from v_0, M trips are connected and in v_f, M trips arrive. This is written as:

$$\sum_{v \in V} \sum_{k \in D_v} w_{v_0,0,v,k,b} = M \tag{13}$$

$$\sum_{v \in V} \sum_{k \in D_v} w_{v,k,v_f,8,b} = M \tag{14}$$

The continuity of the sequence is established as:

$$\sum_{v_1 \in V_e} \sum_{k_1 \in D_{v_1}} \sum_{b \in B} w_{v_1,k_1,v,k,b} = \sum_{v_2 \in V_e} \sum_{k_2 \in D_{v_2}} \sum_{b \in B} w_{v,k,v_2,k_2,b} = 1, \quad \forall v \in V, k \in D_v \tag{15}$$

The last constraint say that operators cannot be transported more than TE hours, from/to locations and camps, in each daily journey. Mathematically, this is expressed as:

$$\sum_{v_1 \in Ve} \sum_{k_1 \in D_{v_1}} \sum_{b \in B} w_{v_1,k_1,v,k,b} tr_{o(v),b} + \sum_{v_2 \in Ve} \sum_{k_2 \in D_{v_2}} \sum_{b \in B} w_{v,k,v_2,k_2,b} tr_{d(v),b} \leq TE \tag{16}$$

where $o(v)$ and $d(v)$ denotes the origin and final destination of trip v, respectively.

To include the zones in the model we first define the parameter $Z_v \in \{1,\ldots,nz\}$ which shows the index of the zone to which the trip v belongs to. In this manner, we establish the compatibility between trips belonging to the same zone. Then we need to add to the definition of $comp_{v,k,vv,kk,b}$, the condition:

- If $k < kk$, $Z_v = Z_{vv}$ and $d_{v,vv,b} + 10 + \frac{1}{3} \leq h^0_{vv,kk} - h^f_{k,v}$ then $comp_{v,k,vv,kk,b} = 1$.

Then the model for crew assignment is defined by the objective function (12) subject to Constraints (13), (14), (15) and (16).

If we consider as a set of nodes containing all pairs (v,k), and construct an arc between nodes (v,k) and (vv,kk) if $comp_{v,k,vv,kk,b} = 1$ for any base b, then the model can be seen as a flow problem in this graph, similar to several crew scheduling and rostering models found in bibliography, for example.

4 NUMERICAL EXAMPLE

In this section, we present a numerical instance of a real case, transporting mineral products and supplies between mines and several places (other mines, plants, ports, etc.). The case includes a set of trains running for a 7-days period, say Monday to Sunday. Each train is represented by a code, as follow:

$$T = \left\{ \begin{matrix} 1203-1204 & 1220-1221 & 1250-1253 & 1701-1702 & 1703-1706 \\ 1709-1714 & 1711-1712 & 201-206 & 207-202 & 208-205 \\ 209-210 & 213-214 & 241-240 & 243-242 & S1101 \\ EMEL & EPAMPA1 & EPAMPA2 & S1201 & S101 \\ DISPAA1 & DISPAA2 & DISPCC & & \end{matrix} \right\}$$

For every train $t \in T$, the set K_t has at least 80 elements (the possible locations for crew replacements), value JE_t is set at value 12 hours or 10.5 hours, depending of t. We only consider cyclical trains, that is to say, $T = T_c$, and every train operate seven days. Moreover, there are 5 camp bases where crews can stay for the 10-hours rest time:

$$B = \{CAMPCMZ, CALAMA, CAMPMEL, OLLAGU, PNORTE\}$$

The maximal travel time admitted for transportation of crews between bases and locations for replacements is $TE = 2.5$ hours. There are 3 operation zones, Z_1,Z_2 and Z_3, and 2 zones for changes in common areas $Zc_1 = Z_1 \cap Z_2$ and $Zc_2 = Z_2 \cap Z_3$. We test the model for the number of crews $M = 92{,}93$ and 94, knowing that for $M \leq 91$ the problem turns infeasible.

The two models, partitioning and crew assignment, run in 4 seconds to find an optimal solution. Obviously, the objective function improves with the number of crews, essentially because as the number of crews increase they can be located closer to camp bases and the marginal cost of hire an additional crew is not included in the models. The number of total crew replacements is the same in three cases because of the number of crew does not affect the partitioning model. This is shown in the following table:

As an example, we show here the scheduling for Crew 6:

Table 1. Comparison.

Total crews (M)	92	93	94
Total change points	83	83	83
Objective function (12)	564.31	544.14	539.58
Time of computing (s)	4.625	4.781	4.781
Crews for zone Z_1	15	16	17
Crews for zone Z_2	56	56	56
Crews for zone Z_3	21	21	21

Table 2. Crew scheduling.

Crew 6	day 1	day 2	day 3	day 4	day 5	day 6	day 7
Segment (sub-trip)	1703–1706_3	1703–1706_3	1711–1712_2	1711–1712_2	1711–1712_2	1711–1712_2	1703–1706_2
Origin – Destination	K49 – CMZ	K49 – CMZ	K97 – MEL	K97 – MEL	K97 – MEL	K97 – MEL	LLANO – K49
Initial time – Final time	07:20–18:09	07:20–18:09	17:22–04:15	17:22–04:15	17:22–04:15	17:22–04:15	22:11–08:30
Initial base for Crew 6	CAMPCMZ	CAMPCMZ	CAMPCMZ	CAMPCMZ	CAMPCMZ	CAMPCMZ	CAMPMEL
Final base for Crew 6	CAMPCMZ	CAMPCMZ	CAMPMEL	CAMPMEL	CAMPMEL	CAMPMEL	CAMPCMZ

5 CONCLUSIONS

The aim of this work was to create a computer software, based on two mathematical models that represent the two main issues for the railway company that transports minerals and supplies in the North region of Chile. The company uses the system to generate the sequence of relay points for crew replacements and then, based on this itinerary, decide the crew assignment to the drivers. The two implemented models are presented in this paper and can be used to generate different efficient feasible solutions very quickly, depending on different scenarios tested by the user. Moreover, the speed of calculations permits the user to generate in some minutes several efficient diagrams (in terms of practical loads for the crews), compared with traditional processes, based on exchanging hand-made files along several weeks of negotiations.

The software tool was developed to provide a friendly environment for user interaction. The computerized tool is currently operating in a train transportation company, but the model could be adapted to tackle other kinds of crew scheduling problems, especially those arising in urban or interurban transportation systems. The main benefit for the company is not only of economic nature, but also the tool permits to facilitate the negotiations between management and the unions, providing objective solutions for the decision-making process.

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