Bottleneck-Analysis of Multimodal Transportation

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ABSTRACT

This paper presents an analysis to determine the impact of bottlenecks on multimodal transportation chains. A bottleneck-analysis in general is a process related approach to identify shortages. In relation to transportation it is concerned with analysis of resource planes, depth of optimization of multimodal transportation, consideration of timeliness and concurrency while using resources, analysis of transactions within the network, etc. This paper also show the development of the bottleneck analysis, experiments evaluating the impact on multimodal transportation, analysis of simulation results and conclusions

KEYWORDS

Bottleneck-analysis, best case analysis, worst case analysis, real case analysis, multi-criteria approach, scenario analysis

INTRODUCTION

Identifying shortages is of great value due to its immense impact onto the multimodal transportation chains. Hence in this paper an approach to determine the impact of bottlenecks onto the operation of multimodal transportation chains is introduced. In general a bottleneck-analysis is a process related approach to identify shortages. In relation to transportation a bottleneck analysis deal with

- Analysis of resource planes
- Optimization depth of multimodality transportation
- Consideration of timeliness and concurrency while using resources
- Analysis of transactions within the network,
- Etc.

Identifying of shortages on the one hand deals with discovering the dependencies within a sequence of actions, and on the other hand showing the dependencies through which the different components are conditional with their related actions. As a result of this, as case study approach, shortages can be identified which may show different intensive impacts on optimal or sub-optimal behavior of transportation processes. Hence the main advantage of a bottleneck-analysis is the possibility of the identification of shortages and, if possible, rectification on the very spot achieving optimal transportation chain.

In general the results obtained by a bottleneck analysis can be differentiated between best case results, worst case results, und real case results, based on the respective analytical approach. Assuming that the bottleneck-analysis in transportation deals with the calculation of the adequate availability of resources, the three different cases are:

- **Best Case Analysis**: resources for multimodal transportation chain are available and no shortage will appear. This result in a high priced solution, basically the resources available can't be used in an optimal way, because there are more resource available than necessary.
- **Worst Case Analysis:** resources for multimodal transportation chain are not available in the required amount or at the worst only one component is available but several of which are needed. Henceforth shortages will appear. Result is a cheap priced solution, basically resources available are not adequate.
- **Real Case Analysis:** real available resources for multimodal transportation chain have been taken into account. Basically the solution achievable is in between beast case and worst case because the results obtained by the real case analysis are sub-optimal.

Due to complexity and time and cost constraints, identifications of bottlenecks in the transportation chain are not trivial to do. Because identification and elimination of shortages is, from a general perspective, only a first step of finding the possible/optimal solution Because afterwards it can be discovered that the criteria based objective function, is sub-optimal due to another shortage, identified after the elimination of the first one. In general this will result in a specific iterative routine which the bottleneck-analysis has to pass through as long as the desired optimal transportation behavior is not achieved.

MULTI-SHORTAGE BOTTLENECK-ANALYSIS

A schematic sketch of several shortages used in our bottleneck-analysis is shown in Figure 1.

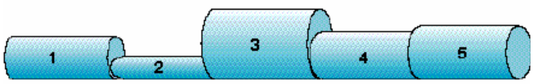

Fig.: 1 Bottleneck-Analysis with several shortages

The model principle behind the shortages, shown in Figure 1, is a hydrodynamic approach, which constitute a practical way in calculating flows. In multimodal transportation this can be assumed as trucks which have loaded containers at the container terminal of the harbor of Hamburg, driving now to their final delivery destination, or passengers in an airplane which have arrived at the airport of Hamburg and are still waiting for the airplane stairway to de-board the plane, etc.

Let the resource shortage be an airport shortage. Let the airplane stairway being component 1, the passenger bus being component 2. As a result of resource shortage the passengers have to wait at the very first for the stairway to be able to de-board the airplane and thereafter they have to wait for the passenger bus which is not present on time. Hence the passenger bus is the primary bottleneck in this case study.

In general the de-boarding process with its underlying transaction chain, as shown in Figure 1, contains the following components:

- Component 1: airplane stairway
- Component 2: passenger bus
- Component 3: baggage carousel terminal
- Component 4: baggage trolley
- Component 5: personnel baggage carousel

Based on this assumptions for the components in Figure 1, the bottleneck-analysis show a sequence of hidden shortages that 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 case study analysis, and the others are the secondary shortages.

Moreover, beside the set of shortages given by the used resources, weighting functions can be added to the components´, in order to calculate the respective output delay. In terms of an optimization of the resources' management, calculating the output delay as part of the transaction chain result in a more sensitive parameter, compared with the pure identification of the shortage caused resources´. Based on the output delay as part of a transaction chain the calculated transaction time is characterized from the point of time de-boarding the plane up to the arrival at the baggage carousel in the terminal.

In general the bottleneck analysis allow, as it is shown in Figure 1, the entire utilization analysis from sink to source, and concurrently the identification of opportunities for optimization. But rating an optimization has to consider the different views of stakeholders and the airport operator. The last mentioned will be a global view while the former be more local views. The views guessed can be local or global operating procedures, decision making processes, interpretation of data exchanged, optimization strategies, etc.

MULTICRITERIA APPROACH

As soon as shortages can be allocated, their impact on the overall time delay due to the sequences of hidden shortages can be calculated. This procedure result in the multi criteria approach, which is based on the assumption that several occasions have to be taken into account for decision making purposes, meaning that a set of alternatives exist, e.g. A ≠ 0. As consequence of the multi criteria approach, by calculation a weighting function $f : A \rightarrow R^q; q \geq 2$ has to be solved. Let $f_k : A \rightarrow R$, with $f_k(a) = z_k$ ($k \in \{1;\ldots, q\}$; $a \in A$), whereas $f(a) = (z_1;\ldots; z_q)$ is essential, than the weighting function is a so called criteria of the objective function. 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 f_k', be minimized, than the maximum criteria can be defined as a substitute for $f_k = - f_k'$.

AIRPORT BOTTLENECK-ANALYSIS

Assuming delays in air transportation one has to consider that the distinction between primary and secondary delays are based on the cause of the delay which is important for decision making.

Primary delays corroborate a belief in so called distributions of

- Flight time,
- Arrival time,
- Ground time.

- Accomplishable delay compensation through optimization of an objective function to that effect that, for example, the function will be maximized; for each criteria a higher value will be preferred opposite a lower value
- Accomplished improvement to compensate delay

Normally distribution assumptions are summarized in a model which allow statistical data analysis [1].

Secondary delays can be expressed as so called Domino-effect, because they start with the distribution assumptions' of the primary delays. Secondary delays in air transportation, as a consequence of primary delays, can for example, result in delays of connecting flights, that are scheduled in the respective time tables. The consequences of connection delays can be estimated with mathematical models which allow statistical calculations (see Chapter 3 in [2]). The outcome of which is a throughput estimation (see Chapter 5 in [3]) as result of the delay which from now on 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. Based on the previous described delay analysis and taking into account that a delay in the range of minutes is seen as problematical for the inner German air transportation schedule, a distribution graph can be composed which show the probability of delays over the time delay in minutes Based on composed distribution graphs shortages can be identified und their rectification through a representative selection of objective functions, following the multi-criteria approach, can be calculated, which finally results in appropriate adjustments.

Figure 2 show a composed distribution graph on this note. As it can be seen from Figure 2 the short time delays are dominant to form the probability model for the German air transportation schedule. Hence for the Bottleneck analysis it is of importance to identify whether the allocated resources for jobs on the Apron will run without shortages, which means that the jobs will be done in an optimal manner. Otherwise it must be proven whether the job can be done with a restricted number of alternatives', meaning a non empty set of alternatives´.

Moreover, Figure 2 shows that beside the short time delays mid term time delays > 10 minutes and longer could happen too, indicated by the column > 10 minutes. If time delays > 10 minutes up to > 60 minutes are taken into account, the previously composed distribution graph will become a saddle graph with two maxima

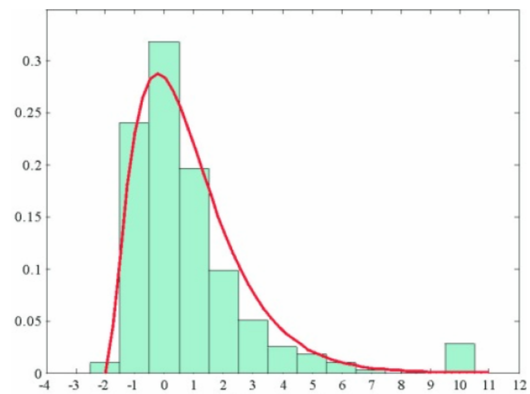

Fig.2: Distribution graph of delays (Abscissa: time delay in minutes, negative sign show earlier arrival; Ordinate: Probability of delays)

ELBTUNNEL BOTTLENECK-ANALYSIS

To analyze the impact of traffic shortages due to closing of one or more tunnel tubes of the river Elbe tunnel in Hamburg for maintenance and/or reconstruction work, as well as a terrorist attack which may destroy one or more tunnel tubes, a traffic network model was developed, based on a slight modification of VITS (Virtual Intermodal Transportation System), that supports multi-modal traffic and provides a reasonable tradeoff between macroscopic computational efficiency and microscopic/agent-oriented accuracy that require data nearly impossible to obtain. The traffic network, a graph, based approach, consist of nodes and links. For the road mode trucks and cars can be modelled individually, i.e. attributes including current location, speed, and destination are assigned. Vehicles stochastically appear at any node (inter-arrival time is exponentially distributed) and traverse fixed routes, i.e. a sequence of road links, reaching their destination. Each vehicles´ speed on link *i* currently traversed is sampled from a normal distribution with mean set such that the expected link travel time $\hat{t}_i$ amounts to

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

subject to free flow travel time t_i (depending on speed limit), link capacity C_i, and flow during the last period x_i. Flow x_i and link capacity C_i are measured in terms of cars, using an equivalence factor of 2.5 cars per truck. The non-freight car traffic flow x_i is chosen such that trucks account for 25% of overall traffic. All Vehicles´ speeds are updated every 7.5 minutes.

The application area the traffic simulator was developed for (but not limited to) is 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, or destroyed tunnel lanes, as a consequence of a terrorist attack, 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 analyzed, are sufficient with respect to given target performance measures for further enhancement. Figure 3 depicts the Hamburg bottleneck network, consisting of 16 nodes (of which seven are network boundaries) and 18 links. Most nodes denote freeway junctions or exits; in this topology (that does not claim to reflect a level of detail sufficient to produce valid results).

The bottleneck analysis is based on the following specific assumptions:

- Elbtunnel has been destroyed by a terrorist attack
- Vehicles travel detour through the city of Hamburg, 150.000 vehicles per day
- Bottleneck analysis done based on the case study routes from
    - Flensburg to Hannover
    - Hannover to Flensburg
    - CTA via junction Waltershof

Table 1. Experimental results: Topology as shown in Figure 3, with traffic traverse the City of Hamburg.

Title	Obs	Mean	Min	Max
Vehicle travel time BAB_nach_Flensburg_10-BAB_nach_Hannover_13 (Truck)	8209	4.64422	0.77415	11.24317
Vehicle travel time BAB_nach_Hannover_13-BAB_nach_Flensburg_10 (Truck)	8561	3.4221	0.77415	8.88513

CONCLUSIONS

From the simulation runs it can be seen that a potential terrorist attack on the river Elbe tunnel will have a huge impact on the transportation chain on metropolitan Hamburg´s, bottleneck network, which can be estimated.

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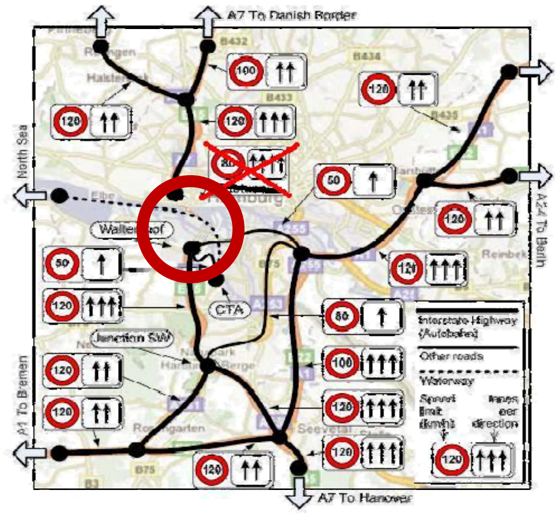

Fig. 3: Hamburg Network without Elbtunnel passage

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