GRASS FORAGE TRANSPORTATION PROCESS MODELING

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Abstract. The grass forage production, silage making in particular, on the farms in the North-West of Russia involves quite many vehicles for field-to-storage transportation of mown and air-cured grass. The share of relevant operating costs is 53-65 % of the total costs, while the energy inputs account for 59-75 %. Therefore, an urgent task is to simulate the traffic flows and to search for the rational transportation options with due account for the forage land area, grass yield, number and capacity of storages, and the distance between the harvesting and storage places. The transportation problem in silage making was solved by the linear programming method through seeking the extreme point of the objective function – the least transport works. For calculation, the source data were processed and summarised in tabular matrices according to the developed algorithm. Two harvesting options of grass for silage were considered: in the first option the grass was ready for harvesting on all the fields at the same time; the second option had different grass maturing time. The problem solving resulted in an optimal transport work plan for silage making in the form of a network diagram, which allowed to schedule the forage land harvesting and to sequence the filling up the storage facilities in compliance with the agro-technical time limits. This approach was tested for several farms in the North-West region of Russia and 4 to 15 % lower transport workswere obtained.

Keywords: modeling, grass, transportation, algorithm.

Introduction

In the farm crop growing, the technological mechanised operations cannot be ahead of schedule or delayed without affecting the crop yields. These operations are interlinked by the factors of time and product quality, which influence the general farm profitability.

Currently, the responsible farm specialists make up the work plans following from the flow charts and personal experience without the detailed estimation (modelling) of cultivating conditions of a particular farm crop on a particular field [1; 2]. However, only the up-to-date modelling methods can ensure the reliability of the forecasts associated with the functioning of interacting machines with due account for production conditions and environment [3].

The grass forage making, silage and haylage in particular, involves quite many vehicles to transport the air-cured grass to the storages, the number of which, as a rule, does not correspond to the number of fields [4-7].

The share of relevant operating costs on the farms in the North-West of Russia is 53-65 % of the total costs, while the energy inputs account for 59-75 % [8]. The route optimisation reduces the energy inputs by up to 8 % and the harvesting time – by up to 32 % [9; 10]. Besides, due to the applied crop rotations, different fields located at different distances from the storage facilities are covered with grasses with different yields and maturing time. Therefore, the objective is to minimize the grass transportation efforts by identifying the traffic flows and transported volumes from particular fields to particular storages at the least cost [11; 12].

As a rule, there are two options for grass harvesting. In the first option, the grass is mature and harvested on all the fields at the same time. The second option has different grass maturing time. The transportation problems of the first and second options differ from each other. A minimum-effort plan needs to be developed to organise the transport works so that the forage harvester runs at full capacity [13].

In this connection an urgent task is to simulate the traffic flows and search for rational options for grass forage transportation, taking into account the area of forage land, grass yields, number and capacity of storages, and the distance between the harvesting and storage places.

The study objective was to solve the two relevant transportation problems for both harvesting options.

Materials and methods

In the study, the followingnotations were used:

- n – number of fields;
- m – number of storages, in general $n \neq m$;
- l_{ij} – transportation distance from the i-th field to the j-th storage, km;
- $q_1,\dots, q_n$ – amount of grass forageharvested from each field, t;
- $Q_1, \dots, Q_m$storage capacities, t;
- x_{ij} – optimal amount of grass forage transportedfrom the i-th field to the j-th storage, t.

The problem is solved by the matrix of grass forage transportation shown in Table 1.

Table 1

Matrix of grass forage field-to-storage transportation

Storages	Fields			
	1	2	i	n
1	x_{11}	x_{12}	x_{1i}	x_{1n}
2	x_{21}	x_{22}	x_{2i}	x_{2n}
j	x_{j1}	x_{j2}	x_{ji}	x_{jn}
m	x_{m1}	x_{m2}	x_{mi}	x_{mn}

Method for solving the transportation problem for simultaneous grass maturing in all the fields – Option 1

This transportation problem in the general case has a standard solution [14]. However,this solution is not applicablein forage production for the following reasons:

- as a rule, the harvested forage amount is smaller or equal to the capacity of available storages;
- the storages are filled with the forage one after another;
- harvesting of each field should not be interrupted to harvest another field. If the harvesting of one field started, it should be completed on time.

Therefore, the linear programming method was applied. The problem was presented as a system of equations with the objective function and a system of constraints. The problem was solved by seeking the objective function's extreme point – the least transport works under the specified restrictions on the storage capacities and the forage amount supplied from each field.

When minimizing the totaltransport works in tonne-kilometres (tkm),the objective function(1) will have the form:

$$G = l_{11}x_{11} + l_{12}x_{12} + \dots + l_{1n}x_{1m} + l_{21}x_{21} + l_{22}x_{22} + l_{2n}x_{2m} + \dots + l_{nm}x_{nm} = \sum_{j=1}^{m}\sum_{i=1}^{n} l_{ji}x_{ji} \rightarrow \min \tag{1}$$

The objective function is supplemented by the following constraints:

- the amount of forage transported from the i-th field should be equal to the amount of forage harvested in this field (2)

$$\sum_{j=1}^{m} x_{ji} = q_{ji}, i = \overline{1,n}; \tag{2}$$

- the amount of forage supplied from n-fields to the j-th storage should not exceed its capacity(3)

$$\sum_{j=1}^{n} x_{\mathrm{ji}} \le Q_{\mathrm{j}}, j = \overline{1,m}. \tag{3}$$

To solve the system (1-3) of a certain order, the sums in the equations should have particular summands. For example, for two storages and four fields the system will have the form (4):

$$
\begin{aligned}
&l_{11}x_{11}+l_{12}x_{12}+l_{13}x_{13}+l_{14}x_{14}+l_{21}x_{21}+l_{22}x_{22}+l_{23}x_{23}+l_{24}x_{24}=\min,\\
&x_{11}+x_{12}+x_{13}+x_{14}\le Q_1,\\
&x_{21}+x_{22}+x_{23}+x_{24}\le Q_2,\\
&x_{11}+x_{21}=q_1,\\
&x_{12}+x_{22}=q_2,\\
&x_{13}+x_{23}=q_3,\\
&x_{14}+x_{24}=q_4.
\end{aligned} \tag{4}
$$

Method for solving the transportation problem for different grass maturingtime – Option 2

In the case of different grass maturing time, the forage harvesting should be scheduled in such a way as to ensure the least transport works and the complete filling of some storages with the grass of each maturing term.

There is no general solution to such problems due to the variety of possible conditions and constraints [8]. However, the problem can be stated and solved by one of the heuristic methods for any specific conditions [15; 16].

The problem solution was considered by an example with the conditions shown in the matrix in Table 2, namely, grass maturingterm, the forage amount harvested from the fields, the storage capacity, and transportation distance.

Let us assume that the first maturing term of grass is registered in the fields 1 and 4; the second maturing term – in the fields 2 and 3; the third maturing term – in the field 5. Under such a statement, this problem cannot be formalised as a linear programming problem due to the required grass forage harvesting conditions.

In our case, the harvest time corresponds to the grass maturing term.

Table 2

Matrix of grass transportation from fields to storages under different grass maturingterm

Field	Grass maturing term, day	Forage amount, t	Storage capacity, t Transportation distance, km			
			Q_1	Q_2	Q_3	Q_4
1	s_1	q_1	l_{11}	l_{12}	l_{13}	l_{14}
2	s_2	q_2	l_{21}	l_{22}	l_{22}	l_{24}
3	s_2	q_3	l_{31}	l_{32}	l_{33}	l_{34}
4	s_1	q_4	l_{41}	l_{42}	l_{43}	l_{44}
5	s_3	q_5	l_{51}	l_{52}	l_{53}	l_{54}

The following algorithm was developed to solve this problem.

Step 1. Possible variants of reserving (assigning) particular storages to particular fields are identified by the storage capacities and the grass yields. Under these variants, the storages are filled with the grass harvested in each maturingterm.

Step 2. The formulas for calculating the transport works are identified for each variant.

Step 3. The transport worksare calculated for all harvest time limits.

Step 4. The variant with the least transport works is selected.

A tabular form is used in Step 1. For the data in Table 2, the possible variants of reserving (assigning) the storages to the fields are shown in Table 3.

Table 3

Variants of reserving (assigning) particular storages to particular fields

Harvest time	Fields	Variant 1	Variant 2	Variant 3
1	$q_1 + q_4$	$Q_1 + Q_4$, or Q_2, or Q_3	$Q_1 + Q_3$, or Q_2, orQ_4	$Q_1 + Q_2$, or Q_4, or Q_3
2	$q_2 + q_3$	$Q_2 + Q_4$, or Q_1, or Q_3	$Q_2 + Q_3$, or Q_1, orQ_4	$Q_2 + Q_4$, orQ_1, orQ_3
3	q_5	$Q_3 + Q_4$, or Q_1, orQ_3	$Q_3 + Q_2$, or Q_1, orQ_4	$Q_1 + Q_3$, orQ_2, orQ_4

Results and discussion

To solve the transportation problem with a single grass maturing term – Option 1, an algorithm and programme were created for the following conditions: four fields – q_1, q_2, q_3, q_4 and two storages – Q_1, Q_2. The storage-to-field distance matrix is shown in Table 4. The storage capacities and the forage amounts transported from the fields to the storages are shown in Table 5. The mathematical model for solving the transportation problem for these conditions has the form (4), the solution of which is shown in Table 6.

Table 4

Storage-to-field distance matrix

Storage	**Distance to the fields, km**			
	q_1	q_2	q_3	q_4
Q_1	2	3	4	6
Q_2	7	5	6	1

Table 5

Storage capacities and amount of forage transported from the fields to the storages

Storage capacity, t		**Amount of forage harvested on a particular field, t**			
Q_1	600	q_1	q_2	q_3	q_4
Q_2	1000	300	450	500	350

Table 6

Transportation problem solution with a single grass-maturingterm

Storages	**Fields**				
	q_1	q_2	q_3	q_4	Sum
Q_1	300	300	0	0	600
Q_2	0	150	500	350	1000
Sum	300	450	500	350	1600

Overall transport works to supply the two storages with the forage harvested on four fields is

$$300 \times 2 + 300 \times 3 + 150 \times 5 + 500 \times 6 + 350 \times 1 = 5600 \text{ tkm}.$$

The schedule offield harvesting and storage fillingcreated from the transportation problem solution is shown in Fig. 1.

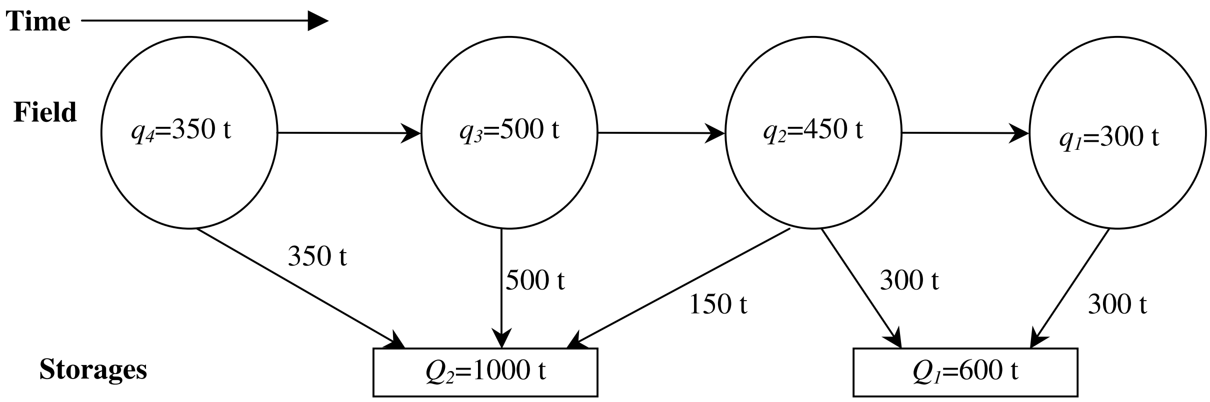

Fig. 1. **Schedule of the field harvesting, forage transportation and storage filling**

Field q_4 is harvested first, with 350 t of grass being transported to storage Q_2. Field q_3 is harvested second, with 500 t of grass being transported also to storage Q_2. Field q_2 is harvested third, with 150 t of grass being transported also to storage Q_2 thus filling it up.

The rest grass from field q_2 300 t are transported to storage Q_1. The last field harvested is field q_1, with the grass being transported to storage Q_1 and filling it up.

In the agricultural enterprise "Oktiabrskoye" located in the Volosovsky District of Leningrad Region, the overall transport works in harvesting grass for silage under the same initial conditions were 5850 tkm. The transportation according to the simulated variant resulted in 4.3 % lower silage transport works.

To solve the transportation problem when harvesting the grass with different maturing term – Option 2, an algorithm and programme were created for the following conditions: three grassmaturing terms – $s_1 \ldots s_3$, four storages – $Q_1 \ldots Q_4$, and five fields – $q_1 \ldots q_5$. The conditions of the problem solved in *Microsoft Office Excel* are shown in Table 7.

Table 7

Transportation problem solution for different grass maturing terms

Storage capacity, t			Grass yield on the fields, t				
			q_1	q_2	q_3	q_4	q_5
Q_1 =	1000		1100	800	1200	900	2000
Q_2 =	2000	Grass maturing terms	s_1	s_2	s_2	s_1	s_3
Q_3 =	2000		1	2	2	1	3
Q_4 =	1000						

Distance matrix, km					
	*q*1	*q*2	*q*3	*q*4	*q*5
*Q*1	2	3	6	6	4
*Q*2	6	1	4	3	3
*Q*3	8	9	3	5	7
*Q*4	11	5	6	7	4
Grass maturing terms	1	2	2	1	3

The forageamount harvested from the five fields is equal to the capacity of the four storages, i.e. all the storages must be filled up. Following the conditions for grass forage harvesting shown in Table 7, there are three candidate solutions to the problem of traffic flows from the fields to the storages for the three harvest times, which are presented in Table 8.

Table8

Candidate solutions of the problem of grass forage transportation from fields to storages for three grass harvesttimes

Harvest time	Fields	Storage use variants		
		Variant 1	Variant 2	Variant 3
1	q_1 = 1100 q_4 = 900	Q_2 = 2000	Q_1 = 1000 Q_4 = 1000	Q_3 = 2000
2	q_2 = 800 q_3 = 1200	Q_3 = 2000	Q_2 = 2000	Q_1 = 1000 Q_4 = 1000
3	q_5 = 2000	Q_1 = 1000 Q_4 = 1000	Q_3 = 2000	Q_2 = 2000

Calculations in *Microsoft Office Excel* showed that Variant 3 had the least transport works – 28100tkm. Accordingly, a rational harvesting optionwascreated as shown in Fig. 2 in the form of a network diagram.

In the agricultural enterprise "Kalozhytsy" located in the Volosovsky District of Leningrad Region the harvesting of grass for silage from five fields and filling the mown and air-cured grass mass in five trenches required the transport works of 37,500 tkm. The simulated harvesting schedule shown in Fig. 2provided 14.3 % lower silage transport works.

Table 9 shows the modelling results of grass forage transportation for silage making both during the simultaneous harvesting of forage land, and for different grass maturing terms inseveral farms in Leningrad Region.

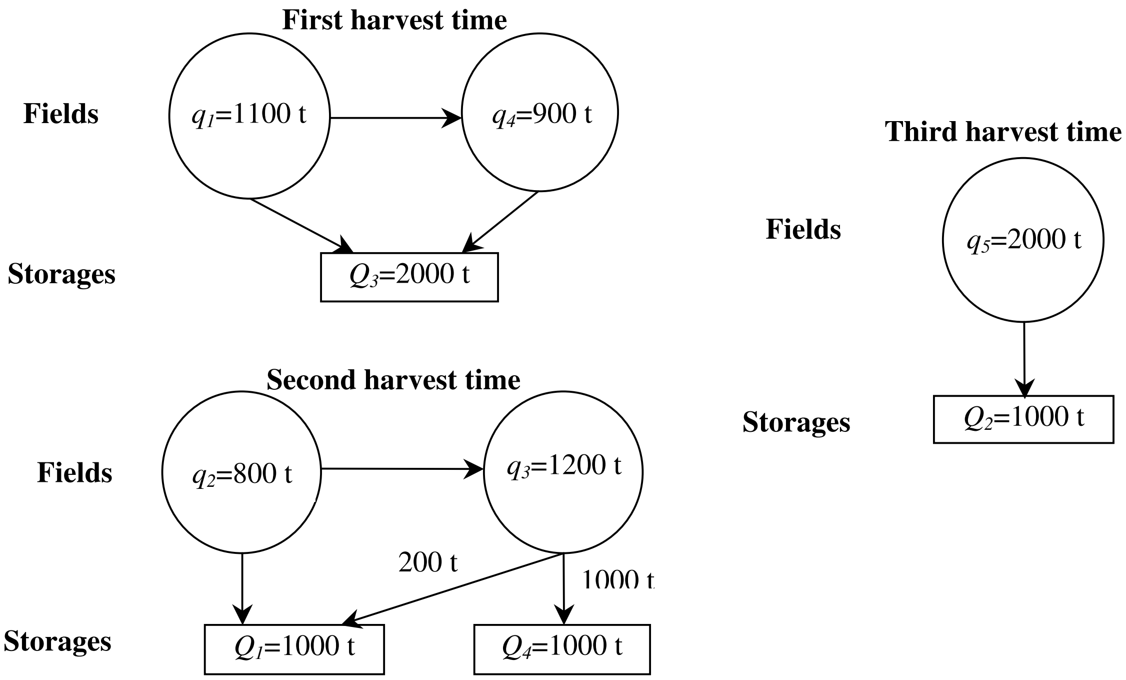

Fig. 2. **Rational harvesting option of the fields with three harvest times**

The simulated variants demonstrated 4-15 % lower transport works associated with transportation of air-cured grass from the field to the storage compared to the currently applied patterns.

Table 9

Efficiency of the simulated variant of grass forage transportation

Farm	Harvest conditions	Transport works, tkm		Efficiency, %
		Currently applied variant	Simulated variant	
"Oktiabrskoye", Volosovsky District	Simultaneous grass maturing	5 850.0	5 600.0	4.3
"Verevo" Gatchinsky District	Different grass maturing terms	30 700.0	28 100.0	9.1
"Kalozhytsy", Volosovsky District	Different grass maturing terms	37 500.0	32 800.0	14.3

Conclusions

1. The share of transport works in harvesting the grass for silage amounts to 53-65 % of the overall operating costs. To model the rational options for transporting the air-cured grass from the fields to the storages, special algorithms need to be created, since the standard solution methods are not applicable due to specific features of grass forage production.
2. The forage transportation modelling is much more complicated when harvesting the grass with different maturing terms. To solve this problem, the options analysis approach is proposed.
3. When solving the problem of a rational grass forage transportation variant, a network diagram of the harvest is created.
4. For the farms in the North-West of Russia, the transportation of air-cured grass from the field to the storage according to the simulated variants contributes to 4-15 % lower transport works.

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