Bottleneck-Analysis on Intermodal Maritime Transportation Chains

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ABSTRACT
Scenario analysis often is used to determine bottlenecks in multimodal transportation and logistics chains. Bottleneck-analysis itself is a process related approach to identify shortages in multimodal transportation and logistics supply chains, and concerned with analysis of resource planes, optimization of multimodal transportation chains, consideration of timeliness and concurrency using resources, transaction analysis, multi-criteria approach, etc. Henceforth, the scenario analysis has to include the evaluation of the impact on intermodal transportation chains, the results of which can be obtained from simulation.

1. Introduction

Bottleneck-analysis is a process related approach to identify shortages in transportation supply chains. Bottleneck-analysis in this sense means predicting potential bottlenecks, in order to improve the transportation supply chains performance on the flight. This is concerned with analysis of resource planes, optimization of the transportation chains, consideration of timeliness and concurrency using resources, transaction analysis, etc.

Bottleneck-analysis often is used when a symptomatic description of transportation supply chains is based on vagueness and/or fuzziness which includes relative words like "too hot", "not enough", "not as fast", "insufficient", etc. which call for a so called innovative algorithmic solution. Such an innovative solution could be fuzzy reasoning, etc. In all cases the respective transportation supply chains are underperforming in comparison with previous assumptions and/or constraints. But whenever it is necessary to change the throughput or what else of the transportation supply chains, the bottleneck-analysis is the vital state-of-the-art method to overcome the foregoing mentioned problems of transportation supply chains by ascertaining the respective bottlenecks affecting the local transportation chain on the basis of defined key measures which play a key role in managing shortages. The interplay between them determines the specific characteristic strength and weakness profile of the intermodal transportation chain under investigation. Henceforth, identifying shortages deal with discovering the dependencies in a sequence of actions, showing the dependencies through which the different transportation supply chains are conditional with their related actions.

Shortages generally can be identified through a scenario planning and analysis approach, which show different intensive impacts on optimal or sub-optimal behavior of the transportation process. Therefore the main advantage of a bottleneck-analysis is the possibility to identify shortages and, if possible, their rectification on the very spot to achieve better and/or optimal transportation supply chain behavior. In agreement with this constraints shortages can be considered as weakest part of a chain, as shown in Figure 1.

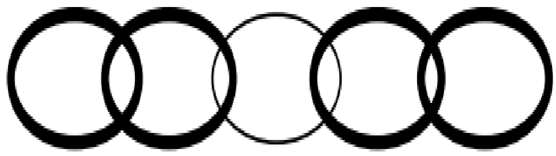

Fig. 1: Transportation chain with strong and weak parts

Therefore, the results obtained through bottleneck analysis can be classified by different categories. Assuming that bottleneck-analysis in maritime transportation has to deal with the calculation of adequate availability of resources, the resulting categories are:

- ***Category 1:*** Bottleneck analysis show no shortages which means that resources required for the intermodal maritime transportation chains are available, a costly solution. Because basically the resources available can't be used in an optimal way, because more resources are available than required. This result in the awareness that there is no category available which result in an optimum to object with even accurately resources, that is effectively required. This problem exists especially at railway carriage which is in comparison with trucks not available on short notice.

- ***Category 2:*** Bottleneck analysis show major shortages meaning that resources required for the intermodal maritime transportation chains are not available in the required amount and/or if the worst comes to the worst only one component is available but several of which are needed. This category is a low cost solution, but the resources available are not adequate.
- ***Category 3:*** Bottleneck analysis show minor shortages which means that resources required for the intermodal maritime transportation chains exist. Basically the achievable solution is in between category 1 and 2 which can be introduced as the beast and the worst case scenarios. The result obtained by category 2 is called sub-optimal.

Due to complexity and constrains like time and cost, identification of bottlenecks in the maritime transportation chains is not a trivial task. Because identification and elimination of shortages generally is only the first step in finding the possible and/or optimal solution. So far a shortage is identified and rectified it can be discovered that the criteria based objective function is sub-optimal due to another shortage, identified eliminating the first one, which result in the so called multi-shortage bottleneck analysis. This will result in intelligent algorithms the bottleneck-analysis has to pass through in order to find out the desired optimal transportation behavior.

2. Multi-Shortage Bottleneck Analysis

Multi-shortages can be introduced as an order of connections of shortages which are mostly hidden because their impact becomes active as soon as the previous shortage has been identified and rectified. A schematic sketch of multi-shortages is shown in Figure 2.

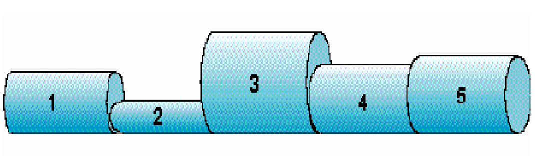

Fig. 2: Bottleneck-Analysis of multi-shortages

The idea behind the above multi-shortage approach is a hydrodynamic model which constitutes the practical possibility calculating flows.

In general terms the hydrodynamic model approach represents the introduction of the Bernoulli equation in the logistics domain. In case of traffic observation this approach was proved and tested, see [1, 2].

Hence, shortages can be assumed being represented through their respective flow. This flow could be expressed by the number of ships passing river Elbe per hour in the direction of CTA (Container Terminal Altenwerder), container trucks passing through river Elbe tunnel per hour, etc.

In this intermodal maritime transportation chain case study it is assumed that trucks are loading containers at the container terminal CTA, represented by component 1; in numbers 340 trucks per h.

Let river Elbe tunnel passage being component 2 representing that two from four tunnel tubes are closed for construction works. In numbers only 250 trucks can pass per h. As a result of this resource shortage trucks begin queuing and more and more trucks have to wait at the very first before traversing the Elbe tunnel tubes, before being able to drive to their final destination. This process is called congestion. After traversing river Elbe tunnel no further congestion occur, represented by component 3. Later on two road reconstruction work area remain represented by components 4 and 5 which don't have that much influence on the traffic. Therefore, passage through river Elbe tunnel – component 2 – is the primary bottleneck.

Moreover, beside the above mentioned set of shortages determined by missed resources, weighting functions can be added to the components´, in order to calculate the respective output delay. In terms of optimizing the resources' management, by calculating the output delay as part of the intermodal maritime transportation chains which result in more sensitive parameters, compared with a pure identification of shortage caused resources´.

Based on the output delay representing the shortage of the investigated intermodal maritime transportation chains the calculated transportation time can be characterized by the time loading containers from the container ships up to the time passing river Elbe tunnel and arrival at the final destination without or with a congestion. It should be noted that this approach can cause some problems, Because in between the container ship and the further transport by trucks the containers normally are temporarily stored in this case study. Hence, this storage buffer absorbs the oscillations of approaching trucks. The better approach is a container terminal CTA which run automated guided vehicles (AGVs). After loading at the ship container bridge the AGVs are unloaded by automatic stacking cranes, which result in the logistic fixed coupling constraint, because the AGVs have to wait such long until the stacking crane is uploading. In contrast with conventional VanCarrier containers can directly transferred to the stacking cranes, and the VanCarrier can continue to work. This constraint is called in logistics the loose coupling approach. The loose coupling approach is the preferred one most CTA operator agreed to accept, meaning using the VanCarrier instead of the AGVs.

Based on the foregoing mentioned assumptions the bottleneck-analysis of the series connection of shortages as shown in Figure 2 show a sequence of hidden shortages which one after each other will be discovered once the previous has been identified. However the shortage of component 2 is the primary one in the this bottleneck analysis the others are the so called secondary shortages.

Hence, the bottleneck analysis allow an entire utilization analysis from sink to source, and concurrently the identification of opportunities for optimization. From a more general perspective this refer to transhipment nodes in the intermodal transportation chain which minimize the dwell time of the goods (e.g. containers) in order to increase the productivity of the overall chain. For this reason the forward and the backlash motion must be completely without any time lag. But rating an optimization has to consider the different stakeholder views. Stakeholders are ship owners, port managers, transport companies, etc. The first mentioned will be a more global view while the others will be more local. The global and local views are obtained from the different operating procedures, the decision making processes, the interpretation of data exchanged, the underlying optimization strategies, etc. In general the workflow of this process can be described through a sequential step approach:

Step 1. Identify shortage: Position with the least flow rate in the transportation supply chain will be determined. Designation can be done by different methods.

Step 2. Use identified shortage in optimal manner: Selected shortage will be analyzed with regard to its non-optimal use. Through shortage optimization the flow rate can be increased. Each identified shortage should be assigned with an ancillary resource.

Step 3. Managing shortages: Since shortage means limiting resource flow rate in the transportation supply chain the overall throughput has to be adapted in such an extent that an optimal utilization of the shortage is achievable.

Step 4. Expand shortage: So far no adequate result was achieved after optimization, enhancing resources' capacity has to be taken into account.

Step 5. Start again with step 1.: So far a shortage was rectified, it is possible a new so far hidden shortage can show up, which is the so called secondary shortage. Insofar this shortage will become problematic one should start the sequence again with step 1 in order to optimize the whole transportation supply chain.

3. Multi-Criteria Approach

As soon as shortages are allocated their impact on overall time delay etc. due to the sequence of hidden shortages can be calculated. The calculation procedure to be used is so called multi-criteria approach, which is based on the assumptions that several occasions have to be taken into account allowing decision making. Generally the approach can be described as follows:

Let a set of alternatives A exist, e.g. $A \neq 0$. As consequence of the multi-criteria approach, by calculating a weighting function f with $f : A \rightarrow R^q$ with $q \geq 2$, A can be solved.

Let $f_k : A \rightarrow R$, with $f_k(a) = z_k$ ($k \in \{1;\ldots, q\}$ with $a \in A$, whereas $f(a) = (z_1;\ldots; z_q)$ is essential, than the weighting function f is the so called criteria of the objective function f_k.

Let the objective function f_k, ($k \in \{1\ldots q\}$ be a maximum, than for each criteria a higher value will be preferred opposite a lower value.

Let the objective function be minimized expressed by f_k', than the maximum criteria can be defined as a substitute for $f_k = - f_k'$.

4. Maritime Bottleneck Analysis

As foregoing mentioned different methods for bottleneck analysis are known, such as:

- Capacity utilization method
- Queuing time method
- Elapsed time method
- Shifting bottleneck method,
- Etc.

Bottlenecks in maritime transportation chains can be sea and/or land based, with regard to their potential resulting delays. Moreover the distinction between primary and secondary delays which are based on the cause of the delay is important for the decision making process.

The capacity utilization method refer to the utilization of the different resources and calculate the resource with the highest capacity utilization as shortage. This can be calculated after [3] as follows:

$$B = \{i \mid p_i = \max(p_1; p_2; :::, p_n)\}$$

with p_i as capacity utilization of the i-th resource. The advantage is the intrinsic simplicity.

In contrast the queuing time method determine the shortage in relation to the queuing time of the resources before loading and uploading containers for transportation within the supply chain. This can be calculated after [3] as follows:

$$B = \{i \mid W_i = \max(W_1;W_2; :::;W_n)\}$$

with W_i as queuing time utilization of the i-th resource. The advantage of the method is its easy implementation.

The shifting bottleneck method, in contrast to the sole bottleneck approach, request average active time stamps of shortages based on which it will be possible to estimate the timeliness shortages are moving. This will allow to identify non shortages too. Because this method is able to differentiate between the probability of the existence of shortages and the existence of non shortages. Moreover this method allow to separate between primary and secondary shortages due to the average shortage over time [4]. But the primary methodological problem of this method is its implementation and computing time required.

Figure 3 show the principle of moving shortages of the shortages M1 and M2. As shown in Figure 2 at a specific time stamp the shortage is caused by the active task which may have the longest runtime. Therefore, the moving shortage is based by the overlap of shortages, as shown in [5].

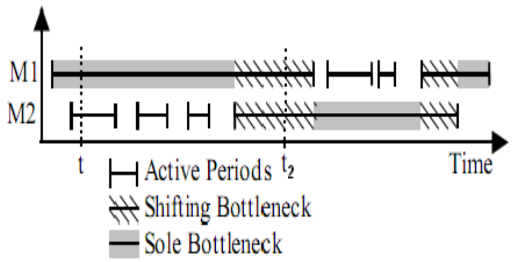

Fig. 3: Moving shortages after [5]

Primary delays as a result of shortages corroborate a belief in so called distributions of

- Shipping time,
- Arrival time,
- Quay time for uploading/loading.
- Accomplishable delay compensation through optimization of an objective function to that effect that the function will be maximized; for each criteria a higher value will be preferred opposite a lower value
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- Accomplished improvement to compensate delays
- Etc.

In general distribution assumptions can be summarized in a model which allow statistical data analysis [6]. But the problems are with secondary delays which can be expressed as so called Domino-effect. Because they start with the distribution assumptions' of the primary delays. Secondary delays in maritime transportation, as a consequence of primary delays, can for example, result in delays of

- Delayed arrival of trucks
- Delayed arrival of trains
- Delayed arrival of feeders
- Etc.

for uploading and loading the containers.

The consequences of connection delays can be estimated using mathematical models which allow statistical calculations. The outcome is a throughput estimation as a result of the delay which can be compared with the original assumptions, to show the implications of the delay from a general perspective as well as for a single case study.

Based on composed distribution graphs shortages can be identified and their rectification through a representative selection of objective functions f_k, following the multi-criteria approach, for simulation, which finally result in appropriate adjustments.

Figure 4 show a composed distribution graph on this note. As it can be seen from Figure 3 that short time delays are dominant for the probability model for the maritime transportation chains.

For the Bottleneck analysis it is of importance to identify whether the allocated resources for the several transportation chains will work without shortages. This means that the tasks will be done in an optimal manner. Otherwise it must be proven whether the task can be done with a restricted number of alternatives', meaning a non empty set of alternatives´.

Moreover, Figure 4 show that beside short time delays mid term time delays > 10 hours and longer could happen too, indicated by the column > 10 hours. If time delays > 10 hours up to < 60 hours are taken into account, the previously composed distribution graph will become a so called saddle graph with two maxima.

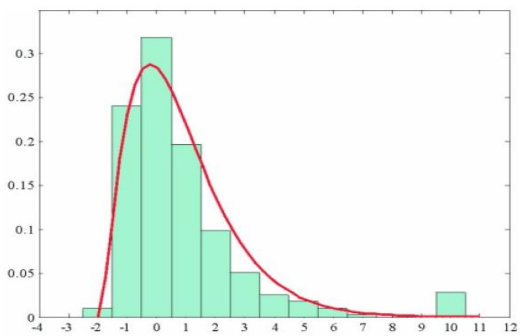

Fig. 4: Distribution graph of delays (Abscissa: time delay in hours, negative sign show earlier arrival; Ordinate: Probability of delays)

5. Elbe Tunnel Bottleneck Analysis

To analyze the impact of traffic shortages for metropolitan Hamburg as part of the bottleneck analysis the developed traffic network model has to take into account the following criteria:

- Simulation and performance evaluation of traffic flows; traffic prediction not required.
- Traffic network under investigation freely customizable in terms of topology, i.e. nodes/ links, flow offered per origin-destination-route, link speed, lane numbers, and capacity.
- Uncomplicated customization for scenario analysis and evaluation, e.g. increasing number of lanes, speed limit, etc.
- Intermodal-mode Support.
- Traffic flow visualization desirable, but not necessary.

These requirements are met by the Virtual Intermodal Transportation System (VITS) simulation framework which implements statewide intermodal traffic of Mississippi and Alabama implemented on the ProModel discrete event simulator. A complete and detailed description can be found in [7].

VITS discrete event traffic simulator covers road, rail, and water mode; the methodology used combines aspects of so called microscopic and macroscopic traffic simulation: In principle, trucks representing road traffic are modeled individually: To each truck, attributes denoting speed and destination are assigned. However, for computational simplification each of the model's truck entities can be parameterized to represent more than one truck for the purpose of road utilization and speed calculation, etc.

The given network topology consist of nodes e.g. interstate highway junctions, exits, plants, ports. other locations important for freight traffic, such as links like road, rail, or waterway segments each of which connect two nodes, etc.

Trucks continuously appear at any node; their inter-arrival time is exponentially distributed with a higher mean during day-time than at night. Each truck traverses a fixed route, i.e. a sequence of road links that depends on the origin-destination node pair assigned to the vehicle. A truck that eventually reaches its destination node thereafter is removed from the system.

Calculating the speed of a truck along a road segment abstracts from microscopic vehicle interaction, while applying the Bureau of Public Roads equation [8], because speed depends on the macroscopic parameters of road capacity and utilization.
The speed assigned to link from which trucks' speeds are derived by sampling a normal distribution during the next period e.g. one hour is set such that the expected travel time ˆ*ti* required for traversing the link amounts to [9]

$$\hat{t}_i = t_i \left[1 + \alpha \left(\frac{x_i}{C_i} \right)^{\beta} \right]$$

subject to free flow travel time *ti* (constrained e.g. by the relevant speed limits only), link capacity *Ci*, and flow during the last period *xi*. Parameters a and b are set to 0.45 and 7.5, respectively, as suggested in [8]. The flow *xi* is measured in terms of passenger cars and estimated by counting trucks entering the link since the last speed update, applying an equivalence factor of 2.5 passenger cars per truck.

The non-freight passenger car traffic is not modelled explicitly; the flow *xi* is chosen such that trucks account for 25% of the overall traffic.

In [7] it is intended to replace the estimation of the truck equivalence factor and passenger car to truck-ratio with more accurate numbers, e.g. equivalence factor depending on road and terrain type in the future. Link capacity depends on road type, speed limit, number of lanes and passenger car units per h per lane as suggested in [10].

In contrast to road, rail, and water modes traffic density influencing travel times; trains and barges appear at nodes connected to rail or waterway links and traverse each link on their route at constant speed that is assigned to each link individually. Rail, tracks' and rivers' capacities are assumed to suffice for any rail and barge traffic offered, thus always traversing relevant links at desired speed.

Despite single mode transportation, in which trucks, rails, and barges that appear with respect to an exponentially inter-arrival time traverse links on different single-mode routes, VITS also provides intermodal transfers, in which routes served by different modes may be linked: For example, the freight delivered to a port by trucks is loaded onto a barge, so that barge departures are not sampled from a random distribution, but depend on truck arrivals at the port as well as the barge to truck capacity ratio and the duration required for loading. Thus, interdependencies between the different modes of transportation can be traced down and bottlenecks influencing the intermodal network's overall performance can be identified.

The traffic simulator was developed for (but not limited to) the metropolitan area of Hamburg, providing a tool for bottleneck-analysis evaluating the impact of shortages due to closed tunnel lanes as a result of maintenance and/ or reconstruction, onto the transportation chains of the Metropolitan region of Hamburg. Such an investigation typically includes performance measures like vehicle travel times, link speeds, or throughput, yielding a valuable decision support tool by offering judgement whether solutions, as part of the scenario analysed, are sufficient with respect to given target performance measures for further enhancement. Figure 5 depicts the Hamburg bottleneck network, consisting of 16 nodes and 18 links. Most nodes denote freeway junctions or exits; in this topology [9].

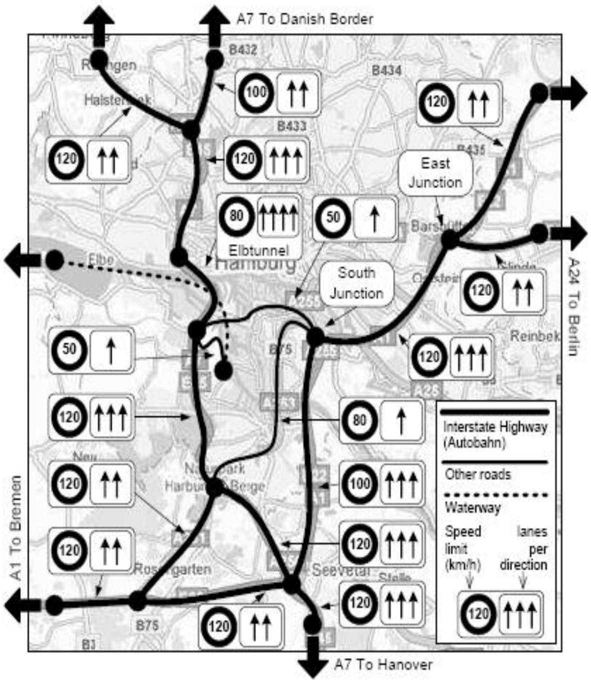

Fig. 5: Hamburg Road Network

The scenario under investigation focus on a network in which

- two of four pipes of river Elbe tunnel are closed, e.g. due to maintenance reasons, reducing the number of lanes from four to two per direction
- transit traffic from east to west A1 Bremen to A24 Berlin and vice versa doubles.

The results for these scenarios are shown in Table 1.

Speed update policy / scenario	Average TT all vehicles (hours)	Average TT A7 northbound (hours)	Average TT A1/24 westbound (hours)	Average speed link Elbtun. N (km/h)	Average speed link Junc. S to E (km/h)
VITS/1	0.58±0.01	0.79±0.03	0.62±0.01	79.3±0.1	115.4±0.2
VITS/2	0.64±0.02	0.93±0.05	0.62±0.01	70.2±0.2	115.4±0.2
VITS/3	0.75±0.01	0.75±0.03	1.00±0.04	79.3±0.1	108.9±0.3
Inst/1	0.46±0.01	0.52±0.01	0.60±0.01	78.4±0.1	115.0±0.3
Inst/2	0.47±0.01	0.54±0.01	0.60±0.01	70.9±0.2	115.1±0.3
Inst/3	0.53±0.01	0.52±0.01	0.71±0.01	78.4±0.1	108.7±0.3
Freeflow	0.39±0.00	0.40±0.00	0.54±0.00	80.0±0.0	120.0±0.0

Table 1. Simulation results for VITS' speed update policy (i.e. vehicles' velocity adjusted on entering new links only) versus the suggestion of instant speed updates of vehicles in between two nodes [7].

6. Quality Assurance

From the simulation runs it can be seen that closing tunnel pipes of the river Elbe tunnel due to repair or reconstruction work will have a huge impact on the intermodal maritime transportation chain on metropolitan Hamburg´s bottleneck network which can be estimated.

7. References

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