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Transport Work for the Supply of Pine Sawlogs to the Sawmill

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Abstract: The aim of the presented research is to characterize the scale of transport work performed on the supply of large-size pine wood to the sawmill, with indication of factors influencing structure and parameters. Analyzes were carried out for deliveries to a sawmill in northern Poland, which supplies pine sawlogs and long wood assortments. The distance of deliveries on public and forest roads was determined, as well as transport work for each type of road and the total value. The transport work was defined as a multiplication of driven kilometers with the load and the weight of the load in ton kilometers. Data on the transport distance were obtained on the basis of information from the driver, and the parameters of the transported pine sawlogs from the delivery note. Based on the collected data over a period of 12 months, the transport work was determined for selected courses. The total transport work for the 1509 analyzed deliveries was 3,447,486 ton-kilometers (tkm). The average transport work for one course amounted to 2286 tkm and was characterized by a high variability SD = 1207. The minimum value of the transport work was recorded at the level of 83 tkm, and the maximum as much as 7803 tkm. The median of the analyzed deliveries was 2220 tkm, while the first quartile Q1 = 1358, and the third quartile Q3 = 2997. With very similar cargo volumes (m^3) and cargo weight (kg) the transport distance and the total number of deliveries have a significant effect on the transport work performed with the transport of timber. Purchase of wood in seven forest districts located up to 50 km from the sawmill accounts for 30.1% of the analyzed deliveries (1509), resulting in only transport work at the level of 476,104 tkm, which is only 13.8% of the total transport work of all deliveries.

Keywords: round wood transport; wood supply chain; transport work optimization; sawlogs deliveries; sawlogs sourcing

1. Introduction

In Poland, there is one dominant round wood supplier (44.7 million m^3 in 2018 [1]): the State Forests National Forest Holding. The wood offered throughout the country is sold by 430 State Forest Districts, and the buyers are the highly dispersed and fragmented sawmill industry [2,3]. In such a situation, ensuring a properly functioning, direct wood supply chain [4,5], which is of great importance in the costs of timber harvesting [6,7], enables optimization [8,9].

In the literature on the improvement of the efficiency of wood transport to sawmills, the following issues can be distinguished:

- Cooperation of companies (the seller, sawmills and the carrier) contributing to the reduction of wood transport costs by 4–20% [10–15]. The cooperation of the companies may also contribute to reducing the demand for timber trucks [16] and the reduction of transport work [17].
- Planning of deliveries to a sawmill in the context of reducing drivers' working time and improving transport efficiency [18–20].

- Analysis of the deliveries related to timber transport and the possibility of their reduction [19–23].
- Maximizing use and increasing vehicle load capacity to improve the efficiency of timber transport [24–28].
- Transport of timber with increased load weight and its impact on the environment and infrastructure [29–33].

One of the latest analyses carried out in the transport of wood is the reduction of exhaust emissions. The latest results of Finnish research show unequivocally that the use of vehicles with a maximum permissible weight of 76 Mg in 2017 allowed to reduce the distance traveled by 4% and 0.1 Mt in reduction of CO_2 emissions in road transport [24]. Other Finnish simulations show that 76-ton trucks had a 12% lower productivity, 4% higher fuel consumption and a 6% higher transport cost compared to 84-ton vehicles [25]. Increasing the permissible weight of the transport vehicle in Finland has contributed to the reduction of CO_2 and nitrogen oxides NOx emissions and economic benefits [34]. The recently published results of research in Poland concerning the transport of large-size pine wood indicate that reducing the volume of load from 30 m³ to 25 m³ results in a significant, 17% increase in the quantity of deliveries, which directly lead to higher fuel consumption, increased transport costs and CO_2 emissions [35].

Aim and Scope of the Research

The aim of the presented research was to analyze the transport work performed during the delivery of large-size pine round wood to the sawmill as well as to determine the size and structure of the transport work. It was assumed that the main factors influencing the volume of transport work is the location of the single wood load (forest district, sub-forest district, stand) that determines the transport distance and the weight of the transported round wood. It was also assumed that the number of transports from individual forest districts had a significant impact on the total transport work performed on the deliveries of roundwood to the sawmill, and it may constitute the basis for optimizing transport work.

The research was related to transport work analyzes depending on the period of their realization and the distance from the State Forest District. The data of the location and related deliveries on public and forest roads were analyzed.

2. Material and Methods

The transport work in ton-kilometers was defined as the multiplication of the kilometers traveled on forest and public roads with the load and the weight of the cargo for each route and the total value for all analyzed transports. For each, State Forest Districts took into account the number of deliveries, the average weight of a load and the transport distance (minimum, average and maximum). The distance with the load was determined on the basis of the delivery note and the weight of the load from weighing the vehicles.

Large-size wood is wood with a thin end diameter of 14 cm (excluding bark), calculated in single pieces. In terms of quality and size, large-size wood is divided into four classes—A, B, C, D—and into two sub-classes—general purpose wood and special purpose wood. The large-size general purpose wood is comparable to the assortment defined as sawmill wood. Medium-size wood is wood with a minimum diameter of 5 cm and more (excluding bark), with a thick end diameter of up to 24 cm, calculated in single pieces, in pieces as groups and in stakes [36,37].

Relevant analyzes were carried out for the supply of pine sawlogs in the period from 1 April 2016 to 29 March 2017, to a sawmill in northern Poland. The transport was carried out by external companies acting on behalf of the plant. The delivery date, from the recipient's documents (sawmill) and the delivery note issued by the State Forest, allowed for the analysis for each month.

Each truck was weighed as it entered and exited the sawmill. The weight of the load was determined on the basis of weighing the truck with sawlogs and after unloading (tare) in the plant.

The place of harvesting the wood is specified on the delivery note by the State Forest, by providing the unique forest address from the information system of the State Forests (SILP).

Kilometers driven on forest and public roads with round wood were based on information from the driver when accepting the delivery. Having accurate location (from the delivery note) it was possible to verify (control) authenticity of the information and eliminate incorrect data provided by the driver. Data on the average fuel consumption in liters per 100 km for individual delivery were obtained from truck drivers. On this basis, the average combustion in L km^{-1} was calculated for one course (delivery) and for one cubic meter of transported sawlogs (total combustion for the course divided by the volume of transported wood in L·m^{-3}).

The results were analyzed statistically using the STATISTICA 12 package. The Kruskal–Wallis test was used to determine the significance of the differences. Additionally, a multiple comparison test of mean rank (Dunn's test) was performed. Analyzes were performed at the significance level of 0.05.

3. Results

In the analyzed period 280,380 m^3 of pine sawlogs was transported to the plant, with 9797 deliveries of wood from 54 forest districts. The analysis covered 1509 (13.97%) of randomly selected timber transports carried out over a period of twelve months from 40 forest districts, where a load per truck was obtained from one place, single stand. In the analyzed 1509 transports, 44,336 m^3 of round wood was delivered to the sawmill.

3.1. Characteristic of the State Forest Districts

The characteristics of Forest Districts: average distances from the sawmill, load weight and number of deliveries presented in Table 1. Most of the analyzed 129 sawlogs transports to the sawmill were carried out from the Korpele Forest District, with average distance of 34.3 km. Mileage range with load from 25 to 57 km. In the analyzed deliveries, 30.1% (454 courses) were carried out from the forest districts: Wielbark, Nidzica, Szczytno, Jedwabno, Korpele, Przasnysz and Parciaki. They are located closest to the plant, in 50 km radius (average transport distance).

Table 1. Summary of the number of deliveries, average load weight and transport distance on a public road from forest districts to a sawmill according to the average distance.

State Forest District	Number of Deliveries	Average Load Weight (t)	Deliveries with Cargo on a Public Road (km)			
			Average	SD	Minimum	Maximum
Wielbark	49	30.61	8.2	4.6	3	23
Nidzica	25	29.87	19.1	11.4	24	70
Szczytno	93	30.38	20.7	5.5	7	38
Jedwabno	58	32.00	29.6	11.4	7	47
Korpele	129	29.28	34.3	7.1	25	57
Przasnysz	64	30.37	41.5	7.6	26	64
Parciaki	36	31.81	48.5	12.4	30	81
Myszyniec	10	31.25	54.5	14.2	36	76
Spychowo	46	30.60	57.1	7.8	28	68
Olsztyn	60	30.85	57.3	11.7	37	90
Nowe Ramuki	76	29.02	61.9	10.5	40	91
Strzałowo	72	29.35	61.9	9.4	40	84
Mrągowo	14	30.87	66.4	6.8	58	84
Wipsowo	28	28.44	74.0	12.3	48	105
Olsztynek	27	30.52	75.8	9.6	64	99
Maskulińskie	61	30.67	79.4	11.2	60	120
Nowogród	79	30.23	79.7	7.1	64	98
Dwukoły	4	38.81	81.9	4.6	75	84
Jagiełek	40	29.29	82.5	8.5	63	112

Table 1. *Cont.*

State Forest District	Number of Deliveries	Average Load Weight (t)	Deliveries with Cargo on a Public Road (km)			
			Average	SD	Minimum	Maximum
Ostrołęka	41	31.89	85.9	20.9	58	132
Kudypy	48	29.85	86.0	9.9	74	123
Pułtusk	49	30.12	90.8	15.8	75	136
Pisz	119	29.64	91.3	13.5	57	116
Stare Jabłonki	21	29.96	106.6	11.2	96	138
Wichrowo	32	31.36	109.8	8.5	90	127
Miłomłyn	7	29.75	111.0	4.1	106	116
Bartoszyce	3	37.78	114.7	15.5	99	130
Drygały	84	31.79	114.8	14.5	60	160
Giżycko	71	30.18	120.9	10.9	95	150
Płaska	18	30.30	121.1	9.3	205	238
Srokowo	3	33.25	126.0	29.5	93	150
Ostrów Mazowiecka	7	33.38	132.6	10.1	118	145
Iława	21	31.22	134.3	10.4	114	160
Wyszków	2	31.15	135.0	7.1	130	140
Orneta	2	31.68	138.0	4.2	135	141
Susz	6	29.60	155.5	15.9	127	167
Łochów	4	32.53	166.3	2.5	165	170
Szczebra	1	28.30	215.0	-	215	215
Żednia	2	30.80	225.0	7.1	220	238

In the first years of operation of the plant, the source of wood supply was all forest districts in north-eastern Poland. Too much diversification of suppliers required the involvement of a significant number of transport vehicles (companies). As the sawmill developed, the pine sawlogs purchasing area was significant reduced, resulting in an average transport distance 70 km on public road.

The reduction of the purchasing radius resulted in a smaller demand for the number of trucks, and consequently reduced the number of transport companies cooperating with the plant. The cooperation was based on the principle of assigning one transport company to one State Forest Districts. It significantly improved the quality of provided transport services, execution of delivery schedules, information flow and cost reduction, and increased control throughout the wood supply chain.

3.2. Characteristics Sawlogs Deliveries and the Weight of the Load

The realization of the analyzed deliveries to the sawmill was associated with the total load deliveries (on public and forest roads) at the level of 113,728 km. The average distance of deliveries with cargo was 75.4 km and was characterized by high variability SD = 39.1 (Tables 1 and 2) in the range from 3.0 km to 274.5 km (Table 2).

Table 2. Characteristics of analyzed parameters in wood transportation to sawmill.

Measure	Mean	SD	Min	Max	Q1	Median	Q3
Mass of load (t)	30.32	2.20	21.75	38.91	28.80	30.20	31.75
Total driving with load (km)	75.4	39.1	3.0	274.5	45.2	74.0	98.0
Transport work (tkm)	2282	1207	83	7803	1358	2220	2997

Notes: SD. standard deviation; Q1. first quartile; Q3. third quartile.

The greatest number of deliveries (on a public and a forest road) was recorded in the range of 70 ÷ 80 km-186 and 80 ÷ 90 km-182 transports. In 24 cases, timber was transported over a distance of more than 200 km. Most deliveries were made within 100 km from the plant, 75.35% of transports being within this radius (Figure 1).
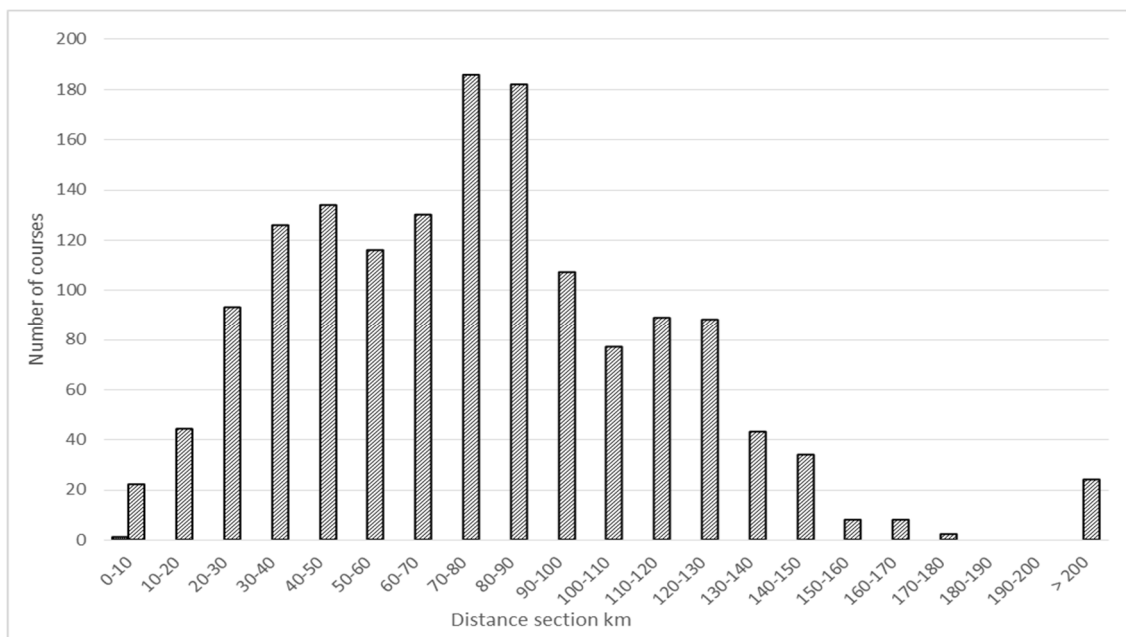
Figure 1. Number of deliveries in 10 km sections with load.

The average load weight for each delivery was 30.32 t and very similar between forest districts (SD = 2.20 and median 30.20), although the Kruskal–Wallis test showed statistically significant differences. Detailed analysis using the multiple mean rank comparison test (Dunn's test) showed that the masses of individual wood loads in transports from 18 forest districts did not differ from each other (Figure 2).
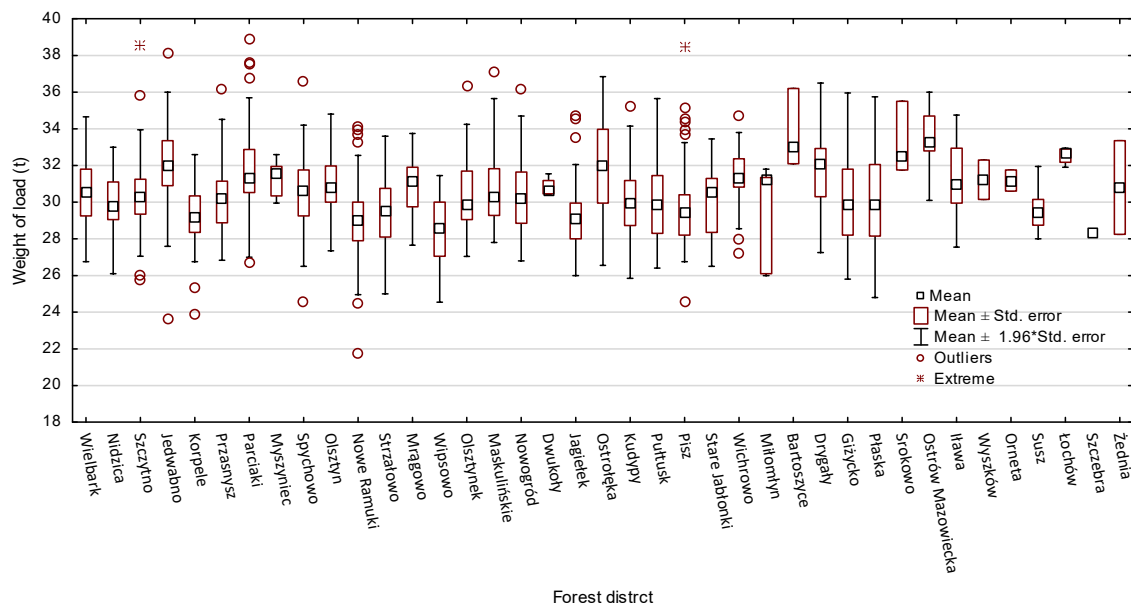

Figure 2. Weight of deliveries from individual forest districts (forest districts in the order of distance from the sawmill).

3.3. Fuel Consumption in Sawlogs Deliveries

The roundwood to the sawmill was most often delivered by Man, Scania, Volvo and Mercedes trucks with a motor power from 410 to 620 HP and a capacity of 12.0 ÷ 16.3 L. Drivers reported fuel consumption in the range from 38.0 to 87.0 L 100 km^{-1}. Calculation of fuel consumption per kilometer and summary calculations for each sawlogs delivery were made. Transport distance with load was used

for all calculations. Having also registered the volume of transported wood (m^3), the fuel consumption index for the transport of 1 m^3 of wood was calculated. Average fuel consumption was at the level of 0.561 L km^{-1} with small differences in results, SD = 0.055 (Table 3). For the individual deliveries of wood to the sawmill, fuel consumption from 4.80 L to 225.94 L was recorded with an average of 77.11 L. The calculated fuel consumption index for 1 m^3 transport was on average 2.62 L·m^{-3} with the result range from 0.16 to 7.63 L·m^{-3} (Table 3).

Table 3. Fuel consumption characteristics for sawlogs delivered to a sawmill based on transport distance with load.

Measure	Mean	SD	Min	Max	Q1	Median	Q3
Fuel consumption (L·km^{-1})	0.561	0.055	0.380	0.870	0.530	0.570	0.598
Fuel consumption per 1 m^3 of delivered wood (L·m^{-3})	2.628	1.286	0.16	7.630	1.600	2.568	3.406
Fuel consumption per delivery (L)	77.116	38.099	4.800	125.940	46.170	76.160	99.456

Notes: SD. standard deviation; Q1. first quartile; Q3. third quartile.

3.4. Transport Work

The total transport work for the 1509 deliveries was 3,447,486 ton-kilometers (tkm). The average transport performance of one course amounted to 2286 tkm and was characterized by a high variability of SD = 1207. The minimum value of transport work was recorded at the level of 83 tkm, and the maximum as much as 7803 tkm. The median of the analyzed deliveries was 2220 tkm, while the first quartile Q1 = 1358 and the third quartile Q3 = 2997 (Table 2). Transport work for a single course is on a comparable level in all months, but the analysis using the Kruskal–Wallis test showed statistically significant differences ($p = 0.0000$). The comparison of the transport work for the trips carried out in individual months with the Dunn test shows statistically significant differences only when the results are compared in the months of XI to I; III; IV, VI and X as well as III from I, IV and X and the last different pair are IV from VIII, as shown in Figure 3. Statistical analyzes did not include trips in July and December due to insufficient sample. It was caused by planned breaks in the plant related to maintenance period and suspension of sawlogs deliveries.
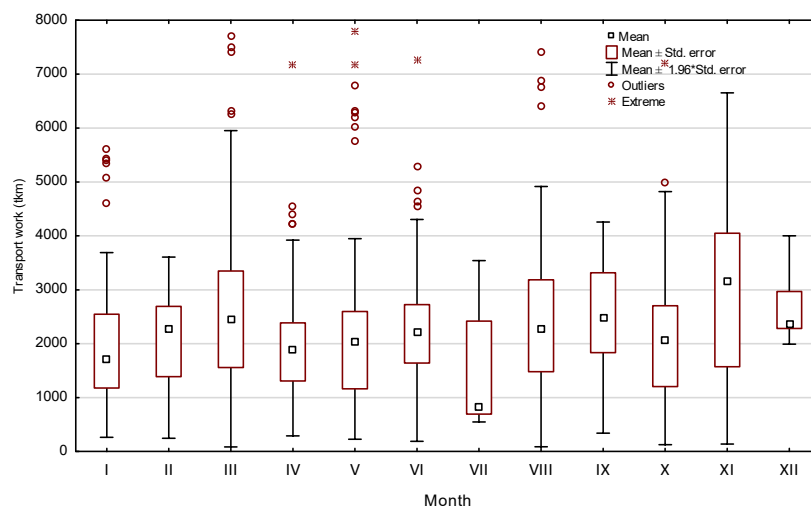

Figure 3. Characteristics of transport work for individual deliveries depending on the delivery month.

The analysis of transport work for a single course according to forest districts showed very large differences (Kruskal-Wallis test $p = 0.0000$), as shown in Figure 4. With very similar cargo volumes (m^3) and cargo weight (kg), which was shown in previous analyzes and in Table 1, the transport distance has a significant effect on the transport work performed with the transport of timber.
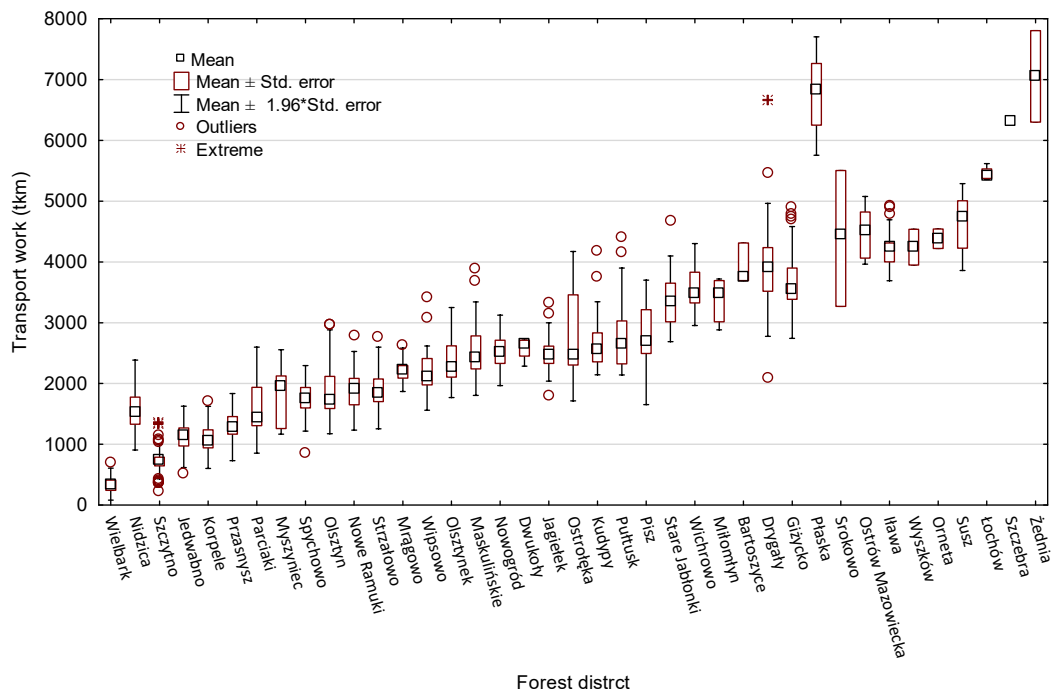
Figure 4. Characteristics of the transport work of individual deliveries from forest districts according to the transport distance.

The total transport work performed for the deliveries of wood from each forest districts depends on the distance from the sawmill and the number of deliveries made. The results presented in Figure 5 clearly show that the supply of pine sawlogs in the nearest forest districts requires much less transport work, for example in the Korpele Forest District. Purchases of round wood in remote forest districts, even with a smaller number of deliveries, are characterized by a high amount of transport work, as in the case of the Drygały or Giżycko Forest Districts. Purchase of wood in seven forest districts (Wielbark-Parciaki) up to 50 km from the sawmill (Table 1) accounts for 30.1% of the analyzed deliveries (1509), resulting in only transport work at the level of 476,104 tkm, which is only 13.8% of the total transport work of all deliveries.
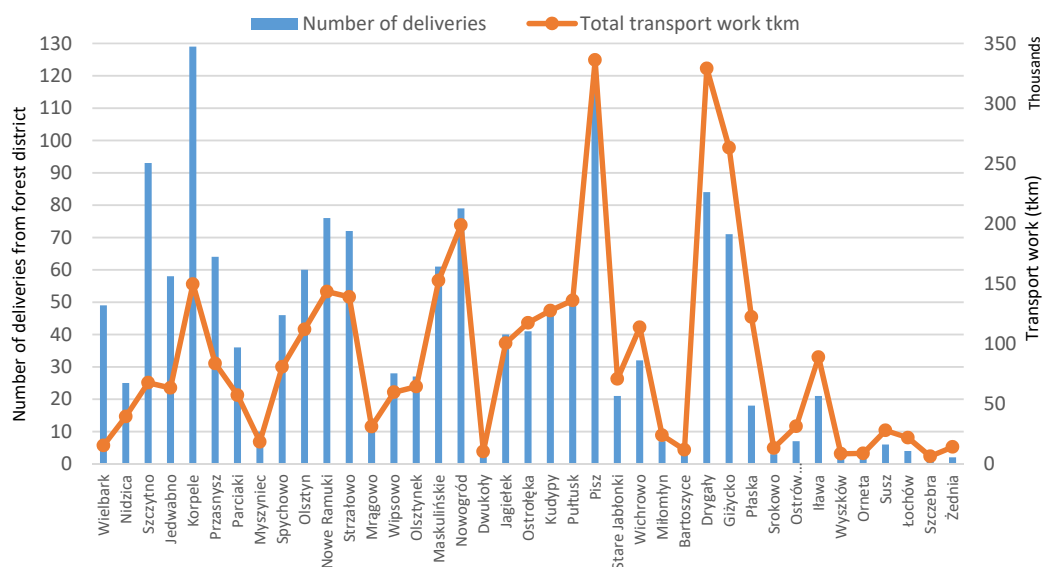

Figure 5. The completed transport work for the deliveries of timber from individual forest districts and the number of deliveries (forest districts in the order of distance from the sawmill).

4. Discussion

By making theoretical optimization by doubling the number of deliveries, made only from the closest 14 Forest Districts, with an average distance from 8.2 km to 74.0 km (in the range of min = 3.0 km to max = 105 km, Table 1), it is possible to reduce the generated transport work. Delivering the same amount of wood (at the level of 44,340 m^3) would require transport work at the level of 2,103,819 tkm, which is 39% less than in the analyzed case. By increasing the number of deliveries from the nearest forest districts threefold with an average transport distance of 8.2–57.1 km (with a range of 3.0–81.0 km), it would be possible to reduce the transport work to the level of 1,694,279 tkm, thus 51% less than in the analyzed case. At the same time, the delivery of the same wood quantity would require cooperation with only the nine closest forest districts. The sale offer of pine sawlogs by State Forest in the analyzed area is on much higher level then analyze sawmill capacity. Theoretically, this situation allows to reduce sawmill purchase circle to maximum 50 km. Harvesting and sales offer of large-size roundwood in seven forest districts (from Wielbark to Parciaki, Table 1) within 50 km from the sawmill is at the average annual level of 43,000 m^3 per State Forest District. The sales offer from 30,000 m^3 (Parciaki) up to 67,000 m^3 (Jedwabno) depends on the forest structure and is connected with 10 years Forest Management Plan. Within 50 km from the sawmill, the annual sales potential of large-size wood in seven State Forest Districts is 303,000 m^3 of wood per year. This is more than the annual demand of the analyzed sawmill. Unfortunately, the wood sales rules in Poland limits this solution. The sale of roundwood is made through an electronic restricted tender, where the State Forest sets and establishes rules for evaluating the submitted offers [38]. The presented optimization could take place in a situation of lifting the current restrictions on wood purchase. In a situation where all roundwood planned for sale by State Forest would be sold through online auctions without any restrictions, it would be possible to purchase enough quantity of sawlogs through a sawmill in the nearest State Forest Districts. On the other hand, such a solution would also have a negative impact on the possibility of selling wood by forest districts located further away from the sawmill, in the areas where there are no other significant buyers.

Based on the analyzes, the average fuel consumption was on the level 0.56 L·km^{-1}. Austrian studies show higher values at the level of 0.77 L·km^{-1} [39], which may result from a different type of assortment, road condition and different topography. With the average transport distance from the forest to the sawmill at the level of 75.4 km, with an average load volume of 29.34 m^3 [40], the amount of fuel needed to transport 1 m^3 of pine sawlogs in the conducted research is 1.44 L·m^{-3}. These results are consistent with other studies, which show the value of 0.73 L·m^{-3} at a transport distance of 31.4 km [41]. A reliable indicator for analyses and comparisons of variable loads (volume and mass) can be the mass of 1 m^3 of wood in the load, which amounted to 1033.87 kg·m^{-3}, with similar results in the population at SD = 57.87, and a median of 1031.61 kg·m^{-3} [40]. Fuel consumption per 1 m^3 of wood is primarily determined by the transport distance and the size of the load [42].

Rijkswaterstaat [43] presents calculations (estimation) that, with a reduction in transport distance of approximately 20 million kilometers per year, CO_2 emissions decrease by 0.016 Mt per year (per 1 km reduction of 0.0008 t). Assuming the estimates presented by Rijkswaterstaat [43], the reduction of the analyzed 113,728 km of deliveries by 39% (44,354 km) and 51% (58,000 km) in the first and the second analyzed delivery variant, respectively, allows to estimate the reduction of CO_2 emissions at the level of 35.5 t and 46.4 t. However, in order to fully assess the environmental impact of transport, estimation methods should be used for specific route sections, given that the amount of pollutant emissions is strongly influenced by speed, load and gradient index [44].

The calculations were presented for 1509 transports (14%) of all completed 9797 deliveries to the sawmill, so the total reduction in transport work, mainly kilometers traveled, and thus the reduction of CO_2 emissions may be much higher.

5. Conclusions

Most of the deliveries of pine sawlogs to the sawmill, 180 transports, were related to the deliveries from distance of 70 ÷ 80 and 80 ÷ 90 km. 30.1% of deliveries to the sawmill (454 courses) were made from distances of up to 50 km (average transport distance).

With very similar loads of round wood, the transport distance has a significant impact on transport work, which does not depend on the delivery date.

It is possible to optimized (reduce) the round wood deliveries, and thus transport work, as a result of a change in the structure of sawlogs sourcing by the sawmill. The annual potential of the roundwood sold in the closest State Forest Districts is higher than the sawmill capacity, but the current Wood Sales Rules limit this possibility.

Conflicts of Interest: The authors declare no conflict of interest.

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