Optimization of back freight Transportation systems

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Abstract:
The optimization of the transport route by reducing empty runs to the maximum possible extent is of major priority in roundwood transportation due to increasing fuel costs and for decreasing CO_2 and other GHG emissions. A swap of similar roundwood piles with shorter transport distance to other industry destinations (wood-swap) by solving the transportation problem and the subsequent optimized cyclical route selection of cooperating industries enable this. The spatial analysis of the solution of the transportation problem in combination with the analysis of catchment areas using THIESSEN-polygons seem important elements for both the strategic planning of sales activities and the catchment areas for forest roundwood products.

Keywords: roundwood transportation, back freights, optimization, distribution logistics, transportation problem, reduction of empty runs

1 Introduction

In Germany between 40 to 50 mill. m³ of roundwood annually are transported by truck. Assuming a payload of 28 m³ per truck and an average transport distance of 160 km per load result in about 1.5 mill. trips with a total transport distance of approximately 200 mill. km p.a. Hence, at an average fuel consumption of 43 litres of diesel per 100 km for loaded roundwood trucks each transported m³ of wood is charged with about 2 litres. Taking no technological modifications into account there are two possible solutions for a reduction of the total transport distance: the swap of roundwood piles (wood-swap) on the one hand and the optimized route selection on the other. A further cooperation of wood mills enables the combination of both.

2 Environment description, definitions and literature

In Germany roundwood carriers are mostly independent contractors with usually no more than one ore few trucks that are usually only suitable for the transportation of roundwood assortments. They are furthermore specialized in regional transport, operating within a radius of < 200 km. A forest owner or wood purchaser concludes a contract for the roundwood transport order directly with the carrier and the payment is regulated as a function of distance through freight rates. The carrier is then responsible for the timely delivery of the roundwood to the destination and for the organisation of the trips from and to his base. On average loading and unloading accounts for 80 minutes and the driving times are restricted to eight hours per day. Carriers mostly work for several customers which they choose with regard to the location of the place of loading and the destinations in order to generate back freights. Due to limited information on the piles in a given region, a carrier can only compile a certain proportion of the overall possible back freights.

A transport route can be defined as a cycle with an identical starting point and destination. Here the shortest route mill-pile-mill shall be named 1-cycle or normal route (fig.1, left). In the figures the circles represent the piles or sources and the squares the mills or sinks respectively. Furthermore, cargo runs of the trucks are presented as solid and empty runs as dotted lines.

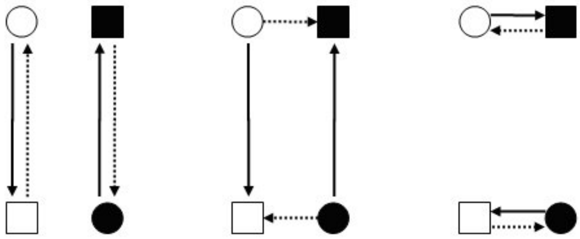

Figure 1: Normal route (left), 2-cycle with reduction of empty runs by back freight (middle) and the so-called "transportation problem" with swap of the piles (right), squares = mills, circles = piles.

There are two classes of assortments in a given region:

- Competing assortments are of a similar type and can thus be allocated to several mills
- Non-competing assortments can only be assigned to one single mill.

This classification is valid on a regional base. Industrial roundwood might e.g. be a competing assortment in a region with several pulp mills whereas in another one with several sawmills and one pulp mill it might be a non-competing product.

The reduction of empty runs and route optimization in roundwood transportation are both issues deemed promising in the forestry literature, yet applicable procedures, methods and realized examples are relatively rare (HIRSCH, 2006). DOMSCHKE (1997) describes basic procedures for the computation of optimal routes in spatial networks as well as linear transport and transhipping problems. Generally spoken, a tour exists of a number of locations and road sections that are affected by a means of transport (BLÖCH a. IHDE, 1997). An optimal route is a tour where all locations and road sections have to be reached or passed under definite conditions. This problem is known as the *travelling salesman problem* (Route of minimal length through several cities, GRITZMANN a. BRANDENBERG, 2005, p. 290) or as the *Chinese postman problem* (Route of minimal length to all post boxes of an area, GRITZMANN a. BRANDENBERG, 2005, p. 231). Theoretically, the travelling salesman problem can be transferred to roundwood transportation, where the number of cargo runs from the different forest locations to the different mills corresponds to the shortest routes on the road network. A tour connecting these cargo runs with minimal empty runs then is the route of a "travelling salesman". An extension to that is the *Vehicle Routing Problem*, also known as the multiple *travelling salesman problem,* where goods are delivered from central depots to different customers. The round trips correspond to the tours of the single trucks with limited carrying capacity (GOLDEN et al. 2008). Generally heuristics like tabu search are used for the solution of these problems (GLOVER, 1986, GLOVER u. LAGUNA, 1997). HIRSCH (2006) modifies the description of the *Vehicle Routing Problem*, as he defines the carrier's home base exclusively as a depot, being starting point and destination of a day's route. The optimization is being carried out for a certain time frame and a given number of piles that are allocated to distinct destinations. Restrictions for the optimization are: opening hours of the mills, driving hours, gross vehicle weight limitations on the forest roads as well as maximum carrying capacity. The cargo runs are then to be connected to form routes of minimal costs under the given restrictions. HIRSCH (2006, 2010) uses the tabu search heuristics mentioned above for the optimization of roundwood transport. CARLSSON a. RÖNNQVIST (2007) try to compute back freights directly using linear optimization which results with an increasing number of mills and piles in a rapid increase of variables. Others aim at optimized delivery times in the mills, try to optimize the wood transportation processes under the aspect of the wood supply chain (BODELSCHWINGH, 2006, BAUMANN, 2009) or analyze roundwood transportation costs (BORCHERDING, 2007).

3 The Transportation problem

In a paradoxical - yet likely probable - transport situation two carriers pass each other transporting competing assortments on normal routes in opposite directions (fig. 1, left) Swapping the piles based on cooperation of the customers would lead to a minimal transport distance (fig. 1, right).

Already in 1939 KANTOROWICZ pointed out the problem of the distribution of goods in his book "Mathematical methods in the organization and planning of production". Programmatically he writes here: “There are two ways of increasing the efficiency of the work of a shop, an enterprise, or a whole branch of industry. One way is by various improvements in technology; that is, new attachments for individual machines, changes in technological processes, and the discovery of new, better kinds of raw materials. The other way - thus far much less used - is improvement in the organization of planning and production.” In the year 1941 F. L. HITCHCOCK published a paper entitled „The distribution of a product from several sources to numerous localities“, where he names the problem to solve the *transportation problem*. Here the distribution of piles (storage locations of wood in the forest; sources) to the mills (of the wood industry; sinks) has to be computed in a way that the mills’ demand is covered and the total distance of all transport routes is minimal (HITCHCOCK, 1941).

To achieve an exact solution to the transportation problem, DANTZIG developed in 1966 (p. 343) a formal procedure. The piles p_i, $i = 1 \ldots m$ at the forest locations $F_1 \ldots F_m$ function as sources. Each pile consists of a certain number of truckloads of the same roundwood product regarding species and assortment. The piles are to be transported to the mills of the wood industry $W_1 \ldots W_n$ with the respective demand $b_1 \ldots b_n$. c_{ij} represents the transport distance from forest location i to mill j and the number of truck loads from forest location i to the consumer j is x_{ij}. The target function to be minimized is thus:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} c_{ij} \qquad [1]$$

The piles of the forest locations here cover the mills’ demand, which result in the equations [2] and [3]

$$\sum_{j=1}^{n} x_{ij} = p_i \qquad i = 1 \ldots m \qquad [2]$$

$$\sum_{i=1}^{m} x_{ij} = b_i \qquad j = 1 \ldots n \qquad [3]$$

furthermore

$$\sum_{i=1}^{m} p_i = \sum_{j=1}^{n} b_j \qquad [4]$$

Moreover, within the given index range it is $x_{ij} \geq 0$. The system of equations of the simplex-tableau can be developed from [1], [2] and [3] with [1] as the target function (DANTZIG, 1966, p. 345). Here the sources cover the demand at the sinks and the supply from the wood sources corresponds furthermore to the demand at the sinks.

Example: In the 2010 fiscal year the Bayerischen Staatsforsten (Bavaria State Forest Enterprise) marketed approximately 2.9 mill. m³ of softwood super-regionally. (SMALTSCHINSKI et al. 2011). The traditional planning solution of the central Bavarian sales organisation (fig. 2, left) has been compared to an optimized solution (fig. 2, right). The optimization results in savings of 2.2 mill. km, or almost 12 % of the total transport route. The average transport distance from forest to mill for the different assortments can be derived for an economic assessment of transport distances and sales proceeds.

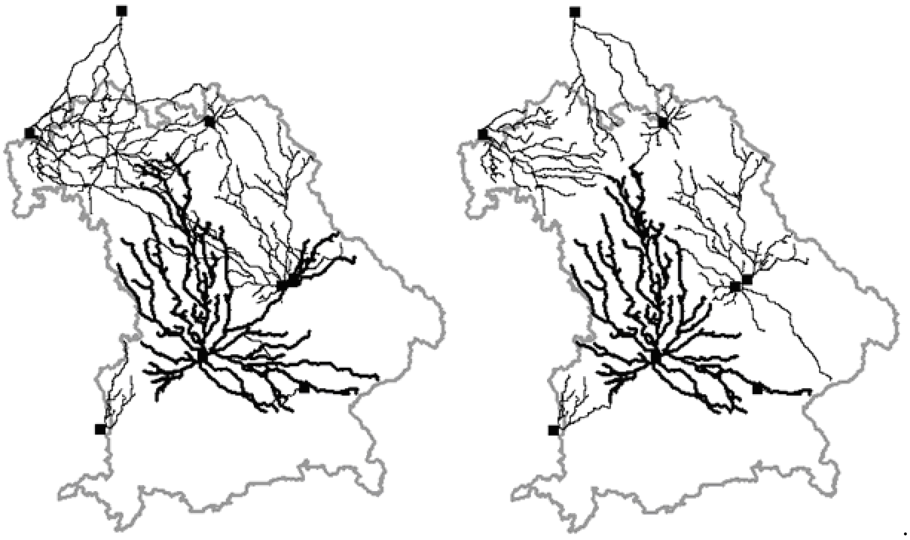

Figure 2: Assortment: pallet pine. Routes after traditional planning (left) and routes after optimization (right), routes to the mills black, to one mill bold black, country border grey.

The optimized transport routes identified resemble river systems separated by watersheds (Fig. 2, right). Conversely, for a particular assortment, optimized catchment areas for mills can be derived from the optimized transport routes. This spatial analysis of catchment areas assists strategic planning to identify regarding transport the optimal customer locations for the different assortments. Thus the paradoxical transport situation, in which two trucks transporting the same assortment in opposite directions pass each other en route, will no longer occur with optimized allocation. The depicted approach results overall in a clear reduction in transport distances and thus transport costs, but also in a reduction in CO_2 and other GHG emissions from roundwood transport.

4 Optimization of cyclical routes

Back freights or the reduction of empty runs in the transport of roundwood are related to a certain number of sinks (mills of the wood industry) and to their associated sources (piles of roundwood in the forest). The traditional way of reducing empty runs through the generation of back freights equals a 2-cycle with a pair of corresponding piles and mills (fig. 1, middle). A reduction of empty runs is possible under the condition that the following inequation is true:

$$\Sigma \text{ cargo runs} > \Sigma \text{ empty runs} \qquad (5)$$

The inequation described (5) is only reasonable for optimally allocated competing products after solving the transportation problem. Otherwise a swap of piles would be worthwhile (fig. 1, right). In the calculations the optimally distributed competing products can be included after the swap with the non-competing products.

For several mills (n > 2) there might be spatial constellations of piles and mills, where the distance of empty runs can not be reduced with 2-cycles (fig. 3, left) The computing time increases with 3-cycles as more combinations need to be checked regarding condition [1]. Fig. 3 right shows the different combinations of tour sequences for three mills without consideration of the piles.

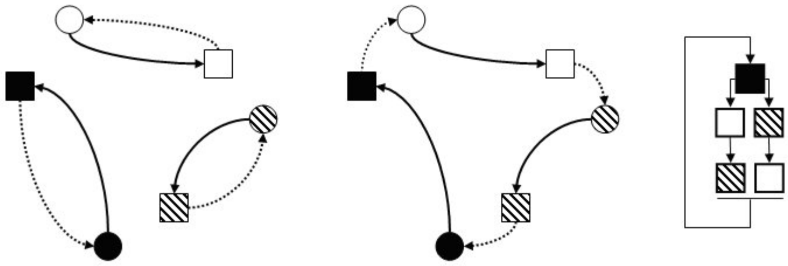

Figure 3: Three sinks (squares) and three sources (circles). Normal routes with 1-cycles (left), reduction of empty runs 3- cycles (middle), combinations of cycles for 3 mills (right).

The starting point of such a circle route is irrelevant: a cycle through the mills (1, 2, 3) is identical to one through the mills (2, 3, 1). Analogous to fig. 3., cycles to the order n can be compiled for n mills (n-cycles). Given that n is the number of mills and k is the order of the maximal possible cycle, the equation (6) generally describes the number of cyclic route combinations (SMALTSCHINSKI, 2010):

$$Z_{n,k} = \sum_{i=2}^{k} \binom{n}{i} (i-1)! \qquad \text{with } 2 \le k \le n \qquad (6)$$

Equation (6) indicates the number of route combinations to check at an optimization. It shows that the number of combinations increases for k = n with increasing n so dramatically, that calculations for about 40 mills require already very long computation times. The gradual optimization involves all possible combinations of sinks and sources, for which the sum of empty runs is less than the sum of cargo runs (5). The optimal cycle will be selected, the pile statuses are updated by the cargos realized, and the procedure starts again until 2-cycles or cycles of higher order are no longer possible. For a given number of sinks the procedure has the disadvantage of a rapid increase in the number of combinations, with an effort of **O**(n!). Regarding this increase, the problem is NP-hard.

5 Test with five catchment areas

Initially the solution of (6) seems unwieldy due to the high computing time. Therefore an experiment has been conducted to analyze the gain in accuracy for higher cycle combinations for an area of the dimension 120 times 120 km. There were five mills of the wood industry in this area and along forest roads 150 piles had been placed, each between one and nine truck loads of size, generated from random numbers. This resulted in 712 single truck loads. The catchment areas oft he mills were defined by THIESSEN-polygons with their inherent characteristic that each point within a polygon has a shorter distance to its respective centre (mill, plant) than to the other polygon centres. Four variants have been calculated with identical location of the piles but different allocation of the roundwood to the mills (fig. 4). At first the piles of variant 0 had been allocated to the mills randomly and then the percentage of pile allocation to the mills‘ catchment areas had been increased to: 50 % for variant 1, 75 % for variant 2 and 100 % for variant 3. For these four variants the route combinations $Z_{5,k}$, with k from 2 to 5, have been calculated. The results are shown in fig. 5.

6 Discussion of the results

The result disproves the assumption that a higher complexity in calculations also results in a clearly higher precision. Already for $Z_{5,3}$ the difference to $Z_{5,5}$ drops clearly below 1 %. In (6) with k smaller n the approximation towards the optimum happens very rapidly, taking less than one minute for the optimization calculation. The presented combinatorial procedure seems more efficient regarding time than heuristic approaches or linear programs. The degree of possible reduction of empty runs largely depends on the spatial location of the piles and the mills. The highest total driving distance of the normal routes (82.000 km) and the largest reduction of the transport distance (30 %) due to reduction of empty runs can be achieved if the piles allocated to the mills were randomly distributed in variant 0 across all catchment areas. Consequently the total driving distance of the normal routes decreases (63,000 km variant 1, 46,000 km variant 2) as well as the proportion of the reduction of empty runs (24 % and 15 % respectively), the more piles are within the mills' catchment areas. The total driving distance of the normal routes reaches a minimum of 31,072 km, in variant 3 – a result that cannot be achieved by reduction of empty runs in any of the other variants.

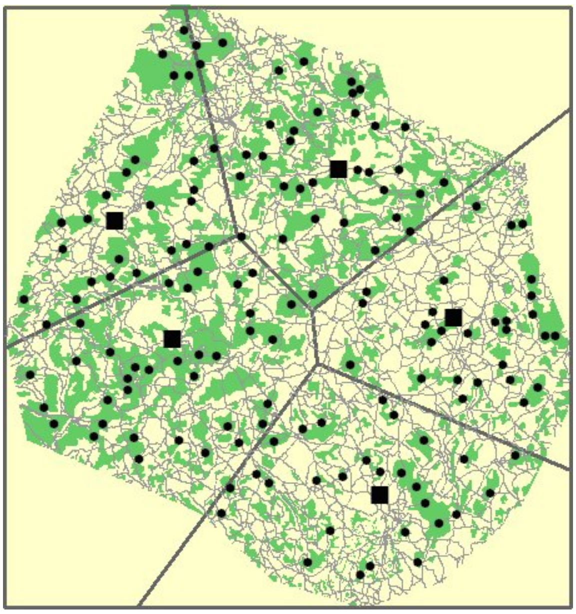

Figure 4: Research area with 5 mills (squares), 150 piles (points), roads and THIESSEN-polygons as catchment areas of the wood industry. Extent is approx. 120 x 120 km.

The catchment area (THIESSEN-polygons) of a sink has the highest impact on the reduction of empty runs or the overall length of a transport route (= sum of empty and cargo runs). Here, the catchment areas were computed as THIESSEN-polygons. One of the characteristics of these polygons is that every point within a polygon has a smaller distance to their own center than to the other centers. In different variants, the sources were more and more concentrated within the catchment area. The more the sources disperse around the catchment area, the larger becomes the reduction of empty runs; however, the total length of the transport route also increases. The compensation of this increase by the reduction of empty runs never reached the minimum sum of route lengths, provided that all sources were located in their catchment areas and a reduction of empty runs was no longer possible. In any case, the application of combinatorial reduction of empty runs is only reasonable after the solution of the transportation problem (fig. 2, right).

On average, the reduction in transportation costs is proportional to the reduction of empty runs. The analysis of catchment areas and positions of the sources provides answers regarding the location of a mill and its dimensioning with respect to roundwood supply and transportation costs. The combined analysis of the type of sales and of the catchment areas results in new aspects for the strategic planning of forest enterprises. Moreover it is also suitable for application in companies of the wood industry to shape the distribution areas of the roundwood supply to its mills in the context of its business environment. Thus it constitutes a holistic approach for strategic planning in a business environment where forestry and industry are not integrated. A reduction of empty runs either leads to lower transportation costs or, at constant transportation costs, allows a larger catchment or distribution area of the mill.

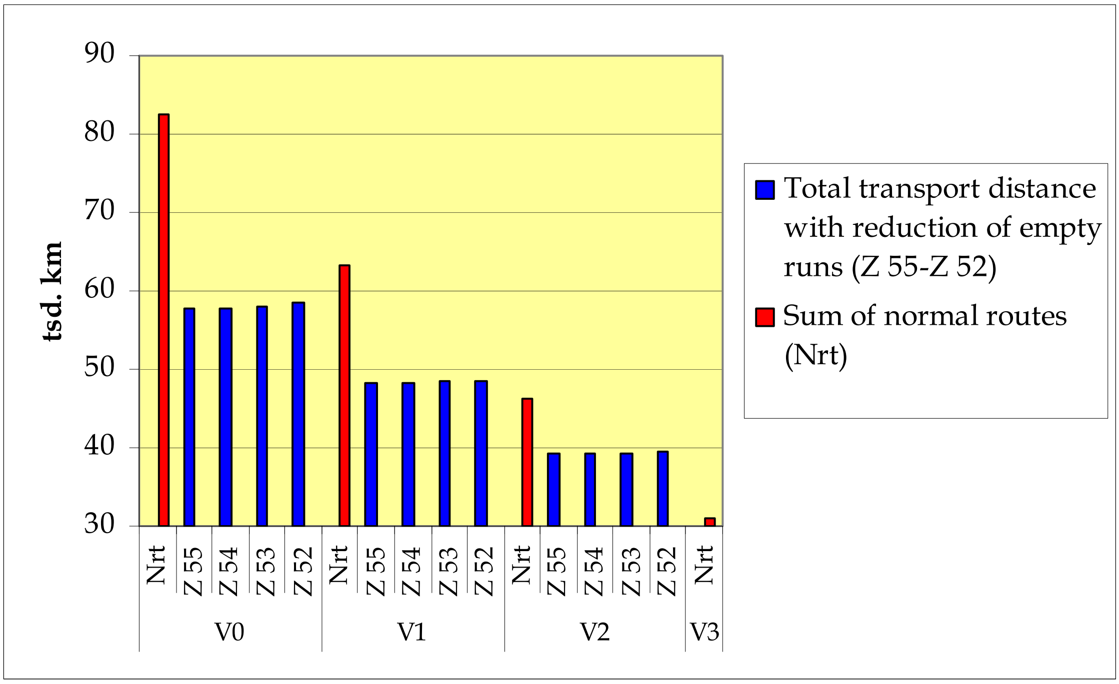

Figure 5: Results of the optimization by reduction of empty runs for the variants V0 to V3 and different cycle combinations from (3).

Increasing transportation costs continuously gain more importance as a limiting factor for the roundwood supply. This can only be compensated to a certain extent by the reduction of empty runs. Hence it might again be of increasing relevance in the future to orientate the location and the production capacity more towards the available roundwood supply in the natural catchment areas. This also holds for the distribution of competing products from the forest to the mills.

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