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A modelling approach to the transport support for the harvesting and transportation complex under uncertain conditions

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Abstract. The article proposes a modelling approach based on structural and parametric identification of the transport support of the harvesting and transportation complex. The efficiency and effectiveness of the proposed methods of structural and parametric identification for the development of a system for harvesting and transportation complex operation has been proved. A mathematical model based on fuzzy logic has been developed. It reflects the interaction and interference of the weather-climatic, technical and technological parameters of transport support and its elements. A simulation method of transport support for harvesting and transport complex has been developed. The basis of the method is an algorithm for constructing a flow chart for the transport system operation consisting of structural and parametric identification levels and a mathematical model for the winter wheat harvesting transportation. A special feature of the method is the consideration of the weather-climatic, technical and technological parameters of the harvesting-transportation complex.

1. Introduction

The large number of parameters of agricultural production, that influence the transport support for the harvest and transportation complex, their compound interrelationships and the lack of certainty of data make it very difficult to construct an adequate mathematical model. Moreover, the very rare repetition of events makes statistical methods of data processing almost unacceptable. First and foremost, it is impossible to obtain a representative sample of data to produce statistically reliable estimates. All this has led us to turn to the mathematical apparatus of the theory of fuzzy sets. Less stringent conditions to a fuzzy measure, versus probabilistic, allow a wide range of subjective data to be added in addition to objective observations. This has made it possible to draw on the experience and expert judgement accumulated over many years of work.

Methods for coordinating harvesting and transport operations in the process of their operational planning and event models in projects at different stages of planning for early grains harvesting are considered in [1,2]. The agrometeorological group of factors is uncontrollable, the disclosure of its impact on the grain harvesting projects intensity is the basis for improving the harvest management efficiency [3]. The need to develop methods and models to take into account the essentials of the agrometeorological conditions influence on the state of the subject of the field work and the trends of its change, as well as the formation of a naturally determined time fund for the relevant work implementation, is an important stage in the development of statistical simulation models of virtual projects and the assessment on their basis of the managerial decisions effectiveness as of reactions to technological risk [4,5]. The stochastic nature of agro-meteorological conditions and their impact on the soil condition determine the variability of the naturally permitted time fund and the methods of cultivation of the soil and crops. Development of methods and models that take into account the agrometeorological conditions influence allows to study the features and tendencies of variability of the efficiency parameters of the adaptive machines technological complexes [6]. The harvesting and transportation process is considered as a nonlinear dynamic deterministic-stochastic model [7] and pays attention to the distribution of harvesting equipment across the fields, based on artificial intelligence methods [8].

However, the available analytical-statistical and statistical-simulation models do not take into account the weather and climate conditions influence, as well as technical and technological parameters, on the transportation process organization for harvesting and solve the problem in mostly deterministic setting.

The implementation of technical and technological solutions alone to improve the transport operations efficiency has not been shown to lead to a fundamental change in the situation with regard to the improvement of the transportations quality and volume [9].

The article is aimed at developing an approach to modelling the transport support of the harvesting and transportation complex in conditions of uncertainty, in particular weather and climatic parameters, on the basis of fuzzy logic with the development of the specific key tasks implementation algorithms.

The need to apply and use the fuzzy logic theory apparatus in transport processes is based on: a large number of unknowns; process complexity; the difficulty to establish quantitative relationships between parameters that affect the control process; the possibilities of formulating expert knowledge about an object (process) only in verbal expression; operational accounting of many conflicting parameters; creating a simpler mathematical model, consistent with practical application. The use of fuzzy logic apparatus in transport systems and processes is one of the modern and promising methods for levelling uncertainty, as evidenced by [10-13]

2. Justifying the use of the weather and climate parameters in modelling transportation support for the harvesting and transport complex

The agricultural production's feature is that it is carried out under the influence of a natural factor, under the conditions of a divergence of the working period and the production period, and the tangible dependence of agricultural production on natural, transport and other features [14].

Significant variability of weather conditions is the main cause of uncertainty in obtaining the results of agricultural activities, in particular with the transport operations.

In general, there is such a pattern: the less defined the external environment, the more difficult it is to make effective decisions. However, in all circumstances, for making informed decisions, it is important to forecast the external environment, that is, to anticipate possible changes and the occurrence of possible events under the influence of such a change [15].

Apart from differences in personal assessments, the environment in which decisions are made is a typical difficulty in determining the best alternatives. For example, the uncertainty of the technology system will be significantly reduced if additional information is provided in the form of weather forecasts for the forthcoming period, or, say, yield forecasts before harvest [16].

According to Handozhko L.A. the development of modern transport systems and technologies is impossible without taking into account the climate factor and is included in the development of technical projects. Productivity, reliability and economy are directly (reliable and economical) and indirectly (productivity) dependent on weather and climate conditions [17].

Hrybyniuk O.M. in his work [18] indicates that the basis for modelling and justifying objective management decisions in the harvesting of early grains is the disclosure of cause-effect relationships resulting from the conditions in which, the grain-stem mass, harvesters and vehicles are.

The difficulty of designing and managing production processes is also that most production and technological factors are a function of the weather factors. Weather factors dictate the choice of work organization, determine its course, qualitative and technical-economic indicators. Failure to take into account weather factors leads to impossibility of objective design and use of technical means, correct organization of works, to low quality indicators, high material and labour costs [19].

Based on processed sources, it is established that weather-climatic factors affect:

– the need to manoeuvre the equipment to minimize the costs of supporting technological processes [20];

– on the correct justification of the annual need for oil products [21]. The climate has an impact on energy conservation in agriculture. Thus, [22] states that scientifically based standards for fuel and energy consumption in climatic zones, levels of electrification and mechanization of agriculture should be adhered to. Efficient organization of use of vehicles is one of the basic principles of measures aimed at energy saving in transport.

– on the variability of the composition of the mutually agreed and interacting machines during the working period and day [23]. According to work [24] in accordance with the existing or anticipated weather conditions, differential application of agricultural machinery is required. In addition, poor logistics are enhanced by the effects of weather conditions on grain yields [25]. The material and technical base of agriculture is largely influenced by natural and climatic conditions. In addition, agriculture located in different natural zones requires different technical means, machine systems, and costs of production per unit of land [26].

According to the author [27], due to insufficient attention to technological issues depending on climatic and soil conditions, the flexible response to changes in weather conditions led to an unjustified increase in costs of production during harvesting.

M.E. Mayboroda in his work [28] emphasizes that the natural and climatic conditions in which the transport is carried out are one of the factors on which the level of technical and operational indicators of the transport process depends. At the same time, one of the factors on which the coefficient of release of the rolling stock on the line depends on the natural and climatic conditions.

Mokhnenko A.S. believes that the efficiency of agriculture depends on the environment (soil, climate, weather conditions) [29].

The implementation of scientific methods for the use of the meteorological information helps to reduce losses in the economy of the state in terms of taking into account the weather conditions, get the greatest effect at the lowest cost [30].

Eric E. Massey emphasizes the relevance of taking into account the effects of climate change into long-term transport planning in [31] while pointing to its relative novelty.

Due to the complex formalization of weather-climatic conditions in the transport process of harvesting, they are usually idealized. For example, in work [32] the author idealizes the downtime of the combine harvester because of the bad weather, and the climatic conditions at a certain point in time for all fields with ripe crops consider the same.

In the work [33] when considering weather factors affecting field work, the authors in the model assume that the delay in field operation due to 1 mm of precipitation in the form of rainfall is equal to one hour.

3. General provisions for the structural and parametric identification of the system

The algorithm for constructing the scheme of transport support for the harvesting-transport complex operation consists of two main levels - structural identification of the system and parametric identification of the system.

In our study, the level of structural identification of the system includes the following steps (Figure 1):

1. Definition of the structure of the model and its elements; and involves development of formal analytical qualities of the model elements, experts' theoretical and heuristic considerations, a priori information about the research object.

2. Defining the dependant and independent parameters in the organization and planning the transport process based on the general analysis. The purpose of this stage is to analyse and explain the components of the system, as well as determine dependant and independent parameters.

3. The next step is the theoretical justification for the influence of independent parameters. For this purpose our research uses the method of Saati analytic hierarchy process [34]. This method allows theoretically to justify the influence of independent parameters of the transport process as ascending for the stage of simulation with obtaining quantitative estimates.
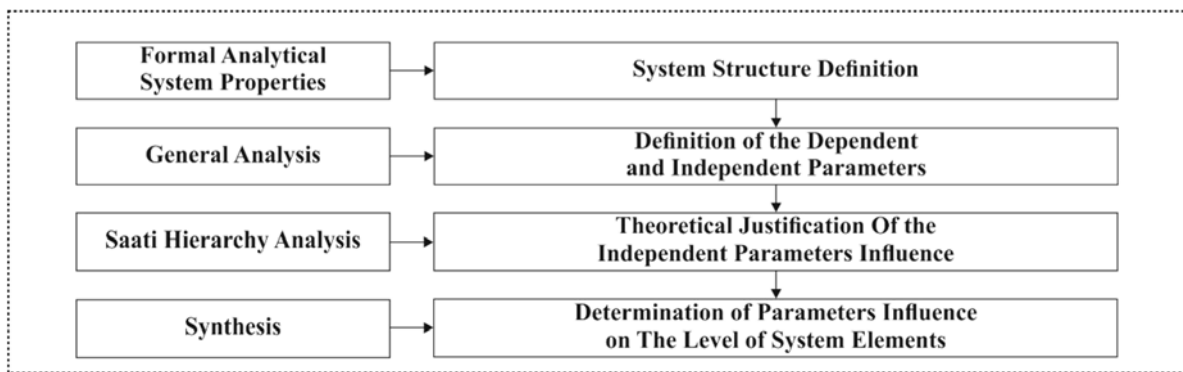

Figure 1. Algorithm for Structural Identification of the System.

4. The next step is to determine the influence of the parameters dependence based on the synthesis method. The purpose of this stage is to establish the relationship between the system parameters. It will occur both in the context of "dependent parameters - independent parameters" and in the context of "dependent parameters - dependent parameters". This step is transitional to the parametric identification of the system.

The level of parametric identification of the system consists of the following steps (Figure 2):

1. The assignment of terms to each of the dependent and independent parameters of the system based on the method of expert estimates. After the terms are assigned for all parameters, go to the next step.

2. Fuzzification of system parameters, i.e. the presentation of fuzzy values of dependent and independent parameters in the form of linguistic truth values.

3. Fuzzy inference is realized by mapping the input data vector to a scalar initial value [35]. To date, the most common models of fuzzy logical inference of Mamdani and Sugeno [36]. The advantages of the Mamdani model are model transparency, comprehensibility to customers - farms, high accuracy of identification with small training samples, and the ability to explain and justify the decision. Each such fuzzy inference forms a separate model, which is responsible for calculating a specific parameter.

4. Defuzzification, that is, the procedure for obtaining a clear result with a fuzzy one. The best method of defuzzification in the construction of applied fuzzy systems is the centre of gravity method [37]. The advantages of the centroid method include a reduction in the amount of computation and an increase in speed [38].

5. Getting the result of the calculation.

6. Validation of the result. When establishing that the calculation result is correct, the final goal is achieved.

If, as a result of modelling, it turns out that the system gives an incorrect result as assessed by practitioners (experts), then it will be necessary to reconfigure the system, for example, set more detailed terms, choose a different fuzzification method, etc.
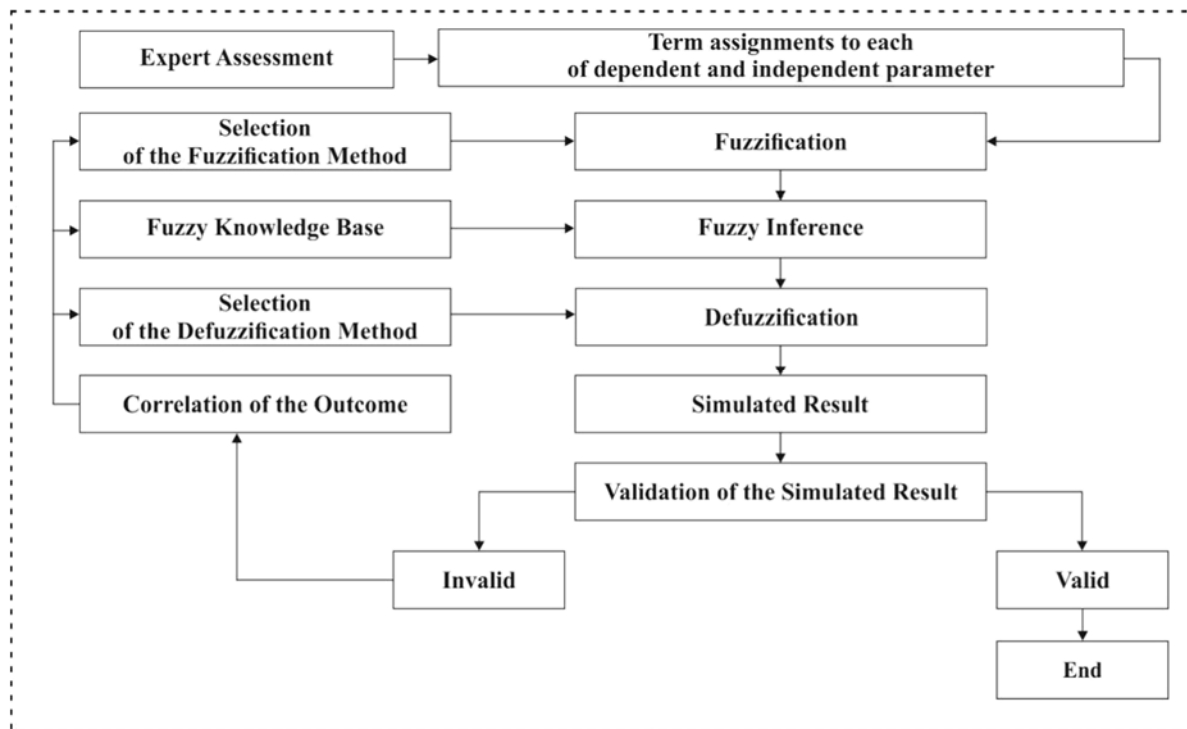

Figure 2. System Parametric Identification Algorithm.

System identification is a cyclic process, which consists in repeatedly choosing the model structure, calculating, according to the selected criterion, the optimal model parameters of the selected structure, and evaluating the properties of the resulting model [39].

When developing the system, the following specialists are involved: analysts, agronomists, and transport engineers, transport operation engineers, managers of agricultural enterprises that are involved in early wheat harvesting, programmers.

4. The implementation of structural and parametric identification of the transportation support system for the harvesting and transport complex

When studying the system of organizing the transport process, the main elements were identified: "Weather and Climate Conditions", characterizing the influence of the external environment, "Field", "Culture", "Harvesting Method", "Harvester", "Road", "Vehicle".

Each of the aforementioned elements of the system for organizing the transport process has been given the appropriate parameters for it, according to which the model was identified (Figure 3).
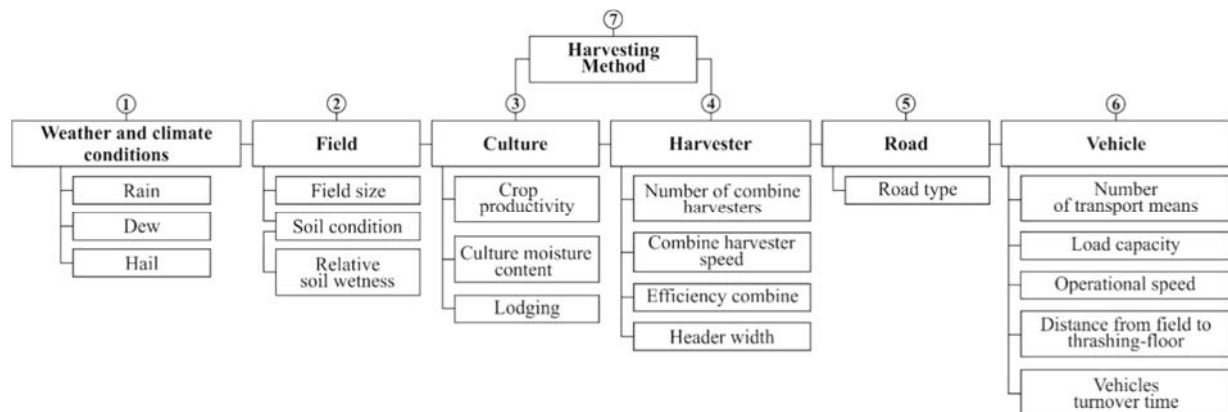
Figure 3. Determining the Structure of the System and its Elements with Parameters in the Organization of the Transport Process of Wheat Early Harvesting.

The second step in accordance with the above methodology of structural identification is the determination of dependent and independent parameters.

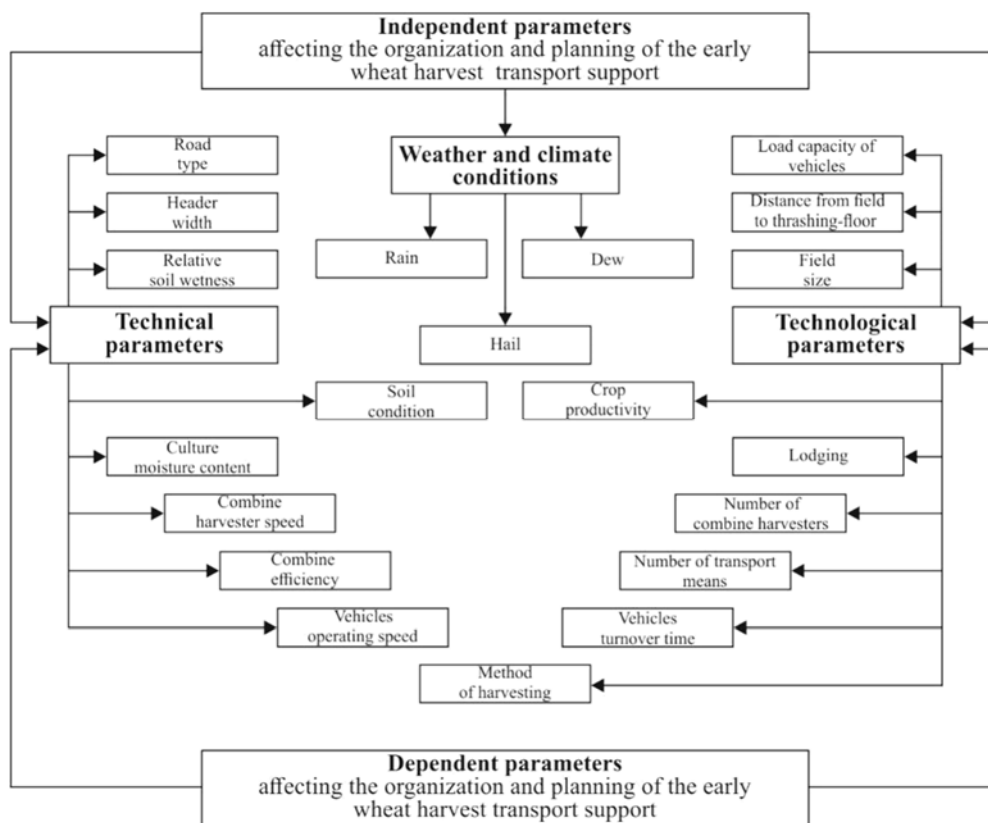Dependent and independent parameters are presented in the form of a diagram (Figure 4).

Figure 4. Dependent and Independent Parameters of the Elements of the Transport Process Organization for the Early Wheat Harvesting.

The third step according to the structural identification algorithm of the system (Figure 1) is the theoretical justification of the independent parameters based on the method of Saati analytic hierarchy process. This approach is described in detail in [40].

The next step is to determine the influence of the dependence of the parameters based on the synthesis method. The purpose of this stage is to establish the relationship between the system parameters. It will occur both in the context of "dependent parameters - independent parameters" and in the context of "dependent parameters - dependent parameters".

As an example, here are a few dependencies. Let us illustrate the influence of the independent parameter "Type of Road" on the dependent parameter "Operational Speed of Vehicles (automobiles)" (Figure 5) and the influence of the independent parameter "Rain" on the dependent parameters "Lodging", "Soil Condition", "Culture Moisture Content" and "Operational Speed of Vehicles (automobiles)" (Figure 6).
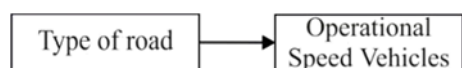
Figure 5. Influence of the independent parameter "Type of Road" on the dependent parameter "Operational Speed of Vehicles (Automobiles)".
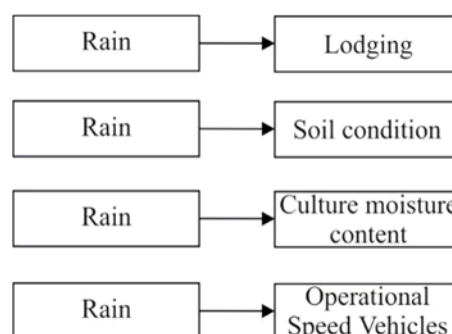
Figure 6. Influence of the independent parameter "Rain" on the dependent parameters "Lodging", "Soil Condition", "Culture Moisture Content" and "Operational Speed of Vehicles (Automobiles)".

The same procedure has been applied to each of 17 parameters. The step of determining the influence of the dependence of the parameters on the basis of the synthesis method is transitional to the system parametric.

The first step of system parametric identification (Figure 2) is the assignment of terms to each of the system parameters based on the expert assessment method.

The research experts [41] in amount of 63 respondents, having more than 10 years practical experience in harvesting wheat, served as resource persons.

The terms are assigned to each of the dependent and independent parameters, using Figure 4. Thus, the terms for the dependent parameters are presented in Table 1.

Table 1. Terms for Parameters.

Parameter	Term	Index
	Lingering	< 20
Rain, mm	Heavy	10
	Short-term	3-5
	High	51-60
Operational Speed of Vehicles	Higher than average	35-50
(Automobiles), km/h	Average	13-35
	Low	12-18
	Long	40 and more
	Higher than average	20-35
Distance from field to thrashing-floor, km	Medium	10-19
	Short	2-9

After the terms are assigned to all parameters, we proceed to the next step - fuzzification of parameters [42,43].

Fuzzy systems can have membership functions of an arbitrary structure, but from a practical point of view, triangular and trapezoidal functions are most popular [44].

We give examples of fuzzification. So, for instance, the analytical form of fuzzification for the "Rain" will be as follows:

Short-term rain

$$\mu(u) = \begin{cases} 0, & u \le 0 \ \text{or} \ u \ge 7,5 \\ 1, & 0 \le u \le 5 \\ \dfrac{7,5-u}{7,5-5} = \dfrac{7,5-u}{2,5}, & 5 \le u \le 7,5 \end{cases} \tag{1}$$

Heavy rain

$$\mu(u) = \begin{cases} 0, & u \le 6,25 \ \text{or} \ u \ge 17,5 \\ \dfrac{u-6,25}{10-6,25} = \dfrac{u-6,25}{3,75}, & 6,25 \le u \le 10 \\ \dfrac{17,5-u}{17,5-10} = \dfrac{17,5-u}{7,5}, & 10 \le u \le 17,5 \end{cases} \tag{2}$$

Lingering rain

$$\mu(u) = \begin{cases} 1, & 20 \le u \le 23,75 \\ \dfrac{u-15}{20-15} = \dfrac{u-15}{5}, & 15 \le u \le 20 \end{cases} \tag{3}$$

The graphic view of fuzzification for the "Rain" parameter will have the following form (Figure 7).
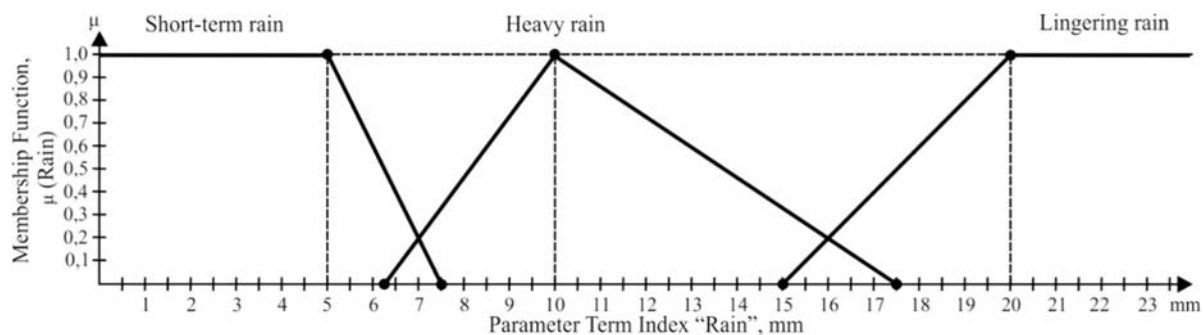

Figure 7. Fuzzification Graph for the "Rain" Parameter

In Figure 7 for the Rain parameter there is a trapezoidal membership function in the initial and final parts of the term, a triangular membership function for the middle part of the term. Let us calculate the membership function μ (u) for the Rain parameter.

At the next stage, after all the parameters are fuzzified, we proceed to the step of fuzzy inference.

A Mamdani model fuzzy inference for the parameters of the transport support system is developed, as illustrated in Table 2.

Table 2. Mamdani model fuzzy inference for the parameters of the transport support system.

IF	Parameter	Term	THEN	Parameter	Term
If	Rain	"Lingering"	Then	Lodging	"Heavy"
If	Rain	"Heavy"	Then	Lodging	"Middle"
If	Rain	"Short-term"	Then	Lodging	"Light"

Thus, based on the implementation of structural and parametric identification of the system, a general approach to modelling transport support for harvesting winter wheat has been developed.

5. Development of an original mathematical model of transport support for the harvesting and transport complex

The mathematical model reflects the interconnection and mutual influence of weather, climate, technical and technological parameters on the elements "Field", "Culture", "Combine Harvester", "Road", "Vehicle".

Based on the decomposition of the system, we obtain individual mathematical models, which simplifies the construction and identification of the model, while maintaining the overall efficiency of the system. Using the model, it becomes possible to conduct a detailed study of transport support during the winter wheat harvesting.

The mathematical model of transport support for winter wheat harvesting is a graph with 9 sources (B), 5 levels of impact stratification (I, II, III, IV, V) and one runoff (C) presented in Figure 8.

In the model, the input parameters act as sources (B): weather and climate - rain, hail, dew; technological parameters - field size, distance from field to threshing floor, load capacity; technical parameters - type of road, header width, and relative soil wetness.

Impact stratification levels break systems down into subsystems in more detail and indicate the interplay and interdependence between system parameters.
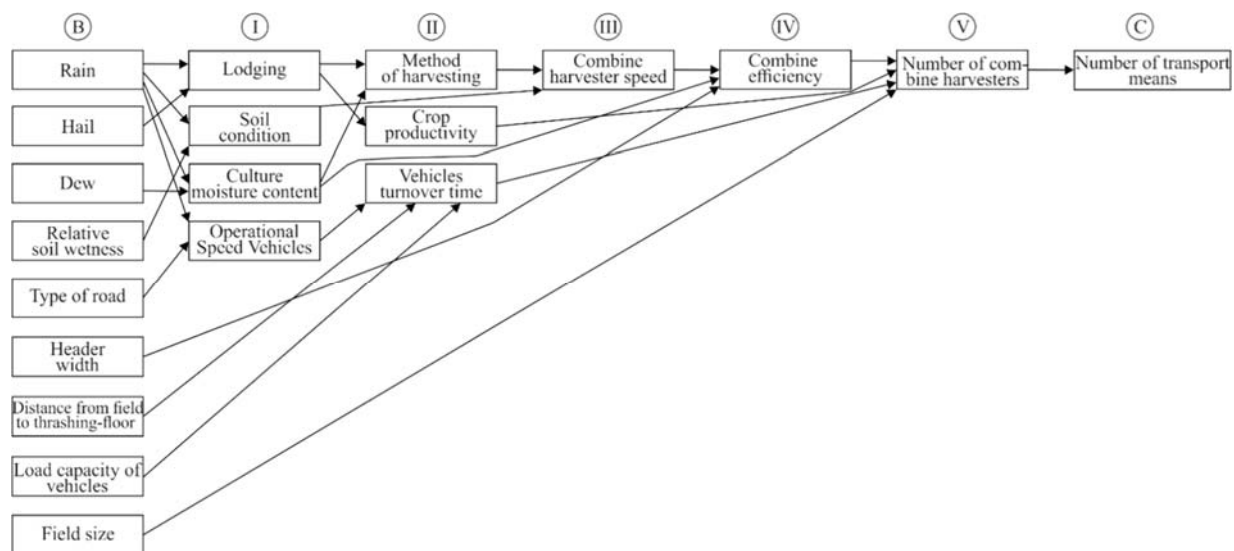

Figure 8. Mathematical Model of Transport Support for Winter Wheat Harvesting.

To better understand and reveal the essence of the mathematical model of transport support in harvesting winter wheat, which is presented on Figure 8, fuzzy mathematical models in the form of linguistic models "Lodging", "Soil Condition", "Culture Moisture Content", "Vehicles (Automobile) Operational Speed", "Harvesting Method", "Crop productivity", "Vehicles (Automobile) Time of Turnover", "Combine Harvester Speed", "Combine efficiency", "Number of Combine Harvesters".

So, according to [45], the linguistic model is a rule base that reflects the general semantic statement of the problem.

As an example, we show a fuzzy mathematical model of "Lodging" in the form of a linguistic model, which will look as follows:

$$
\left\{
\begin{array}{l}
\text{IF "Rain Short term"} \cap \text{"Hail Small"} \rightarrow \text{"Lodging Slight"} \\
\text{IF "Rain Heavy"} \cap \text{"Hail Moderate"} \rightarrow \text{"Lodging Middle"} \\
\text{IF "Rain Lingering"} \cap \text{"Hail Heavy"} \rightarrow \text{"Lodging Heavy"} \\
\text{IF "Rain Short term"} \rightarrow \text{"Lodging Slight"} \\
\text{IF "Rain Heavy"} \rightarrow \text{"Lodging Middle"} \\
\text{IF "Rain Lingering"} \rightarrow \text{"Lodging Heavy"} \\
\text{IF "Hail Small"} \rightarrow \text{"Lodging Slight"} \\
\text{IF "Hail Moderate"} \rightarrow \text{"Lodging Middle"} \\
\text{IF "Hail Heavy"} \rightarrow \text{"Lodging Heavy"}
\end{array}
\right.
\tag{4}
$$

The fuzzy mathematical model of "Lodging" consists of 9 function rules.

A graphical representation of the software implementation of the linguistic model "lodging" will be implemented using the Fuzzy Logic Toolbox application. The "Lodging" model depends on the "Rain" and "Hail" parameters, and when they are taken into account, it is responsible for determining the level of lodging when harvesting winter wheat. Figure 9 presents the view of the Fuzzy Logic Toolbox FIS-editor window after setting the structure of the model "Lodging".
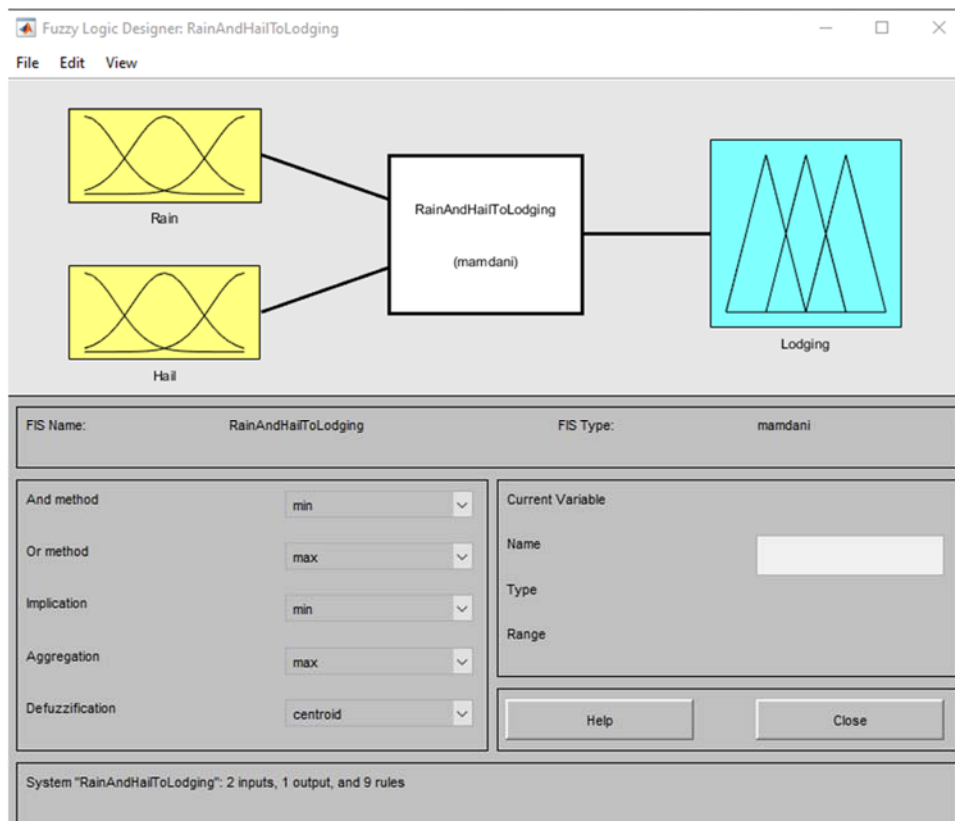

Figure 9. The Fuzzy Logic Toolbox FIS-editor window after setting the structure of the model "Lodging".

The visualization of the fuzzy inference of the "Lodging" model Figure 10 and its graphic view from the input variables "Rain" and "Hail" are shown in Figure 11.
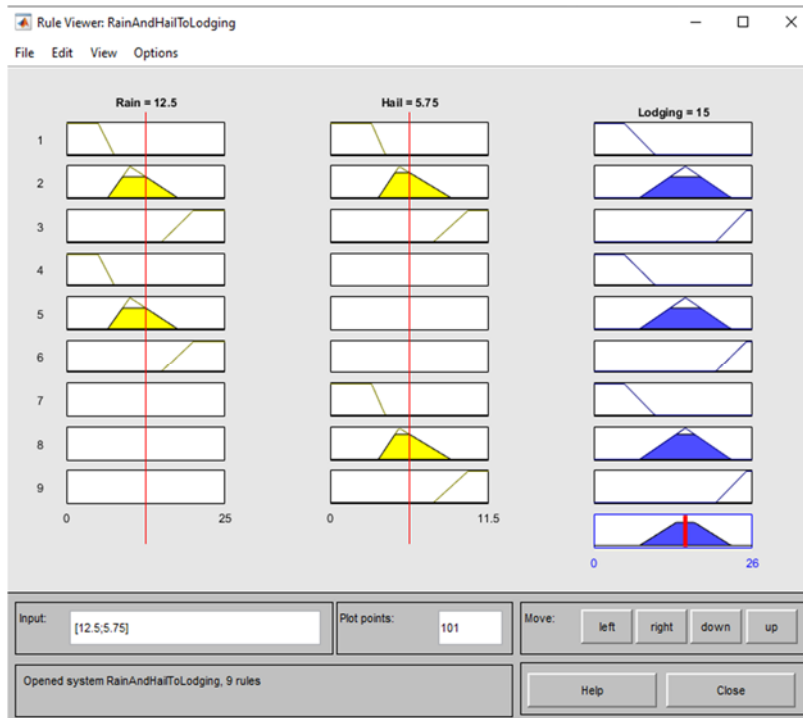
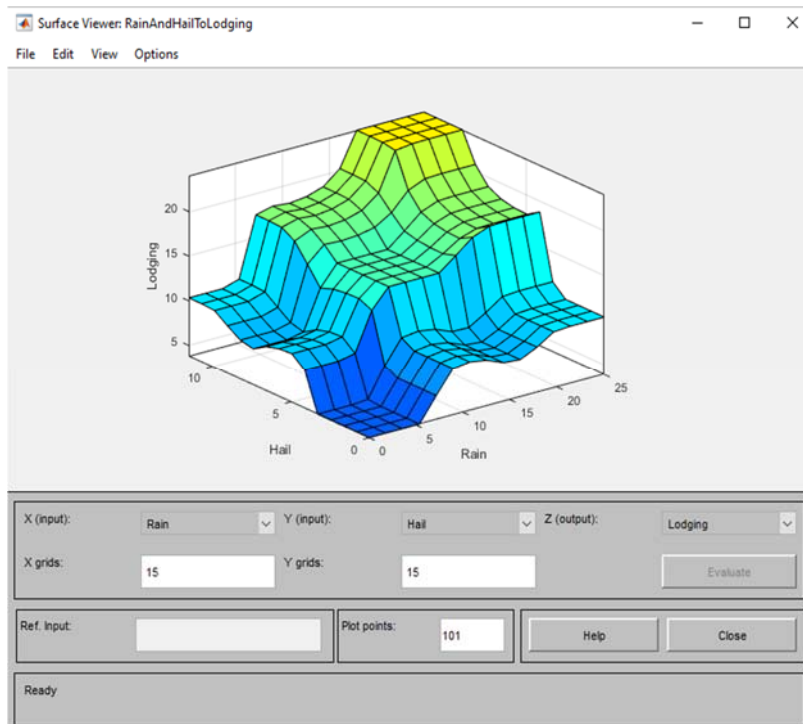**Figure 10.** The visualization of the fuzzy inference of the "Lodging" model

Figure 11. Graphic view from the input variables "Rain" and "Hail"

A mathematical model of transport support built in the Simulink graphical simulation environment is presented in the works [46, 47].

Based on the proposed general mathematical model of transport support for harvesting winter wheat and the algorithms for its implementation, the software was developed in the form of a computer program "Weather Climatic Condition Calculation Agriculture Transport (WCC CAT)" [48] for planning a rational number of vehicles when harvesting winter wheat. Test simulation was conducted on the basis of the peasant (farmer) economy – hereinafter PFE SASHA.
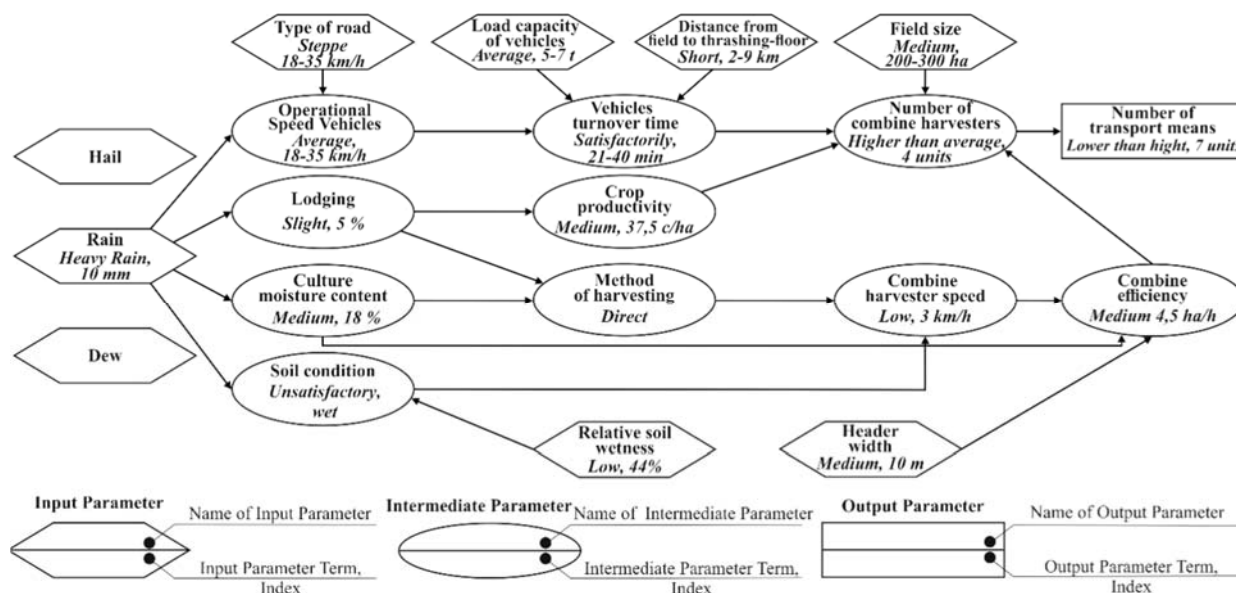

Figure 12. Structural-Logical Scheme for Determining the Number of Vehicles by Day in a Situation When There Was Rain

Using the WCC CAT program, based on the implementation of the structural and logical diagrams of the mathematical model for the situations, the necessary number of cars was calculated that provide the transport process for harvesting winter wheat at the PFE SASHA (Figure 12). Expert analysis of the obtained results shows: weather and climatic conditions have the most significant impact on transport support during the winter wheat harvest; taking into account the influence of the parameters of weather conditions WCC CAT allows to obtain a rational number of vehicles, thereby allowing to reduce the PFE SASHA's total planned need in vehicles by one unit, i.e. 8 vehicles used instead of 9, without violating the harvesting time – 12 days

6. Conclusions

Based on the research, it was found that the existing analytical-statistical and statistical-simulation transport support models do not take into account the weather and climatic conditions and solve the problems of the harvesting and transportation complex functioning in a deterministic setting.

A mathematical model of transport support is developed, which is a graph with 9 inputs, 5 levels of the influence hierarchy and one output. This model, unlike the existing ones, allows to formalize the relationship of the weather, climate, technical and technological parameters of the harvesting and transportation complex.

The simulation method of transport support for the harvesting and transportation complex has been developed. The peculiarity of the method is the accounting of weather-climatic, technical and technological parameters of the harvesting and transportation complex.

The developed method can be used as the basis for the creation of an automated complex for calculating the number of vehicles during harvesting.

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