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THE EUROPEAN FREIGHT TRANSPORT SYSTEM: THEORETICAL BACKGROUND OF THE NEW GENERATION OF BUNDLING NETWORKS

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Abstract

This paper describes theoretical background of the innovative (new generation) of bundling networks emerged in the European freight transport system for the past decade. Four types of the network configurations have been analysed. These are: the 'point-to-point' network, the network of 'trunk line with collecting/distribution forks', the 'hub-and-spokes' network and the 'line' (or 'ring') network. For each configuration, the analytical models for quantifying the total delay and generalised cost of loading units in the network have been developed. In addition, the qualitative outcomes from these models have been discussed.

INTRODUCTION

The European inter-modal freight transport system shares about 1,5% of the total freight traffic volume. In the year 2010, it is expected to share about 2,6% of the total volume. Besides the other measures, the innovative bundling networks (CI, 1996; EC, 1995; EC, 1997 *a*, *b*; EC, 1998 *a, b*) will support such growth. Innovative bundling networks are expected to make the inter-modal transport more competitive to road haulage on distances between 150 and 300 km, and provide its complete domination on the distances longer than or equal to 500 km. In addition, they should enable higher utilisation of the railways' and inland navigation capacities, increase reliability and delivery speed of shipments like containers, swap-bodies and semi-trailers, take over the freight from overcrowding roads, and reduce negative impacts of road haulage on the environment.

Innovative bundling networks are based on the innovative organisation of transport services and new (innovative) technology applied to both transport and handling operations on the loading units (containers, swap-bodies and semi-trailers). Innovations on the organisation of transport services relate to new types of direct and/or shuttle services. New carriage and transport units like rail wagons, trains, barges and vessels represent the new transport technologies. New transhipment and stacking facilities and supporting equipment installed in the terminal(s) represent new terminal technologies. The fast and automated transfer of loading units through the inter-modal terminal(s) represents the innovation of terminal services.

This paper deals with theoretical background of the innovative bundling networks. The objective has been to understand the networks' spatial configuration, traffic scenarios, and time and cost performances. Apart from this introductory section, the paper consists of three sections. Section 2 describes relevant characteristics of innovative bundling networks. In particular, it analyses the processing of loading units while being in the network. Section 3 consists of two parts. First part presents the main assumptions to model these networks. Second part describes the analytical models of different classes of bundling networks. Each model consists of two sub-models. The first one quantifies the total delays of loading units while being in the network(s) under given conditions. The second one quantifies the networks' total generalised costs. The last section (4) presents discussion and conclusions.

STRUCTURE OF THE INNOVATIVE BUNDLING NETWORKS

The analysis carried out in the project TERMINET (EC, 1997*a*, *b*; EC, 1998 *a*, *b*) has identified four basic types of innovative bundling networks. These are the 'point-to-point' *(type P-P)* networks, the networks of 'trunk line with collecting/distribution forks' (*type TCD)*, the 'hub-and-spokes' networks *(type H)*, and the 'line (or ring)' networks *(type L)*.

Each bundling network consists of nodes and links. The freight inter-modal terminals represent the nodes. The links are represented by physical links connecting the terminals like the highways, rail lines, and inland navigation, and transport services. The transport units operated by different transport modes perform these services by carrying the loading units like containers, swap-bodies and semi-trailers between inter-modal terminals. Different types of services can be provided. Usually, these are direct and shuttle train and barge (vessel) services. For example, at international level, both *direct* and *shuttle* rail services usually connect distant terminals. *Direct trains* consist of wagon sequences carrying the loading units with the same origin(s) and destination(s). They are directly routed between two terminals without any intermediate marshalling. *Shuttle trains* have fixed capacity (length) and operate according to regular timetable. These trains avoid marshalling nearby the inter-modal terminal(s). At local level (i.e., on the shorter national and regional distances), *direct* and/or *shuttle 'feeder'* services have been organised to pick-up smaller flows and move them to the terminal(s), where they are bundled into long-distance shuttle or direct services. The capacity of transport units applied to *'feeder'* services is always lower than the capacity of transport units running on the international (long) routes.

The loading units arrive and depart from inter-modal terminals by road haulage (Daganzo, 1991; Hay, 1977; Manheim, 1979). At inter-modal terminals, the exchanging of loading units between transport units operated by different transport modes (road, rail, inland navigation, and short- and deep-sea vessels) takes place. It can be carried out in two ways. First, loading units can stay on the same carriage units, which may be exchanged between different transport units. Classification and assembling (shunting) the trains in shunting yard represent one of the typical examples. Second, loading units can be exchanged by changing the carriage unit. In this case, the loading units can be either *directly* or *indirectly* transhipped from one transport unit to the others. The transhipment takes time depending on the performance of terminal transhipment facilities and equipment, which, apart from determining basic type of handling the loading units, affect the efficiency of terminal operations (EU, 1997 *a, b*).

MODELLING THE INNOVATIVE BUNDLING NETWORKS

Modelling the innovative bundling networks consists of developing the delay and cost models of different network configurations. These models are based on the analysis of network operations, theory of deterministic queuing networks and following assumptions (Newell, 1982; Tarski, 1987):

- Demand for service is expressed by the number of loading units (the customers) requesting service in the network during given period (a day, week). The available transport and terminal capacity always satisfy this demand.
- The inter-modal terminals connected by transport links represent network nodes where the loading units are exchanged between different transport modes. In addition, loading units can enter and/or leave the network through its nodes (e. g., terminals).
- The loading units accumulated at particular locations of the network (i.e., 'buffers') represents the state of the network that changes whenever the 'batch' of loading units enters and/or leave the network.
- 'Buffers' can emerge in the terminals (i.e., the network nodes) and routes (the network links). They may be repeated after regular time (say a day or week) in dependence on the pattern of demand and supply; this 'repetitive' interval is called the network 'cycle'.
- 'Buffering' of loading units while being in the network' causes their delays.
- Costs of particular bundling concepts consist of the inventory cost, transport cost and terminal cost (Daganzo, 1991; Hall, 1987; 1993). The *inventory* cost relates to 'buffering' cost of loading units while being in the network. *Transport* cost consists of the operators' cost to transport the loading units between origin(s) and destination(s). *Terminal* cost consists of handling cost depending on the terminal layout and terminal operating cost.

The delay models

The 'point-to-point' networks with big flows

The *'point-to-point' (P-P)* bundling network serves regular and big freight flows between two intermodal terminals. In general, the network operates as follows: the loading units are delivered from their 'local' origins to the origin intermodal terminal by road haulage. Then, they are loaded onto direct or shuttle train or barge (vessel) and transported to destination terminal. From there, they are distributed (again by road haulage) to their 'final' destinations. Figure 1 illustrates simplified scheme of this bundling network.

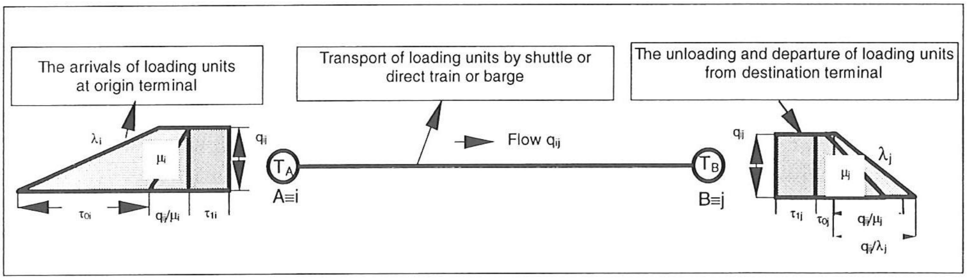

Figure 1 Simplified scheme of the 'point-to-point' network

In Figure 1, the origin and destination terminal are denoted by A and B, respectively, the route connecting two terminals by l_{AB}, and the average speed of transport units by $v_{AB}(l_{AB})$. The flow of loading units, q_{AB} is transported between terminal A and B. Let λ_i be the intensity of collection of loading units at the terminal $A(\equiv i)$. The loading units are assumed to arrive there some time before departure of train, barge, or vessel. This time may vary from the time of preceding departure to the time of closing 'new' departure for loading. The period between the arrival of the first and last loading unit of the batch q_{AB} is τ_{0i}.
The total loading time is dependent on the size of batch $q_{AB} \equiv q_{ij}$, and loading rate μ_i. When the batch q_{ij} has been loaded, the transport unit is inspected and dispatched after period τ_{1i}. The transport unit arrives at terminal $B(\equiv j)$ after time $l_{AB}/v_{AB}(l_{AB})$. Then, the batch q_{ij} is unloaded. The intensity of unloading at terminal $B(\equiv j)$ is μ_j. The inspection and preparation of transport unit for unloading is carried out in time τ_{1j} and τ_{01}, respectively. Like at the origin terminal, the loading units that have arrived at the terminal (j) can be either placed in the terminal's 'buffer' area and wait for picking-up or directly transhipped to road haulage, and vice versa. The intensity of leaving terminal (j) is λ_j. Time for processing the batch q_{ij} through the network defines the network's 'cycle'. This 'cycle' may be repeated in both directions after some time. It has been assumed that the successive 'cycles' have not affected each other. The total delay of loading units while being the network can be estimated as follows:

$$D_{ij}=D_{b_i}+D_{Tij}+D_{bj}=\left[\tau_{0i}+\tau_{1i}+q_{ij}\left(\frac{1}{\mu_i}-\frac{1}{2\lambda_i}\right)\right]q_{ij}+\left(\frac{l_{ij}}{v_{ij}}\right)q_{ij}+\left[\tau_{1j}+\tau_{0j}+\frac{1}{2}\frac{q_{ij}}{\min(\lambda_j;\mu_j)}\right]q_{ij} \quad (1)$$

The symbols D_{bi}, D_{Tij} and D_{bj} denote the total 'buffer' delay at origin terminal (i), route (ij) and at destination terminal (j), respectively. The other symbols have been explained above.

The networks of 'trunk line with collecting/distribution forks' (TCD)

As the observation of bundling processes is expanded to a wider area around the main origin and destination terminal(s) of the 'point-to-point' network, the network of 'trunk line with collecting/distribution forks' *(TCD)* can be identified. It consists of the origin and destination 'local' terminals, which are assigned to the corresponding trunk terminals. At this bundling concept, the flows of loading units move between 'local' terminals. These terminals can be either uni-modal or inter-modal. In Figure 2, the origin 'local' terminals are denoted by T_{di} $(i=1,2,.., N)$. The destination 'local' terminals are denoted by T_{aj} $(j=1,2,.., M)$. The flow of loading units between origin and destination 'local' terminal *(i)* and *(j)*, respectively, is denoted by q_{ij}. Handling of loading units at these terminals is carried out in a similar way as in case of the 'point-to-point' network(s). The loading units are transported by direct or shuttle 'feeder' trains (or barges) from the 'local' to trunk terminals, and vice versa. At the trunk terminal T_A, the loading units are regrouped into the longer direct or shuttle transport units (trains or barges), that are dispatched along trunk route l_{AB} to the trunk terminal T_B.

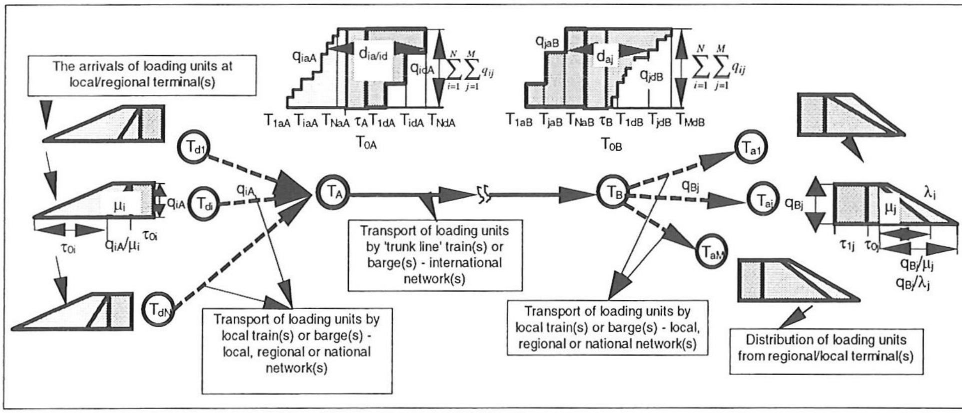

Figure 2 - Simplified scheme of the network of 'trunk line with collecting/distribution forks'

In the rail-based networks, both 'local' and 'trunk' terminals may operate like 'local' and 'regional' shunting yards, respectively. In particular, the delays of loading units during their passing through the 'trunk' terminals are dependent on the number, capacity, and timetable of the inbound 'local' trains and outbound 'trunk' trains. In addition, the strategy and 'speed' of shunting depending on the size and type of shunting yard may significantly affect these delays (Petersen, 1977 *a, b*). In Figure 2, T_{iaA} denotes the arrival time of *i*-th 'local' train at terminal T_A $(I = 1,2, ., N)$. T_{idA} denotes the departure time of *i*-th 'trunk' train from the terminal T_A. The arrival time of *i*-th 'trunk' train at terminal T_B is T_{iaB}. The departure time of *i*-th 'local' train from terminal T_B is T_{idB}. In case when all outbound trunk trains have to wait for the wagons of all inbound trains, and vice versa, the delays of wagons (and loading units) may be long. As it can be seen in Figure 2, the maximum number of loading units that can be accumulated in terminal T_A and T_B is equal to $\sum_{i=1}^{N} q_{iA} = \sum_{i=1}^{N}\sum_{j=1}^{M} q_{ij} = \sum_{j=1}^{M} q_{Bj}$. q_{iA} is the batch of loading units moving between the fork terminal *(i)* and trunk terminal *A* ('*i*' is assigned to '*A*') $(i = 1,2,...., N)$, $q_{iA} = \sum_{j=1}^{N} q_{ij}$ $(i = 1,2,. . .,N)$; q_{iB} is the batch of loading units moving from trunk terminal *B* to fork terminal *(j)*, ('*j*' is assigned to '*B*'), $(j = 1,2,...,M)$, $q_{Bj} = \sum_{i=1}^{M} q_{ij}$ $(j=1,2,. .,M)$; *N* and *M* represent the number of origin and sink ('local') terminals assigned to trunk terminals T_A and T_B, respectively. At the origin 'local' terminal *(i)*, the loading units arrive at rate λ_i $(i= 1,2, .,N)$. They may be either directly transhipped to 'feeder' train(s) or placed in the terminal stacking area. The 'local' trains are loaded by intensity μ_i. The intensity of unloading 'local' trains at destination 'local' terminal *(j)* is μ_j. The loading units leave 'local' terminal *(j)* by rate λ_j $(j = 1, 2, . . ,M)$. The time T_{OA} and T_{OB} denote the moments, at which the trunk terminal T_A and T_B changes the operating regime. I.e., at T_{0A}, the terminal T_A closes for the arrivals of 'local' trains and opens for departure of 'trunk' trains. At T_{0B}, the terminal T_B closes for the arrivals of 'trunk' trains and opens for departures of local trains. The total delay of batch of loading units $\sum_{i=1}^{N}\sum_{j=1}^{M} q_{ij}$ can be computed as follows:

$$D = D_B + D_T = \sum_{i=1}^{N}\left[\left(\tau_{0i} + \tau_{1i} + q_{iA}\left(\frac{1}{\mu_i} - \frac{1}{2\lambda_i}\right)\right) + (T_{0A} - T_{iaA}) + (T_{idA} - T_{0A} + \tau_A)\right] q_{iA}$$

$$+ \alpha_A \frac{\left(\sum_{i=1}^{N}\sum_{j=1}^{M} q_{ij}\right)^2}{\mu_A} + \alpha_B \frac{\left(\sum_{i=1}^{N}\sum_{j=1}^{M} q_{ij}\right)^2}{\mu_B} + \sum_{j=1}^{M}\left[\begin{array}{l}(T_{0B} - T_{jaB}) + (T_{jdB} - T_{0B} + \tau_B) + \\ \left(\tau_{1j} + \tau_{0j} + q_{Bj}\left(\frac{1}{\mu_j} - \frac{1}{2(\min(\lambda_j; \mu_j)}\right)\right)\end{array}\right] q_{Bj} +$$

$$+\left(\sum_{i=1}^{N} q_{iA}\frac{l_{iA}}{v_{iA}} + \sum_{i=1}^{N}\sum_{j=1}^{M} q_{ij}\frac{l_{AB}}{v_{AB}} + \sum_{j=1}^{M} q_{Bj}\frac{l_{Bj}}{v_{Bj}}\right) \quad (2)$$

where

τ_{0i}, τ_{0j} is the time between arrival and loading of batch q_{iA} at 'local' terminal *(i)*, and the time between arrival and departure of batch q_{Bj} from 'local' terminal *(j)*, respectively (minutes, hours),

τ_{1i}, τ_{2j} is the time for preparation transport unit to depart from local' terminal *(i)*, and the time for preparation transport unit for unloading after arrival at 'local' terminal *(j)*, respectively, (minutes, hours),

α_A. α_B is binary variable taking the value '*1*' if the service of loading units at 'trunk' terminals *A* and *B* is realised just after arrival of the whole batch q_{iA}, and q_{iB}, respectively, and the value '0', otherwise,

l_{iA}, l_{AB}, l_{Bj} is the length of route connecting the 'local' terminal *(i)* and 'trunk' terminal *A*, the trunk terminals *A* and *B*, and the 'trunk' terminal *B* and 'local' terminal *(j)*, respectively, (km),

v_{iA}, v_{AB}, v_{Bj} is the average speed of transport unit (train/barge/vessel) on the routes l_{iA}, l_{AB} and l_{Bj}, respectively (km/h).

The 'hub-and-spokes' networks

The 'hub-and-spokes' networks *(H or HS)* usually consist of one hub ('central') node and several spokes ('peripheral' nodes). Simplified scheme of this network is shown in Figure 3. The spokes denoted by T_i $(i = 1,2,..,N)$ can be connected with hub *H* and among themselves by direct or shuttle trains carrying the loading units.

The loading units enter and/or leave spoke terminals (i.e., the network) by road haulage. After entering the network, loading units are transhipped from trucks to train(s). Then, the trains being either direct or shuttle are dispatched to hub *H*. The loading units can pass through hub *H* either by staying on the same carriage units (wagons) all the time (direct train) or by changing them (shuttle trains). In the former case, the wagons are exchanged between trains by carrying out 'classical' shunting. In the later case, the loading units are exchanged between different carriage units (wagons) during their staying in the hub.

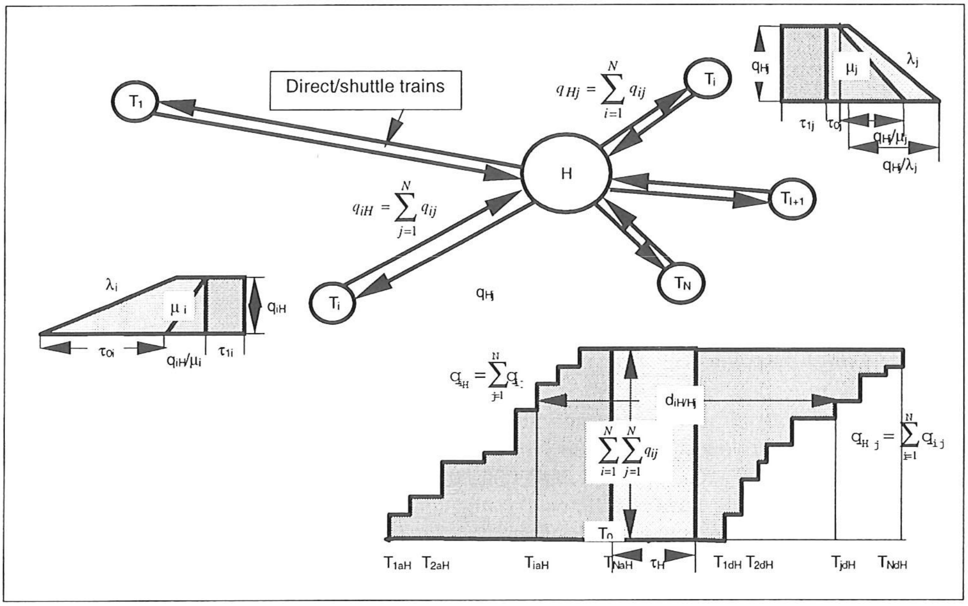

Figure 3 - Simplified scheme of the 'hub-and-spokes' network

Handling of carriage, transit and loading units may cause their 'buffering' and delays. Figure 3 shows that the 'buffers' of loading units have similar 'form' as those of *TCD*-bundling network. Transhipment of loading units at spoke terminals T_i and shunting of trains at hub H are analogous to the corresponding operations carried out at the 'local' terminals T_{ai} and T_{aj}, and 'trunk' terminal T_A and T_B, respectively.

If the flow of loading units between spokes *(i)* and *(j)* is q_{ij}, the resulting flow of loading units on the routes *(iH)* and *(Hj)* is equal to q_{iH} and q_{Hj}, respectively (see Figure 3). The total number of loading units passing through the hub H is equal to the sum of all individual flows $q_{ij}\,(i,j \in N;\ i \neq j)$.

The total delay of loading units served in the network during one 'cycle' can be estimated as follows:

$$D = D_B + D_T = \sum_{i=1}^{N}\left[\tau_{0i} + \tau_{1i} + q_{iH}\left(\frac{1}{\mu_i} - \frac{1}{2\lambda_i}\right) + (T_0 - T_{iaH})\right] q_{iH} + \alpha_H \left(\sum_{i=1}^{N}\sum_{j=1}^{N} q_{ij}\right)^2 7\mu_H + \\ + \sum_{j=1}^{N}\left[(T_{jdH} - T_0 + \tau_H) + \tau_{0j} + \tau_{1j} + q_{Hj}\left(\frac{1}{\mu_j} - \frac{1}{2[\min(\lambda_j;\mu_j)]}\right)\right] q_{Hj} + \sum_{i=1}^{N}\sum_{j=1}^{N} q_{ij}\left(\frac{l_{iH}}{v_{iH}} + \frac{l_{Hj}}{v_{Hj}}\right) \tag{3}$$

where

λ_I, λ_j	is the intensity of arrival and departure of loading units at/from spoke terminals *(i)* and *(j)*, respectively,
μ_I, μ_j	is the intensity of loading/unloading of loading units in spoke terminals *(i)* and *(j)*, respectively,
T_{iaH}	is the arrival time of a train running from spoke *(i)* and hub *(H)*,

T_0	is the time when all trains arrived from N spokes are ready to be shunted at the hub H,
α_H	is binary variable taking the value '*1*' if shunting starts after the arrival of the last among N trains at the hub *(H)*, and the value '0', otherwise,
μ_H	is the average rate of shunting, which is assumed to be approximately constant and not dependent on the train and wagon characteristics,
T_{jdH}	is the departure time of train running from hub H to spoke *(j)*.
τ_H	is the total time needed for shunting N trains; shunting is assumed to start just after the arrival of the last train from the batch of N trains,
l_{iH}, l_{Hj}	is the length of route connecting the spoke *(i)* and *j)*, via the hub *(H)*,
v_{iH}, v_{Hj}	is the travel speed of train along the routes l_{iH} and l_{HJ}, respectively.

The 'line' ('ring)' bundling networks

The 'line' ('ring)' network is a line or ring configuration where the uni- and/or inter-modal terminals are located in line or ring in relation to direction of flows of loading units. The rail and inland navigation (barges' and vessels') direct and/or shuttle services usually connect the terminals. The exchange of loading units between different combination of transport modes like rail/rail, truck/rail, truck/barge, rail, and truck/short and deep-sea vessels takes place at these terminals. The loading units can enter and leave the network at the terminals that represent their origin(s) and destination(s).

Figure 4 illustrates the scheme of *'ring'* bundling network. Like in the preceding cases, the 'buffers' of loading units emerge in the terminals where they are collected and distributed. At these terminals, the 'collecting/distribution' transport units meet the transport units running in the ring (line). For example, at the terminal T_i, the loading units, which should be sent to some other location, are collected with intensity λ_{ai} (loading units per unit of time). After some time, the batch of loading units, q_{ai} has been accumulated.

Two possibilities for proceeding the batch q_{ai} to final destination can be applied. First, if the transport unit is immediately available, the batch of loading units can be directly loaded (transhipped) to it. Otherwise, the batch will be stacked in the terminal's 'buffer' area and wait for free transport unit to come and pick-up it. In that case, waiting time of the batch q_{ai} is τ_{ai} (minutes, hours, and days).

The intensity of loading that is dependent on the available facilities and equipment installed in the terminal and/or transport unit itself is denoted by μ_{ai} (loading units per unit of time). After being transported to terminal T_i, the batch q_{di} of loading units is unloaded. The intensity of unloading is μ_{di} (loading units per unit of time). Loading and unloading can be carried out in two ways, sequentially and simultaneously. Sequential loading/unloading means that the whole batch q_{di} is unloaded and then, the whole batch q_{ai} is loaded. Simultaneous transhipment is carried out 'in parts', e.g., firstly, one loading unit from the batch q_{di} is unloaded and then one loading unit from the batch q_{ai} is loaded, etc. After the batch q_{ai} is wholly loaded, it is transported to final destination. The unloaded batch q_{di} is either directly transhipped to the other transport units already being in terminal (trucks, trains, barges or vessels) or stacked in the terminal's 'stack' area. The waiting time of the batch to be picked-up is τ_{di}. The 'emptying' rate of terminal T_i is λ_{di} (loading units per unit of time). The batch q_{ai} consists of loading units having the origin at terminal T_i and destination at other terminals T_j $(i \leq j \leq N)$, e.g., $q_{ai} = \sum_{j=i}^{N} q_{ij}$. The batch q_{di} consists of the loading

units having

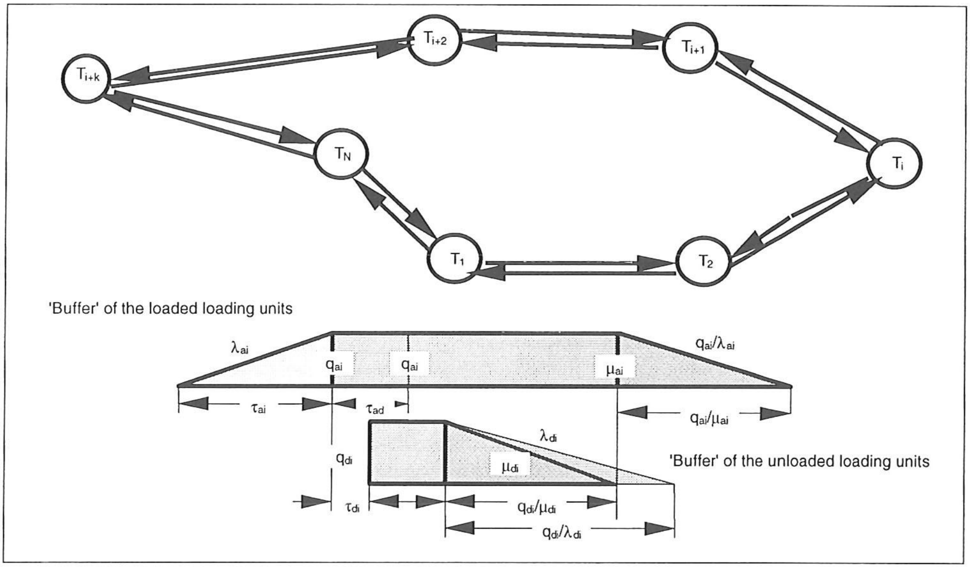

Figure 4 - The simplified scheme of the 'line' or 'ring' network

the origin at terminal T_j and destination at terminal T_i $(1 \leq j \leq i)$, e.g., $q_{di} = \sum_{j=1}^{i} q_{ij}$. Thus, the number of loading units transported between any two terminals, T_i and T_{i+1} is equal to $q_{i,i+1} = \sum_{k=1}^{i} \sum_{j=i+1}^{N} q_{kj}$. The delay of loading units while being in the network can be estimated as follows.

$$D = D_B + D_T = \left[\sum_{i=1}^{N} \left(\begin{array}{l} \alpha_{ai} \dfrac{q_{ai}^2}{2\lambda_{ai}} + (\tau_{ad} + \tau_{di} + \beta_i q_{di} / \mu_{di}) q_{ai} \\ + \left(\tau_{di} + \dfrac{1}{2} \dfrac{q_{di}}{\min(\lambda_{di}; \mu_{di})} \right) q_{di} \end{array} \right) \right. \\ \left. - \gamma_i \left(\dfrac{q_{ai}^2}{2\mu_{ai}} \left(\dfrac{\mu_{di}}{\mu_{ai} + \mu_{di}} \right) \right) \right] + \sum_{i=1}^{N} \frac{l_{i,i+1}}{v_{i,i+1}} q_{i,i+1} \tag{4}$$

where

$$q_{ai} = \sum_{j=1}^{N} q_{ij}^0 \; ; q_{di} = \sum_{j=1}^{i} q_{ji}^0 \; ; \text{and} \quad q_{i,i+1} = \sum_{k=1}^{i} \sum_{j=i+1}^{N} q_{kj}^0 \quad \text{for} \quad i = 1,2,..., N-1 \tag{4a}$$

τ_{ad} is the inter-arrival time of batches q_{ai} and q_{di},

α_i is binary variable, which takes the value *'1'* if batch q_{ai} instantly emerges at the terminal *(i)*, and value *'0'*, otherwise,

β_i is binary variable, which takes the value *'1'* if batch q_{ai} is loaded after completion of the unloading of batch q_{di}, and value '0', otherwise,

γ_i is binary variable, which takes the value '1' if loading and unloading of batches q_{ai} and q_{di} at terminal (i) are simultaneously performed, and value '0', otherwise,

q^0_{ij} is the 'local' flow of loading units originating from terminal (i) and sinking in terminal (j) ($i \neq j$; $i,j \in N$),

$l_{i,\,i+1}$ is length of the route connecting terminals (i) and (i+1),

$v_{i,i+1}$ is the average speed of transit unit (barge, train) running between terminals (i) and (i+1).

The cost models

The 'point-to-point' networks with big flows

In order to estimate the total cost of the 'point-to-point' bundling network, the following expression has been developed:

$$C_{ij} = C_I + C_{TR} + C_{TE} = \left(D_{bi} + D_{Tij} + D_{bj}\right)p_{ij}\,r_{ij} + c(d_{i0}, V_{i0})f_{i0} + c(d_{ij}, V_{ij})f_{ij} + c(d_{j0}, V_{j0})f_{j0} + \left(\frac{b_{0i} + b_{1i}}{u_i Q_i} + \frac{b_{0j} + b_{1j}}{u_j Q_j}\right)q_{ij} \tag{5}$$

where

D_{bi}, D_{Tij}, D_{bj} is the delay of loading units while passing through the terminal (i), route (ij) and terminal (j), respectively,(loading unit-hours),

p_{ij} is the average value of shipment belonging to the batch q_{ij} (ECU per loading unit),

r_{ij} is the average 'inventory charge' of shipment belonging to the batch q_{ij} (fraction of ECU value per unit of time),

$c(d, V)$ is the transport cost on the route d when the transportation is carried out by the transport unit of capacity V (ECU per dispatch),

f is the frequency of transport units to serve the batch q_{ij} (departures per period),

b_{0i}, b_{1i}; b_{0j}, b_{1j} is the total handling and operation cost of terminal (i) and (j), respectively, (ECU per year),

Q_i, Q_j is the volume of traffic planned to be handled in terminal (i) and (j), respectively, (loading units per year),

u_i, u_j is the average utilisation of the terminals (i) and (j), respectively.

In dependence on the basic network configuration, the delay of batch q_{ij} can be estimated by using eqn. (1), (2), (3) and (4). 'Generic' form of the transport cost function, $c(d,V)$ can be expressed either in linear or log-linear form as follows

$$c(d,V) = a_0 + a_1 d + a_2 V \quad \text{or} \quad c(d,V) = a^0 d^{a_1} V^{a_2} \tag{5a}$$

where

a_0 is fixed transport cost not dependent on the route length and capacity of transport unit (ECU/dispatch),

a_1 is the average cost per unit distance (ECU/km),

a_2 is the average cost per unit of capacity of transport unit (ECU per tonne or ECU per loading unit),

d is length of a route (km),

V is the carrying capacity of transport unit (it can be expressed either by tonnes or number of loading units per transport unit),

For any transport mode, the frequencies on routes connecting the particular spokes can be determined based on the assumption that the demand is always satisfied, i.e.,

$$f = q / \lambda V \tag{5b}$$

where

q is the flow of loading units on a route (loading units per period),

λ is the average utilisation of transport units running on the route,

V is the average capacity of transport unit (it is expressed by the number of loading units per transport unit),

The networks of 'trunk line with collecting/distribution forks' (TCD)

Total cost of the network of 'trunk line' *(TCD)* can be determined in a similar way as in eqn. (5), of course by introducing the necessary modifications related to the specific configuration of the network. Considering a 'generic' scheme of this network shown in Figure 2 and corresponding eqn. (2) for determination the delay of loading units while being in the network during one 'cycle', the total network cost per 'cycle' can be estimated as follows:

$$C = C_I + C_{TR} + C_{TE} = \sum_{i=1}^{N}\sum_{j=1}^{M}\left[\begin{array}{l}(D_{biA} + D_{TiA} + D_{bA} + D_{TAB} + D_{bB} + D_{TBj} + D_{bBj})p_{ij}r_{ij} + \\ + c(d_{i0}, V_{i0})f_{i0} + c(d_{iA}, V_{iA})f_{iA} + c(d_{AB}, V_{AB})f_{AB} + \\ + c_{Bj}(d_{Bj}, V_{Bj})f_{Bj} + c(d_{j0}, V_{j0})f_{j0} + \frac{b_{0i} + b_{1i}}{u_i Q_i} q_{iA} + \\ + \left(\frac{b_{0A} + b_{1A}}{u_A Q_A} + \frac{b_{0B} + b_{1B}}{u_B Q_B}\right)(q_{iA} + q_{Bj})) + \frac{b_{0j} + b_{1j}}{u_j Q_j} q_{Bj}\end{array}\right] \tag{6}$$

where the symbols are analogous to those in preceding equations.

The 'hub-and-spokes' networks

The 'hub-and-spokes' network *(HS)* is shown in Figure 3. By using the expression (3) and (5), the total cost of this configuration can be determined as follows:

$$C = C_I + C_{TR} + C_{TE} = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\begin{array}{l}(D_{bi} + D_{TiH} + D_{bH} + D_{THj} + D_{bj})p_{ij}r_{ij} + c(d_{i0}, V_{i0})f_{i0} + \\ + c(d_{ih}, V_{ih})f_{iH} + c_{Hj}(d_{Hj}, V_{Hj})f_{Hj} + c(d_{j0}, V_{j0})f_{j0} + \\ + \frac{b_{0i} + b_{1i}}{u_i Q_i} q_{iH} + \frac{b_{H0} + b_{H1}}{u_H Q_H}(q_{iH} + q_{Hj}) + \frac{b_{0j} + b_{1j}}{u_j Q_j} q_{Hj}\end{array}\right] \tag{7}$$

where the notation is analogous to one in previous equations.

The 'line' ('ring') bundling networks

Simplified scheme of the 'line' or 'ring' bundling network is shown in Figure 4. By using eqn. (4) and (5), the total network cost can be determined like in the preceding cases as follows:

$$C = C_I + C_{TR} + C_{TE} = \sum_{i=1}^{N} \left[D_{bi} p_i r_i + c(d_{i0}, V_{i0}) f_{i0} + c(d_{0i}, V_{0i}) f_{0i}\right] + \sum_{i=2}^{N} c(d_{i,i-1}, V_{i,i-1}) f_{i,i-1} + \sum_{i=1}^{N} \left(\frac{b_{0i} + b_{1i}}{u_i Q_i}\right)(q_{ai} + q_{di}) \quad (8)$$

where all symbols are analogous to those in the preceding equations. .

DISCUSSION AND CONCLUSIONS

"Buffering' of loading units causes their delays while being in the bundling networks. It represents an inherent characteristic of the networks' operations. This characteristic is dictated by the nature of the process itself and can not be avoided anyway. At the same time, it reflects the presence of 'contradiction' in the 'generic' structure of innovative bundling networks. On the one side, the batches of loading units are desired to be as great as possible (e.g., they should promptly fill-in direct and shuttle trains or barges scheduled by convenient frequency from the standpoint of users). On the other side, large batches create large 'buffers' requesting a relatively large 'buffer' area (extra space) in the terminals as well as convenient facilities and equipment, which would be capable to efficiently manage them. In addition, the movement of loading units through terminals reduces the average delivery speed and thus increases total delivery time. Since the 'batches of loading units' are depreciated at the rate proportional to the network's time and value of shipment, the larger batches are less desired again, particularly in cases when more 'expensive' and 'perishable' goods are transported.

Nevertheless, some gains from implementation of different innovative bundling networks can be achieved. In particular,. the larger batches of loading units moved at higher speed will request engagement of smaller number of larger transport units and their 'higher' utilisation, as well as consumption of less labour at the transport side of the logistics chain(s). This will increase the efficiency of transport operations in the network and thus make the reduction of total and average cost per unit of network output possible (say ECU/t-km). These direct savings may compensate the extra costs imposed on the loading units due to passing through the terminals.

Moreover, the replacement of road haulage with trains and barges on the main freight corridors may produce few positive effects. First, the utilisation rate of rail and inland navigation capacities may be increased. Second, these modes may specialise for specific services that can improve their competitiveness on the freight transport market(s). Third, the substitution of road haulage for equivalent volume of operation of bundling networks may reduce the negative impacts on the environment (the air pollution and congestion). However, except in specific cases, these networks are not able to completely eliminate the negative environmental affects, particularly at local level, due to inevitable need for using trucks to deliver and distribute the flows of loading units to/from begin and end intermodal terminal(s), respectively.

The models of total network cost can be applied to estimate the cost performance of bundling networks. This attribute may be used for comparison and evaluation of particular bundling concepts. Nevertheless, in some sense, it may be dubious due to following reasons: First, each network is established to serve specific market(s). The volume, time and spatial characteristics of demand usually dictate the network layout, i.e., the number, length and intensity of services on the routes, as well as the capacity of facilities and equipment installed in terminals. Second, the number and type of combinations of different transport modes used in the network can also hinder the usefulness of this criterion to the networks' evaluation and fair comparison. Therefore, the average cost per loading unit processed in the network during a 'cycle' has seemed to be more appropriate criterion for such purpose. Division of total network cost by total number of loading units that have been transported in the network under given circumstances can compute the average cost.

The concept of the total and average delay and cost could be applied to the sensitivity analysis of network cost with respect to the changes of influent parameters. As it has been shown in this analysis, the delay of loading units and total network cost will be greater as the network is larger (e.g., if it consists of a greater number of terminals and routes). As well, if the flows of loading units are greater and if the time of their passing through the network is longer, both delays and cost will be higher. The other influent parameters on delays and cost can be represented by terminal technology (the NG terminals may provide lower terminal cost), combination of different transport modes and their inherent characteristics like the capacity of transport units, their utilisation, operating speed, etc.

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