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Optimization of locomotive allocation in Finland

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Abstract

The railway systems contain many complex problems such as the locomotive allocation problem. The use of optimization tools has improved significantly in the past decade as the companies have started to realize the economic potential of using optimization tools in their planning process. The aim of this thesis is to find out how suitable mathematical models presented in the literature are to problems occurring in Finland. The models are compared with respect to requirements needed to be satisfied in Finland. The requirements are defined after interview with local locomotive allocation planners and their foremen. In addition to the matching of Finnish requirements the computational times reported by the authors are taken into account as obtaining solution in reasonable time is a major factor when comparing the models. As a result there are no models that can be directly adapted into Finnish problems.

Keywords Optimization, locomotive, railway, Finland, modelling, commodity flow

Contents

1 Introduction

Planning the allocation of locomotives is one of the major decisions that railway companies do every day (Piu and Speranza, 2014), while the other major decisions are timetable planning and crew scheduling (Caprara et al., 2007). The planning of locomotive allocation is especially important as it has strong impact on crew scheduling and finding an efficient solution to wield the locomotives yields into significant savings (Eskola, 2015).

In the past ten years the use of mathematical models has been growing in the railway industry around the world. This can be noted from the surveys made by Cordeau et al. (1998), where the authors state that not many companies have realized the economic potential of using mathematical models in planning of locomotives. Later Caprara et al. (2007) note that some companies have started using optimization as support in their planning. In the most recent survey made by Piu and Speranza (2014), most of the models are researched with companies such as CSX, Deutsche Bahn AG and Nedeslande Spoowegen, which indicates that optimization tools are now part of the planning tools of railway companies.

The plan provided by models usually surpass the plans made by railway companies in terms of costs. However Piu and Speranza note that in some cases the models are so simplified that it's questionable how well the plan could be used in real life. Nevertheless there are still models that are sophisticated enough to be compared to plans made by real planners such as Vaidyanathan et al. (2008) and Jaumard et al. (2014), which both achieve better results than company planners and could be applicable in real life.

The objective of this thesis is to provide insight to the question: How easily could the models presented in the literature be applied to Finland? This thesis doesn't answer the question of how big savings could be achieved by optimizing the plan of locomotives. The thesis is limited to studies that focus on locomotive planning and can be applied to cases where multiple locomotive types and both passenger and freight trains can be used.

In order to provide an answer to the thesis' question, the requirements and special characteristics in Finland need to be defined. These are acquired by interviewing the planning personnel in the Finnish railway company. These VR Group people are locomotive usage planners, controllers and their foremen. Otherwise the thesis is based on the literature.

The thesis is composed of four major parts. The first part presents the general problem and a very simplified mathematical model for it. The second part takes a look at the special characteristics of Finland and what requirements they lead to. The third part contains the review of the literature. In this section three models are compared with respect to requirements that apply to Finland. The three models are selected according to two criteria: How well they model the requirements of locomotive assignment problem in Finland and how easily they can be solved. The models chosen represent best fitting models to both criteria and a compromise between these two criteria. The fourth and last part sums up the results from comparison of the models made in the previous section.

2 General locomotive allocation problem

This section describes a simplified version of the locomotive assignment problem as a multi commodity flow problem. This approach is used in many of the studies in the literature to construct models for locomotive assignment problems (Piu and Speranza, 2014). In this approach the locomotives are seen as commodities, stations as nodes with a time attribute and trains as arcs between them (Ahuja et al., 2005; Piu and Speranza, 2014; Jaumard et al., 2014). The trains have both start and end times and stations, which are in this case nodes in the network.

The multi commodity flow problem is based on a space time network of nodes and arcs. Each arc connecting two nodes has a direction and a cost that must be paid by each unit of commodity flowing through the arc. More about the mathematical background of the multi commodity flow problem can be read from the book of M.S. Bazaraa et al. (2010).

In the basic case there are demand nodes and supply nodes. This approach is selected in some of the studies such as Teichmann et al. (2015), but in most cases the problem is modeled as a circulation problem. This means in this context that there are no supply or demand nodes. Each node represents station in space time network and is associated with a time $t(u)$ and a location $l(u)$. For example in the real life there can be a station A, but in the network there is station A with time attribute. In general each time something happens in a station there is a node for it with different time than the other nodes representing the same station. The arcs can represent either trains between stations or the waiting within a station. Note that each one of these arcs (u, v) connects the nodes u and v such that u has lower time than v. In each is therefore going forward in time. There are only two exceptions. One is for arcs representing trains passing midnight between Sunday and Monday. Moreover, the last node v of a given station is connected to the first one, say u, by a waiting arc (v, u). Also in this case are arc goes from a node v having later time than the u. This is required for having a feasible solution of the circulation problem. Additionally to ensure that problem is the feasible, there are arcs that can be used for rebalancing. These represent the movement of locomotive without a train, so in this case locomotive isn't pulling anything. This ensures that each stations has as many locomotives at the start and end of the week. An example of a space time network can be seen in in figure 1.

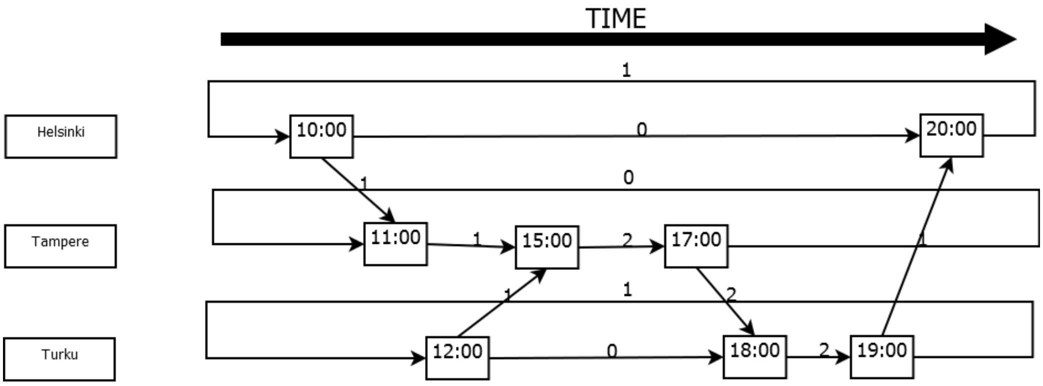

Figure 1: Example of commodity flow problem in space time network. Arcs represent trains or waiting within station, the number in each arc tell number of locomotives using the arc. The nodes are described with boxes and have the time attribute written into them. Each node has the location of station mentioned on the left side.

Next a simplified circulation problem is defined. We denote N the set of nodes that represents stations in space time network. The set of arcs is defined as A and are form (u, v), where $u \in N$ is the start node and $v \in N$ is the end node. There are three subset in A, the set A_T contains all the arc that represent trains, the setA_W contains all arc that represent waiting of a locomotive within same station and the arcs connecting the last node in time to first node of the same station. We also define the set A_c containing all arcs (u, v) with $t(u) > t(v)$. In order to ensure the feasibility we add also subset A_L that contains all arcs needed for rebalancing. These three subgroups form the set A and there holds that $A = A_T \cup A_L \cup A_W$.

Next the constraints needed for locomotive assignment problem will be defined.

First of all we have to ensure that locomotives don't disappear or come from nowhere. So we have to ensure that for each node the number of incoming locomotives corresponds to number of leaving locomotives. This must be true for each type of locomotive $k \in K$, where K is the set of different locomotive types. The number of locomotives of type k in the arc (u, v) is $x_k(u, v)$ where $x_k(u, v)$ is an integer variable.

$$\sum_{(z,w)\in N, z\in A} x_k(u, w) = \sum_{(w,z)\in N, z\in A} x_k(w, v) \quad \forall w \in N, \forall k \in K \tag{1}$$

Next thing that needs to be defined is that all trains must have at least the minimum amount of *traction*. The minimum traction of a train is the minimum amount of locomotives needed to pull the train, this need be satisfied with single locomotive type. In practice this means that if train needs two locomotives of type A or type B, the constraint is not satisfied it train has one locomotive of type A and one of type B. To model minimum traction for each train (u, v) it is associated with a quantity $min_k(u, v)$. This represent a minumum number of locomotives of type k needed to pull train. In addition we need a binary variable $y_k(u, v)$ for each arc, that tells if the arc is used to satisfy the traction requirement, because only one locomotive type can be used to pull the train. Therefore constraint can be defined as,

$$y_k(u, v) \cdot min_k(u, v) \leq x_k(u, v) \quad \forall (u, v) \in A, \forall K \in k \tag{2}$$

$$\sum_{k\in K} y_k(u, v) = 1 \tag{3}$$

Note that there can be also more locomotives than those needed for pulling the train. They can also be of different locomotive type, but they cannot be used to satisfy the traction requirement.

Because there are many countries that have both electrified and non-electrified tracks we also define $type_k(u, v)$ which tells if the locomotive of type k can be used to pull the train. If locomotive type k cannot pull a train (u, v) the $type_k(u, v)$ is set to 0, if type can be used the value is set to 1.

$$y_k(u, v) \leq type_k(u, v) \quad \forall (u, v) \in A, \forall K \in k \tag{4}$$

We want also to be able to limit the number of locomotives in the train. This is because the train can otherwise became too long or heavy. In order to make a constraint that limits the total number of locomotives we need to define $max(u, v)$ that tells the maximum number of locomotives that can be attached to a train.

$$\sum_{k \in K} x_k(u, v) \leq max(u, v) \quad \forall (u, v) \in A \tag{5}$$

As there are multiple locomotive types and we have only a limited number of each type, we define constraint to limit the number of locomotives in the plan. Because the problem is circulation problem of real world space time network all arcs go forward in time the number of locomotives stays constant in the whole network in a given time. Therefore we can count the number of locomotives from any moment of the time in system. The easiest moment is the midnight between Sunday and Monday. All arcs passing this moment, and only those, are in the set A_c. So the number of locomotives of type k in the plan is,

$$\sum_{(u,v) \in A_c} x_k(u, v) \leq max_k \quad \forall k \in K \tag{6}$$

where max_k is the number of locomotives of type k available to be used in the plan.

Now the circulation problem is defined except for the objective function. The main costs come from assigning the locomotives to train and therefore we will make a cost based objective function. We could also select minimizing the number of locomotives in plan, but that isn't wanted, as will be presented in next section.

For the cost of having locomotive type k in a train (u, v) we have a cost $c_k(u, v)$. Now the objective function can be written as,

$$\min \sum_{k} \sum_{N} x_k(u, v) \cdot c_k(u, v) \tag{7}$$

Now we have a very simple mathematical model about the locomotive allocation problem. It has only 5 constraints and an objective function.

As said this model is very simplified and even simpler than the most simple model presented in this thesis. The model has possibility to *light travel* which means locomotive traveling between stations without train. This is the set is called A_L in this simply model. The other important way for rebalancing the number of locomotives is *dead heading*, which means that locomotive moves as wagon in a train. This happens when the locomotives in arc (u, v) has the corresponding $y_k(u, v) = 0$. Besides dead heading there is possiblity to have *excess traction*. This means the amount of locomotives that are same type as the pulling locomotives, but above the required amount of traction. For example train A needs one locomotive of type B to be pulled, if two type B locomotives are attached the train has one excess locomotive/traction. In this model the amount of excess traction can be calculated by subtracting the $min_k(u, v)$ from $x_k(u, v)$ if the $y_k(u, v) = 1$.

The model doesn't take into account time the locomotive needs to transfer from arriving train to departing train. As such the model assumes that locomotive is available with the same moment it arrives to station, which obviously isn't possible as the locomotive needs to be uncoupled from the train and then transfer to next one and be coupled with the wagons. In addition to be coupled to wagons the coupling locomotives together into *consists* needs time. Consist means locomotives that are coupled together. Moreover there is a time needed for *consist busting* if train has at least one locomotives that doesn't continue to same train. Consist busting means creating or breaking consist in the rail yard.

3 Specifications of the Finnish locomotive allocation

The Finnish version of the locomotive allocation problem is naturally very similar to the ones in other countries. As elsewhere all trains must be driven and the cost must minimized. There are however a few quite distinctive features in Finnish rail road network and business environment overall. The section is based to interview with VR personel (Eskola, 2015).

3.1 Special characteristics

Firstly there is no distinction between freight locomotives and passenger locomotives. This isn't common elsewhere in the world as usually the locomotives only drive either passenger trains or logistic trains, which can be seen from the survey made by Piu and Speranza (2014). The sharing the same locomotives gives advantages of scale and thus helps saving costs and is why it's seen best way in Finland (Eskola, 2015). However it makes the problem also harder to solve as it comes more heterogeneous with different rules. This comes well forth when models have to take into account that locomotives can be coupled and decoupled for trains to have correct amount of traction. This is called consist busting, which is quite common in Finland at the moment.

The second difference is that the planning is usually made for each week in a year as the traffic in the network varies so much (Eskola, 2015). Therefore it is more crucial to be able to get solutions in reasonable time and them to be as feasible as possible in real life. The variety of traffic comes from many different sources such as track works, holidays, seasonal shifts and the fact that logistic and passenger trains vary on different intervals (Eskola, 2015). These all make the planning environment very lively.

The third characteristic comes from the Finnish geography and population. Finland is a country with very large area and low population. This makes the network sparse and distances very long. This means that in the planning things as fueling and maintenance need to be taken into account. This means that it must be ensured that diesel locomotives have change to be fueled after some time.

The fourth difference is that in many countries there is possibility to rent locomotives to or from other companies, this is case for example in (Teichmann et al., 2015). Therefore minimizing the cost is almost equivalent to minimizing the number of locomotives needed. This is because surplus of the locomotives maybe rented for other companies. In a long term minimizing the number of locomotives leads to reduced costs also in Finland, but in the short term minimizing the number of locomotives doesn't minimize the costs. This leads to a slightly different and a more complex objective function as the actual costs have to be calculated and minimized instead of the number of locomotives needed.

Other things that are also worth of mentioning are:

1. There are many locomotive types in use
2. Consists busting is relatively common
3. Light travel is relatively common
4. Dead heading is relatively common
5. Time needed between train to train connection might wary greatly

These are each taken into account in many models encountered in the literature, but they aren't general assumptions that are made for each model, as each company has it's own special characteristics. Thus some of requirements are sometimes left out, as it might lead to great decrease of computational time and therefore make the model and optimizer much more attractive for solving that specific case.

3.2 Requirements

As stated in previous chapter, our objective is to minimize the cost for each week. We can assume that the benefit of trying to minimize the number of locomotives is not equivalent to minimizing the costs. Because of that our objective function has to take following things into consideration.

1. Cost of running train with locomotive type k
2. Cost of having excess traction of locomotive type k on train
3. Cost of having locomotive type j dead heading
4. Cost of light traveling between stations
5. Costs of creating and breaking consists of locomotives

The objective function has therefore five sources of costs that the model should aim to minimize. Most important are the parts 1 and 4, as they are the most markable sources of costs. The parts 2 and 3 can be mostly modeled with costs of running train, but keeping them separately leads to more accurate outcome. The last part 5 is for keeping the consists intact if possible as it also takes time to break or create them. In the simplified model the costs 1 - 4 could be taken account, if the variable $x_k(u, v)$ would be split into three separate variables. One representing the pulling locomotives, one excess traction and last dead heading locomotives.

From the special characteristics and simplified model in the previous section we get following requirements for the model needed in Finland for the plan in order to be feasible in the real life.

The requirements to model that must be satisfied are,

1. Model has to be able to handle multiple locomotive types
2. All trains must have enough traction
3. Trains don't have too much locomotives attached
4. The activities needed between train to train connection need to be modelled.

5. Locomotives have to be able to forms consist and deform these when necessary
6. Locomotives have to be able to travel without a train when necessary
7. The parking capacity of each location is limited in meters
8. Diesel locomotives have to be fueled after predefined distance traveled
9. The number of locomotives used can't exceed the number of available ones

The requirement 1 is for making sure that model can handle multiple locomotive types. Some models are only developed for single locomotive type and those aren't applicable in Finland. This is taken into account in the simple model presented in chapter 2.

The requirement 2 seems first very obvious. However if the model deals only with passenger trains this requirement is often not needed as single locomotive is often sufficient. Because in Finland locomotive are used to drive both passenger and freight train that might need even three locomotives this comes important thing to take into account. This requirement is taken into account in the simple model presented in the chapter 2.

The requirement 3. this is needed because the trains have maximum number of free space for locomotives that cannot be exceeded. If the train comes too long, there might not be enough space in the track for passing trains. The maximum number of locomotives in a train is taken into account in the simple model presented in chapter 2.

The requirement 4 is probably most difficult to model as it means that actions needed to get locomotive from arriving train to departing train must be taken into account. Usually this includes taking the train of from wagons and coupling it to next wagons as well the transfer time to in front of next wagons. This might however vary as next train sometimes has same wagons and locomotive does not have to be decoupled and can continue in practice instantly.

In addition to breaking the consists and coupling train to wagons there is time locomotive needs to direction change or turnaround. This means that for example locomotive that is coming from north can continue faster to train that has same direction. If the next train would be heading back to north, the locomotive would need extra time to turnaround in the rail yard. Activities aren't taken into account in the simple model presented in chapter 2.

The requirement 5 is for the need to use locomotives efficiently. The locomotives needed for passenger trains need almost in all cases only one locomotive, whereas the logistic trains need in many cases two or three locomotives. In many places the locomotives simply must be coupled or decoupled as there might be one train with two locomotives coming and two trains leaving that need only single locomotive. Consist busting is taken into account in the simple model presented in chapter 2, but the time needed for operation isn't.

The requirement 6 is as well for the need to use locomotives efficiently. There are stations that have very one-sided traffic meaning there is either many trains more arriving than departing or vice versa. Light travel is particularly necessary if the station has only little traffic and lays near other stations. Light travel is taken into account in the simple model presented in chapter 2. However the set of light travel arcs is predetermined and so even if the model is optimized the result isn't guaranteed to be optimal, as there might be better set of light travel arcs.

The requirement 7 limits number of locomotives one stations can host, the might be separate tracks for diesel and electric locomotives, in this case electric can use only electrified parking tracks, but diesel can use both. Parking requirement isn't taken into account in the simple model presented in chapter 2, but could be added with new constraint, without introducing new variables.

The requirement 8 is of course for that diesel locomotives cannot drive with empty gas tank and this has to be taken into account in planning decisions as the plan could easily become infeasible otherwise. Fueling isn't taken into account in the simple model presented in chapter 2.

The requirement 9 for not exceeding the number of locomotives available is important as there is four types of locomotives in use at Finland. If the number of locomotives can't be limited the model will naturally only use two locomotives types out of four. These would be cheapest electric locomotive and cheapest diesel locomotive. This might be good for strategic planning, but not good for shorter term planning, as in the real life there wouldn't be enough locomotives.

3.3 Possible challenges

Greatest challenges for optimizing the problem will most likely come from the sheer size of the problem. Therefore the requirements that increase the size of problem are most probably the most difficult to take into account.

The modeling of light travel between stations (requirement 6) seems the hardest thing to take into model and optimization as it can lead into exponential growth of possible connections. For example train that arrives into stations A can take also next train allocation from stations B or C. In most cases traveling between stations isn't wise thing to do, as it's very expensive, but sometimes it is necessary or very beneficial. For example there might be two stations quite near each other and other has arriving train at 11:00 and other leaving at 15:00. If we assume there is no other traffic at these stations it's very obvious that locomotive should light travel between those stations rather than wait for the next train to leave at the original station.

The other thing that increases the size of problem is consists busting and time it takes (requirements 4 & 5). Both are very important features that need to be handled in some way. As if stations has more train departing than arriving, usually the cheapest way is to put extra locomotives to some of the arriving train and decouple them so each departing train has enough traction. If the ability to put extra locomotives to train and decouple isn't supported the only thing model can take is to use expensive light travel to correct imbalances. If the time needed for decouple isn't taken into account the plan is usually not feasible as there isn't enough time to make the transaction from train to train and so departing train gets delayed. The same problem comes when the turnaround or direction change times hasn't been taken into account.

The requirement 9 for limiting the number of available locomotives can also create challenges. Especially as it might make the problem infeasible as there isn't locomotives to serve all trains. This isn't likely to happen, but possible nevertheless.

Also the fueling (requirement 8) is usually hard thing to take into account, but the lack of that is not as significant as light travel and consist busting. It can be said non critical, because the chances that fueling isn't possible in time are quite low and often affect more freight trains that have a little bit more flexibility than passenger train.

4 Comparison of models

This section contains the three different approaches to model the locomotive allocation problem. The reason to select these three models to more accurate analysis is getting good look at the strong and weak sides of complexity of model. Because of this one of the models is very simple and second is the most accurate and thus the complex found in the literature.

However the accuracy of the model isn't only thing that is taken into account. Another as important factor is the time needed to obtain a solution. Thus for the third model to be presented, a study that represent relatively accurate model with reasonable computational times is selected. Comparing the computational times can be very deceiving in this kind of problesm. However obtaining a solution is such a major factor that this will be nevertheless done. In order to truly compare the models and the algorithms they would need to be tested into same specific problem and then compared the times, optimality and real life feasibility of the plans to each others.

Naturally there are more studies in this field than the three selected see e.g Piu and Speranza (2014). But they each had some drawbacks, why they didn't get to be chosen. The two most notable studies left out were studies presented by Vaidyanathan et al. (2008) and Ziarati et al. (1997). Both of these have quite good model for reality and were able to generate a solution in reasonable time.

Especially the study of Vaidyanathan et al. (2008) had one major drawback from Finnish perspective. They changed the commodities into consists instead of using locomotive types. This makes the problem much easier to solve and inherently takes many of the constraints. However this comes with the cost of losing possibility to consist busting, which is very much needed in Finland. This alone makes the study infeasible to Finland.

4.1 Simple model

This section presents the simple model to solve locomotive assignment problem. The selected solution is presented by (Teichmann et al., 2015). It is done with Czechs railway company and uses real data provided by the company.

The model of Teichmann et al. is one of the most simplest met on literature and thus very good starting point for evaluation of models to Finnish problem. The simple solution is good starting point, because we have two main criteria for model, the accuracy of reality and the computation time. Simple model shows the limits of computational time and thus gives a border line to how fast the problem can be solved.

The authors don't speak with terms of dead heading and light travel as is done in this study. In their terms the dead heading means traveling without a train. While there isn't possibility to transport locomotives in trains (Teichmann et al., 2015). Therefore if the original study is read there is danger of confusion unless the reader pays attention to true meaning behind the words.

4.1.1 Overview of solution

The model presented captures the most essential things needed to model locomotive planning, but hardly anything else. The model has only four constraints that need to be satisfied (Teichmann et al., 2015). The constraints in model are:

1. All trains are driven
2. Number of locomotives used doesn't exceed number of locomotives available
3. Number of locomotive assignments doesn't exceed number of available locomotives in station
4. Each train has next and previous task (start and end tasks are modeled separately)

The objective function model has is quite comprehensive. It takes into account costs for owning locomotives, running a route with own locomotive or renting one for route, and cost for light travel between station and a train (Teichmann et al., 2015). So it is as close as the model allows it to be the objective function described in section 2. The missing costs are the cost for dead heading and consist busting.

4.1.2 Comparison to Finnish requirements

The results of comparison between the model and requirements made earlier are shown in the table 1. The simplicity of model has it is upsides, such as fast calculation times, but in terms of fitness to Finland the model is too simple.

The model supports multiple locomotive types that are in the study type diesel or electric and may have restricted routes, as not all trains travel in electrified tracks (Teichmann et al., 2015). The requirement 1 is therefore met.

Table 1: The met requirements of Teichmann et al. model

Requirement	Yes	No	Partly
1 Using multiple locomotive types	x		
2 Assigning correct amount of traction	x		
3 Limiting maximum number of locomotives		x	
4 Activities between train			x
5 Consist busting		x	
6 Light travel	x		
7 Parking		x	
8 Fueling		x	
9 Available locomotives	x		

All trains have at least the minimum amount of traction as required in the requirement 2 (Teichmann et al., 2015). So the requirement 2 is also satisfied. The number of locomotives used for plan can be limited even by accuracy of starting station. This satisfies the requirement 9 of limiting the number of locomotives available.

The requirement 3 for having maximum amount of locomotives for train isn't supported by this model. Hence it can be said that the model actually has upper bound, as the number of locomotives of type in train is fixed. Because this isn't a parameter user can change, the result is that model doesn't have met this requirement.

The model doesn't take fueling into account as required (requirement 8). This wasn't however critical requirement and possible the authors have seen it as a such also since they also had diesel locomotives. Neither does the model take into account the limited parking space for locomotives (requirement 7) and therefore corresponding requirement is also not met.

The key requirements considering the time needed between trains (requirement 4) and ability to create and break consists (requirement 5) aren't supported. Activities are partly taken into account as there is matrix that gives what possible connections train can take. However this does not take into account the time needed for possible decouple of locomotives and therefore is only marked as partly in the model.

Another key requirement 6 can be seen as supported in the model. This is possible to model with the matrix that gives the possible connection for train and there is no constraint that requires that the arriving and departing train must be in same station and therefore light travel can be seen to be modeled.

As a summary the model is not well fitting to Finland. Most of the key requirements aren't supported, or they are supported only partly.

4.1.3 Other notes and computational results

There is one feature that isn't needed in Finland which is presented in model. The renting of locomotive instead of driving it with own locomotive isn't possible, as there is at the moment only one company in Finland. To solve this issue with extra feature, the ability to rent locomotives can be safely deactivated. This doesn't affect the model any other way and the writers also used it in a test case of their own (Teichmann et al., 2015).

The testing of Teichmann et al. model is done with real life data. Their computational results are presenter in table 2. However the datasets are quite small compared to Finland. In their largest dataset they had 50 trains on average for each day on week, this totals roughly 350 trains in a week. (Teichmann et al., 2015) While in Finland there is roughly ten times more trains to plan. This makes the comparison between times rather difficult, as the number of matrices and possible combinations grow up fast. For example their example the matrix X that is used to describe train to train connections was 50 times 50 so it had 2 500 elements, that is less than 1% of the elements in matrix that would be used in Finland (360 000 elements) and is only for one loc type. Because there are currently 4 types of locomotives used in Finland the matrix would have over one million elements and 4*600! of possible train to train combinations.

Table 2: Summary of the computational results of the model

Author	Teichmann et al.
Time	$\leq$ 1 second
# Trains	$\leq$ 50

The research group managed to get optimal results with model extremely fast - under 1 second with standard desktop computer (Teichmann et al., 2015). However because of so different sizes of the problem it is hard to give an estimate how long this model would need to find an optimal solution in Finland.

The author didn't provide any further knowledge about the algorithm they used to solve the problem or the optimality of the solution. Easiest and clearest way would be to give optimality gap to solution that isn't integer one. Therefore we don't have knowledge about the efficiency of algorithm or goodness of solution.

4.1.4 Conclusion

In general the model isn't very suitable in Finland as it might be able to generate plan within a reasonable amount of time, there is simply too many constraints that aren't taken into account in the model and thus the plan made could be infeasible. The most important missing elements are:

1. Consist busting and time required for the activity isn't supported
2. Dead heading in trains is not modeled

The more specified list of requirements and their matching is presented in table 1.

The computational times with model were excellent, but because the datasets used were only fraction of the size used in Finland it is hard to estimate the computation time needed in Finland.

4.2 Model with the highest accuracy

Ahuja et al. have published two articles about optimization of locomotive usage in Canadian railways. The first article is published in 2005 by Ahuja, Liu, Orlin, Sharma, and Shughart and later one in 2008 by Vaidyanathan, Ahuja, Liu, and Shughart. The former has more general mathematical model of problem and is so more fitting to Finnish version of problem than the later publication. Although even the later one could be applied into Finland as well, the solution provided wouldn't just be as efficient as from the first model.

The model is chosen because it represents approach that models the real world constraints most closely the ones needed in Finland. These results can be seen in table 4. The study has also been cited by almost every markable article published afterwards and it was the first one to model constraints in such a high accuracy (Piu and Speranza, 2014).

The model is developed together with Canadian railway company that provided the datasets used and plan to compare the results from the optimizer.

4.2.1 Overview of solution

In Ahuja et al. study the light travel arcs are created before hand and treated as "trains", with distinction that these routes can be used, but they don't have to be used. (Ahuja et al., 2005)

As stated earlier Finnish has so called sparse network, which means in this case that distances between stations are long and the number trains running between them are in many cases very limited. Because of limited availability of trains the efficient way for balancing the number of locomotives between stations is very critical. In this mode there is two ways to deal with imbalances, light travel and dead heading Ahuja et al., which are the methods to deal with imbalances. The same method was used in the simply model defined in the section 2.

The constraints of the model are quite extensive and they are analyzed in more detail on next chapter. The constrains model has are categorized into two different categories. Hard constraints must be satisfied, whereas the soft constraint have a penalty in objective function. The constraints are:

The hard constraints in study of Ahuja et al. are:

1. Each train must have the minimum amount of traction
2. Each train (u,v) is assigned locomotive types that can pull the train
3. The maximum number of pulling locomotives in a train is limited
4. Each train can be assigned at most 12 locomotives, including both the pulling and dead heading locomotives
5. The number of assigned locomotives of each type is at most the number of available locomotives of that type.

The soft constraints in study of Ahuja et al. are:

1. Consistency in the locomotive assignment (if a train runs five days a week, then it should be assigned the same consist each day it runs)
2. Consistency in train-to-train connections (if locomotives carrying a train to its destination station connect to another train originating at that station, then it should preferably make the same connection each day that both trains run)
3. Same-class connections (trains should connect to other trains in the same class)

4. Avoiding consist busting as much as possible.

The objective function the model has is also quite extensive. It takes into account the following costs:

The objective function in Ahuja et al. model.

1. Cost of ownership, maintenance, and fueling of locomotives
2. Cost of pulling and dead heading locomotives
3. Cost of light traveling locomotives
4. Penalty for consist-busting
5. Penalty for inconsistency in locomotive assignment and train-to-train connections
6. Penalty for using single locomotive consists

This corresponds quite perfectly of what was specified in chapter 2 previously. The last two constraints aren't so desired, but can easily be left out from objective function. Otherwise all wanted costs are taken into account.

4.2.2 Comparison to Finnish constraints

The results of comparison between the model and requirements made earlier are shown in the table 3. In general the results were excellent and only one of the nine isn't satisfied and one other is satisfied only partly.

Table 3: The met requirements of Ahuja et al. model

Requirement	Yes	No	Partly
1 Using multiple locomotive types	x		
2 Assigning correct amount of traction	x		
3 Limiting maximum number of locomotives	x		
4 Activities between train	x		
5 Consist busting	x		
6 Light travel	x		
7 Parking			x
8 Fueling		x	
9 Available locomotives	x		

The first requirement 1 is taken into account in the model and there can be any number of locomotive classes needed.

The requirement 2 that each trains has enough traction is calculated based on needed power and the power the locomotive or consist of locomotives produces and satisfies the requirement.

There is possibility to limit the number of locomotives in train and thus the requirement 3 is satisfied.

The activities constraint is modeled quite well. The arriving consist can either go to station, where it has to be stay for time that would be needed for changing consist or it can stay as same consist and continue directly to next train. There are parameter for both of these time, so it can be adjusted as needed. Therefore the requirements 4 and 5 is satisfied.

The possibility to light travel without timetable is modeled in the study. The set of most likely candidates to be used, is generated between stations that have imbalances. This isn't a perfect way to handle them, but the model doesn't limit the possibility to have enough routes to generate optimal plan. Thus the requirement 6 to travel without train is satisfied.

The requirement to limit maximum number of parked locomotives is easy to take into account as the stations have two attributes, location and time. Thus there is a transfer each time time passes and then the number of locomotives transferring in station from time 10:00 to 10:01 can be limited. This isn't modeled however and so the requirement 7 is marked as partly satisfied.

The requirement 8 for fueling isn't taken into account, but is mentioned by the authors as possible expansion of the model with maintenance constraints.

The last requirement 9 about limiting the number of locomotives available is taken into account in the model as already stated in previous chapter under the hard constraints of the model.

As a summary the model is closest to requirements in Finland met in the literature. The only missing requirement is fueling, which was regarded as non critical. The other one that is marked as partly supported is restricting the number of locomotives in station, but it can be easily added to model if needed.

4.2.3 Other notes and computational results

The model was tested with large instances of data similar with size of in Finland. However the solver wasn't able to find optimal solution even in large computation times (Ahuja et al., 2005).

The authors were however able to modify the model and use algorithm to generate solution with close to optimal one. The simplification was done by changing the problem to one day problem. This was possible as they noticed over 94% of trains run in 5 or more day in a week. Thus they were able to use the single day solution for whole week and then use neighborhood search algorithm to make plan feasible and improve solution. (Ahuja et al., 2005) The algorithm is described in detail in their study (Ahuja et al., 2004). The time algorithm needed to obtain solution was under 1 hour even for large datasets Ahuja et al. (2005). Computational results for both approaches are presenter in table 4.

Table 4: Summary of the computational results of the model

Author	Ahuja et al. (2005)	Simplification
Time	$\geq$ 72 Hours	$\leq$ 30 minutes
# Trains	3 000 -3 500	3 000 -3 500

Because they weren't able to generate the optimal solution of the plan at all. The reaserch group can't give any optimality gaps of the achieved solution. They however give comparisons to plans made by real planners and the advantege is very signifigant, $9.2 million of obtained solution compared to $13.5 million of planner made solution. This however gives only a directional picture of situation as we don't know how close to optimality the solution was and how good was the plan made by planners.

4.2.4 Conclusion

The model presented by Ahuja et al. has very good accuracy in terms of describing the problem. The only requirement not satisfied is fueling, which was regarded as non critical.

However due the complexity of model, it was impossible to obtain optimal solution with the model. With simplification of model to daily problem and use of neighborhood search algorithm they were able to generate close optimal solution in reasonable time.

The model would be almost perfect to Finland, if the optimization would work. The heuristic method is however also very viable option to be considered in Finland and the model should be tested in Finland to evaluate its potential. The greatest loss of not reaching an optimal solution is that now there isn't knowledge about the optimality gap of obtained solution.

4.3 Model presented by Jaumard et al.

The solution presented by Jaumard et al. is one of the most recent ones found in the literature. It's selected because it has both high accuracy of reality and fast computation times to reach optimal solution. The model is developed with Canadian railway company and the datasets used are quite same size as in Finland.

4.3.1 Overview of solution

Jaumard et al. present new concept called trains strings. The string means that two trains are set together before optimization and driven with same units of locomotive, so changing traction inside string is prohibited. Doing this allows the modelling of tight turns where there would not be time for consist busting. Otherwise the network would be much bigger. This is because consist can transfer from train to train much faster than it could if there is consist busting needed. (Jaumard et al., 2014) In summary there are two times that are used when for a train to train is determined is there enough time between. The first time is shorter and allows faster transfer and is used only inside train strings, where the locomotives stay together whole time. The other one is longer and allows changing the consist and is used by the optimizer, as all the tight turns are constructed to inside train strings.

The optimization is based on train strings and the optimizer adds new strings to model as long they keep improving the solution. This way it is possible to achieve an optimal solution of the LP relaxated of the model, without having to generate very large matrices. The method authors use is known as column generation (Jaumard et al., 2014). So in the resulting solution the number of locomotives might not be integer. The solution obtained via column generation is then converted heuristically into integer solution, but this method isn't explained in greater detail.

The constraint of model are extensive and are described in below:

1. The number of locomotives used is no larger than number available
2. The locomotives need to in maintenance every within 90 days of previous maintenance
3. Train can only belong to one sting at time
4. The consist busting cannot happen if time in train to train connection is less than expressed in parameter

5. The number of locomotives simultaneously in specific maintenance shop is limited

The objective function isn't cost based, which is a problem in Finland as stated in chapter 2. It takes into account two objectives.

1. The number of locomotives used in plan
2. The number of consist busting operations in plan

The objective function could however be modified to take into account the costs needed. The affect to performance of optimizer would have to be tested, but most likely the effect wouldn't be severe.

4.3.2 Comparison to Finnish constraints

The results of comparing between the model and the requirements specified in chapter 2 are presented in table 5.

Table 5: The met requirements of Jaumard et al. model

Requirement	Yes	No	Partly
1 Using multiple locomotive types	x		
2 Assigning correct amount of traction	x		
3 Limiting maximum number of locomotives		x	
4 Activities between train	x		
5 Consist busting	x		
6 Light travel			x
7 Parking			x
8 Fueling		x	
9 Available locomotives	x		

The model supports the first two requirements given. The ability to use multiple locomotive types (constraint 1) and to ensure that each train has at least the minimum traction (constraint 2). Also the requirement 9 for limiting the number of available locomotives is taken into account for each locomotive type separately. Three requirements are therefore met.

The maximum number of locomotives that a train can have at a time is not restricted (requirement 3), but this could be added as a constraint by using existing variables and adding a parameter matrix that would tell the maximum number of locomotives possible to have in a train.

The model does not take fueling into account as required in requirement 8. However this was not a critical requirement.

The requirement 7 for the maximum number of locomotives in station is not taken into account in model, but it can be added to model if needed, without introducing new variables.

The key requirements of considering the time needed between trains (requirement 4) and the ability to create and break consists (requirement 5) are both supported. This is done by defining two times for a locomotive to transfer from train to train, if the consist stays exactly same, the smaller time is used and if at least one of the locomotives is changed then the longer time is needed.

Another key requirement (requirement 6) about light travel is also supported in the model. This is however somewhat limited as the routes have to be predefined. Basically it is the same as in other models as well, the difference is that the authors doesn't explain their algorithm for the generation of the light travel routes. As a result the constraint is marked as partly satisfied.

As a summary the model isn't perfect, but quite well fitting to Finland. It describes the problem in accuracy high enough and it can be easily modified to satisfy the requirements 3 and 7. The partly satisfied requirement 6 is also modeled in the same way as in the other models considered in this thesis.

4.3.3 Other notes and computational results

The model has one unique feature compared to other ones in this thesis. It takes into account the maintenance (Jaumard et al., 2014). Even though it isn't mentioned in the requirement list, it is useful also in Finland. The model is constructed for time based maintenance, but in Finland the maintenance is mostly based to kilometer count. However this is not a problem, because the need for maintenance is a initial value locomotive gets. As the planning period is usually one week the need for kilometer based maintenance is known before the optimization and locomotives can be labeled manually via this criteria.

The datasets the authors use in the model are obtained from a Canadian railway company and are large having over 1 000 trains and locomotives in the planning period (Jaumard et al., 2014). This size is enough to be compared the instances in Finland.

The authors obtained good heuristic solutions under 5 hours of computational time and in most cases under 30 minutes of computation time . However as they state, the optimal solution is only obtained for the problem that has given train strings and thus there might be better solution with different set of train strings that the algorithm wasn't able to find. (Jaumard et al., 2014). The general results of computational times are presented in table 6.

Table 6: Summary of the computational results of the model

Author	Jaumard et al.
Time	$\leq$ 4 Hours
# Trains	$\approx$ 1 000

The authors also presented optimality gaps of their integer solution whichwere between 6.72 % and 0.12 % from the optimal solution of the LP-relaxtion. Note however that the objective was to minimize the number of locomotives, not the costs of plan.

4.3.4 Conclusion

The model satisfies most of the key constraints by allowing the consist busting, dead heading and light travel. It lacks few of the non critical requirement, but these could be added as constraints if needed. The list of requirement matching is presented in table 5.

The objective function of the model is based on minimizing the fleet size and consists busting. In order to be used in Finland the objective function would have to be changed as minimizing the number of locomotives doesn't yield direct savings in Finland.

The computational results obtained with the model appear very promising as the computational times were always under 5 hours and in most cases under 1 hour.

In summary the model appears to be one the best fitting we found in the literature and with few modifications it's effectiveness could be tested with real life data.

5 Results

The results are presented in table 7. The requirements 1, 2 and 9 are satisfied by all of the models. These were requirements for supporting the planning with multiple locomotive types, ensuring that each train has at least the minimum amount of traction and limiting the number of locomotives that can be used. The modeling of fueling (requirement 8) was not present in any of the models.

Table 7: Comparison of the models

Requirement	Teichmann et al.	Ahuja et al.	Jaumard et al.
1 Using multiple locomotive types	Yes	Yes	Yes
2 Assigning correct amount of traction	Yes	Yes	Yes
3 Limiting maximum number of locomotives	No	Yes	Partly
4 Activities between train	Partly	Yes	Yes
5 Consist busting	No	Yes	Yes
6 Light travel	Yes	Yes	Partly
7 Parking	No	Partly	Partly
8 Fueling	No	No	No
9 Available locomotives	Yes	Yes	Yes
Total (Yes + Partly)	4 + 1	7 +1	5 +3

The remaining requirement make show the differences between the models. The requirement 3 for limiting the number of locomotives in a train was supported only by the model presented by Ahuja et al. (2005). For the model presented by Jaumard et al. the constraint would be easy to add, but that could affect the solution method. For Teichmann et al. (2015) the constraint would require introducing new variables.

The most problematic requirement (requirement 4) seemed to be the modeling of the activity times between the trains. This was solved however by both Ahuja et al. and Jaumard et al. Their models take into account the time needed for consist busting and the time needed to transfer a locomotive from train to train. The model by Teichmann et al. takes only into account the transfer time needed between trains, as the model doens't support consist busting (requirement 5).

The ability to light travel (requirement 6) was modeled by Teichmann et al. and by Ahuja et al. Both allow locomotives to travel from one station to another station without a train. In the Teichmann et al. this was allowed freely, whereas in Ahuja et al. it was allowed only by using predefined routes and times. The same method was used in the model presented by Jaumard et al..

The last requirement (requirement 7) wasn't supported by any of the models, but in the modelof Ahuja et al. the constraint could be added directly.

Table 8: The Computational results of the models

Author	Teichmann et al.	Ahuja et al. / Simplification	Jaumard et al.
Time	$\leq$ 1 second	$\geq$ 72 hours / $\leq$ 30 minutes	$\leq$ 4 Hours
# Trains	$\leq$ 50	3 000 - 3 500	$\approx$ 1 000

The computational times reported by the authors are summarized in table 8. The fastest model was Teichmann et al. that could be solved under one second, but with a quite small set of trains. Jaumard et al. could obtain heuristic solutions within a reasonable time for quite a large set of trains. The model of Ahuja et al. wasn't able to provide any solution before simplification. However after the simplification they were able to obtain heuristic solutions to the problem in less than 30 minutes. These solutions were based on the optimal solution of a daily problem, which was then heuristically expanded for the weekly problem problem.

As a whole the solutions of Ahuja et al. and Jaumard et al. appear to be the most matching and fast enough to be used as support in planning. Both of the models would however need to be developed further to be able generate solution that can satisfy all the constraints needed. This might affect the computational results and thus would need to test with real data, before the fitness could be actually judged.

6 Conclusion

The aim of this thesis was to find out how well the models presented in the literature could be adapted to problems occurring in Finland. To be able to answer the question the requirements that the model has to satisfy were defined. Each model was then compared with respect to these requirements. In addition, the computation time needed to obtain a solution was taken into account.

With these two criteria three models were selected for more accurate study. Each one representing a different accuracy to the problem, most times this increased accuracy comes with the expense of an increased computational time. Because of this the models selected were the simplest one, the most accurate one, and one that was in between of the first two.

None of the studies in the literature would be directly applicable to Finland, as each of them lack some features needed. However, the construction of a model that takes into account all needed requirement wouldn't seem impossible task. The difficult part would be finding a way to solve the problem in reasonable time. This is what the research group of Ahuja et al. was facing (Ahuja et al., 2005).

As a result two of the most promising candidates were the models presented by Ahuja et al. and Jaumard et al. The advantage of the first model was that it had the best fitting model and the weaknesses that the authors weren't able to obtain an optimal solution. Solving this model with heuristics they were able to generate a solution and that was much better than the plans made by real company planners. On the other hand the model presented by Jaumard et al. wasn't so accurate, but was able to generate solution in reasonable time.

The next step would be to adapting these models and test them into same case in Finland. After this it would be possible to compare the results and judge speed, optimality and feasibility of the plans generated from the models. After that the model could be developed further to better fit into Finnish problem.

In the light of the results the longer term vision of unifying all the planning in railway companies into single entity based on mathematical model doesn't look to be very near as solving even one of it's subsets proves to be highly demanding task.

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Yhteenveto

Rautatieyhtiöissä on monia matemaattisesti haastavia ongelmia. Yksi merkittävimmistä niin matemaattisesti kuin taloudellisesti on vetureiden käytön suunnittelu. Tämän lisäksi kaksi muuta merkittävää suunnitteluprosessia ovat junien aikataulujen suunnittelu ja henkilöstön työvuorojen luonti. Tässä työssä keskitytään vain vetureiden käytön suunnitteluun ja sen optimointiin sekä matemaattiseen mallinnukseen. Lisäksi työ on rajattu vain veturienkäytön suunnitteluongelmaa kuvaaviin ja useita veturisarjoja tukeviin malleihin, joita voidaan käyttää niin matkustaja- kuin tavaraliikenteen suunnittelussa.

Viimeisten kahdenkymmenen vuoden aikana tietokoneiden laskentatehoa hyödyntävä suunnittelu on yleistynyt rautatieyhtiöissä. Ennen 2000-luvun vaihdetta vetureiden käytön matemaattisella mallintamisella ei nähty suurta taloudellista hyötyä. Kaksikymmentä vuotta myöhemmin liki kaikki yliopistoissa tehtävä vetureiden käytön optimointiin liittyvä tutkimus tehdään yhdessä paikallisten rautatieyhtiöiden kanssa. Samaan suuntaan ollaan menossa myös Suomessa.

Usein mallien avulla tuotetut ratkaisut ovat ylivertaisia yhtiöiden omien suunnittelijoiden tekemiin. Osa malleista on kuitenkin rakennettu niin yksinkertaisiksi, että niiden tuottama suunnitelma ei ole aina kaikilta osin toteuttamiskelpoinen. Parhaimmat kirjallisuudessa esitetyt mallit ovat kuitenkin kehitetty yhdessä rautatieyhtiöiden kanssa. Ne kuvaavat ongelmaa niin tarkasti, että luotua suunnitelmaa voidaan käyttää myös todellisuudessa. Myös näissä tilanteissa tietokoneen tarjoama ratkaisu voittaa suunnittelijoiden tekemät suunnitelmat.

Tämän kandidaatintyön tarkoituksena on arvioida kirjallisuudessa esitettyjen matemaattisten mallien soveltuvuutta Suomen olosuhteisiin. Tämä tehtiin määrittelemällä Suomen erityisolosuhteet VR:n suunnittelijoiden avulla. Näiden pohjalta voitiin luoda vaatimukset, joihin mallia verrattiin. Ehtojen vastaavuuden lisäksi huomioon otettiin myös kuinka nopeasti ongelma pystytään ratkaisemaan. Koska tähän suoraan vastaaminen on erittäin vaikeaa, käytettiin vertailukeinona tutkimusryhmien raportoimia laskenta-aikoja. Tämän lähestymistavan suurin heikkous on että ajat eivät ole vertailukelpoisia keskenään. Jotta vertailu olisi objektiivisempi, pelkän ratkaisuun kuluneen ajan lisäksi huomioon otettiin myös ratkaistavan ongelman koko ja saadun tuloksen laatu eli kuinka lähelle optimaalista ratkaisua päästiin.

Vertailuun valittiin edellä mainittujen kahden kriteerin perusteella kolme erilaista mallia: yksinkertainen, tarkka, ja malli, joka täyttää kummatkin kriteerit mahdollisimman hyvin. Näin laskenta-aikojen ja mallintamisen tarkkuuden rajat saadaan selville, sekä tarkkuuden kasvattamisen vaikutus laskenta-aikaan.

Tärkeimmiksi vaatimuksiksi mallille asetettiin mahdollisuus kertoa veturisarjan yksilöiden määrä, kyky tasapainottaa lähtevien ja saapuvien vetureiden määrä sekä mallintaa ratapihalla tarvittavat vetureiden toisiinsa liittämiset ja niistä purkamiset. Näiden lisäksi sen on kyettävä mallintamaan myös rataosien sähköistykset, vetureiden tankkaukset sekä rajallinen pysäköintitila asemilla. Kaikkiaan vaatimuksia, joihin malleja verrattiin, määritettiin yhdeksän kappaletta.

Vaatimusten lisäsi myös tavoitefunktion, eli tavoiteltavan asian määrittely on merkittävä päätös. Kirjallisuudessa tähän on valittu pääosin joko vetureiden määrän tai kustannusten minimointi. Koska Suomessa tavoitteena on saavuttaa säästöjä lyhyen aikavälin suunnittelussa, kohdefunktio eli optimoitava asia sisältää suunnitelman aiheuttamat kustannukset. Tämä sisältää kullekin veturisarjalle määritellyt kilometrikustannukset, veturien toisiinsa kytkemisen ja irrottamiset, sekä hinaus- ja moniajokustannukset.

Kirjallisuudessa monet malleista sisälsivät useita määritellyistä kriteereistä. Näiden pohjalta useimmat olivat päättäneet mallintaa asiaa hyödykkeiden virtausongelmana. Tässä lähestymistavassa ongelmaa käsitellään verkko-ongelmana, joka sisältää tiedon sekä ajasta että paikasta. Tallaista verkkoa kutsutaan aikapaikkaverkoksi, joka koostuu kaarista ja niiden alku- ja päätepisteiden muodostamista solmukohdista.

Verkon solmukohdat rinnastuvat oikean elämän asemiin, sillä erotuksella, että solmulla on myös tieto millä ajanhetkellä asema esiintyy verkossa. Sama fyysinen asema voi esiintyä näin ollen useita kertoja eri solmukohtana.

Solmukohdat toimivat kaarien alku- ja päätepisteinä. Nämä kaaret voivat edustavat kahta asiaa: ensinäkin ne vastaavat junia, esimerkiksi Helsingistä klo 10:00 lähtevä juna alkaa asemaa tuona ajanhetkenä vastaavasta solmusta ja päättyy Turkua klo 12:00 vastaavaan solmuun. Junien lisäksi kaaret voivat kuvata odottamista asemalla. Esimerkiksi Turkuun saapunut veturi voi jäädä asemalle lähteäkseen klo 14:00 takaisin Helsinkiin, koska solmukohdille on määritelty aika, ovat Turkua kuvaavat solmut klo 12:00 ja 14:00 erillisiä. Näiden välillä täytyy siis olla kaari, jota pitkin veturin voivat siirtyä ajassa eteenpäin.

Kaikki kandidaatintyöhön valitut mallit ovat mallintaneet ongelmaa yllä kuvatun aikapaikkaverkon avulla. Yksinkertaisin malli on odotusten mukaisesti nopein ratkaista ja parhaiten vaatimuksiin sopiva puolestaan kaikkein hitain. Tulokset siis vastaavat tehtyä hypoteesia työn alussa.

Työssä tarkasteltu yksinkertainen malli on kehitetty tšekkiläisen rautatieyhtiön kanssa ja testattu aidolla aineistolla eli todellisella rataverkolla ja junilla. Suomeen verrattuna määrät olivat kuitenkin erittäin pieniä, joten nopea laskenta-aika ei olisi itsestäänselvyys, jos junien määrää kasvatettaisiin vastaamaan Suomen määrää. Lisäksi mallista puuttui joitakin kriittisiä ominaisuuksia, jotka tekisivät koko suunnitelmasta todennäköisesti toteuttamiskelvottoman – tai vähintään hyvin tehottoman. Tärkein puuttuva ominaisuus oli mahdollisuus purkaa ja kasata vetureita pareiksi tai ryhmiksi. Tämän takia esimerkiksi paikkakunnalla seisovaa kahta veturia ei voisi kiinnittää suurempaa vetovoimaa vaativaan junaan, vaan veturipari pitäisi ajattaa muualta paikalla. Tallainen toiminta Suomen kaltaisessa pitkien etäisyyksien maassa tuottaisi huomattavia lisäkustannuksia.

Ryhmä ei myöskään selittänyt tarkemmin omaa ratkaisualgoritmiaan. Näin jäi epäselväksi, oliko saatu tulos todella optimaalinen vai heuristiikoin saatu tulos. Heuristisilla menetelmillä ongelma ratkaistaan erilaisia ”peukalosääntöjä”-käyttämällä, osalla niistä voidaan saada optimaalinen ratkaisu, mutta ei kaikilla. Yksinkertaisin sääntö olisi yhdistää saapuva veturi ensimmäiseen lähtevään junaan.

Parhaiten Suomen olosuhteita vastaava malli täytti liki kaikki vaatimukset, lukuun ottamatta tankkausvaatimusta. Malli oli kehitetty yhdessä kanadalaisen rautatieyhtiön kanssa, jonka antaman testausaineiston junien määrä oli hyvin lähellä Suomen tasoa. Ongelmaksi muodostui kuitenkin, että ryhmä ei pystynyt saamaan optimaalista ratkaisua edes kolmen vuorokauden laskenta-ajalla näin laajaan ongelmaan.

Tutkijat onnistuivat kuitenkin saamaan heuristisen ratkaisun ongelmaan, joka oli huomattavasti halvempi kuin yhtiön omien työntekijöiden laatima suunnitelma. Vertailu nykytilanteeseen on kiinnostava, erityisesti kyseisen yrityksen näkökulmasta, mutta ongelmallista yleistää muihin tilanteisiin. Mallista ei voi sanoa, että se saavuttaa aina 10 % paremman tuloksen kuin ihminen, sillä ihminen voi päätyä samaan ratkaisuun tietokoneen kanssa. Siksi vertailu pitäisi tehdä esimerkiksi ei-kokonaisluku ratkaisuun, joka kertoisi teoreettisen optiminen ongelmalle. Usein optimaalinen kokonaislukuratkaisu on paljon haastavampi saavuttaa, kuin optimaalinen ratkaisu liukuluvuilla. Tässä yhteydessä seurauksena olisi että juniin voidaan määrätä puolikkaita vetureita. Kokonaisuutena esitetty malli oli hyvin kiinnostava, ja jopa heuristisella ratkaisulla voisi hyvin olla käyttöä suunnittelun tukena myös Suomessa.

Kolmas ja viimeinen malli kuvaa todellisuutta hyvin, mutta ei aivan yhtä tarkasti kuin edellä mainittu tutkimus. Myös tämä malli on kehitetty yhdessä kanadalaisen rautatieyhtiön kanssa ja testattu todellisella aineistolla, jossa junien määrä oli noin neljäsosa Suomen vastaavasta.

Tutkimusryhmä ratkaisi työssä ongelman kahdessa osassa. Ensin etsittiin optimaalinen ratkaisu sarakkeiden luonti -menetelmällä. Näin saatu tulos muutettiin heuristisesti kokonaislukuratkaisuksi. Etuna tässä menetelmässä on, että saatua kokonaislukutulosta voidaan verrata teoreettiseen optimiratkaisuun, joka saatiin ensimmäisessä vaiheessa sarakkeiden luonti-menetelmällä.

Laskenta-aikojen ja ratkaisun laadun puolesta malli vaikutti lupaavalta. Ratkaisu saatiin lähes poikkeuksetta alle tunnissa ja kaikilla kerroilla alle neljässä tunnissa. Myös ratkaisun laatu oli hyvä, sillä kokonaislukuratkaisujen kustannukset olivat lähellä teoreettista optimia, eron vaihdellessa 0,12 % ja 7 % välillä. Mallissa oli mahdollista suunnitella myös vetureiden tarvitsemat huollot, joita ei alun perin määritelty vaatimuksiksi. Tämän mahdollistaminen on kuitenkin hyödyllinen lisäpiirre mallissa. Mallin suurin heikkous on sen tavoitefunktio, joka on määritelty minimoimaan vetureiden ja parinpurkujen määrää. Sen vaihtaminen kustannuksia minimoivaksi on kuitenkin mahdollista, ilman uusien muuttujien lisäämistä.

Yhteenvetona tutkituista malleista voidaan todeta, että yksikään ei olisi valmis sellaisenaan sovellettavaksi Suomessa. Kaikista malleista puuttui joko jotain kriittisiä vaatimuksia, tai niiden ratkaisu ei onnistunut kohtuullisessa ajassa. Seuraava askel olisi kehittää malleja sekä niiden ratkaisualgoritmeja ja testata niitä Suomen testiaineistolla. Työn tulosten perusteella parhaan lähtökohdan antaisi mallin rakentaminen työssä esitettyjen kahden tarkemman mallin pohjalta. Molemmissa näissä oli runsaasti hyviä puolia ja vain vähän vaadittavia muutoksia, joiden toteuttaminen olisi suhteellisen helppoa. Itse mallin rakentaminen ei olisi haastava osuus, vaan sopivan ratkaisualgoritmin löytäminen, jotta ongelma saataisiin ratkaistua tavoitellussa ajassa.

Tutkimuksen tulosten valossa rautatieyhtiöiden toive yhdistää kaikki rautateillä tapahtuva suunnittelu yhteen optimoitavaan malliin vaikuttaa kaukaiselta, sillä jo yhden yksittäisen osan ratkaiseminen kohtuullisessa ajassa aiheuttaa haasteita. Tulevaisuudessa tietokoneiden ja matemaattisten mallien edelleen kehittyessä tämäkin tulee varmasti toteutumaan.