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Lowest Cost Intermodal Rail Freight Transport Bundling Networks: Conceptual Structuring and Identification

Ekki Kreutzberger[1]
OTB Research Institute, Delft University of Technology

Bundling, the process of transporting goods belonging to different flows in a common vehicle (like train, barge or truck) or other unit during part of their journey, is a core business of the transport sector. Operators periodically evaluate their service networks and adjust their bundling operations. The adjustments respond to changing cost structures, changing competition and changing situations in terms of demand and performance requirements. One can distinguish direct bundling from different types of complex bundling, such as hub-and-spoke or line bundling. Complex bundling networks have intermediate exchange nodes and longer routes, but less vehicle routes. The latter means that required network volumes could be lower, service frequencies higher or vehicle loads larger. In this sense, complex bundling allows smaller flows to participate in the advantages of large-scale operations and therefore is an important option to successfully develop intermodal transport.

The additional impedance of complex bundling networks has been and still is an incentive for intermodal rail freight operators to switch from complex to direct bundling. However, the flow sizes of many rail relations are too small for direct bundling. If nevertheless direct bundling is applied, trainloads or service frequencies decline and/or small flows will shift to the road sector.

In this paper, which focuses on intermodal rail freight networks, we analyse the trends of bundling innovation, and discuss the operational mechanisms in bundling networks and their quantitative impact for the number of train routes, service frequency, the size of trainloads, and required network transport volume. Furthermore we identify which bundling types lead to large trainloads and lowest costs, given certain network transport volumes and certain service frequency requirements. On the basis of a large-scale comparison of bundling networks with large trainloads and ones with lowest costs we conclude, that a large trainload is a good first indicator for lowest cost network: if an intermodal basic bundling network has the largest technically allowed trainload and this is larger than of competing bundling types, the envisaged network is likely to also have the lowest network costs.

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[1] PO box 5030, 2600 GA Delft, NL, T: +31152787695, M: +31614167574, E: E.D.Kreutzberger@tudelft.nl.

1. Introduction

This paper addresses the bundling[2] of intermodal rail freight flows in the framework of service network design and the question which type of bundling leads to best results according to alternative network design objectives. After giving an overview of the challenge and design options the paper focuses on the objective of minimising operational costs. The paper's objective is to improve understanding of the impacts of bundling choices.

The starting point of the paper is the observation of a clear trend in the intermodal rail sector: many operators are busy simplifying their bundling networks in a, as it seems, rather one-sided way, namely towards direct bundling (the term is explained in Sections 2 and 3) neglecting or not aware of other business opportunities. In this paper we argue that in certain situations other bundling options perform better and that they often represent an additional business opportunity.

On the basis of this perception one may question what the backgrounds are for the one-sided bundling trend. The question is important for the type of analysis we carry out in this paper. Two factors seem to play a dominant role. One is that some operators have the simple network design objective to maximise profits on the short term. In this case the actor will only provide services where conditions are extremely favourable, typically direct services, whether aware of the one-sided bundling choice or not. Such attitude is quite typical for many new rail operators.[3] The second reason seems to be confusion about the true benefits of bundling alternatives. We observe approaches resembling a lack of system thinking, characterised by a focus on single routes instead of entire networks[4], or other confusion, such as mixing up functional (e.g. direct versus other bundling) and physical (e.g. rail-rail exchange by means of shunting, terminal exchange etc.) features.[5]

Confusion can easily emerge, as transport networks are a complicated thing. Take a hub-and-spoke network (explained in Section 3). Many of them have different numbers of incoming and outgoing routes at the hub, different frequencies, transport volumes and trainloads per route, maybe also a mix of directed and all-directional bundling in the same network. In addition, the spokes have different lengths, the train roundtrips different speeds, and the back and forth flows have significantly different sizes. Given so many special features, it is difficult to understand the impact of a bundling choice, for instance why to choose hub-and-spoke instead of direct bundling. What actually is the quintessence of bundling alternatives, namely the different number of train routes through the network, is overlapped by many irregularities, which tend to distract from the quintessence.

Given the paper's objective, the analyses for this paper refer to simplified network layouts, flow and other characteristics. We analyse the performances of alternative bundling types, focusing on

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[2] = Consolidation.

[3] A good example is the Swiss operator BLS on the early 2000s, who concentrated on direct services with block trains and rejecting additional more complicated types of operations. BLS Chief executive officer Stahl: "We are a lean business. We only operate block trains … We carry out no shunting and we own no marshalling yard" (Hughes, 2003, in an article with the title "Lean, mean policy generates profit"). More complicated operations that are profitable but less profitable, are not carried out or only by competitors, a cherry-picking practice by the lean operator.

[4] An example is Notteboom (2008) in his chapter on the "Bundling of freight flows …": "There are three key decisions for service planners to make: the service frequency, the loading capacity of the transport equipment used and the number of stops at intermediate nodes". And "he has to assess … service demand" A figure outlining the typical markets of different services focuses on the single route instead of all network routes.

[5] This also occurs for professional practitioners, such as organised in the KV Technologieplatform 2000+ (1995). They positioned bundling alternatives according to distance and network transport volume, including the new modular train system. The latter however, is not bundling specific and can only be positioned, if the involved bundling type would be mentioned.

the number of train routes through a network, and including the impedances due to exchange operations at intermediate nodes and to the typical detours of trains in some bundling types. But the analyses abstract from all irregularities, which are typical for real-life networks, but a burden for a good understanding of bundling choices. The simplification of the analysed networks consists of the strict geometry of terminal locations, the symmetry between the beginning and end of networks, the exclusion of all-directional bundling, the equal distribution of network flows across all network relations, the same performance requirements, for instance service frequencies, for all rail relations, and same rules for roundtrip speeds of trains for all routes. With these attributes the relation between input (situational and design variables) and output (performances) is relatively easy to understand.

We emphasise the consequences of the network simplification when drawing conclusions, in particular when discussing the competitiveness of intermodal rail networks.

The paper is structured as follows. Section 2 explains the principles of bundling choices. Section 3 presents the major bundling types and discusses their properties. Both Sections contain the definitions of terms used in this paper and not already defined before. Section 4 briefly describes the major trends for intermodal rail bundling networks. In Section 5 we elaborate the major impacts of bundling choices for what we call the central bundling variables: required network transport volume, trainload, service frequency and the number of train routes in a network. Section 6 illustrates the meaning of these impacts in terms of typical markets of alternative bundling types. Section 7 explains the calculation of train, PPH, node exchange and unimodal road costs on the level of single routes. Section 7 is about network costs, explaining how route costs are aggregated to the network level, then showing the results: in which transport landscape do which bundling types have lowest operational costs, and which of the lowest cost bundling networks may be competitive with unimodal road transport? Section 9 summarises the conclusions.

2. The principles of bundling

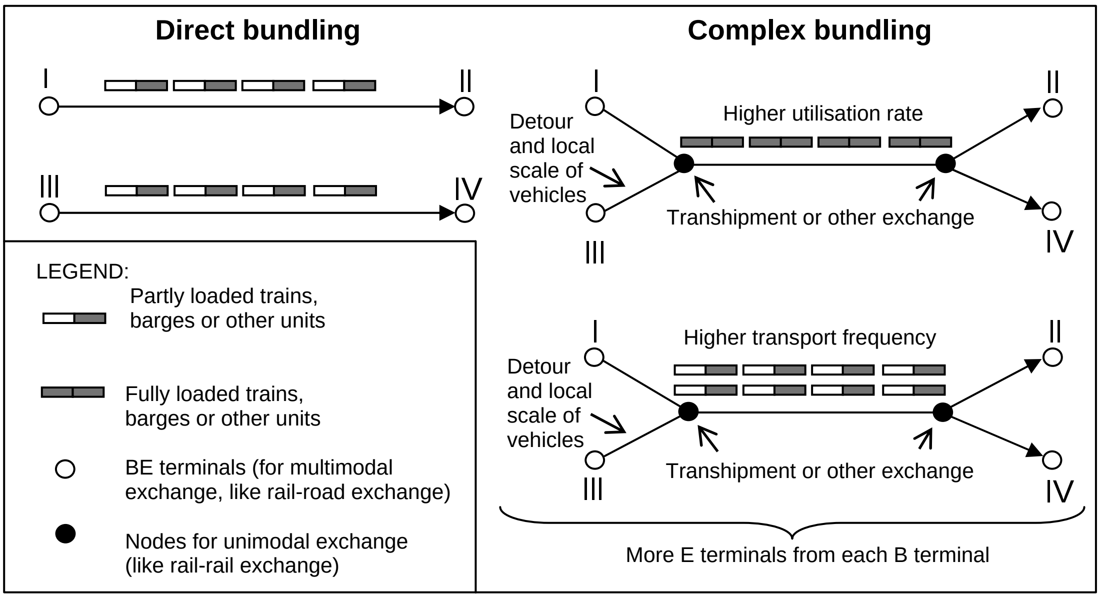
Bundling or consolidation, the process of transporting goods belonging to different flows in a common vehicle (like truck or train), *intermodal load unit* (like container or swap body) and/or *shipment unit* (like pallet) during part of their journey, is a core business of the transport sector. Operators periodically evaluate their networks and adjust their bundling operations, meaning that type of bundling, degree of network concentration, service frequency, vehicle load and/or employed physical means are altered. Potential reasons for adjustments are a change of flow sizes and directions, of performance requirements, of the share of an operator in the market, or of costs of operational components (e.g. labour, energy).

In Figure 1 two transport configurations are compared. In the left one there are two trains (or vehicles of other modes), one running from terminal I to terminal II, the other one from terminal III to terminal IV. Each train in this example is only partly loaded[6] and runs directly from its *begin-* to its *end terminal* (respectively *B-* and *E terminal*). The trains do not visit intermediate exchange nodes. We call this *BE bundling* or – as in practice – *direct bundling*.

If one instead transports these load units in common trains during a common part of their journey, one can increase the size of trainloads (leading to larger loading degrees as shown in the upper right network in Figure 1 or to longer trains), or one can increase service frequencies (lower right network in Figure 1). In the example of Figure 1 also the *network connectivity* is

[6] By load units or freight in other units.

enlarged meaning that more E terminals are accessed from each B terminal.[7] These improvements in many cases lead to lower train costs, lower pre- and post haulage costs and/or a higher transport quality. The condition for such improvements is the presence of intermediate exchange nodes, where load units are exchanged between vehicles. For such type of bundling we have introduced the umbrella term *complex bundling*. It stands for a group of bundling types explained in Section 3, amongst the one shown on the right side of Figure 1.[8] Complex bundling allows smaller flows achieving advantages comparable to those of as larger flows in BE networks.



The figure only shows main mode transport (e.g. rail transport) and no *pre- and post haulage* (= *PPH*).

Figure 1. The principle and impacts of (complex) bundling

Complex bundling also has disadvantages as (right side of Figure 1) longer routes (detour), longer operational time, in many cases additional exchange of load units at intermediate nodes, and in some cases local rail transport. The additional train distance, exchange handling and local transport imply higher costs, while the additional time of train operations can increase train and load unit costs.

The challenge of the network designer is to identify the bundling type, which has the best balance between advantages and disadvantages in terms of operational, generalised or social costs.[9] What is best depends on the bundling and network design aims and strategy of an operator or any transport policy. Some examples: is the network design objective of a railway company maximal short-term profit, or – under conditions to be specified – maximal long-term profit or maximal revenue? Are low-cost or high-quality markets addressed or both? Are other objectives, typically from public authorities, taken along, such as transport sustainability, network connectivity and regional accessibility, and/or societal welfare? One of the differences between short- and longer-term profitability is the willingness to provide services, which currently have no or only a

[7] If the network connectivity was the same on both sides of Figure 1 and there were flows from both begin terminals to both end terminals, there would be four train routes in the network instead of only two, and each of them would – with the right network as reference – have half of the trainload shown in the left network.

[8] Up to now there is no appropriate umbrella term except the term hub-and-spoke networks type used by researchers (e.g. Mayer, 2001 or O´Kelly and Miller, 1994) and practitioners (e.g. Denis, 2000). We find this term confusing because it also refers to a concrete complex bundling type.

[9] *Generalised* costs are the sum of transport prices/costs and the value of transport quality. Social costs include the external costs of the transport system.

restricted profitability but promise to become very profitable. The following sections discuss which objectives are served by the bundling options.

The design objective of the networks we compare in Section 8 is maximal revenue under condition of network profitability. We minimise operational costs, given a work daily departure on each train route of a network.[10] The network must have lower costs than bundling alternatives and be competitive.

3. Bundling types and their properties

We identify five basic bundling types (Figure 2). Next to the direct network (= begin-and-end network = *BE network*) there are four complex bundling networks, namely the *hub-and-spoke network* (= *HS network*), the *line network* (= *L network*), the *fork network* (= *trunk-collection and distribution network* = *TCD network*) and the *trunk-feeder network* (= *TF network*).

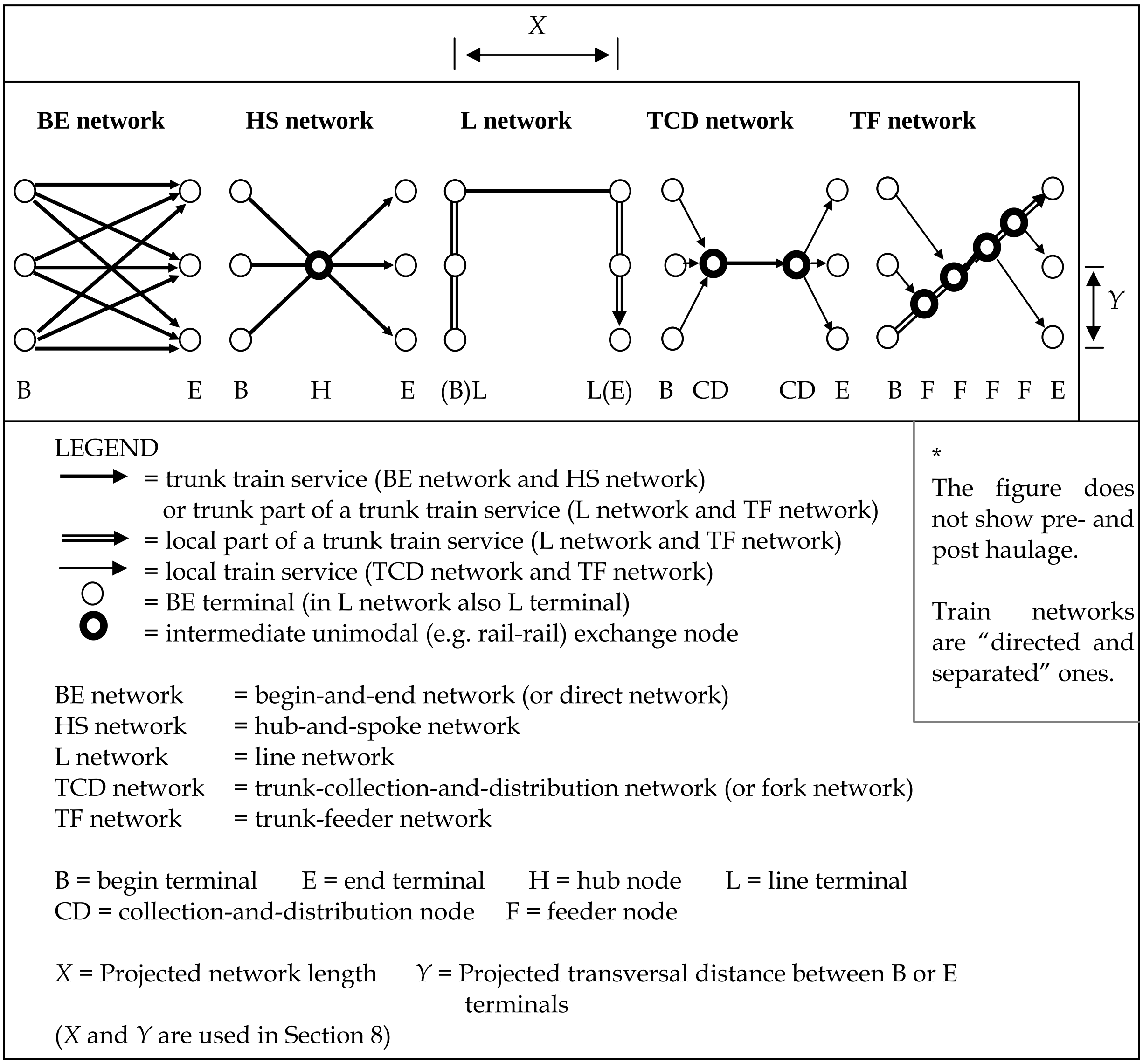


Figure 2. Basic bundling network types

[10] = Example of the common rail practice according to the research project SPIN (NEA *et al.*, 2002).

Further bundling distinctions are *directed* [11] versus *all-directional*, *separated* [12] versus *diffuse*, and *transit* [13] versus *return* networks. The exchange at intermediate rail-rail exchange can take place *simultaneously* or *sequentially*. Finally, all operations can be carried out by different physical means, for instance – at intermediate nodes – by exchanging single wagons at gravity shunting yards, wagon groups at flat shunting yards or transhipping load units at terminals. The corresponding train types are *single wagon trains*, *wagon group trains*, and – of there are no shunting yards but only terminals in the network – *block trains* or *shuttles*. The latter two have same wagon compositions and train lengths during an entire or several sequential services respectively. Wagon group trains with rather constant lengths during a service are called *complete trains*. Block trains and shuttles can also run in complex bundling networks.

The basic bundling types differ in the number of train routes, number and function of intermediate exchange nodes, and the presence of local train networks. As can easily be seen in Figure 2, in directed, separated, transit and symmetric versions of the basic bundling networks the number of trunk train routes R_B in the BE network is N^2, N being the number of BE terminals at each end of the network. In the HS network the number of trunk routes is N, in the other three bundling types it is 1.

The impact of the different number of trunk routes is evident. Given full trainloads on any trunk route and same frequencies throughout the network in all bundling alternatives, the BE network requires the largest transport network volume, the HS network a medium volume, and the other three networks the smallest volume. Alternatively, the frequency or trainload can be varied, implying relative low frequencies or small trainloads in the BE network, medium ones in the HS network, and relative high or large ones in the other three bundling networks. We elaborate the quantities in Section 5.

With regard to intermediate exchange nodes, HS networks have one, the hub (= H), a rail-rail node. L networks have several line nodes (= L), rail-road nodes. TCD networks have two rail-rail nodes, the CD nodes. TF networks have several feeder nodes (= F) where rail-rail exchange takes place. If the intermediate exchange is terminal transhipment, the average number of load unit exchanges at intermediate nodes additional to BE networks is 0 for L networks, $(N-1)/N$ for HS networks, 2 for TCD networks and – dependent on the size of N – between 1 and 2 for TF networks. In other words, in L networks the number of load unit exchanges is the same as in BE networks, the L nodes "only" causing delays. In HS networks with a small N the average number of load unit transhipments at the hub is small.

TCD and TF networks have local train networks. In the separated and transit versions of L networks trunk train services have local network parts. To keep L networks efficient, the distance between B terminals or E terminals must be short in comparison to the part between the last B and first E terminal, the trunk part, in which the trainload is maximal.[14]

4. Trends in bundling network development

The roots of rail networks, certainly networks for general cargo, lie in the world of complex bundling, hence the right side of Figure 1. Apparently, from the very beginning flow sizes were smaller than train capacity resulting in the need to apply complex bundling. The wagonload

[11] As in Figure 2: all flows from "left" to "right".
[12] As in Figure 2: no flows between B terminals or between E terminals.
[13] As in Figure 2: all trains continue their journey at an intermediate exchange node instead of returning. The only exception is at the interface between trunk and local networks.
[14] A promising alternative for the separated L network with relative long trunk routes is de the diffuse L network, in which the loading and unloading at each L terminal contributes to achieving full trainloads during the entire journey.

network became the central rail freight configuration. In the post-war period with emerging road competition and growing factor costs, the railways were increasingly forced to modernise their production system. Wagonload networks were streamlined by cutting out network layers, concentrating train routes in networks, in some countries serving the economical centres more and better than the less urbanised regions, and/or focusing more strongly on wagon group trains instead of single wagon trains. The result were simplified and mixed intermodal/non-intermodal networks. In addition, dedicated intermodal networks were implemented which had similar bundling structures as the simplified mixed ones. In both cases shunting dominated the scene. Intermediate L nodes could only be served by dropping and picking up wagon (group)s at a next-door shunting yard. The wagons would have to be moved between the yard and terminal by local or other locomotives. The ultimate result of the streamlining was the dedicated intermodal BE service.

The functional core of the streamlining could be summarised as follows. BE services are the best rail product wherever full trainloads required frequency levels can be organised. Many flows, however, were and still are too small to facilitate by direct bundling. So, reduction of costs by eliminating intermediate node exchange is easily accompanied by cost increases due to the decline of trainloads, level of service (frequencies) and/or by loss of market shares. In other words, when minimising costs there is a fundamental tension between minimising route impedances and maximising trainloads. This is well illustrated by the streamlining of the maritime intermodal rail network in France in 2005, when the former HS network of CNC/SNCF-fret was substituted by a BE network. This transformation was accompanied by an improvement of the profitability, and a substantial decrease of network connectivity, service frequencies and market shares. Experts expected the shares to decline by one third (CNT, 2004).[15]

One may argue, for the French or other examples, that the growth of flows eventually justifies to abolish complex. This perception, however, neglects that if intermodal rail transport is to increase its market shares, there is a continuous need for complex bundling: while flow sizes are growing, complex bundling flows move into the direct service market, while former truck flows become suitable for complex rail bundling. Secondly, the supply side is busy with scale leaps. Different European railway companies have already tested intermodal trains with lengths of 1000m[16], implying a scale increase of 40-70%. If introduced on a commercial basis, BE flows may become complex bundling flows again.

Given this fundamental and ever-green tension, much was expected by the technical innovation wave that started in the 1980s and had its peak in the 1990s. Railway companies, producers of handling equipment and trains, consultants and universities in France, Germany, the Netherlands, Switzerland, Sweden launched new concepts for terminals, trains, shunting means and load units, which where so different from existing ones, that they represented a new generation (NG) of equipment. As far as bundling is concerned, the NG equipment waked the hope that one could reduce the impedances (costs, time, unreliability) of complex bundling substantially justifying to apply complex bundling on a larger scale.

The technical innovation implemented so far, however, has been quite modest. In the Netherlands and Belgium terminal transhipment has been introduced at intermediate rail exchange nodes, the Antwerp Mainhub terminal substituting shunting for intermodal flows. Comparable are the hub initiatives in Basel and Duisburg. In Switzerland, Austria and the

[15] See Kreutzberger (2008) Subsection 4.6.2.

[16] The expected relevance of trainload for cost reduction has encouraged the Swiss (Nieuwsblad Transport, 2003; Vogel, 2000), French, Belgian, and Dutch railways to experiment with even longer trains, (up to 1000m or even 1500m length). RailNed expects the costs of such trains to be 10 to 25% lower than those of 700m long trains (Nieuwsblad Transport, 2000). Similar sizes are expected by SNCF, SNCB and ERS (LIIIFT, 2005), although the expectation then is that – given cost thresholds – a length increase from 700m should not stop at 850m but at once move to 1000m (Sigma Consult, 2004).

Netherlands new terminals, trucks rail wagons and load units developed for horizontal transhipment allow operating rather small terminals in less densified regions. The French Autoroute ferroviaire is effective in terms of fast rail-road exchange of semi-trailers in direct and complex bundling networks.

The gap between the ambitions of the technical innovation wave and the real implementation is large, resembling a withdrawal. There have been obvious reasons for innovation failure[17], but there are also good reasons to continue technical innovation in certain transport markets:

- the pressure to reduce costs still is large, given the competition between modes and the fact that many railway companies do not cover the costs of their intermodal operations[18];
- quality improvement is essential to penetrate into certain markets, and the need to include complex bundling in the portfolio of operation types is not only present for operators serving smaller flow areas;
- there still are interesting and credible options to support performance improvements by innovative technical means.

The current state-of-the-art of implemented and non-implemented but promising technical and non-technical innovation comprises the following configurations (selection):

- dedicated intermodal networks with complex bundling, wagon group trains and lean network layouts (restricted number of BE terminals per network) have very acceptable performances in terms of costs (on the basis of Gaidschik *et al*., 1994) and dwell times of trunk trains at intermediate exchange nodes. As far as rail-rail exchange is concerned, also the dwell times of load units are acceptable. This production system has been the "backbone" of the European railway system in the 1990s (KombiConsult and K+P, 2007);
- for the less-than-wagongroup market there is a need for terminal transhipment at intermediate exchange nodes, because the shunting of single wagons at gravity shunting yards is costly. This market may require NG terminal types. The terminals may also improve rail performances for the wagon group market: while costs and handling times of the terminal exchange are comparable for HS networks and better for L networks, all sorting at the begin terminals becomes abundant;
- for certain distance classes there is a severe need to accelerate the handling at intermediate exchange nodes, in order to manage complex bundling within critical time windows. Also this may be a market for NG equipment.

Concluding, while the number of BE services is increasing, complex bundling in principle remains important for the competitiveness of intermodal rail transport, and potentially contributes to achieving larger market shares of rail transport. The challenge is to improve the average efficiency of complex bundling by focusing on the successful or promising configurations, and avoiding other ones, such as shunting based L networks.

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[17] Major reasons for failure were conceptual contradictions within a concept, the supply of solutions where there were no problems v.v. (e.g. not every acceleration of operations improves the relevant performances), technological optimism, lack of knowledge about the non-technical innovation having taken place, and competing investment and development strategies of railway companies.

[18] Germany (DB Cargo according to Deutscher Bundestag, 1995), Italy (Trenitalia according to Laguzi, 2001), France (SNCF Fret according to Hahn, 1998; CNC according to Delavelle *et al*., 2003), the UK (Freightliner according to ECMT, 2003), Railion Netherlands up to 2005 (Kennisinstituut voor Mobiliteitsbeleid, 2007) and Europe (ICF according to Müller, 2005). On the other side, the German rail operator KombiVerkehr, partly owned by the DB, has made profits with its intermodal operations.

5. The performances of bundling networks

There is an *inescapable* and *flexible* quantitative relation between what we call the central bundling variables, namely the network transport volume, the number of vehicle routes, the service frequency on a route, and the vehicle load, all with reference to the same period.

The relation is inescapable in any network. We formalise the relation for our simplified networks. The vehicle load L of trunk trains (in the trunk parts) of train services is equal to the network transport volume V_n divided by the number of vehicle routes R_B and the service frequency F (Equation 1)[19], or the quotient of route transport volume V_r and service frequency. The vehicle load cannot exceed the technical maximum $L_{\max}$, which is marked by maximal train lengths (in Europe up to 700m) and maximal axle load.

In a top-down approach the vehicle load is: $$L = \frac{V_n}{R_B * F} = \frac{V_r}{F} \leq L_{\max} \quad (1)$$

in which:

$$R_B \begin{cases} = N^2 & \text{in the BE network} \\ = N & \text{in the HS network} \\ = 1 & \text{in the L-, TCD- or TF network.} \end{cases} \quad (2)$$

In a bottom-up approach the vehicle load is the product of the vehicle capacity $L_{\max}$ and the loading degree λ of the vehicle (Equations 3 and 4).

Bottom-up $$L = L_{\max} * \lambda \quad (3)$$

$$0 \leq \lambda \leq 1 \quad (4)$$

"Inescapable" means that if three of the four central bundling variables (V_n , F , R_B, L) are given, the fourth one is definite. It also means that when comparing the bundling alternatives, the different number of trunk routes per bundling network needs to be compensated by the value of at least one of the other four bundling variables. We call this the bundling kite relation (Figure 3). The term "flexible" refers to the perception that any of the central bundling variables can be calculation input or output. The choice of variable to compensate for R_B gives name to the approach. We distinguish the frequency, network transport volume or vehicle load approach. In the *frequency approach* (Equation 5) the network and vehicle load of the compared bundling networks are the same and the service frequency F_B is bundling specific and varies. The index $_B$ expresses, that the values of corresponding variables are bundling specific. In the *network transport volume approach* (Equation 6) the frequency and vehicle load are the same in all compared bundling networks and the required network volume $V_{n\,B}$ is bundling specific and varies. In the *vehicle load approach* (Equation 7) the network volume and service frequency are the same in the compared networks, while the vehicle load L_B is bundling specific and varies.[20]

Frequency approach: $$F_B = \frac{V_n}{R_B * L} \quad (5)$$

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[19] The inescapable relation is also present for non-simplified networks.

[20] In the vehicle load or the frequency approach the network transport volume is "temporarily" given. This is in line with other research, for instance Daganzo (1999), and does not neglect the fact that the service performance influences the demand, namely the network transport volume.

Network transport volume approach: $$V_{n\,B} = L * R_B * F \qquad (6)$$

Vehicle load approach $$L_B = \frac{V_n}{R_B * F} \qquad (7)$$

One may argue that Equations 5, 6 and 7 are derivates of each other, making it unnecessary to explicate two, if one has already been presented. The three equations, however, are not really full derivates as the variable to compensate for the bundling specific number of trunk routes R_B is different in the three approaches. The difference is formalised by attaching the suffix index B to different variables in each of the approaches. This triple approach to our opinion helps combating confusion about organising best bundling configurations. One can of course decide to simultaneously compensate the different number of trunk routes by frequency, trainload and required network transport volume, in which case the suffix is attached to all three variables. Then the three equations would be full derivates of each other.

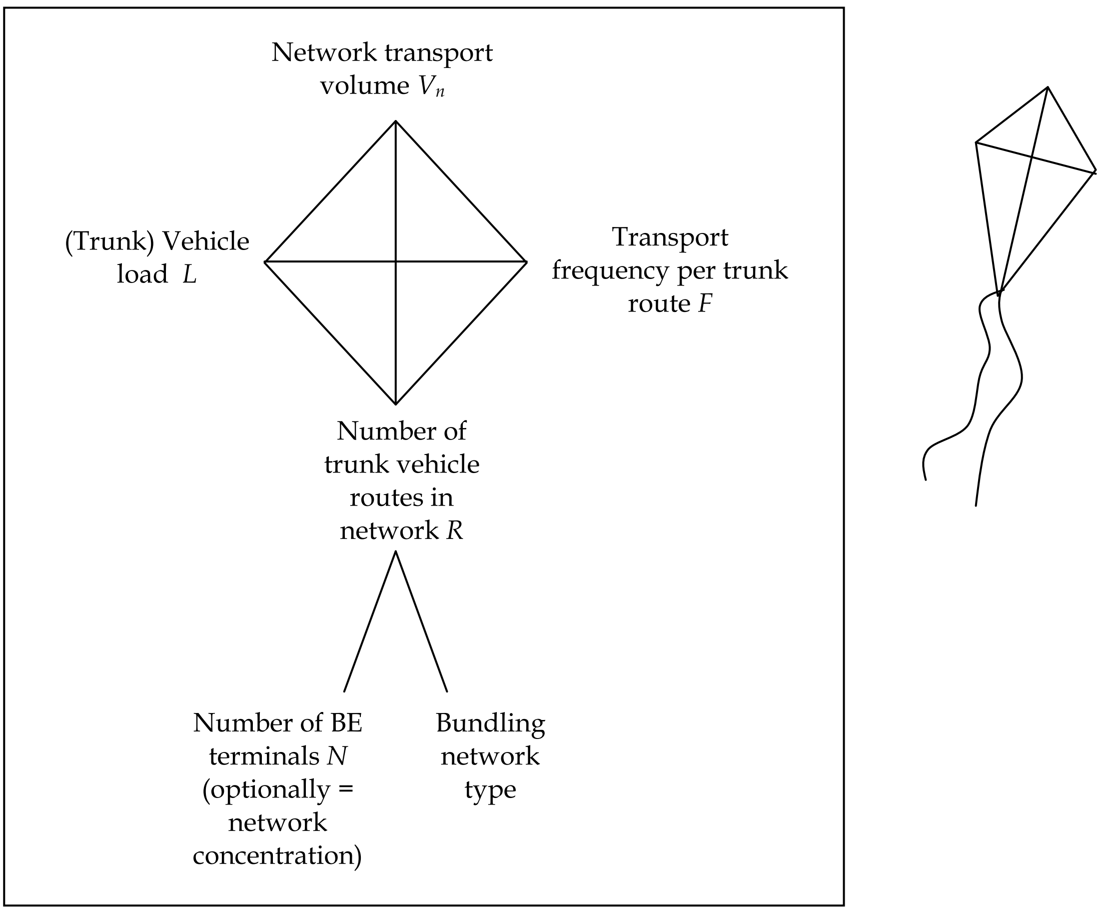


Figure 3. The variables of the "bundling kite"

The triple approach is also useful to demonstrate what the design variables are when compensating for the different number of trunk routes, and how an approach matches with the design objective. To the right of the equation we find the design variables, to the left a performance impact. The design variables differ in each approach. The vehicle load or network transport volume approach correspond with a quality objective of the network designers, as the service frequency is defined ex-ante and not negotiable. The frequency or vehicle load approach can match with a sustainability objective, as the required network transport volume, for instance a rather small volume, is defined in advance and in principle not at stake. One can solve this approach in a low-cost or quality directed way with respectively the vehicle load or frequency as dependent and bundling specific variable. The frequency or vehicle load approach can be used for the design objective of achieving low costs, because the trainload is predefined and not negotiable. The consequence is a large network transport volume requirement or a low frequency.

Table 1. Quantities for the example of Figure 1 in the frequency, network transport volume or vehicle load approach

	BE network	HS network	L network	TCD network	TF network
Frequency approach					
N	3	3	3	3	3
R_B	9	3	1	1	1
F_B	1	3	9	9	9
L #	56	56	56	56	56
V_n	126 000	126 000	126 000	126 000	126 000
Network transport volume approach					
N	3	3	3	3	3
R_B	9	3	1	1	1
F	1	1	1	1	1
L	56	56	56	56	56
$V_{n\,B}$	126 000	42 000	14 000	14 000	14 000
Vehicle load approach					
N	3	3	3	3	3
R_B	9	3	1	1	1
F	1	1	1	1	1
L_B 1	6	19	56	56	56
V_n 1	14 000	14 000	14 000	14 000	14 000
L_B 2	19	56	168	168	168
V_n 2	42 000	42 000	42 000	42 000	42 000
L_B 3	56	168	504	504	504
V_n 3	126 000	126 000	126 000	126 000	126 000

LEGEND:

N	= number of BE terminals on one side of the network
R	= number of trunk vehicle routes
F	= Service frequency per day on each route
L	= Vehicle load per service
V_n	= Network transport volume per year
1, 2, 3	= Alternative examples in the vehicle load approach
Index B	= bundling specific
#	= train length of 700m (= 70 load units) * loading degree = 80% = 56 load units

Table 1 illustrates the quantitative mechanisms in the bundling kite, the table referring to the networks in Figure 2 (N = 3). The trainload is expressed in number of load units and as the product of train length and loading degree. Given an annual network transport volume of 126.000 load units and 700m long trains with a loading degree of 80% (-> 56 load units[21]) the different number of trunk vehicle routes (9:3:1:1:1) is compensated by service frequency (1:3:9:9:9). In the vehicle load approach it is compensated by vehicle load. Given an annual network transport volume of 14.000 load units, the trainload is 6:9:56:56:56 load units. If the network transport volume is 42.000 load units per year, trainloads are 19:56:168:168:168 load units. In case of an annual network transport volume of 126.000 load units trainloads are

[21] A load unit is with the TEU-factor of 1,5. A fully loaded train with a length of 700m then has 70 load units.

56:168:504:504:504 load units. In the first example L-, TCD- or TF networks have the largest technically allowed vehicle loads, in the second example this is the case for the HS network, in the third example for the BE network. As far as vehicle load stands for low costs, the three examples illustrate, that there is no best bundling type in general, but only in relation to a certain network transport volume and frequency requirement.

The other way around, the network transport volume requirements differ per bundling type. Given a trainload of 56 load units and one departure per work day, the required annual network transport volume is 126.000 load units in the BE network, 42.000 in the HS network and 14.000 in the other three networks. This is the result of the vehicle load approach.

As already indicated, the three approaches can be mixed.

Concluding, the bundling kite mechanisms explain how a same number of BE terminals imply a different number of trunk vehicle routes leading to very different network performances in terms of vehicle load, service frequency and or required network transport volume. The mechanisms are in contradiction to the perception that the number of "points served" (like the number of BE terminals served) is a relevant indication for network performances (e.g. Jara-Diaz *et al*., 2001). What the impact of this number really is very much depends on the involved bundling type.

6. Markets of bundling alternatives

As trainload is an important factor of train costs per load unit, we are interested in the network configurations, which allow organising large trainloads. Methodologically speaking, we are dealing with the vehicle load approach. Figure 4, a bundling market diagram, displays the situations, namely combinations of network transport volumes, number of BE terminals and service frequency, in which a certain bundling type generates trainloads which are sufficient to fill a train of 700m length with a loading degree of 70% or more. The X-axis of each block (three blocks, one for 2 departures per work day, the others for 1 or 2/7th departures per work day) mentions the number of BE terminals per network (= input). The Y-axis shows how large the network transport volume is (= input). The cells point out in which combination of network transport volume, service frequency and number of trunk routes a 700m long train has a loading degree of 70% or more (= output), the number of trunk routes being derived from the mentioned variables applying Equation 2.

Evidently the network transport volume requirements are larger in case of two departures per working day (left block) than for one departure per working day (middle block) than for two departures per week (right block).

Take the middle block, L-, TCD- or TF networks require about 14.000 load units per year and HS networks up to 175.000. Given larger network transport volumes, the train lengths in the HS network exceed technical maxima (70 load units). And in case of smaller network transport volumes, train lengths or loading degrees become quite small implying an increase of transport costs per load unit. BE networks require a network transport volume of up to three million load units a year (N = 10 BE terminals), or 500.000 (N = 4 BE terminals).

Figure 4 shows that the basic bundling types are quite complementary in terms of being suitable for certain network transport volumes. This is not the case if one compares composed bundling networks, such as multiple or hierarchical HS networks. The markets of competing composed bundling networks often show more overlap. In an earlier publication (Kreutzberger, 2005) about HS networks we give an impression of such overlap.

*Figure 4. Bundling market diagram rail (700m trains, trainloading degrees ≥ 70%, *)*

	2 departures / work day									**1 departure / work day**									**2 departures / week**								
Number BE terminals →	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
LUs in 1 direction ↓																											
3.000.000									BE																		
2.000.000							BE	BE																			
1.000.000					BE											BE	BE										
500.000			BE											BE												BE	BE
475.000			BE											BE												BE	BE
450.000			BE											BE											BE	BE	
425.000			BE										BE	BE											BE	BE	
400.000			BE										BE												BE	BE	
375.000													BE												BE	BE	
350.000									HS				BE											BE	BE		
325.000								HS	HS				BE											BE	BE		
300.000		BE						HS	HS				BE											BE	BE		
275.000		BE					HS	HS	HS			BE												BE			
250.000		BE				HS	HS	HS	HS			BE												BE			
225.000		BE				HS	HS					BE											BE	BE			
200.000					HS	HS						BE											BE				
175.000				HS	HS	HS												HS				BE	BE				
150.000				HS	HS						BE						HS	HS				BE					
125.000	BE		HS	HS							BE				HS	HS	HS	HS				BE					
100.000	BE	HS	HS											HS	HS	HS					BE						
75.000		HS											HS	HS							BE						
50.000	HS									BE	HS	HS								BE				HS	HS	HS	HS
25.000	3	3	3	3	3	3	3	3	3	HS									BE		HS	HS					
12.500										3	3	3	3	3	3	3	3	3	HS								
6.250																			3	3	3	3	3	3	3	3	3

HS net technically in-feasible

Core area of HS net

HS net has rather short trains

LEGEND

BE = BE network

HS = HS network

3 = L-, TCD- and TF network

* = directed and separated versions of bundling networks.

250 days a year.

7. The costs in bundling networks

7.1 Introduction

If trainload is a good first indicator for identifying bundling networks with the lowest costs, then a market diagram as Figure 4 is also a useful tool in the identification process. The network costs, however, are not only a function of trainload and associated train lengths, but also depend on the distance, train roundtrip design, exchange handling and pre- and post-haulage. In generalised cost functions also the costs of transport quality are taken into consideration. This paper is restricted to operational costs. The costs per single service are analysed or explained in Subsection 7.2 (train), 7.3 (node exchange and PPH), and 7.4 (unimodal road transport). All values refer to the year 2002.

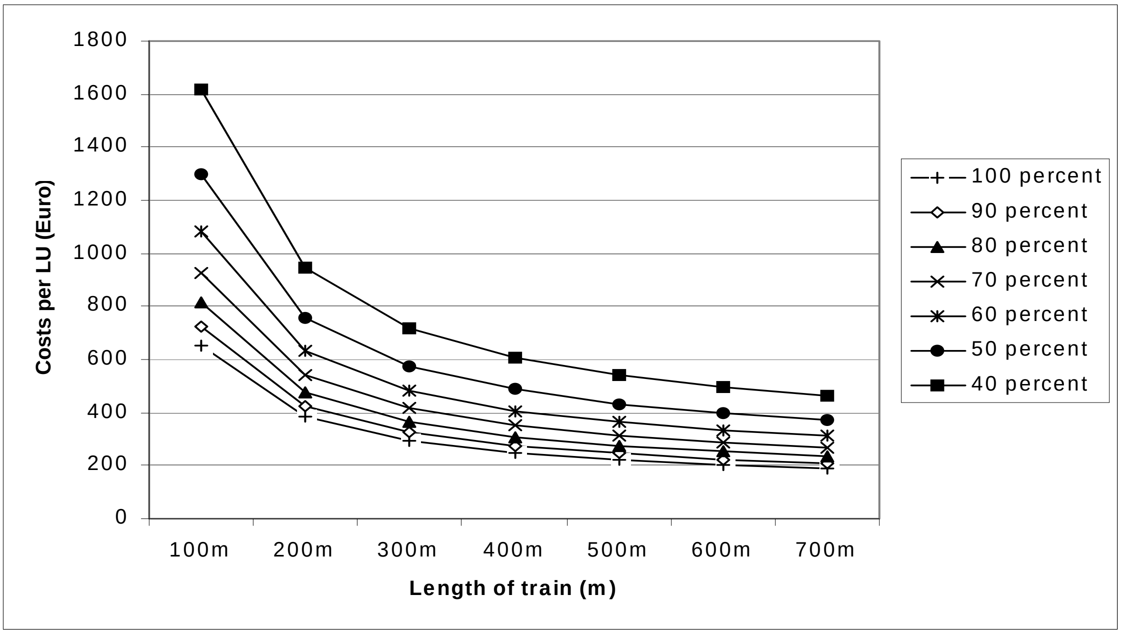
7.2 Train costs per single service

The trains in the cost calculations are shuttles of block trains. The costs are calculated for all reasonable combinations of train lengths and loading degrees. The train costs per load unit of a single service are calculated as the sum of fixed (capital, labour, fixed maintenance) variable (energy, variable maintenance, infrastructure user charge per train-km) and surplus (overhead, taxes, profit) costs. The input values are collected from a large number of sources (described in Kreutzberger, 2008), choosing middle values where the European ranges are large, like for energy and infrastructure charges. The operational time incorporates quick and proven handling times at BE terminals and intermediate exchange nodes. L networks are assumed to be terminal based, avoiding local shunting costs. The operational time per roundtrip is transformed to periodical roundtrip time, which is the cost relevant train time. The periodicity of a service aims at achieving the same departure time on departure days and the same arrival time on arrival days. The costs have been calculated for alternative roundtrip assumptions, resulting in a range from low to high roundtrip productivity[22]. The cost results in this paper refer to a medium roundtrip productivity of the train.

The plausibility of the output examined by comparison with reference dates[23]. The typical result is information as shown in Figure 5, train costs per load unit in dependency of train length and loading degrees and corresponding trainloads.

[22] The envisaged periodical roundtrips of trains are a multiple of 48 hours (= night-jump departure and arrival times) or 24 hours. The two options are varied again, by assuming that the locomotive is assigned to new tasks at the BE terminal, if the dwell times of wagons are rather long.

[23] Dependent on the roundtrip productivity, our costs per train-km vary between 19 and 22 Euros, (except for a few extreme values), a level slightly lower than NEA and higher than in the European research project on long intermodal freight trains, LIIIFT. Reference values are: 22,61 Euro for a train of 585m length (NEA, 2004); the cost calculations for a train of 700m length in Belgium and France (internal non-published calculations of the LIIIFT project, 2005), which lead to lower costs; Up to 23 Euro per train-km, dependent on routes and train characteristics, according to the RECORDIT project (Vaghi et al., 2002). Envisaged trains have relatively short lengths.



*Shuttle or block train. Distance = 600km, half roundtrip wagons and locomotive = 24h and of driver = 12h.

*Figure 5. Train cost-price per load unit, dependent on vehicle load (Euro/LU *).*

7.3 Node exchange and PPH costs

The exchange costs depend on the technical level (fork lift trucks, reach stackers, sliding techniques, cranes?) but are mainly influenced by the utilisation rate of the exchange node.[24] An important question is whether to incorporate the fixed costs of the exchange node as if the node was exclusively used by the envisaged network, like in facility location models, or as if we are dealing with a public exchange node being used by different networks. In this case the commercial risk of covering fixed node costs is a network external issue. We assume the latter to be the case and include constant total exchange costs in demand amounts, in accordance to tactical service network design as discussed by Crainic (2003). Our amounts have already been described in Section 3. The values are adopted from other research including the TERMINET project.[25]

A similar approach is chosen for PPH. The costs are incorporated as constant total costs in demand amounts, and the values are adopted from other research.[26] PPH is calculated for different PPH directions from the BE terminals. The extended direction to the rail transport is the most favourable configuration for intermodal transport. If much PPH transport takes place in the perpendicular or reverse direction, intermodal transport is less competitive, although to some distance still competitive, as the analysis of eccentric egg-shaped service PPH areas of Nierat (1997) illustrates.

In addition, the costs have been calculated for different PPH distances, namely 25km, 50km and 100km at each end of the chain. Long PPH distances reduce the competitiveness of intermodal transport. The results in Section 8 refer to the shortest PPH distance.

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[24] Bontekonings and Kreutzberger, 2001; for the influence of technical level and utilisation rates of terminals also see Ballis and Golias, 2004; Ballis, 2004.
[25] Bontekoning and Kreutzberger, 2001.
[26] Including Kreutzberger, Aronson and Konings (2006), Transcare (1996) and the IMPREND project (Buck et al., 1999).

7.4 Unimodal road transport

The calculation of unimodal road costs is, like for train costs, based on factor costs, labour costs representing fixed costs. A crucial factor is the loading degree of trucks. Our comparisons assume trucks to be loaded in two directions. This optimistic assumption reduces the competitiveness of intermodal rail transport. If unimodal road trucks are loaded only in one direction, the costs per load unit double increasing intermodal competitiveness substantially.

8. Network costs

8.1 Overview

In this section we calculate the rail and door-to-door costs of bundling networks, identify lowest cost bundling types and analyse their competitiveness with unimodal road transport. The alternative bundling networks provide in a same network performance in terms of transport volume, network connectivity and service frequency.

The calculations are carried out for a large number of networks differing in network layout and network transport volumes. The aim is to draw conclusions with regard to bundling choices, which are robust for many situations, and to recognise up to where or from whereon the conclusions are valid.

The network layouts are typical for the European context and systematically varied. The network lengths[27] X are 300km, 600km, 900km, 1200km and 2100km, the network widths ΣY are defined by the distance Y (= 25km, 50km, 100km, 200km) between B terminals or between E terminals, and the number of BE terminals on one end of the network N (= 2, 3, 4, 5, 6, 7, 8, 9, 10). The analysed networks are not wider than long ($\Sigma Y \leq X$). On the basis of Figure 4 and given a service frequency of one departure per working day, we expect network transport volumes of up to 14.000 load units per year and direction to be best served by L-, TCD- or TF networks, ones between 35.000 and 125.000 load units by HS- or BE networks, dependent on the number of BE terminals, and ones above the 250.000 load units always by BE networks.

Together these are 146 layouts times five bundling types and times 4 network transport volumes.

8.2 Problem description and methodology

The calculations are carried out in five modules, the distance and time module, the cost module (for the route level described in Section 7), the bundling kite module, and the enumeration module.

Our simplified network layouts enable us to calculate train costs as shown in Figure 5 for entire networks in an efficient way, namely on the basis of network-averaged train distances and times. The network-averaged periodical roundtrip time is derived from the route specific periodical roundtrip times.[28]

The following step is to determine which of the combinations of train length and loading degree in Figure 5 – then on the network-averaged level – applies. This is the function of the bundling kite module. In the vehicle load approach the trainload is derived from the network transport volume, taking account of the service frequency and the number of trunk routes, on its term derived from the number of BE terminals and the bundling type (Equation 2). The calculated

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[27] X and Y indicate the geographical locations of BE terminals and are used to model the distances of train routes (see Figure 2).

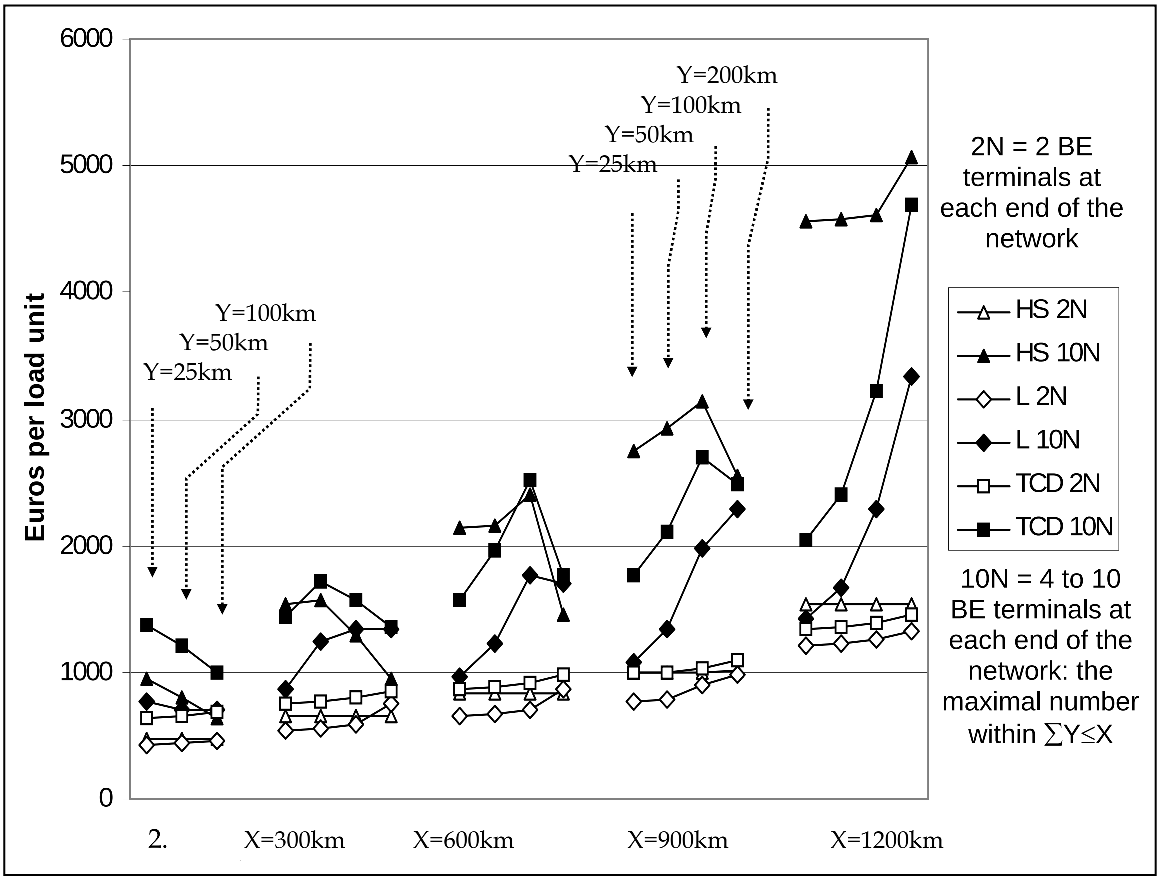
[28] Instead of deriving it from the network-averaged operational roundtrip times which would represent a wrong approach.

trainload is used to appoint the relevant cell in network cost tables as Table 5. If the trainload matches with several combinations of train length and loading degree, the one with the lowest costs per load unit is chosen.

8.3 Results

8.3.1 Lowest cost networks

The results, the network-averaged costs per load unit for alternative bundling types and network layouts (*X*, *Y*, *N*) are presented in selective figures as Figure 6. The selection consists of restricting the presentation to networks with *N*=2 BE terminals and *N*=10 BE terminals or the largest number within the constraint *ΣY* ≤ *X*, and to HS-, L- and TCD networks. For the envisaged network transport volume in Figure 6 the trainloads in BE networks are so small making BE operations so expensive that their presentation is not required.



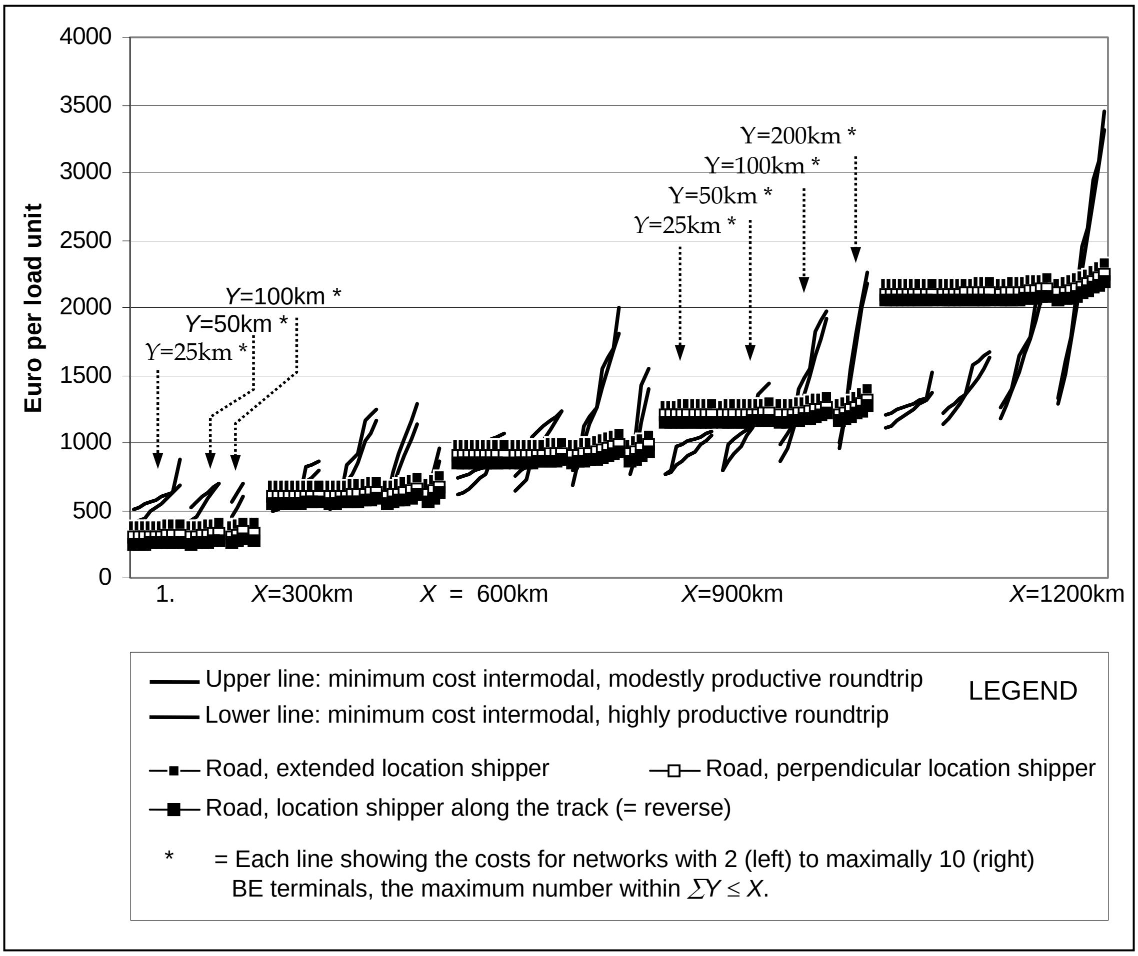
*Train and node handling costs. Medium roundtrip productivity of trains (night-jump departure and arrival times of trains; shorter roundtrips for locomotives than for wagons). The shown networks are thin (2 BE terminals at each end of the network) or wide (the maximum of 4-10 BE terminals at each end of the network within ∑Y≤X).

*Figure 6. Network-averaged rail costs per load unit (Euros) in HS-, L- and TCD networks. Network transport volume = 14.000LUs/y**

8.3.2 Competitive lowest cost networks

The question whether lowest cost bundling networks are also cost-competitive with unimodal road transport, refers to door-to-door transport. Train, exchange (now including BE terminals) and PPH costs are compared with corresponding unimodal road costs. Unimodal road networks are assumed to be BE networks. The results can be presented in figures like Figure 7, displaying the network-averaged intermodal door-to-door network costs per load unit for each of the 146 network-layouts. As in Figure 7 the network transport volume of all cases is 14.000 load units, the shown intermodal networks are mainly L networks, HS networks in some cases and other bundling networks in a few cases (Section 8.3.1). The lowest intermodal costs are displayed for two train roundtrip models, a modestly and highly productive one.

These costs can be compared with the corresponding network-averaged unimodal road costs, from which the PPH costs (for the extended, perpendicular and reverse PPH direction) are subtracted. For intermodal costs beneath the unimodal road costs intermodal transport is competitive.



** PPH = 2*25km, unimodal road trucks loaded in two directions.

*Figure 7. Competitiveness of lowest cost bundling networks relative to road transport. Network transport volume = 14.000 LUs/y ***

The competitiveness results ought to be understood in awareness of the underlying assumptions. As we are dealing with simplified networks, intermodal transport costs are relative low contributing to a competitive impression about intermodal transport. On the other side, the shown road costs are based on the assumption that trucks are always loaded, which in reality is not the case and therefore lets the competitiveness of intermodal rail transport appear less than it is. The impact of varied roundtrip productivity of trains is shown, just as the impact of PPH directions. One could add sensitivity analyses focusing on higher or lower roundtrip productivity for PPH and unimodal road transport.

In awareness of these assumptions, the result for V_n = 14.000 load units per year (Figure 7) is that the lowest costs bundling networks are hardly ever competitive at *X*=300km, more competitive at *X*=600km, quite often competitive at *X*=900km or 1200km, and most often competitive at *X*=2100km. The competitiveness is present in about 65% (extended location, any roundtrip), 50% to 60% (perpendicular location, modestly to highly productive roundtrip) or 45% to 55% (reverse location, modestly to highly productive roundtrip) of the analysed networks.

The *general picture for all network transport volumes* is that intermodal competitiveness is quite restricted for short networks, except for thin versions with productive train roundtrips and extended PPH. The longer the networks, the more an intermodal network becomes competitive, also for other PPH directions than the extended one and wider networks.

8.3.3 The influence of operational facets on intermodal rail door-to-door costs

The trainload is one of the most important factors of intermodal performance. Its improvement is, as Table 2 indicates, important and only exceeded by other improvement types, if the network distance is relative short. PPH improvements can be larger for distances of *X* up to 600km, the acceleration of train roundtrips for distances of *X* up to 300km. The reduction of exchange costs leads to modest cost reductions, although in TCD- and TF networks the cumulative effect of 3 to four handlings can make the difference, at least for network distances of up to *X*=600km.

Table 2. Indications of cost reductions (Euro/LU-km) induced by measure types

1	2	3	4	5
Input ↓	Vehicle load from 500m/70% to 700m/100 % **	Roundtrip acceleration ***	Pre- and post haulage improvement (25km at two sides) ****	Reduction costs at two BE terminals *****
1) Distance 300km Roundtrip: 80/12/12/8 *	-0,21	-0,25	-0,43	-0,11
2) Distance 300km Roundtrip 80/24/24/8 *	-0,32		-0,43	-0,11
3) Distance 600km Roundtrip 80/12/12/12 *	-0,15	-0,11	-0,23	-0,06
4) Distance 600km Roundtrip 80/24/24/12 *	-0,20		-0,23	-0,06
5) Distance 900km Roundtrip 60/36/36/19 *	-0,21		-0,16	-0,04
6) Distance 1200km Roundtrip 40/48/48/34 *	-0,21		-0,12	-0,03
7) Distance 2100km Roundtrip 30/96/96/74 *	-0,24	-0,11	-0,07	-0,02
8) Distance 2100km Roundtrip 20/120/120/109 *	-0,29		-0,07	-0,02

* The roundtrip input is: Average link speed (km/h) / Time locomotive per half roundtrip (h) / Time wagons per half roundtrip (h) / Time driver per half roundtrip (h).

** Derived by dividing cost reductions as visible in Figure 5 by door-to-door distances.

*** Quotient of the change of train costs and door-to-door distances. The costs refer to a train with a length of 550m and a loading degree of 80%. column refer to the reduction of train costs per km (door-to-door distances).

**** Quotient of the change of pre- and post haulage costs and door-to-door distances.

*****Quotient of the terminal cost range of 50-20=30 Euro and door-to-door distances.

Our analyses also confirm that wherever the bundling kite mechanisms imply relative large trainloads, the largest trainload is a good first indicator for lowest cost networks. Train distances and times and the exchange costs at intermediate nodes do not change the outcome. The only relevant exceptions emerge when the network transport volume is relative small. Here trunk train distances and times, the presence of local train networks and the difference with regard to intermediate exchange nodes are more distinctive than trunk trainloads. Given out assumptions, L networks are more competitive than TCD- or TF networks in most cases. The burden of lower loading degrees in the local parts of local networks lets HS networks have the lowest costs in a substantial part of the analysed networks, although their trainloads are smaller than of the L trains in their trunk network part.

9. Conclusions

The choice of bundling type affects the number of train routes through the network. The quantitative relation between the central bundling variables, namely number of train routes through the network, (required) network transport volume, trainload, and service frequency is "inescapable", meaning that if the value of one changes, so does the value of at least one other variable. This conclusion is valid for simplified networks, which are the subject of this paper, and real-life networks.

We analyse the impact of bundling choices for simplified networks. These enable the researcher and reader to focus on the quintessence of bundling choices and not to be distracted by the large number of special network features. The simplification includes the strict geometry of BE terminals, network symmetry, equal flow sizes for all network relations and frequencies for all network services.

The most important difference between bundling networks is the number of vehicle routes through (parts of) the network. These can be compensated by one or more of the other central bundling variables. If compensation takes place by difference in required network transport volume, one can say that BE networks require relative large volumes, HS networks medium ones and L-, TCD- or TF networks relative small volumes. Alternatively, the different number of vehicle routes can be compensated by different service frequencies and/or different vehicle loads. The last contributes to bundling alternatives having different train costs per load unit. The larger the trainload, the lower the train costs per load unit. But the trainload cannot exceed technical maxima (the capacity in number of load units or tonnes of a train with a maximal length, e.g. 700m). For this reason there is no such thing as a best bundling type in general, but only a best bundling type for a certain combination of network transport volume, number of BE terminals served and required transport quality (e.g. service frequency). Given directed and separated networks, a service frequency of one train departure per work day from each BE terminal, and 2-10 BE terminals at each end of a network:

- L-, TCD- and TF networks have lowest costs in most cases for an annual network transport volume of up to about 14.000 load units. For some network layouts HS networks have lowest costs although they have relatively small trainloads. The main reason is that the large trainloads in L- TCD- or TF networks are only present in a restricted or even small part of the networks. L networks tend to have lower costs than TCD and TF networks, mainly due to the high costs of short feeder trains;

- HS networks most often have the lowest costs for network transport volumes of up 175.000 load units, unless the number of BE terminals (and train routes) is small;
- BE networks always have lowest costs for larger networks transport volumes.

The trainload is good first indicator for a lowest cost network: if a certain bundling type has (near to) maximal trainloads it is likely to have lower costs per load unit than a competing bundling type with smaller trainloads. This is the result of a large-scale comparison of bundling networks. The relevance of trainload in comparison to other cost relevant operational fields (roundtrip design, pre- and post haulage, node exchange) is also confirmed by indicative calculations. Only for short distances the cost reduction of improved train roundtrips or improved pre- and post haulage operations can have a larger impact.

The paper analyses the cost-competitiveness of lowest cost intermodal rail bundling networks, given a number of crucial assumptions. One is the simplification of rail networks we analysed leading to an optimistic analysis of intermodal competitiveness. On the other side, and not less relevant, we assume trucks in unimodal road transport always to be loaded, which deviates substantially from practice and implies a pessimistic outcome of intermodal competitiveness. The results of sensitivity analyses have been presented along with the main results, in particular the shape of the PPH service area, and the roundtrip productivity of trains. These have effect, especially for short network distances.

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