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Research Article

Timber Transport – Reduction of Empty Runs by Back Haulage and Triangle Routes

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Abstract

Back haulage or triangle routes are a suitable means of achieving a reduction in empty runs in timber transport. The calculation is done using linear programs. One problem with linear programs is the high complexity caused by the combinatorics involved in generating the routes. This can be reduced if the characteristics of back haulage or triangle routes are taken into account. The complexity then drops drastically and well-compatible linear programs are obtained. The methodology presented in this study was tested for the harvest sizes of the 2015 fiscal year of the Bavarian State Forest Enterprise. Pure back haulage routes lead to a reduction in empty runs of 17.2% and the combination of back haulage and triangle routes lead to a reduction of 20.2%.

Introduction

The routes used to transport timber generally consist of around 50% of trips without cargo. The study aims to reduce empty runs in timber transport through back haulage or triangle routes. A reduction in empty runs at this amount, in any case, has the following advantages:

- Reduced empty kilometers
- Lower costs and emissions
- Increased revenue
- Boost asset utilization
- Increasing transport capacity
- Optimized fuel consumption

These advantages leverage the efficiency of a company. In the forestry sector, the first studies on modeling back-hauling routes were carried out by Carlsson and Rönnqvist [1]. Palander, et al. [2,3] developed a back haulage model, to minimize the transport costs for direct transport (one-way) and back haulage routes (two-way) for k assortments. Back haulage routes were combinations of two one-way routes. A similar model minimizing empty runs through back haulage was developed by Carlson and Rönnqvist [4]. Determining optimal allocations of timber were combined with all possible back haulage routes and solved together. The models cited above lead to an enormous number of decision variables; however, they are still referenced today [5]. Further studies embed back haulage models in the optimization of the supply chain [6] or are solved implicitly through the vehicle routing problem [7]. The complexity of the optimization models increases significantly and they become NP-hard. Solutions are found by applying meta-heuristics, evolutionary or swarm algorithms [8], or hybrid genetic algorithms [9]. As an alternative, mixed-integer linear programming formulations and column generation algorithms can also be used [10].

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All of these models share the characteristics of high complexity, as they all rely on the ability of linear programming to expand the full combinatorics of all nodes well beyond the need to discover, in particular, back haulage routes or other cycles.

This study is limited exclusively to the methodology of reducing empty runs. The analysis of back haulage and triangular routes results in criteria that allow for routes whose decision variables lead to improving the result. This approach leads to a dramatic reduction in the complexity of the programs without affecting the optimization result.

Method

The methodological development is based on a region with forests in which the quantities of k assortments have to be transported from sources to sinks. An available network of roads forms the basis for calculating the shortest distances (times, transport costs) from all available sources to all sinks. In general, the calculations are performed using the algorithm of Dijkstra [11], and the results are stored in a cost relation with the attributes (source, sink, km). The supply of sources or the demand for sinks may consist of a single or several assortments. The reduction of empty runs shall be calculated by a linear program with $z = c^T x \rightarrow \max$ as objective function subject to $A x \leq b$. The vector c refers to the reduction of empty runs, and the vector x of decision variables refers to back haulage or triangle routes. The matrix A contains the incidence values of these routes, whereas the vector b refers to the supply of the sources and the demand of the sinks defined by truckloads as transport units (tu). Then, the possible sets of various transport routes strictly follow logical definitions and constraints in the model derived because of elementary combinatorics and arithmetics. The following definitions hold:

- In general, an assortment is defined by tree species, length, mean diameter, and quality. On the other hand, pulpwood can consist of spruce and pine. The definition of an assortment depends on regional practices.
- A 1-cycle is the most common route while transporting timber. This cycle is defined by a source f, a sink t, and an assortment a. The triple (f, t, a) defines the route t→f→t. The edge f→t of the route is a cargo run, and the edge t→f is an empty run. The length of cargo and empty runs are assumed to be equal. (Figure 1).
- A 2-cycle (back haulage) is the combination of two 1-cycles (f1, t1, a1) and (f2, t2, a2) both cargo runs are connected by empty runs in the form t1→f2→t2→f1→t1. The empty runs in a 2-cycle are t1→f2 and t2→f1 (Figure 1).
- A 3-cycle (triangle route) is the combination of three 1-cycles (f1, t1, a1), (f2, t2, a2) and (f3, t3, a3). The three cargo runs are connected by empty runs in the form t1→f2→t2→f3→t3→f1→t1. The empty runs in a 3-cycle are t1→f2, t2→f3 and t3→f1 (Figure 1).
- A cost table with the attributes (f, t, km) is available to determine the distances of cargo and empty runs. The sum of cargo runs of a 2- or 3-cycle is called ckm and the sum of empty runs is ekm. The reduction of empty runs is defined by rer = ckm − ekm, which is a measure of the efficiency of a 2- or 3-cycle. The objective function $c^T x$ contains rer for the costs.
- Other impedances include the costs of transport or emissions. In Central Europe, the transport costs refer to the cargo runs and are a linear relationship of the form c = a + b km. The emissions as costs relate to the consumption of a truck. In Central Europe, the consumption of a truck is 42 liters of fuel for cargo runs and 34 liters for empty runs. A constant factor for loading and unloading should be added. Both impedances depend linearly on the variable distance in km.

Figure 1 initially shows a standard 1-cycle with an empty run share of 50%. Next to the right follows a 2-cycle, where two cargo runs are connected by shortened empty runs. It doesn't matter whether the truck starts at the black or white sink; always the same cycle is performed. Only one of the two options shall be included in a linear program to avoid redundancies. In the 2-cycle shown, the assortments are different.

If the assortments are the same, then by exchanging the assignments of sources to sinks (Figure 1, exchange of sources), two 1-cycles with the shortest possible lengths of empty and cargo runs are formed. The two 1-cycles then have an optimal distribution. Back freight with a reduction in empty runs therefore is no longer possible. This situation changes if a white assortment is added to the two black assortments (Figure 1, 3-cycles). The three cargo runs can be connected by empty runs, whereby the sum of the empty runs is significantly shorter than the sum of the cargo runs. In any case, 2- and 3-cycles are only valid options if the sum of the cargo runs is greater than the sum of the empty runs.

These obvious preconditions need to be considered when forming 2- or 3-cycles. Otherwise, if not, their number and the number of related decision variables will increase extremely and may lead to runtime excess and possibly numerical problems when solving such a linear program. However, the increase in decision variables can be drastically reduced if

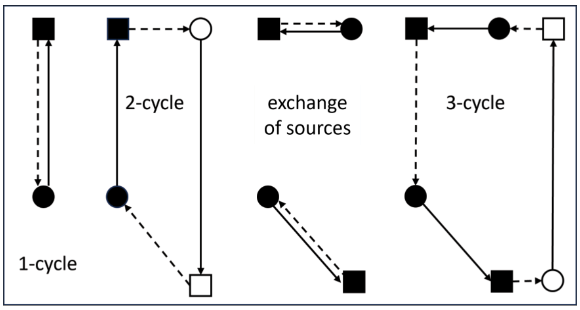

Figure 1: The different types of cycles. Circles ● sources, squares ■ sinks, black and white □■○● indicate different assortments. Dotted lines … follow empty runs, solid lines _ are cargo runs.

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a-priori information derived from the cycle rules is used, as shown above, which excludes redundant decision variables or those variables that do not contribute to improving the result of the linear program. The feasible region of the linear program is not touched nor restricted by this approach. This can be shown for 2-cycles that meet the following criteria to reduce the number of decision variables:

1. An optimal distribution of the quantities of wood for each of the k assortments corresponds to the solution of the well-known Transportation Problem [12]. The solutions of the k Transportation Problems form a relation C1 with the attributes (f, t, a, tu), where f and t denote the nodes of sources and sinks for a certain assortment a, with the transport units flowing from f to t. C1 has significantly fewer allocations for an assortment, as was the case before the linear program was solved. The 1-cycles of C1 form the material to construct 2-cycles. This leads to a first fundamental reduction of possible 2-cycles and results in a minimum transport distance with 1-cycles.

2. 2-cycles are the combination of two 1-cycles (f1, t1, a1) and (f2, t2, a2) from C1. The equation a1 = a2 then applies to a single assortment. As a solution set for the Transportation Problems, C1 contains a minimum distance, which refers to the empty as well as the cargo runs. This minimum cannot be further reduced (Figure 1, exchange of sources). Consequently, 2-cycles cannot be created for a single assortment, which could lead to a reduction of empty runs. This holds for all combinations of 1-cycles a1 ≠ a2. Furthermore, the 2-cycles (f1, t1, a1, f2, t2, a2) and (f2, t2, a2, f1, t1, a1) describe the same cycle. The condition for a valid 2-cycle can be tightened to a1 < a2. The possible combinations decrease by a little more than half because there are only k(k-1)/2 ways to combine two of k assortments.

3. The 2-cycle (f1, t1, a1, f2, t2, a2) also contains the edges f1→t1 and f2→t2, which initially only differ in the assortments a1 and a2. However, if the edges are collinear or overlap at sources or sinks, then no reduction of empty runs is possible. This gives the conditions f1 ≠ f2 and t1 ≠ t2. In practice, these conditions correspond to a zero dot product of the two vectors f1→t1 and f2→t2. As a result, the number of 2-cycles shrinks by about another third.

4. A reduction in the length of empty runs is only possible, if for instance in a 2-cycle the sum of the cargo runs is greater than the sum of the empty runs: rer > 0. This last requirement further reduces the number of valid 2-cycles down to a very small fraction.

All 2-cycles that meet these four criteria form a relation C2 with the following attributes (f1, t1, a1, f2, t2, a2), and it is possible to create a linear program with a reduced number of decision variables. The rows of C2 align with the columns of matrix A in a compact form. The row numbers of C2 return the index values of the tuples of the vector x and the associated cost vector c yields a reduction of empty runs (rer). The objective function $z = c^T x \rightarrow \max$ can be filled directly with these values of C2.

Not all 1-cycles of C1 result in valid 2-cycles. This reduced set of allocations forms the supply of the sources from which the demand for the sinks is determined as the sum of the transport units grouped by sinks and assortments. The information for supply and demand determined in this way depends on the assortment and is used to derive the incidence values of the matrix A and to determine the constants of the vector b. This procedure reduces the rows of A by about a tenth.

The whole linear program with the objective function $z = c^T x \rightarrow \max$ subject to $A x \le b$ is now defined and a solver can do its work. The solution set $x_i > 0$ indicates which 2 cycles are run through and how often. An update for $x_i > 0$ of the 1-cycles of C1 in the form $tu_{C1} = tu_{C1} - tu_{C2}$ results in the remaining 1-cycles.

3-cycles are all combinations of three 1-cycles from C1. Criteria 1 and 4 also apply to 3-cycles. The following criteria 5 and 6 are modifications of criteria 2 and 3:

5. For the assortments of 3-cycles in the form (f1, t1, a1, f2, t2, a2, f3, t3, a3) the inequalities a1 < a2 and a1 ≤ a3 apply. At least one assortment must be different to form a valid 3-cycle (Figure 1, right). The number of possible combinations of 3 from k assortments, taking into account the cyclicity and the inequalities, is $\Sigma\ (k - i)\ (k+1 - i),\ i = 1 \ldots (k-1)$. For $k \in [3, 15]$ the possible combinations are reduced by two-thirds.

6. All sources and sinks of a 3-cycle have to be different. Therefore, these inequalities hold: f1 ≠ f2, f1 ≠ f3, f2 ≠ f3, t1 ≠ t2, t1 ≠ t3 and t2 ≠ t3. The combinations decrease by another third.

Valid 3-cycles form a relation C3. C2 and C3 or back haulage and triangle routes may be combined in a single linear program. Analogous to 2-cycles, the matrix A is filled with the new incidence values of 2- and 3-cycles. The linear program is readily prepared for a solver. After solving the linear program, C1 should be updated analogously to 2-cycles to find the remaining 1-cycles.

The method just presented is two-stage by its intended construction. The first stage consists of solving the Transportation Problem for k assortments.

The second stage refers to the construction of the linear program $Ax \le b$ with the objective function $z = c^T x$ to be maximized to calculate the reduction of empty runs. The decision variables are $x_1 \ldots x_m$ for 2 cycles with four incidence values in the matrix A and $x_{m+1} \ldots x_{m+n}$ for 3 cycles with six incidence values. All 2-cycles have to satisfy conditions 1 to 4 and all 3-cycles have to satisfy conditions 1, 2, 5, and 6. The costs c_i (i = 1 … m or 1 … m+ n) of the objective function relate to the reduction of the empty runs. For each column of the matrix A, its value is (sum of cargo runs) – (sum of empty runs) > 0 (conditions 4 and 6). The objective function $z = c^T x$ should be maximized. The vector b contains the truckloads to be transported for sources and sinks that correspond to

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the solutions of the Transportation Problem. The relational operator is '≤' since not all transport units can be integrated into 2- or 3-cycles.

The resulting assignments of the solution set form the basis to generate 2- and 3-cycles. Criteria 2 to 6 act as filters that eliminate redundant cycles or those that do not lead to any improvement in the solution.

Example

The results of the method will be shown using an example. In a study area, transport units of timber (tu) are stored at sources 701 to 704, consisting of the assortments of pulpwood and sawlogs which are required by sinks 101 to 103. Table 1 contains the necessary data on supply, demand, and costs.

Without prior knowledge of the properties of 2-cycles, all possible assignments of sources to sinks are examined. The assortment sawlogs has 3 assignments and the assortment pulpwood has $4 \times 2 = 8$ possible assignments. The combination of these 11 assignments then results in all conceivable 2-cycles, which form 121 decision variables in a linear program.

The first stage of the method refers to solving the Transportation Problem for each assortment. The result is an optimal distribution for each assortment with a minimum sum of transport routes from sources to sinks. These assignments are 1-cycles (Table 2).

From another perspective, solving the Transportation Problem for an assortment corresponds to a systematic exchange of source-to-sink assignments to achieve minimum impedance (Figure 1, exchange of sources). For example, the assignments have a minimum distance of 36,300 km and a total distance of 72,600 km.

The second stage of the method relates to the generation of 2-cycles and the elimination of unsuitable cycles. The optimal assignments after solving the Transportation Problem deliver the material to generate 2-cycles. These assignments are optimal and may no longer be touched. The number of these assignments drops from 11 to 7 in the example. The combination of C1×C1 only results in 49 2-cycles.

Further analysis of these 49 2-cycles leads to the following insights:

- 2-cycles for a single assortment do not lead to a reduction in empty runs.
- 2-cycles for different assortments are available twice in C1×C1. One is redundant and needs to be eliminated.

These cycles can be excluded using a filter for assortments: $a1 < a2$ (criterion 2, Ch. 2). Applying this filter to the example, 2-cycles are only generated from the optimal assignments of sawlogs and pulpwood. The number of 2-cycles drops down to $3 \times 4 = 12$ decision variables.

Using the optimal distribution, 2-cycles can occur like (101, 703, 102, 703, 101) (Figure 2). Source 703 contains both assortments and the dot product of the 1-cycles involved is greater than zero. Such cycles without a reduction in empty runs can be excluded by the filter: $f1 \neq f2$ and $t1 \neq t2$ (criterion 3, Ch. 2). In the example, the number of valid 2-cycles or decision variables again shrinks from 12 to 9.

For these nine 2-cycles, the reduction of empty runs (rer) is calculated. As a result, only three 2-cycles remain where rer > 0 (Table 3, C2).

The relations C2 (Table 3) contain all the information necessary to determine the linear program to maximize the

Table 1: Data of the example.

Supply			Cost		
Type	a	tu	f	t	km
701	sawlogs	100	701	101	95
701	pulpwood	100	702	101	70
702	sawlogs	100	703	101	32
702	pulpwood	100	704	101	64
703	sawlogs	100	701	102	123
703	pulpwood	100	702	102	92
704	pulpwood	100	703	102	40
Demand			704	102	50
t	a	tu	701	103	32
101	sawlogs	300	702	103	30
102	pulpwood	100	703	103	95
103	pulpwood	300	704	103	64

Table 2: Solution of the Transportation Problem for the example.

C1			
f	t	a	tu
701	103	pulpwood	100
702	103	pulpwood	100
704	103	pulpwood	100
703	102	pulpwood	100
701	101	sawlogs	100
702	101	sawlogs	100
703	101	sawlogs	100

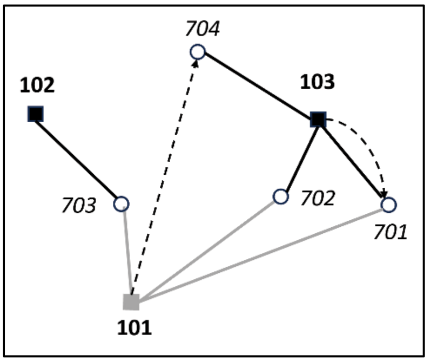

Figure 2: Reduction of empty runs by 2 cycles and the solution of the Transportation Problem (Dotted lines are empty runs and solid lines cargo runs, white circles are sources and squares sinks. The colors gray and black indicate the assortments sawlogs and pulpwood).

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reduction in empty runs. The objective function $z = c^T x = 23\ x1 + 63\ x2 + 40\ x3$ can be generated immediately from C2. Using the relation C1 (Table 2), the incidence values of the matrix A and the constants of the vector b for sources and sinks can be evaluated.

The linear program with the objective function $z = c^T x$ subject to $Ax \leq b$ is complete and can be solved. Its solution is x2 =100 and the objective function has a value of 6,300 km. Compared to the reference distance of 36,300 km this means a substantial advance. We have a saving of 17.6% and the entire transport route is reduced by 8.8%.

The remaining 1-cycles are determined by the solution vector x2 = 100 (701, 101, sawlogs) and (704, 103, pulpwood). The relation C1 (Table 2) is updated in these rows by tu = tu – 100 to determine the remaining 1-cycles. Figure 2 shows the 2-cycle of the solution (t1, f2, t2, f1, t1) = (101, 704, 103, 701, 101). The empty runs of the 2-cycle are drawn as dotted lines.

An analogous procedure as with 2-cycles takes place for a combination of 2- and 3-cycles. The solution results in one 2-cycle (t1, f2, t2, f1, t1) = (101, 702, 103, 701, 101) and one 3-cycle (t1, f2, t2, f3, t3, f1, t1) = (101, 703, 102, 704, 103, 702, 101) (Figure 3). The objective function has a value of 8,500 km. Compared to the reference distance of 36,300 km. This is a saving of 23.4%. The entire transport route is reduced by 11.7%.

Results

For the fiscal year 2015 (7/1/2014, 6/30/2015) the Bavarian State Forest Enterprise provided all harvest data of 7 assortments to test the method for the reduction of empty runs. The annual transport volume is 2.12 million m³. The transported assortments are compiled in Table 4. Timber transport is managed by Bavarian State Forest Enterprise due to the customer contracts and delivered at a place unloaded (DPU).

All assortments can be transported by a standard truck with a crane and trailer. According to legal regulations, a transport unit (tu) corresponds to 22.5 t (metric tons). The centroids of 371 administrative units each around 2,000 ha are taken as the locations of the sources, and 38 enterprises of the wood industry are the spatially located sinks.

First, the optimal distribution was calculated monthly for this data set acting as a base for the calculation of 2- and combined 2- and 3-cycles. The reduction of empty runs by 2- and combined 2- and 3-cycles could then be calculated per month. The results for 2-cycles are summarized in Table 5 and for combined 2- and 3-cycles in Table 6. For better comparison, the results of Tables 5,6 are shown as a diagram in Figure 4.

The results lead to a reduction in empty runs of about 1.29 million km or 17.2% for 2-cycles. With 2- and 3-cycles, the reduction in empty runs is around 200,000 km less with a value of 1.52 million km or 20.2%. These results lead to the following benefits:

Table 3: Valid 2-cycles for the example.

C2								
id	f1	t1	a1	f2	t2	a2	rer	dv
1	701	101	sawlogs	702	103	pulpwood	23	1
2	701	101	sawlogs	704	103	pulpwood	63	×2
3	702	101	sawlogs	704	103	pulpwood	40	×3

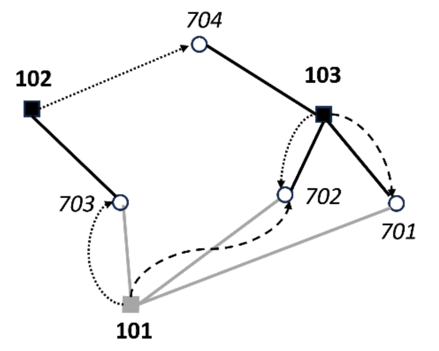

Figure 3: The solution of the example for 2 and 3 cycles. Signatures correspond to Figure 2.

Table 4: Timber harvest by assortments of Bavarian State Forest Enterprise, fiscal year 2015.

Assortment	m³	tu
Beech industrial wood long	187,777	9,883
Oak industrial wood long	19,095	1,005
Spruce industrial wood long	119,205	4,415
Spruce industrial wood short	69,525	2,575
Spruce sawlogs	1,356,021	50,223
Pine industrial wood long	71,199	2,637
Pine sawlogs	300,078	11,114
Sum	2,122,900	81,852

Table 5: Reduction of empty runs for 2-cycles.

Year	month	no of dv	rer(km)	ekm	red(%)
2014	7	7,746	103,962	694,663	15.0%
2014	8	9,384	117,904	719,897	16.4%
2014	9	7,907	83,921	625,267	13.4%
2014	10	10,776	108,609	636,846	17.1%
2014	11	10,120	116,112	711,251	16.3%
2014	12	7,285	79,740	432,574	18.4%
2015	1	7,285	56,679	437,878	12.9%
2015	2	10,139	102,434	540,282	19.0%
2015	3	17,146	200,800	876,387	22.9%
2015	4	12,319	122,954	651,706	18.9%
2015	5	11,020	131,279	643,485	20.4%
2015	6	7,055	65,874	538,724	12.2%
			1,290,268	7,508,960	17.2%

- The existing transport capacity is increased. For the entire fiscal year of the Bavarian State Forest Enterprise, 81,852 tu (Table 4) are to be transported. Dividing the

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total reduction in empty runs in Tables 5,6 by the average length of a 1-cycle of 183.5 km results in an additional freight capacity of 7,032 and 8,269 1-cycles. On the one hand, the transport capacity increases by 8.6% or 10.1% and is available for other timber transports; on the other hand, the utilization of the trucks is improved.

- Transport costs are reduced. Monetary units MU were used to calculate the transport costs, regardless of the national currency. A truck driver has an hourly wage of 30 MU. A liter of diesel costs 1.5 MU and a truck in Central Europe consumes 42 l and 34 l per 100 km for cargo and empty runs. Converting these numbers results in a cost per km of 1.13 MU for cargo runs and 1.01 MU for empty runs. The average empty route length using back haulage or triangle routes is 76.0 and 73.2 km. Under these simplified assumptions, the costs relative to pure 1-cycles decrease by 8.1% (back haulage) and by 9.5% (2- and 3-cycles).
- Emissions are reduced. One liter of fuel corresponds to 2.94 kg of emissions [13]. The average cargo distance is 91.7 km. For the consumption values of the trucks and reduced empty runs just described, the emissions are reduced by **7.7%** (back haulage) and 9.0% (2- and 3-cycles).

Finally, 2-cycles and 2- and 3-cycles were calculated for the entire year. The reference distance for empty or cargo runs after solving the Transportation Problem was 7,384,651 km, about 124,000 km less, as more favorable assignments could be made for the entire data set. For 2-cycles, there was a reduction in empty runs of 1,406,003 km (19%) for 79,815 decision variables. For 2- and 3-cycles there was a reduction in empty runs of 1,581,877 km (21.4%) for 5,610,560 decision variables. These results serve as a comparison model to monthly calculations.

All combinatorics and simplex tableaus were created with SQL in the PostgreSQL database on a standard notebook. The computing times of the combinatorics for a month were on average 2 minutes for 2- and 3-cycles and a few seconds for 2 cycles. The optimization was carried out using the solver lpsolve developed by Berkelaar, et al. [14]. Regarding 2-cycles, the number of decision variables was always less than 20,000 and the solver took less than a second to calculate the solution. The number of 2- and 3-cycles increased to over 5 million decision variables and the associated computing times of the solver grew quadratically (Figure 5).

Discussion

The studies as examined here relate to the methodology of how an identification of 2- or 3-cycles, and the usage of this information may lead to a reduction in empty runs thereof when transporting wood. The data basis is a region in which k assortments are to be transported from sources to sinks as places of supply and demand.

Existing methods for calculating back haulage routes have shown to be very complex. Epstein, et al. [15] refer to programs using over 100,000,000 decision variables. The cause of the complexity often lies in the construction of the back haulage routes, which are formed from the assignments of the unsolved Transportation Problem. The objective function is aimed at minimizing empty runs, whereby the matrix A of the linear program consists of the network incidences of the Transportation Problem for all possible assortments and all

Table 6: Reduction of empty runs for 2- and 3-cycles.

Year	Month	No of DV	rer (km)	ekm	red (%)
2014	7	995,754	127,353	694,663	18.3%
2014	8	1,365,468	138,343	719,897	19.2%
2014	9	1,197,583	105,095	625,267	16.8%
2014	10	1,647,860	123,793	636,846	19.4%
2014	11	1,679,894	135,564	711,251	19.1%
2014	12	1,057,089	95,230	432,574	22.0%
2015	1	436,325	70,259	437,878	16.0%
2015	2	1,568,334	122,639	540,282	22.7%
2015	3	3,365,086	221,343	876,387	25.3%
2015	4	2,289,057	143,410	651,706	22.0%
2015	5	1,969,313	152,981	643,485	23.8%
2015	6	948,382	81,175	538,724	15.1%
			1,517,185	7,508,960	20.2%

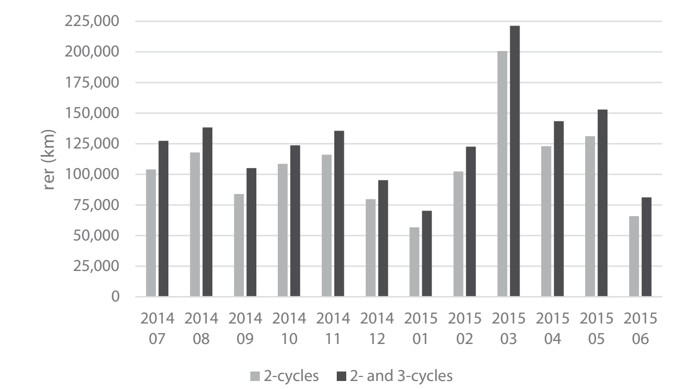

Figure 4: Monthly rer (km) for 2-cycles and 2- and 3-cycles of the fiscal year 2015.

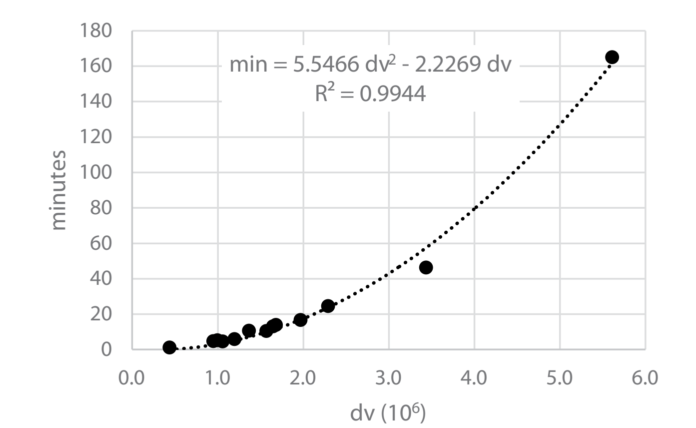

Figure 5: Computing time to solve the linear programs for 2- and 3-cycles depending on the number of decision variables (dv).

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combinations of back haulage routes. The high complexity of the resulting programs leads to either numerical problems in the solution as well as to a suboptimal distribution of assortments [4].

The key procedural step in this study is to identify back haulage cycles before the final optimization process is started. Back haulage cycles hereby are constructed in a systematical way to assure the reduction of this complexity to improve computability as well as a better optimization result. Furthermore, the optimal distribution of the assortments will be maintained.

In the first stage, the transportation problem is solved for the k assortments of a region and the result remains unaffected in the further procedure. The number of optimal assignments is smaller than the number of assignments for an unsolved Transportation Problem. This also reduces the number of possible 2-cycles significantly. On the other hand, the solution to the transportation problem leads to a significant reduction of the total transport distance by about 12% compared to allocation by dispatchers [16].

The complexity is further reduced in the second stage by taking into account the properties of the different cycles (Figure 1). 2-cycles for identical assortments and double 2-cycles for unequal assortments are to be excluded. 2-cycles, in which only one source or one sink is involved, do not result in any improvement over the optimal distribution. Therefore, only 2-cycles are permitted whose 1-cycles involved have a scalar product of zero.

Ultimately, only 2-cycles whose reduction in empty runs is greater than zero are taken and fed into a linear program. The reduction in empty runs as the difference between the sum of cargo runs and the empty runs of cycles is a measure of their efficiency. Maximizing the efficiency of 2- or 3-cycles corresponds to minimizing empty runs. The sum of the empty runs of a 2- or 3-cycle does not contain any information about its efficiency. Overall, the second stage corresponds to a logical 'resolve' of the generated linear program.

Calculating an optimal distribution is part of the tactical planning of a forest enterprise and applies on a rolling basis over an entire year. This plan needs to be revised monthly in the event of unexpected weather conditions (heavy rain, storms, snow), damage caused by drought or beetles, or for nature conservation reasons (Carlsson and Rönnqvist 2005). The results in Chapter 4 are therefore calculated monthly and for the entire year to be able to estimate the losses of a monthly calculation concerning the optimum for the entire year.

The construction of 2- and 3-cycles is based on an optimal distribution of the assortments from sources to sinks. It is a standalone addition to reduce overall routes. The optimal distribution can be determined differently, if, in addition to normal sources and sinks, there are also intermediate storage facilities and longer cargo runs are transported intermodally by train. The minimum cost flow problem is the appropriate model under these conditions [17,18]. It can be used to solve several problems together: The transportation problem (normal sources and sinks), the transshipment problem with additional storage areas for wood (are both sources and sinks), and intermodal transport (truck and train). The solution to the minimum cost flow problem provides optimal distribution of the assortments for trucks and trains. Separately for trucks and trains, the total transport distance can then be minimized using 2- or 3-cycles.

Conclusion

By trying to reduce empty runs through 2-cycles (back haulage) or 3-cycles (triangle routes) the complexity of linear programs could be dramatically reduced without affecting the solution. The reduction in complexity occurs by eliminating all decision variables that do not lead to an improvement in the solution. Reducing empty runs when transporting timber is possible using 2-cycles alone, or a mixture of 2- and 3-cycles by computable linear programs. The combination of 2- and 3-cycles results in an approximately 3% higher reduction in empty runs with higher computing effort. It depends on the user's intentions which option is to be preferred.

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