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Train logistics for the mining company LKAB

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***Résumé* -** Cet article traite du problème de planification de transport ferroviaire à un niveau tactique et opérationnel à l'aide d'une méthode combinant l'utilisation de quatre modèles d'optimisation, soit un modèle des besoins en flux, un modèle de génération d'un horaire de train, un modèle de routage des produits et un modèle de routage des trains. La méthode se divise en cinq phases distinctes regroupées sous deux problèmes, soit la génération d'un horaire de transport, qui est de niveau tactique et le routage des trains, qui est de niveau opérationnel. L'étude est basée sur une étude de cas avec la compagnie LKAB, un leader mondial dans la production de boulettes de fer et très dépendant d'une logistique de transport ferroviaire efficace. Comme sa production est prévue d'augmenter considérablement au cours des prochaines années, il est nécessaire d'identifier le nombre de locomotives nécessaires à ses activités.
***Mots clés* -** Planification; Problème de tournées; Logistique; Transport ferroviaire; Horaire.

***Abstract* -** This article addresses the rail planning problem at a tactical and operational level using a method combining the use of four optimization models, a flow requirements model, a timetable generation model, a product routing model and a train routing model. The method is divided into five distinct phases grouped under two issues, namely the generation of a transport timetable that is on the tactical level and the routing of trains, which is on the operational level. The study is based on a case study with the company LKAB, a world leader in pellets production and very dependent on an efficient train logistic system. As their production is planned to considerably increase over the next years, there is a need to identify the number of locomotives required for their operations.
***Keywords* -** Scheduling; Routing problem; Logistics; Train transport; Timetable.

1 Introduction

Today, more then ever before, natural resources industries depend on their logistic strategies to be competitive. Indeed, the raw material industry is greatly influenced by stock market activities, either positively or negatively. When a hollow in terms of sale price or demand is reached, the companies that do best are most often the ones that have the best logistic planning strategy. Having a good logistic planning strategy certainly involves having optimized transportation planning and efficient inventory management since more than 70% of total logistics costs are generated by these two fields[Rodrigue, 2013].

In the context of iron ore mining industry, transportation from the mining site to harbour is mostly done by railway and thus the planning of train schedule and the inventory control are two management issues which generate significant expenses. Most of the time, these two issues are processed separately from each other which can lead to inconsistencies, when the network is evaluated as a whole. Regarding train scheduling, the overall planning is usually divided into 3 or 4 levels with the common partition between strategic, tactical and operational planning operations [Larsen, 2009] and with more recently the addition of a 4th level known as short-term planning or re-scheduling[Budai, 2007] as shown in Figure 1.

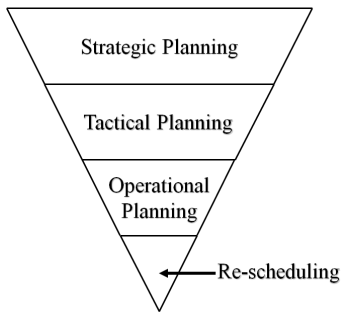

Figure 1: Planning levels for train scheduling

Most studies are dedicated to the solution of one level of planning while addressing the problem from a theoretical point of view which leads to good results in terms of optimization but might lack some constraints to represent the overall problem on a more realistic version closer to the industrial challenge. The objective of the current paper is precisely to address the train timetabling problem in the most representative way possible of the reality. To do so, this study has been done in partnership with a world class leader in iron pellets manufacture for more than 50 years, the Swedish state owned mining company, LKAB. It has two underground mines operating; Kiruna and Malmberget and one open-pit mine, Svappavaara which accounts for nearly 90% of the EU's iron ore production. LKAB is also Sweden's largest carrier with more than 30 million tons hauled by rail each year.

The recent low metal prices combined with a planned increase of the extraction rate in the coming years by the company motivates LKAB to optimize the use of its locomotives so as to maximize their use and minimize the number required to meet its needs. To support LKAB's analysis, we have designed a 5 phases optimization solution which aims to produce a 2 weeks trains scheduling that takes into account the maintenance planning of the locomotives, the inventory management of the entire network and the generation of a fixed timetable. The planning horizon includes some aspect of the tactical planning by generating a new timetable for every 2 weeks of scheduling while taking into account every aspects of the operational planning which leads to the conception of a detailed routing schedule that provides the route of each train including the space and time indications, the product transported, the maintenance activities and the identification of individual locomotive.

The current paper is divided as follow, Section 2 introduces the global solution approach used to solve this problematic. Section 3 is dedicated to the presentation of the mathematical models developed. In Section 4, we present the computational results obtained as output from the models presented in Section 3. Finally, Section 5 conclude the paper followed by propositions for future research.

2 Solution approach

In this section we present the global solution approach used to achieve the integration of many aspects in the formulation of an optimized train schedule on a 2 weeks horizon. The main problem have been divided in 2 sections called the timetable generation problem and the train routing problem. The reason behind this division is the separation between the tactical planning level and the operational planning level. The objective of the first section is to determine a daily timetable that will be repeated each day of the planning horizon. The second section of the solution has the objective of finding a feasible and optimized schedule for all trains of the network on a given planning horizon while including the maintenance planning, inventory management and the identification of the locomotives in the process. These 2 sections are then divided into 5 distinct phases which take the form of 4 different mathematical models (the Flow model is used twice in the solution process) as shown in Figure 2.

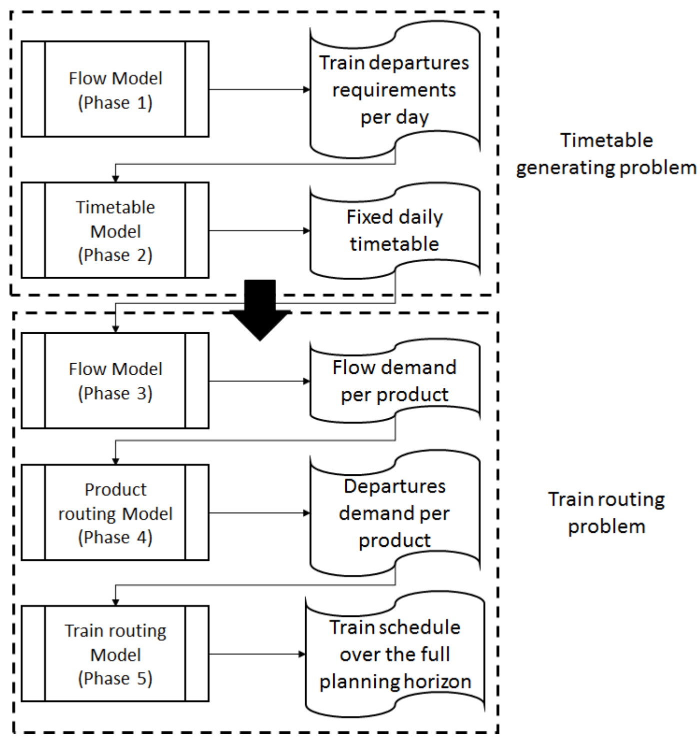

Figure 2: Representation of the overall structure of the models

Phases 1 and 2 are used during Section 1 of the method which consists of the timetable generating problem and are described as follows :

- Phase 1 solves a Linear Programming (LP) problem over two weeks to generate flow requirements. This provides a general minimum requirement on train departures (for each origin/destination combinations).
- Phase 2 solves a Mixed Integer Programming (MIP) problem to determine a daily timetable (same for each day over two weeks) from an extended set of departures time per stations. The choice of the fixed timetable is determine by the requirements from Phase 1. Also, departures of the same day are spread out in the solution. The result of this step is a fixed daily timetable.

Phases 3 to 5 are used during Section 2 of the method which consist of the train routing problem and are described as follows :

- Phase 3 solves an LP problem to generate the overall flow demand per product over the planning horizon while using the fixed daily timetable found in phase 2 as input.
- Phase 4 solves a recursive MIP problem to allocate products to departures based on the flow demand found in phase 3.
- Phase 5 solves a recursive MIP to route individual locomotives and wagons to departures found in phase 4 while planning the maintenance service activities requirement of the locomotives over the planning horizon.

3 Models overview

The following section describe qualitatively the mathematical models which are critical to the train logistics planning process. First off, the main sets used within the models are the terminals, the products, products that have the possibility to enter into a certain terminal, products that have the possibility to exit from a certain terminal, tours starting from terminal i to terminal j, products that have the possibility to be transported on a certain tour, etc. In order to get rid of the continuous time aspect of a certain horizon time planning, we introduced an integer set for each terminals that goes from 1 to N. Here, N is defined as the number of different time slot a train can enter or exit a certain terminal based on the available timetable. A discretization of continuous time in time periods could have been done but would have substantially increase the solution time.

Over the five phases of the solution, the models use a range of parameters that can be divided into five categories as follows: Train parameters, Terminals parameters, Supply/Demand parameters, Timetable parameters and Maintenance parameters.

- **Train parameters** include the maximum number of wagons per train, the maximum volume of product per wagon, the number of locomotives available and the number of wagons available.
- **Terminals parameters** include the distance between each stations of the network, the maximum and minimum stock level at each terminals of the network and the maximum number of departures per day that can occurs at each terminals.
- **Supply/Demand parameters** include the supply and demand per day at each terminals of the network.
- **Timetable parameters** include the origin/destination combinations between each stations of the network, the departure/arrival time of each route, the cost to use a specific route and maximum wagons per train allowed on each route.
- **Maintenance parameters** includes the time required to perform each type of maintenance, the capacity in term of equipment used to perform each type of maintenance, the frequency at which each maintenance service need to be perform, the location of the maintenance facility in the network and the capacity of the maintenance facility.

3.1 Flow Model

The **Flow Model** is used twice during the full planning process. Firstly, it is used to find the number of daily departures needed per tour in order to create a daily timetable repeatable over the full planning horizon. An example of the output of this model during phase 1 is shown in Figure 3.

O/D route	Daily number of trains
1	15
2	15
3	8
4	5
5	3
6	4
7	5
8	5
9	1
10	8

Figure 3: Output of the flow model during phase 1

Secondly, it is run a second time during phase 3 of the process in order to find the exact cumulative flow by product needed over time for each tour. An example of the output of phase 3 is shown in Figure 4 in the form of a graphic.

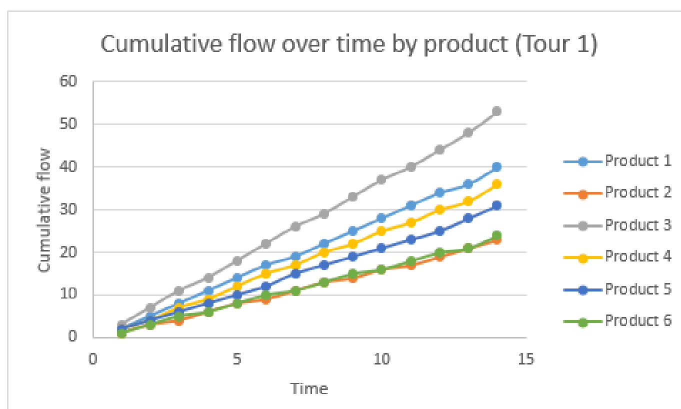

Figure 4: Output of the flow model during phase 3

The objective function of this model is a minimization of a sum including the inventory cost, the backorder cost, the number of trains needed and the maximum flow of product p needed between terminal i and terminal j. The model is subject to a certain set of constraints including the following main ones: balance of flow at each terminals, maximum storage capacity at each terminals, maximum departures of trains at each terminals, respect the capacity of trains in terms of number of wagons and quantity of product by wagon. The variables of daily maximum flow of product p travelling on a given tour (i,j) are constrained to be greater or equal to each daily flow of product p travelling on tour (i,j) over the full planning horizon. These variables are then used to find the daily number of train travelling on tour (i,j) that need to be add in the timetable.

3.2 Timetable Model

The **Timetable Model** is used during phase 2 of the process and has the objective to find a reduced daily timetable that can be repeated over the full planning horizon while satisfying the needs of the network. The model solves a mixed integer programming problem having as objective function a minimisation of the cost related to 2 main decision variables :

- A binary variable related to the initial timetable that is 1 if the departure slot m is used in the reduced timetable
- A binary variable that is 1 if a train carrying the product p leaves terminal i at time slot $x1$ and arrive at terminal j at time slot $x2$

The model is subject to those main constraints :

- Balance of flow at each terminal
- Minimum and maximum storage capacity at each terminal
- Limitation to one train using the departure slot m at terminal i on day d
- Limitation of departure slot m based on trains number needed and departure capacity
- Train balance at each terminal

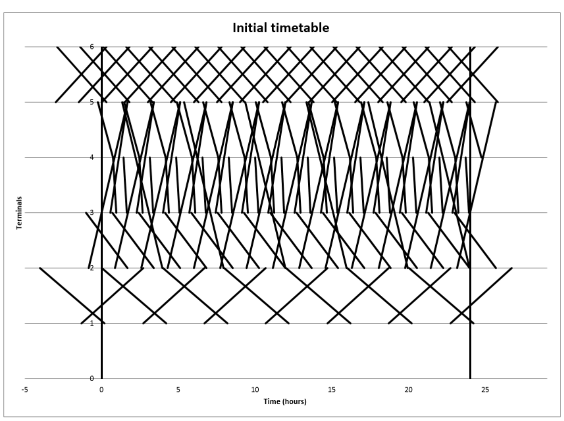

Figure 5: Initial daily timetable

The output of the **Timetable Model** is a daily reduced timetable (Figure 6) obtained from the initial timetable available (Figure 5).

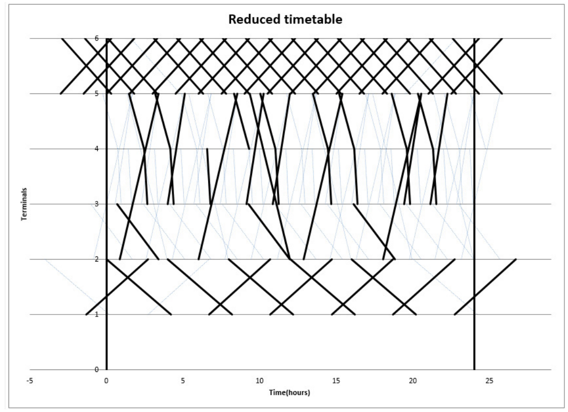

Figure 6: Reduced daily timetable

3.3 Product Routing Model

The **Product Routing Model** determines which products need to be carried on which tours each day with binary variables. This problem is solved for a few days at a time and iteratively moves forward in time solving in order to solve for the entire planning horizon. The model takes the fixed daily timetable found during phase 3 and apply it to each day of the planning horizon in order to obtain a n columns binary variable that indicate the product p carrying on tour (i, j) using departure slot m of the timetable starting on day d.

The objective function is again a minimisation of the backorder cost, inventory cost and number of trains needed over the full planning horizon. It is subject to the following main constraints : balance of flow at each terminals, minimum and maximum storage capacity at each terminals, limitation to one train using the departure slot m at terminal i on day d and limitation of one product p transported per train. The output of the **Product Routing Model** is a train schedule over the full planning horizon indicating the departure time, departure terminal, arriving time, arriving terminal and product carried.

3.4 Train routing Model

The **Train Routing Model** determine how to route the engines given what products are transported on which routes and day. This problem is solved for a few days at a time and iteratively moving forward in time in order to solve for all days. The objective function of this model is a minimisation of cost related to those main decision variables :

- A binary variable indicating which engine to drive the train related to column n
- A binary variable indicating the maintenance type that need to be perform on a certain engine from time $t1$ to $t2$

This 5th and last phase model is subject to the following main constraints :

- Balance of flow at each terminals

- Balance of engines at each terminals
- Minimum and maximum storage capacity at each terminals
- Initial position of the engines
- Minimum of one engine per train scheduled
- Respect of the maintenance capacity facility.

The outputs of this model are graphs of stock level prediction by product for each terminals, a Gantt chart representing the activities over the full planning horizon for each locomotives and a final timetable by product over the full planning horizon. Some examples of those outputs are presented in Section 5 as some results to the case study.

4 Case study presentation

As mentioned, the case study at the center of this study is based on the network of the Swedish mining company LKAB which it's mining operations and rail transportation are concentrated in northern Sweden, see Figure 7.

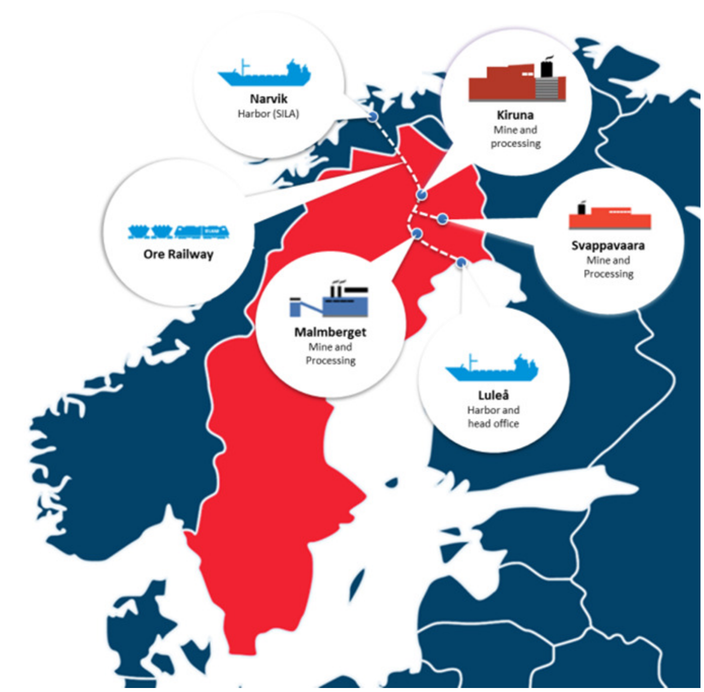

Figure 7: Geographical location of the operations of LKAB

The mining operations are divided within three operating mines including two underground mines in Kiruna and Malmberget and one open-pit mine in Svappavaara. The train transports the ore or pellets to either Lulea, where there is a steel plant and a port for export, or Narvik which is the main export port. The reason for Narvik being the main hub is its capacity to birth larger vessels and that it is ice-free during the winter. Note that all operations take place north of the Arctic Circle which puts the operation under tough conditions, in particular during winter. All operations take place 24/7 year around. The storage operations take place at each of three operating mines, at Narvik and at Lulea. For example, in Narvik there are 10 cisterns directly in the mountain for easy unloading. Each cistern has a capacity of 100,000 tons. The vessels arrive to Narvik or Lulea to bring the products to customers in Europe and other parts of the world.

Each train set has 68 wagons and each wagon has a capacity of 100 tons i.e. each train set carries 6800 tons. According to the base plan LKAB produces and transport 31 million tons of product to the two harbours. The product range that can be transported by rail includes 12 different products with the addition of empty wagons and dead engines which consists of empty locomotives.

The initial timetable that is used by LKAB has 134 different departure times over the full network. This timetable is reduced over the course of the method presented in this paper in order to find a daily timetable that can be repeated over a 2 weeks planning horizon and still respond to product demand. The produced timetable is constrained by maximum number of departures per day for each origin/destination possible routes following the indications shown in Figure 8.

From	To	Max daily departures
Krn	Nvk	15
Nvk	Krn	15
Krn	Mer	8
Svp	Krn	6
Svp	Mbt	3
Mbt	Krn	4
Mbt	Lla	5
Lla	Mbt	5
Krn	Mbt	1
Mer	Svp	8

Figure 8: Maximum number of departures for each origin/destination routes

The schedule for the train sets are determined by an agreement with the Swedish transport administration that is responsible for the operations of the rail network in Sweden. This schedule is determined long time ahead of the actual operations, typically one year earlier. The main key question of the company is how many locomotives are needed to support the train sets used? This question is complicated by the fact that the locomotives are developed specifically for LKAB's operations and the fixed cost to purchase one is very high. In addition, it is not possible to purchase a single locomotive but it is required to buy at least three. Moreover, there is a new type of locomotive planned to be in operation in a number of years. An alternative solution is to rent locomotives used for other cargo trains. The network is currently served by a fleet of 17 locomotives.

5 Computational results

In this section, we describe the computational results that were obtained by applying the models described in Section 3 to the real-life case of LKAB. The models are implemented in the AMPL language, using the CPLEX solver to solve the MIP as well as LP models. The results have been obtained by using a computer equipped with an Intel Core i5-4330M processor running at 2.8 GHz clock speed, using 16 gigabytes of random access memory and operating on a Windows 7 Enterprise system. As regards to the LP Flow model and the MIP Timetable model, the results are shown in Figure 9. We imposed a solving time limit of 600 seconds for the Timetable model which is enough to reach a solution less than 1% away from the best integer solution.

Models	Time in sec.	Nb of variables	Nb of constraints	MIP Simplex Iterations	branch-and-bound nodes
Flow model	0.0156	1586	1522	-	-
Timetable model	600.000	12456	4310	2160080	3304

Figure 9: Computational results for the Flow model and the Timetable model

As mentioned in Section 2, both of the product routing model and train routing model are recursive MIP problem and thus are solve 4 days at a time after which the first day is fixed. This process is repeated until we obtain a full schedule over a 2 weeks planning horizon. The computational results are presented for each iterations of those 2 models as shown in Figure 10 and 11. By summing the time of each iterations, we obtain 27.14 seconds for the Product routing model and 302.22 seconds for the Train routing model.

Time horizon in days	Time in sec.	Nb of variables	Nb of constraints	MIP Simplex Iterations	branch-and-bound nodes
1 to 4	262.28	16995	7061	3953729	167113
2 to 5	4.59	15838	7063	37748	2468
3 to 6	6.13	14850	7063	64017	2380
4 to 7	4.29	13862	7063	56804	3668
5 to 8	1.33	12874	7063	5520	483
6 to 9	5.24	11886	7063	37363	2324
7 to 10	4.09	10898	7063	58499	3711
8 to 11	1.23	9910	7063	2721	42
9 to 12	4.20	8922	7063	72004	2370
10 to 13	3.85	7934	7063	45895	3802
11 to 14	4.99	6946	6951	52953	2504

Figure 10: Computational results for the Product routing model

Time horizon in days	Time in sec.	Nb of variables	Nb of constraints	MIP Simplex Iterations	branch-and-bound nodes
1 to 4	4.48	38613	11717	101	0
2 to 5	2.43	34623	11901	25	0
3 to 6	2.34	33675	12085	26	0
4 to 7	6.13	32731	12269	9367	0
5 to 8	1.7	31787	12453	5110	0
6 to 9	1.87	30843	12637	4743	0
7 to 10	2.11	29899	12821	40	0
8 to 11	1.09	28955	13005	4421	0
9 to 12	2.17	28011	13189	37	0
10 to 13	2.06	27063	13373	75	0
11 to 14	0.76	25413	13528	2568	0

Figure 11: Computational results for the Train routing model

Regarding the practical output obtained at the end of the full process, there is first a timetable by product to illustrate the movement in time of products between each terminals of the network, see Figure 12.

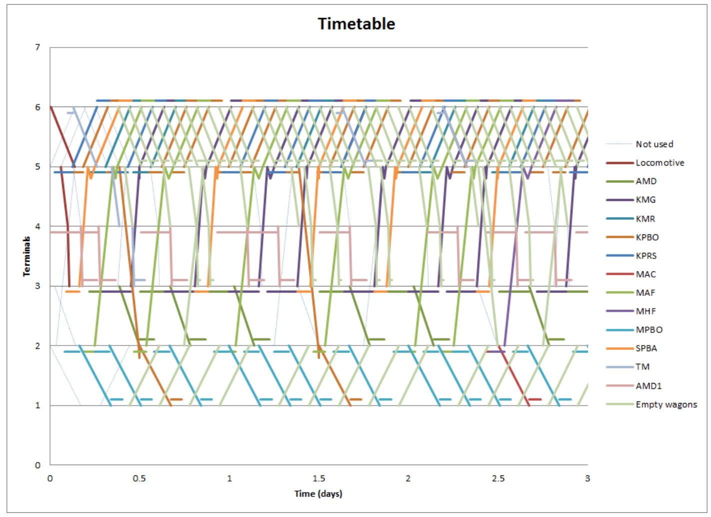

Figure 12: Timetable by product between stations over an horizon of 3 days

Second, we have a locomotives solution illustration in the form of a Gantt chart (see Figure 13) where each unit of the vertical axis represent a unique locomotive and the horizontal axis is the time in days. This representation allows the decision maker to have a comprehensive plan of the use of the fleet of locomotives.

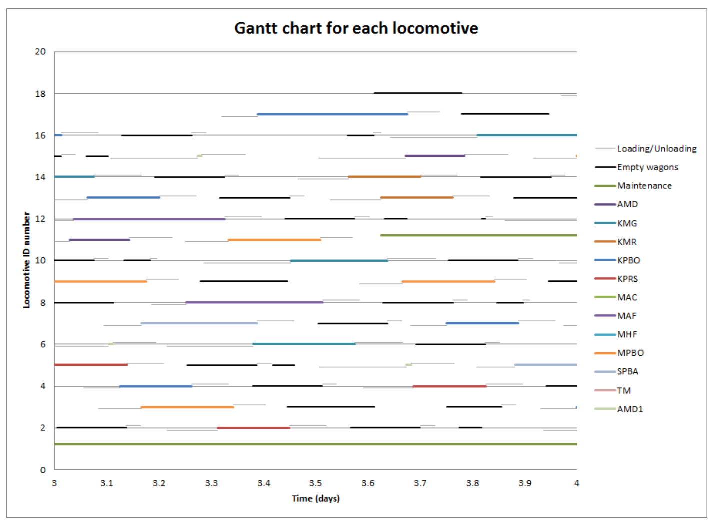

Figure 13: Gantt chart showing the activity perform by each locomotives over an horizon of 1 day

Finally, since the process takes into account the inventory management problem, it is possible to provide a complete vision of stock level by product at each terminals of the network over the 2 weeks planning horizon, see Figure 14 for an example of stock level at the Kiruna terminal. The horizon have been reduced to 4 days to provide a better view of the flow levels.

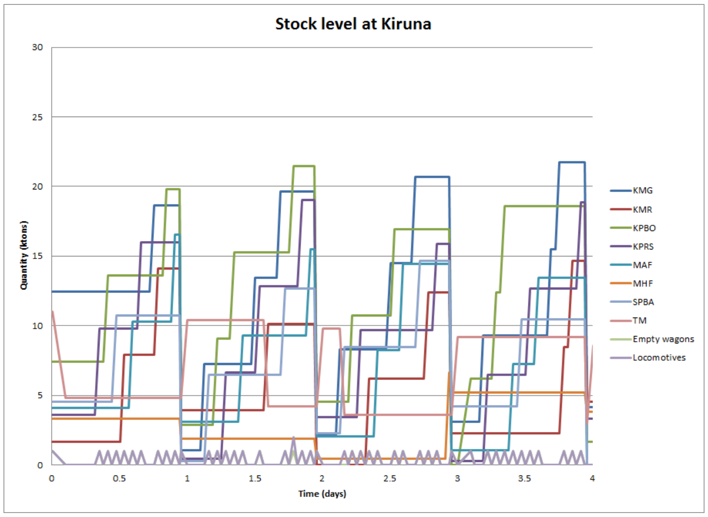

Figure 14: Stock level by product at Kiruna over an horizon of 4 days

6 Conclusion and future research

In this article, we have discussed the rail planning problem at a tactical and operational level in order to response to a real-case situation of freight trains planning with the company LKAB, a world leader in production of iron ore pellets. In order to solve a 2 weeks planning while taking into account the maintenance planning of locomotives and inventory management at each terminals of the network, we proposed a method using 4 mathematical models described briefly in this paper. Several research directions are emerging. It is possible to add some parameters to the study such as the wagons maintenance planning, crew planning and others. An interesting avenue would be to combine the process presented in this paper in a rescheduling level with the add up of simulation taking into account the stochastic aspects of the network such as locomotive breakdowns.

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