# LINES AND SERVICES IN A STRATEGIC MULTI-MODAL FREIGHT NETWORK MODEL : METHODOLOGY AND APPLICATION

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## 1 INTRODUCTION

The presentation of transportation models is obviously not the main topic of this paper. The interested reader can for instance read Ortúzar and Willumsen (1990) for an overview of several aspects related to transport modelling. One of these aspects is the assignment of the demand on a network.

Assignment methods are looking for a way to model the distribution of traffic over a network according to a set of constraints, notably related to transport capacity, time and cost (Thomas, 1991). This type of problem can be solved using optimization methods.

Traditional assignment models are based on cheapest path algorithms. They use networks in which every road (or railway, waterway ...) can be represented by a weighted edge. The total cost of a trip is simply the sum of the costs associated to each link along the path.

Transport models are still imperfect and many refinements can be proposed. Trains for instance, have to follow a predefined planned route, which can differ from the shortest or cheapest one, and is thus not identified by shortest path algorithms. In other words, if the broad transport corridors are in most cases rather well identified, railway transport is often spread over several routes, which is not the way trains are operated in the real World. This is an issue, because track capacity is often an important problem that cannot be ignored. Therefore, the lines defined by the railway infrastructure operators should be explicitly taken into by the network models.

If not, the cost of the computed path will be often lower than the cost on the real route (defined line). Indeed, and especially for freight transport, the lines are mostly designed in order to avoid as much as possible mixed traffic with passenger trains. This increases the quality of service, but makes the routes often longer. Thus, beside the fact that the flows are not correctly rendered by most strategic network models, the total costs for railway transport is underestimated.

## 2 LINES AND STRATEGIC MODELS

The line concept is defined by Delorme (2003) as an ordered sequence of links and nodes along a path. In this definition, the origin node of each link must coincide with the destination node of the preceding link. The route followed by a train coincides partially or totally with a set of lines.

Railway lines are seldom taken into account in large strategic multi-modal network models, because it is often claimed that their implementation only has a limited impact on the results. The real reason is probably that not many, if any, multi-modal models are able to conveniently mix free flows (trucks for instance) and “line” flows.  Lines are however modelled in most tactical or operational railway models such as CAPRES (Lucchini *et al*, 2000) or FASTA (Curchod *et al*, 1992).

Two broad families of strategic models can be identified. The first one, or classical approach, uses separate network layers for the different transportation modes. Therefore, a mix of free and “line” flows can be rather easily implemented. Indeed, and even if it needs some fastidious digitizing work, the “lines” can be directly encoded in the network database. The demand (embedded in a set of origin-destination matrices, one per mode for instance) can then be directly assigned on each “modal” network.

A second approach uses so called “super networks” or “virtual networks”. The idea here is to work on a single network, in which each link represents a particular transportation task. Indeed, a simple geographic network does not provide an adequate basis for detailed analyses of transport operations as the same infrastructure, link or node, can be used in different ways. The basic idea, initially proposed by Harker (1987) and Crainic *et al.* (1990), is to create a virtual link with specific costs for a particular use of an infrastructure. The concept of “supernetworks” proposed by Sheffi (1985) that introduced “transfer” links between modal networks also provides a somewhat similar framework. The NODUS software proposes a methodology and an algorithm which creates in a systematic and automatic way a complete virtual network with all the virtual links corresponding to the different operations which are feasible on every real link or node of a geographic network. This systematic and automatic approach, built upon a special codification of the virtual node labels, is probably the biggest benefit over other software tools such as STAN (Crainic *et al.* 1990), in which most of the tasks that are possible at a given node are to be introduced “by hand”.

In these virtual networks, all the “modal” networks are thus embedded in one single and large network. Mixing free and “line” flows in such a network is not an immediate task, and the main objective of this paper is to propose a methodology that is able to fully integrate “lines” in virtual networks.

## 3 TOWARDS A NEW DEFINITION OF VIRTUAL NETWORKS

The original definition of the virtual networks were already discussed in Jourquin (1995) and Jourquin and Beuthe (1996). The basics will be outlined in this section, followed by a complete explanation of a new, extended definition that integrates the “line” concept.

### 3.1 Virtual network basics

To start with, let us examine the network illustrated by Figure 1 that contains 6 nodes (“A to “F”) and 9 links (1 to 9). The plain lines represent inland waterways (W) and the dotted lines railways (R). Diesel trains (R1) can be used everywhere on the railway network, but electric powered trains (R2) can only be used on the bold links “1”, “2”, “5” and “6”. In the same way, small barges (W1) can be used without restrictions on the waterways, but large barges (W2) are allowed only on the bold links “7” and “8”. Some of these real links can thus be used by several types of vehicles (transportation means), which have different operating costs. The bold nodes “A”, “B”,  “C” and “E” are also locations where (un)loading and transhipments between modes are possible.

Building a virtual network requires that all the possible transport operations are identified. Each operation leads to the creation a virtual link, identified by its two end virtual nodes. The label of each virtual node is composed of four information’s:

- The label of the real node it is generated from;
- The label of the real link it is attached to;
- The label of the transportation mode it refers to (“R” or “W” here);
- The label of the transportation means it refers to (“1” (diesel train or small barge) or “2” (electric train or large barge) in this case).

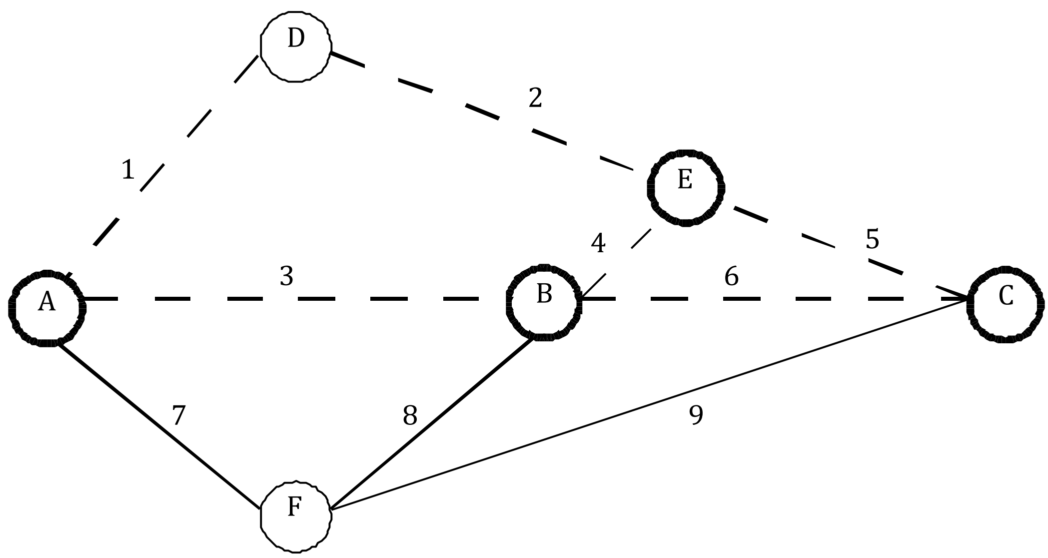


Figure 1: Sample muli-modal network

Note that the weight given to a virtual link can vary with the direction it is used. To solve that problem, in the computer implementation of the methodology, all the virtual nodes are doubled at generation time by adding a + or a – sign to their label ; by the same token, all the links are split into two oriented arrows connecting these new nodes. With the exception of Figure 3, these oriented links will not be represented in this paper in order not to clutter the diagrams.

Obviously, the codification used in the figures is not suitable for real applications. Using a single letter for a node label would indeed limit the size of the real network to 26 nodes. That's why the virtual nodes are coded in the following way:

- A plus or minus sign ;
- 6 digits for the node number ;
- 6 digits for the link number ;
- 2 digits for the mode and 2 digits for the means.

Each label is thus represented by a 16 digits number preceded by a sign.

Figure 2 is a simplified representation of the virtual network that can be generated from the information gathered in Figure 1. Three types of transport operations can be identified:

- The bold lines are virtual links which represent a movement of a vehicle on the real network. The labels of the two end virtual nodes of such virtual links make reference to two different real nodes. The link going from "A1R1" to "D1R1" represents for instance the displacement of a diesel train (R1) between nodes "A" and "D" on link "1", for which a relevant cost can be computed.
- The curved lines represent transhipment operations that can be performed at a node. Therefore, the labels of the two end virtual nodes always refer to the same real node. Moreover, the mode and/or means indicated in the same label vary. For instance, the virtual link that connects "B3R2" to "B8W1" represents a transhipment operation that takes place at node "B", between an electric train (R2) coming from link "3" onto a small barge "W1" that will sail on link "8". Again, the information provided by the labels of the two end virtual nodes allows for the computing of the relevant cost. Note that these operations are not allowed at regular nodes such as "D" or "F".
- The other straight lines represent transit operations inside a node. The link between "F7W2" to "F8W2" is thus to be interpreted as the transit of a large barge (W2) come from link "7" and going to link "8" through node "F". Here also, the information provided by the labels of the end virtual nodes makes it possible to compute a relevant cost that may eventually be null.

Again, Figure 2 is a simplified representation of the virtual network, as the "doubled" virtual links (see above) are not represented. Moreover, the (un) loading operations are also not drawn. These are indeed needed in order to have the possibility to enter and to leave the network. Figure 3 illustrates the full virtual network at node “C”. In this figure, the (un)loading virtual node is labelled “C000”.

A virtual network becomes thus rather complex and it rapidly can contain thousands of nodes and links. It has however an important advantage over classical networks: a shortest (cheapest) path computed in a virtual network can indeed combine *de facto* several transport operations and several transport modes and means. A path can be intermodal, including all the costs involved in the needed handling operations. The interested reader will find more on the methodological aspects of virtual networks in Jourquin and Beuthe (1996), on example applications in Jourquin and Beuthe (2006), and on topics related to flow assignments on virtual networks in Jourquin (2005) , Jourquin and Limbourg (2006) and Jourquin and Limbourg (2007).

### 3.2 Lines and virtual networks

A virtual network is thus a large network in which the different possible transport operations related to several transportation modes and means are represented. Movements of trucks, barges and trains are embedded in the same network. As a consequence, “free” and “line” flows are mixed. To be more exact, lines are even completely ignored in the original definition of virtual networks, because the different virtual links only take the physical characteristics of the real network into account. This only allows avoiding the use of some types of vehicles on some links: In figure 2, no virtual link was created for electric trains on link “4” or for large barges on link “9” for instance.

However, cargo trains that operate on the network described in Figure 1 could very well circulate only on the lines illustrated by Figure 4. The first line is operated by diesel and electric trains and joins nodes “A” and “C”, passing along “D” and “E”. The second line is only operated by diesel trains and joins also nodes “A” and “C”, but along nodes “D”, “E” and “B”. Thus, the railway tracks between nodes “A” and “B” are not used for freight transport, and electric powered trains are not operated between “B” and “C” for cargo, even if it is technically possible.

As a consequence, if lines are not explicitly modelled, an assignment on the (virtual) network will most probably use the link between “A” and “B”, because it is on the shortest (cheapest) path between “A” and “C” that are potential origins or destinations for freight.

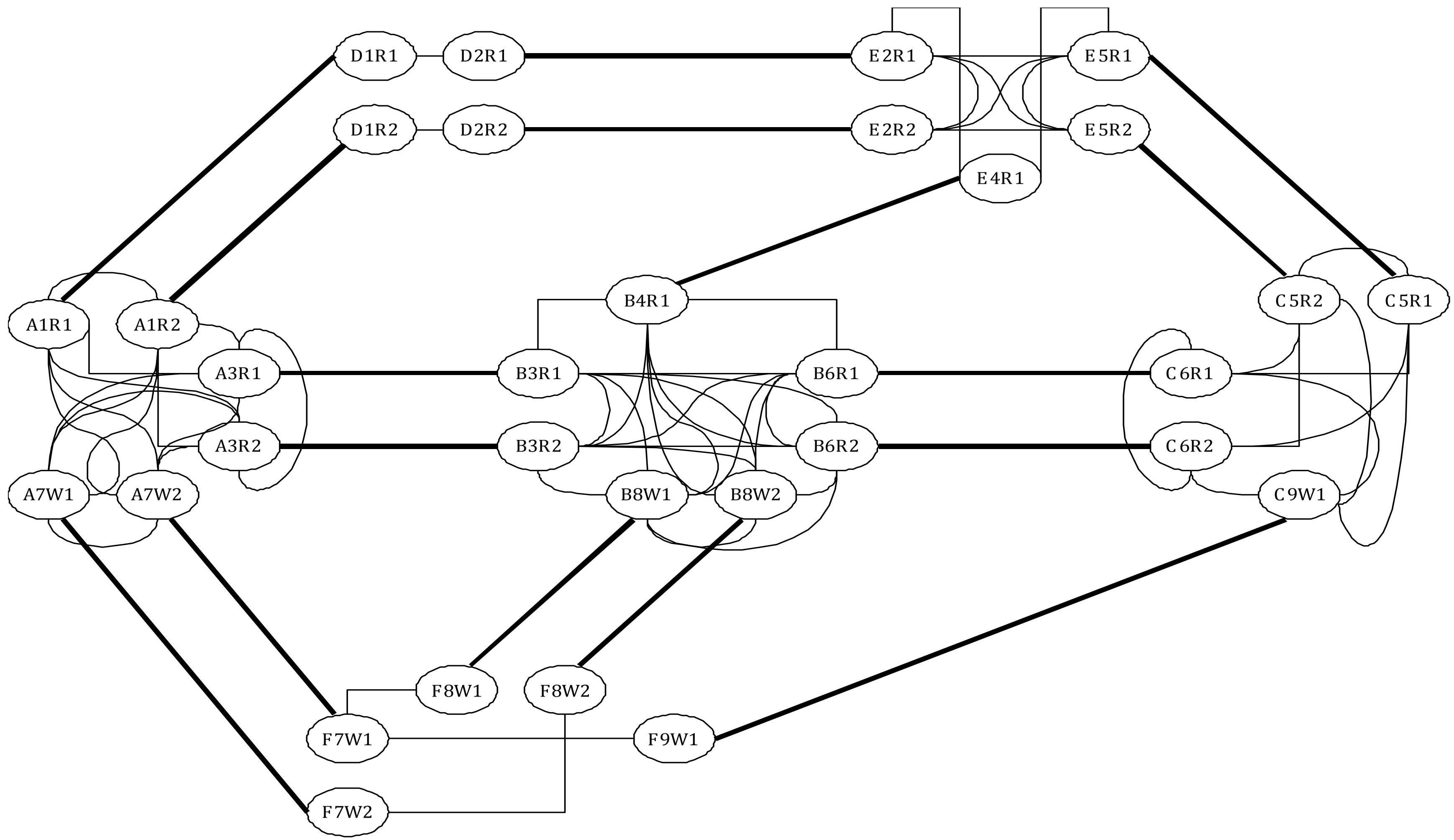


Figure 2: Simplified virtual network

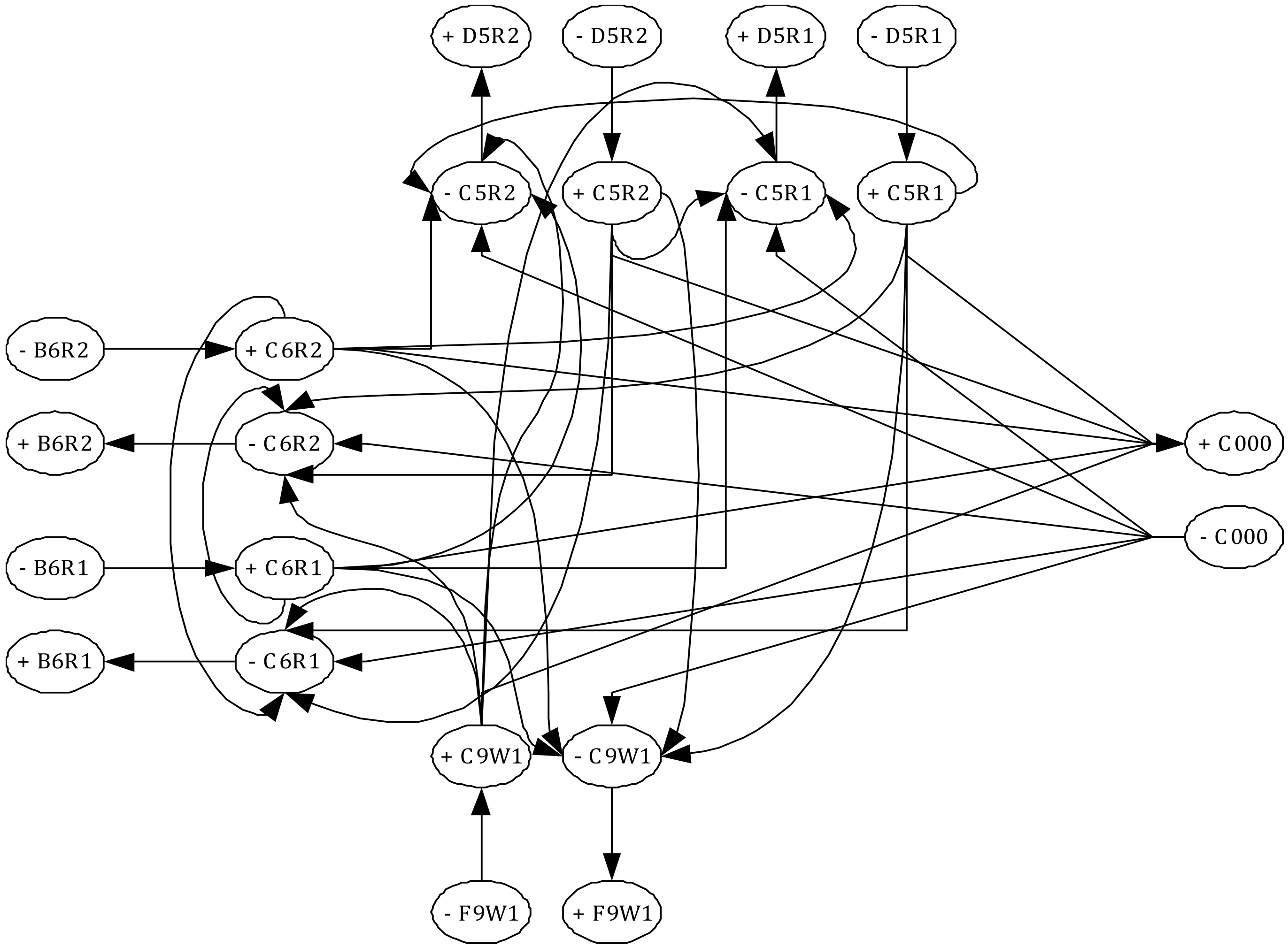


Figure 3: Complete virtual network at node C

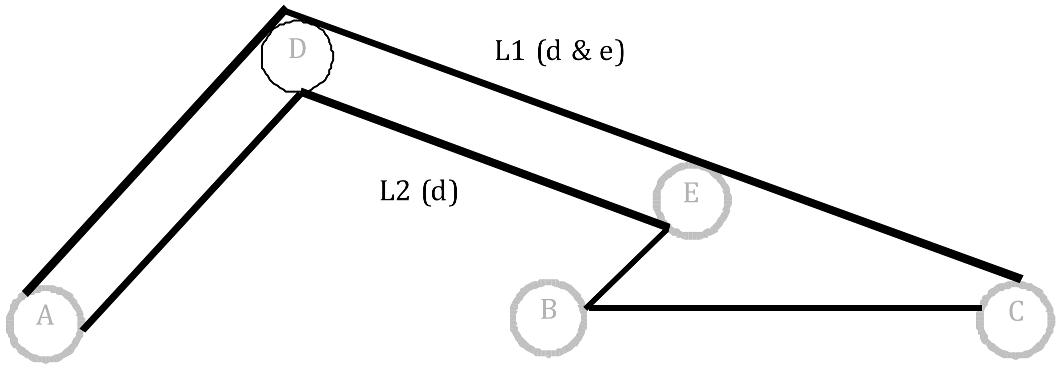


Figure 4: Lines operated on real network (Figure 1)

The definition of the virtual network must therefore be adapted if one wants to model lines.  To achieve this, a virtual link will now be created not only for every possible transportation means on each real link, but also for every line that uses this link. This is illustrated by Figure 5.

A “line” label is added to the label of each new virtual node, and connectors are created only between virtual nodes of the same line. This prevents unwanted switches to another line at regular nodes.  Switches can however be proposed at stop points, such as node “E” where a diesel train that circulates on line “2” could switch to line “1”.

Note that, in order to keep the structure of the labels of the virtual nodes consistent, the labels that refer to free flow modes (such as barges in the given example) will use “0” as “line”, which means “no line”.

The lines themselves must be stored in a database in the way there are defined by Delorme (2003, see section 2). In addition the following information’s are also retained:

- The transportation means that can be used on the line ;
- The list of nodes along the line where a “stop” (and thus line switching) is allowed.

As an example, Table 1 contains the information that was needed to generate the virtual network represented by Figure 5. This data is systematically checked by the algorithm that generates the virtual network, in order to limit the creation of the virtual nodes and links to the needed ones.

In stop nodes, it is made possible to switch from one line to another. Such switches are for instance possible at node “E”, and illustrated in Figure 5 by doted curved lines.

| Line | Links | Means | Stop nodes |
|---|---|---|---|
| 1 | 1, 2, 5 | 1, 2 | A, E, C |
| 2 | 1, 2, 4, 6 | 1 | A, E, C |

Table 1: The lines related data

Note that a same real link can belong to more than one line. In the example illustrated by figure 4, both lines use for instance links “1” and “2”.

This new virtual network with line implementation can now be used as a generic graph on which any assignment procedure can be applied, exactly as for the original virtual networks.

### 3.3 From lines to services

From all what is preceding, one can conclude that a line is a way a given infrastructure is operated. In section 3.2, the methodology used to model lines in virtual networks was outlined. During an assignment, the flows that are transported by “line” modes will now be forced to follow the pre-defined lines, while the other modes still can circulate freely. In other words, the new definition of the virtual networks allows mixing “free” and “line” flows inside a single (virtual) network.

Many authors  (Crainic and Laporte, 1997 ; Crainic, 2000 ; Cascetta and Papola, 2003) extend the concept of “lines” to the one of “services”. The latest concept is broader as it also includes additional characteristics, such as frequency for instance. The frequency has an important impact on the modal choice, as waiting times can be very long for low frequencies, making transport less attractive. The frequency has however no impact on the topology of a (virtual) network, but it has an impact on the cost to be computed on some virtual links. For instance, the cost related to the average waiting time can be added to the virtual links that correspond to the relevant loading or transhipment operations, including those that represent line switching.  The algorithm used to generate the virtual networks doesn't have to be modified, but the data that must be maintained to model the lines must be modified in order to keep track of the frequency on each line. This is illustrated in Table 2. The additional data contained in the last column will be used during the computation of the costs on the virtual links.

| Line | Links | Mean s | Stop nodes | Frequency |
|---|---|---|---|---|
| 1 | 1, 2, 5 | 1, 2 | A, E, C | 1/day |
| 2 | 1, 2, 4, 6 | 1 | A, E, C | 2/day |

Table 2: The lines related data with frequency

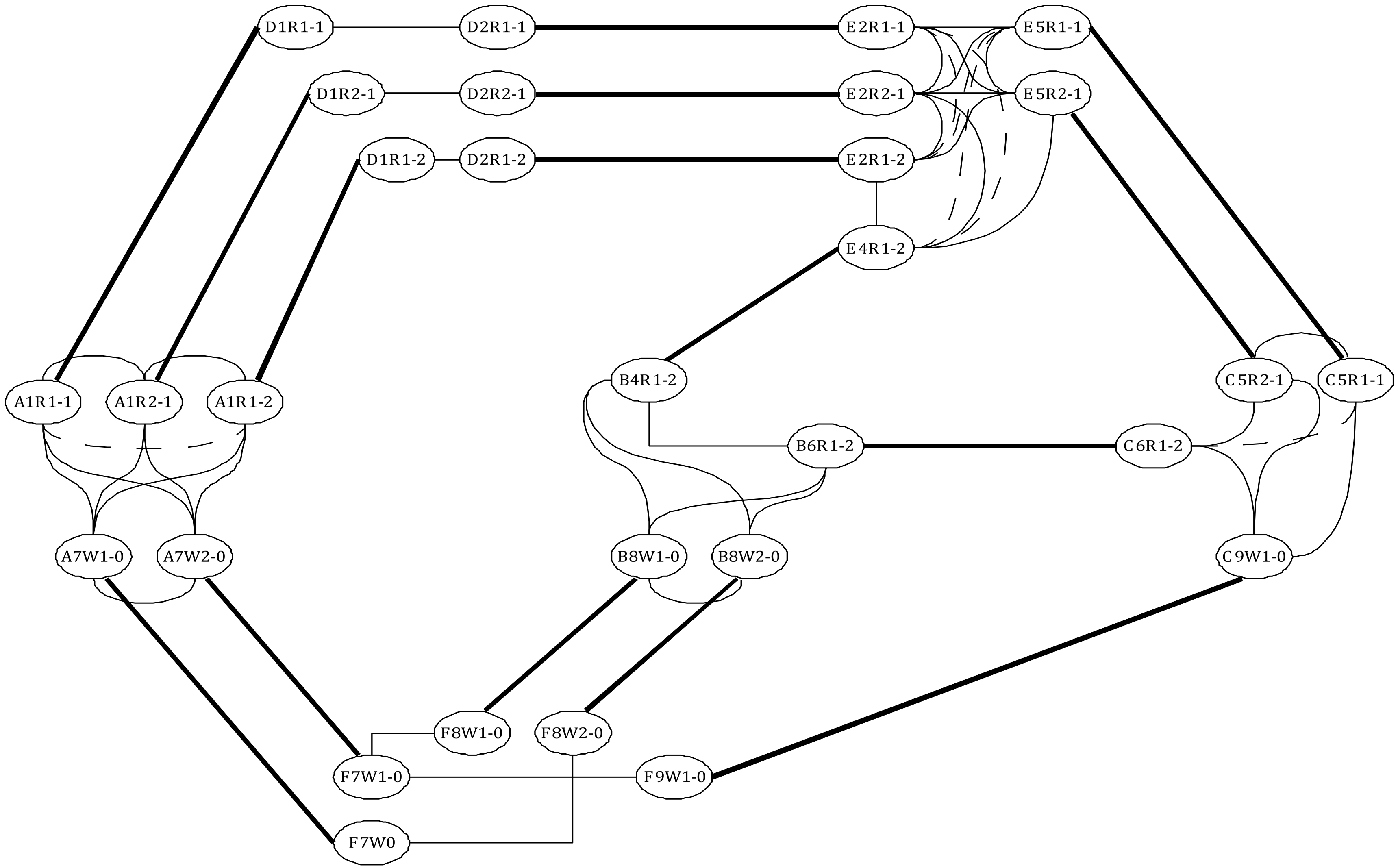


Figure 5: Virtual network with line implementation

## 4 BUILDING A REFERENCE SCENARIO

To experiment the proposed methodology on a real network, a credible reference scenario is needed. Therefore the demand for transport (an Origin-Destination matrix (O-D)) and the supply (a digitized network and a set of transportation cost functions) are needed.

### 4.1 The demand for transport

Matrices for the three transportation modes that are included in our network (road, rail, inland waterways) were published by NEA Transport Research and Training and contain data for the year 2000. They give information about the type of transported commodities (10 NST-R chapters), but only at the European NUTS2 regional level, which is not satisfactory for our scenario that covers the detailed Belgian territory. A more disaggregated matrix is thus needed.

Fortunately, we had some older matrices for 1995, at the NUTS 5 (communal) level, for Belgium. It was thus possible to generate reasonable NUTS5 matrices for Belgium and the year 2000. At the end of the process, 30 matrices (3 modes, 10 NST-R groups of commodities) were generated. The matrices of the different modes were then merged in order to provide a set of 10 multi-modal matrices.

The total collected data represents 792 Million tons, from which 9,98% are transported by waterways, 15,05% by train and 74,98% by truck. The respective figures expressed in tons.km are 13,82%, 20,46% and 65,72%. Even if these matrices are not completely accurate, they represent a good basis for our exercise.

### 4.2 The Belgian Network

A detailed representation of the networks for the different transportation modes is also needed. The railroads and roads networks were taken from the Digital Chart of the World, and further up to dated “by hand”.

The Digital Chart of the World (DCW) is an Environmental Systems Research Institute, Inc. (ESRI) product originally developed for the US Defence Mapping Agency (DMA) using DMA data. The DMA data sources are aeronautical charts, which emphasize landmarks important from flying altitudes. ESRI, when compiling the DCW, also eliminated some detail and made some assumptions for handling tiny polygons and edge matching. Anyway, for the Belgian network, the proposed data can be used for our needs.

The inland waterways network doesn’t exist in the DCW. There is a “drainage” layer, but that is much to detailed, and doesn’t correspond to the waterways on which barges can be used. Therefore, we decided to digitize the corresponding network ourselves.

Finally, the borders of the NUTS 5 regions were obtained from the Belgian National Geographic Institute. This latest data set was used to compute the centroid of each commune, which will then be used as origin and/or destination nodes for the commodities.

All these layers (roads, railways and inland waterways) were connected together, using “connectors” from each centroid to each modal layer. The road network contains about 3.300 links. The figures are respectively about 1.100 and 500 for the railway and inland waterway networks.

## 5 ESTIMATION OF THE IMPACT OF THE LINE MODEL

Several assignment techniques can be applied to virtual networks in NODUS. A detailed discussion over the available alternatives can be found in Jourquin and Limbourg (2006). For the scenario presented in this paper, a multi-flow assignment (Jourquin, 2005) was used. After some calibration, the global performance of the assignment could be considered as satisfactory in the framework of the exercise proposed in this paper.

It is thus time to compare the reference scenario (free flow) with the results obtained using the above proposed new method that explicitly takes lines into account. Therefore the information of the routes followed by the railway lines is necessary. This information was supplied by the Belgian railway company (SNCB). A total of 59 lines where retained. For each line, the list of railway chunks that belong to the line was encoded, for a total of 1276 chunks. This number is larger than the number of railway links (1078), just because a same chunk can belong to more than one line.

The virtual network that was generated for the reference scenario has 51.813 virtual nodes and 97.789 virtual links. For the new virtual network (with lines) these figures are now 51.973 and 115.139 respectively. Thus, if the number of virtual nodes remains more or less unchanged, the number of virtual links increases with about 15%. This has an obvious, but limited, impact on the needed computer memory and on the duration of the assignments.

Even if our reference scenario and maps need some more validation, the lines, as they are defined by the Belgian railway company, clearly become identifiable, having more flow than in the base scenario. In other words, the railway flows are less spread over the network, which is much more realistic.

Moreover, and as expected, the imposed restriction to follow predefined lines reduces the market share for railway transport expressed in tons. But as the trains may have to follow longer routes, the market share expressed in ton.km increases somewhat.

Compared to the reference scenario, the reduction of the transported tons (-1.27%) and the increases of the flows (0.31%) could be considered as limited.

These figures represent however absolute values of more than 2.1 $10^6$ tons and more than 155 $10^6$ ton.km, which is about 5% of what is globally transported by train, showing that the use of the traditional virtual networks clearly leads to an overestimation of the market share for rail transport.

## 6 CONCLUSIONS AND FURTHER PROSPECTS

Multimodal strategic freight transportation network models are rather complex and have to cope with several shortcomings, sometimes simply related to the lack of complete and accurate data on the demand and the supply. They also barely take considerations on operational logistics into account.

Among the identified missing links between strategic and operational models, the fact that some transportation modes such as trains should follow a predefined path, or line, is an issue. Indeed, ignoring this can lead to an underestimation of total railway costs and trip lengths.

This paper presents a procedure than can be applied to virtual networks, which allows to perform assignments that fully and explicitly model lines.

The new virtual network has been applied on the Belgian networks, and the results compared to a calibrated reference scenario. We can conclude that the proposed methodology clearly improves the realism of multi-modal assignments.

Furthermore, the line concept, as it has been defined in the virtual network methodology, could be enlarged to model services. Indeed, a service can be defined as a being a line, to which some other additional characteristics are added, such as frequency for instance. This is ongoing work.


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