Environmental aspects of the development and use of innovative agricultural machinery

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Abstract. The aim of the study is to develop an expert indicator that allows quantifying the environmental properties of knowledge-intensive machine-building products and considering on its basis the environmental aspects of the use of innovative agricultural machinery, taking into account world experience. The methodology provides for the quantification of each of the alternatives according to expert tables showing different levels of environmental impact of the production, use and disposal of the products. On the basis of the developed indicator, a comparative assessment of the competitiveness of 22 domestic and foreign self-propelled sprayers used in the Siberian region was carried out. Market leaders have been identified. The International Eco-Efficiency Index for 12 producing countries of selected sprayers has been investigated. A correlation-regression analysis of the environmental indicator was performed, which showed a rather high correlation of its values with the rank of the producing country at the specified index. The indicator of competitiveness of selected sprayers according to the set of technical characteristics is calculated. The correlation of the indicator “level of environmental impact” with the technical characteristics of the product was found to be less than EPI. The developed indicator and its analysis methodology are recommended for all types of innovative machine-building products at all stages of the life cycle.

1. Introduction

The development and production of competitive knowledge-based machine-building products are one of the factors for increasing the rate of economic growth and improving the standard of living of the population at the current stage of development of the Russian economy. These products are characterized by the prevalence of innovative scientific, technical and organizational solutions at all stages of the life cycle. The decision-makers for the development, production, acquisition, investment of products are producers, consumers, private investors and the State. The main criterion in decision-making is the level of competitiveness of products, quantified through a set of adequate indicators, the increase in the number of which is still relevant at present.

Particularly relevant is the forecast evaluation of the competitiveness of knowledge-intensive machine-building products at the early stages of the life cycle (synthesis of ideas, development and development). In this case, due to the lack of precise values of technical and other characteristics of the product, it is advisable to use expert indicators based on the assessments of specialists in the relevant field of knowledge, representatives from producers, consumers and the State. A number of works of Russian [1, 2] and foreign [3] scientists have been published, which consider the development and research of competitiveness of innovative products of the agro-industrial complex. In some machine-building enterprises of the Siberian region, expert indicators of product competitiveness are used within...
the framework of automated decision-making support systems. In particular, the indicator "significance of information technology" is proposed in [4]. This indicator takes into account the level of information technologies and devices used in the products, the degree of digitalization and robotics of the processes of development, production and use of innovative agricultural machinery and other relevant characteristics currently relevant [5].

Environmental indicators are important in the set of indicators. At the same time, statistical data from monitoring systems of man-made landscapes [6], information systems of agricultural clusters [7], as well as methods of assessment of environmental indicators of various agricultural technologies [8-10] can be used to assess the environmental competitiveness of products within a particular region.

Due to the intense ecological situation in many regions of the country, it is an urgent task to develop indicators that reflect environmental aspects at all stages of the product life cycle. In the development of environmental indicators, it is advisable to be guided by normative documents, such as the Federal Law "On Environmental Protection" (as amended as of 3.06.2016), "Foundations of State Policy in the Field of Environmental Development of the Russian Federation for the Period up to 2030" (approved by the President of the Russian Federation on 30.04.2012). When developing indicators of innovative agricultural machinery to be guided by provisions the Federal scientific and technical program of development of agriculture for 2017-2025 (The resolution of the Government of the Russian Federation from 25.08.2017). The aim of the research is to develop an expert indicator that allows to quantify the ecological properties of knowledge-intensive machine-building products and to consider on its basis the environmental aspects of the use of innovative agricultural machinery, taking into account world experience.

2. Materials and methods

In accordance with the purpose of the study, we have developed a new expert indicator "level of environmental impact" (UE). This indicator is a quantitative characteristic of ecological properties of knowledge-intensive machine-building products, showing the degree of impact on the environment of its production, use and disposal processes.

The indicator "level of environmental impact" is determined by additive multiplicative method by formula

\[ U_E = E_1 \cdot E_2 \cdot E_3 + E_4 \cdot E_5 \cdot E_6 + \sum_{i=1}^{m} \Pi_{i=1} E_{E_{ij}} \]  

(1)

Where \( n \) is the number of criteria in the multiplicative group;
\( m \) is the number of multiplicative groups;
\( K_{E} \) - additional criteria-coefficients of the indicator \( U_E \), taking into account stages of product life cycle and other factors (coefficients of the second level).
\( E_1, E_2, E_3, E_4, E_5, E_6 \) are the factors of the indicator, the values of which are selected from Tables 1-6.

| Scale of environmental impact | \( E_1 \) |
|-----------------------------|----------|
| Possible harmful impact only in the workplace | 10 |
| Impact on an employee in the workplace or in a small area | 5 |
| Impact on all employees of the enterprise or on the population of the neighborhood | 2 |
| Impact on all residents of the city or on a large area | 1 |
| Impact on residents of the region | 0.5 |
| Impact on the population of the country | 0 |
Table 2. Environmental pollution factor of production and use wastes.

| Degree of contamination by waste | $E_2$ |
|---------------------------------|-------|
| There is no harmful waste of production | 10    |
| Production and use waste causes pollution for only a few harmful substances, well below MPC | 4     |
| Multi-substance waste pollution close to MPC | 2     |
| Pollution for many substances is close to MPC or slightly exceeded for several substances | 1     |
| For many substances, pollution is slightly higher than MPC or for several substances significantly higher than MPC | 0.5   |
| For many substances, pollution is significantly higher than MPC | 0     |

Table 3. Factor of influence of the products used on nature and man.

| Impact on nature and man | $E_3$ |
|--------------------------|-------|
| No harmful effect on nature and man | 10    |
| Minor harmful effect on plant and animal world without human impact | 6     |
| A certain influence on the plant and animal world with a periodic minor influence on humans | 3     |
| Slight adverse effects on human health in regular contact with products | 1     |
| There may be a slight deterioration in single contact or a significant deterioration in health upon regular contact with the product, Significant deterioration of health in single contact with products or high probability of harmful impact on future generations | 0.5   |

Table 4. Coefficient of compliance of processes of production and use of products to ecological requirements and standards

| Compliance to ecological requirements and standards | $E_4$ |
|-----------------------------------------------------|-------|
| The products conform to all ecological standards in the majority of the countries of the world | 10    |
| The products conform to all ecological standards of the developed countries | 6     |
| The products conform to the main ecological requirements in the majority of the countries of the world | 4     |
| The products conform to the main ecological requirements in the developed countries | 2     |
| The products do not conform to some ecological standards of the developed countries | 1     |
| The products do not correspond to the majority of ecological standards in the majority of the countries of the world | 0.5   |
| The products do not conform to any ecological requirements in the majority of the countries of the world | 0     |
Table 5. Coefficient of complexity of technologies of processing of production wastes and use of products

| Complexity of technology                                                                 | $E_5$ |
|------------------------------------------------------------------------------------------|-------|
| Waste can be used as raw materials by production of other products without use of special technologies | 10    |
| There is a simple technology of processing of waste without use of special reagents      | 6     |
| The technology of average complexity with use of rather cheap and available reagents are known | 4     |
| Difficult technology of processing of waste with use of standard reagents                | 2     |
| Unique technology of processing of waste with use of expensive and rare reagents         | 1     |
| Technologies for processing do not exist, only waste disposal is possible                | 0.5   |

Table 6. Coefficient of the period of self-decay of not processed production wastes and use of products.

| Period of self-decay of waste                                                      | $E_6$ |
|-------------------------------------------------------------------------------------|-------|
| All harmful production wastes self-decay within a day                                | 10    |
| All waste self-decay within a month                                                  | 6     |
| The most part of waste self-decay less than a month, the others – no more than a year | 3     |
| The most part of waste self-decay less than a year, the rest – no more than 10 years | 2     |
| The main part of waste self-decay from 1 year to 10 years                            | 1     |
| The main part of waste self-decay from 10 to 100 years                              | 0.5   |
| The main part of waste self-decay over 100 years                                    | 0     |

One of the areas of activity with a significant negative impact on the environment is the operation of agricultural machinery. This is particularly relevant from the point of view of the implementation of State programmes, such as the "Framework of State Policy in the Field of Chemical and Biological Safety of the Russian Federation for the Period up to 2025 and Further Perspective" (approved by the President of the Russian Federation on 01.11.2013. № Pr-2573). In terms of pollution with hazardous chemicals (insecticides, herbicides, fungicides, defoliants and others), plant protection machines account for the largest proportion [11].

3. Results of the study and their discussion
We evaluated the most common brands of self-propelled sprayers of domestic and foreign production in the Siberian region by the indicator "level of environmental impact". The expert survey was attended by representatives from machine-building enterprises, producers of agricultural products, departments of agriculture, potential investors. For all machines for each table, experts assigned appropriate quantitative estimates with accuracy to tenths of a point. The arithmetic mean of each of the 6 coefficients and the final UE value for each machine were then calculated. The results are shown in Table 7.
Table 7. Indicators and characteristics of self-propelled sprayers.

| Car Brand               | Producer            | $U_E$ | $R_E$ | $K_T$ | $L_P$ | $W_M$ |
|------------------------|---------------------|-------|-------|-------|-------|-------|
| John Deer 4730         | USA                 | 222.32| 36    | 1.11  | 36    | 245   |
| Case Patriot 4430      | USA                 | 220.86| 36    | 1.10  | 30    | 325   |
| Challenger RG 1100     | USA                 | 224.05| 36    | 1.15  | 36    | 311   |
| Amazone Pantera 4001   | Germany             | 254.84| 17    | 1.19  | 40    | 255   |
| Dammann DT 2500H       | Germany             | 241.21| 17    | 1.14  | 30    | 265   |
| Horsch Leeb PT 330     | Germany             | 242.91| 17    | 1.18  | 36    | 330   |
| Kuhn Stronger 3030     | France              | 246.32| 13    | 1.06  | 36    | 260   |
| Tecnoma Laser 4240     | France              | 239.50| 13    | 0.95  | 30    | 200   |
| Berthoud Raptor 4240   | France              | 224.17| 13    | 1.08  | 40    | 200   |
| Gaspardo Uragano 3000  | Italy               | 227.60| 21    | 0.92  | 30    | 190   |
| Bargam Grimac 3000     | Italy               | 229.58| 21    | 0.90  | 28    | 170   |
| New Holland SP240XP    | Belgium             | 213.94| 45    | 1.13  | 36    | 275   |
| Hardi ALPHA evo        | Denmark             | 227.28| 16    | 1.07  | 40    | 220   |
| Agrifac Condor 4000    | Netherlands         | 227.58| 29    | 1.03  | 40    | 210   |
| Houseman Air-Ride 4000 | Great Britain       | 234.62| 12    | 0.96  | 24    | 230   |
| Jacto Uniport 3030     | Japan               | 225.87| 27    | 1.13  | 32    | 243   |
| Blueming BL-3000       | "Mekosan," Belarus  | 170.00| 44    | 0.62  | 24    | 78    |
| Versatile SX-275       | Rostov-on-Don       | 179.60| 61    | 1.05  | 36    | 225   |
| Bars-3000              | Kazanselmash, Kazan| 135.00| 61    | 0.85  | 24    | 130   |
| Fog-2                  | "Pegas Agro," Samara| 130.00| 61    | 0.66  | 28    | 110   |
| Ruby-3500              | "Rubin," Samara     | 132.50| 61    | 0.87  | 24    | 175   |
| Spray Traker           | Invest-Agro, Voronezh| 137.50| 61    | 0.86  | 28    | 145   |

According to the results of the expert assessment on the indicator "level of environmental impact", the leaders of the selected market segment are Amazone Pantera 4001 sprayers (Figure 1). The top five included two more cars from Germany. The lower lines of the rating were taken by Russian sprayers. The best among them is Versatile SX-275 produced by Rostselmash (Figure 2).

![Figure 1. Amazone Pantera 4001 self-propelled sprayer (Germany).](image-url)
In order to analyse the environmental aspects of the use of the above-mentioned agricultural machinery, it is useful to consider the world experience in assessing the integrated environmental indicators of countries and to identify their possible relationship with the competitiveness indicator developed by us.

In world practice, several integral indicators are used for the integrated assessment of private indicators of the ecological status of regions and countries, as well as their environmental policies [12-14].

We suggest that further analysis be carried out on the basis of the value of The Environmental Performance Index (EPI), taken for the producing countries of the considered self-propelled sprayers. The index was developed by the Yale Center for Environmental Law and Policy with Columbia University and the World Economic Forum.

In 2018, the index was calculated for 180 countries (Figure 3). The calculation was carried out in two large groups: ecological health (protection of human health from adverse environmental factors caused by human activities) and ecosystem viability (protection of ecosystems and use of resources). The two groups are divided into nine categories that cover priority environmental policy issues, such as agriculture, air quality, biodiversity, climate and energy, forests, fisheries, health impacts, water resources, water and sanitation. These 9 categories combine 19 indicators calculated for each country.

Taking into account the values of this index, the ranks of the selected spray producing countries for all years of its calculation were determined (table 8).
Table 8. Ranking of Countries by Environmental Performance (EPI).

| Year | Rank | Country | 2006 | 2008 | 2010 | 2012 | 2014 | 2016 | 2018 |
|------|------|---------|------|------|------|------|------|------|------|
| 2006 |      |         | 0.03 | 0.07 | 0.10 | 0.14 | 0.179| 0.21 | 0.25 |
| 2008 | 6    | USA     | 28   | 39   | 61   | 49   | 33   | 26   | 27   |
| 2010 | 1    | Germany | 22   | 13   | 17   | 11   | 6    | 30   | 13   |
| 2012 | 12   | France  | 12   | 10   | 7    | 6    | 27   | 10   | 2    |
| 2014 | 21   | Italy   | 21   | 24   | 18   | 8    | 22   | 29   | 16   |
| 2016 | 39   | Belgium | 39   | 57   | 88   | 24   | 36   | 41   | 15   |
| 2018 | 7    | Denmark | 7    | 25   | 32   | 21   | 13   | 4    | 3    |
| 2012 | 5    | Netherlands | 27   | 55   | 47   | 16   | 11   | 36   | 18   |
| 2014 | 22   | Great Britain | 5    | 14   | 14   | 9    | 12   | 12   | 6    |
| 2016 | 14   | Japan   | 14   | 21   | 20   | 23   | 26   | 39   | 20   |
| 2018 | 50   | Belarus | 50   | 43   | 53   | 65   | 32   | 35   | 44   |
| 2019 | 32   | Russia | 32   | 28   | 69   | 106  | 73   | 32   | 52   |

For the purposes of our study, the value of the weighted average ecological rank of the \( R_E \) country for the whole period of research, determined by the formula

\[
R_E = \sum_{i=1}^{m} b_i R_{Ei}
\]  

Where \( i \) is the year number, \( (i = 1...7) \);
\( m \) - number of rank measurements for the whole period, \( (m = 7) \);
\( b_i \) - normalized weight factors of \( i \) year calculated in accordance with arithmetic progression

\[
b_i = \frac{i}{m + \sum_{i=1}^{m-1}(m-i)}
\]  

The first year of measurement is 2006 \( (i = 1) \).
The last year of measurements we consider 2018 \( (i = 7) \).
The calculated values of the normalized weight factors are shown in Table 8.
The calculated \( R_E \) rank values are shown in Tables 7 and 8.

Also, for all machines, the competitiveness indicator of \( K_T \) was calculated according to the set of technical characteristics. The correlation analysis methods preselected 8 technical characteristics \( X_i \), most affecting the \( K_T \) index, and calculated the normalized weight factors \( a_j \) for each technical characteristic. The weighted average model was used to calculate the indicator

\[
K_T = \sum_{j=1}^{m} \frac{x_i}{X_{CP_j}} a_j
\]  

Where \( m \) is the number of technical characteristics to be considered;
\( j = 1...m \) - characteristic number;
\( a_j \) - normalized weight factor (Table 9);
\( X_{CP_j} \) is the mean value of the technical characteristic (Table 9).

Table 9. Data for calculation of \( K_T \) indicator and correlation with \( U_E \) indicator.

| j  | Technical Data Sheet | \( x_{CP_j} \) | \( a_j \) | \( \text{corr} (U_E, X_j) \) |
|----|----------------------|----------------|--------|-----------------|
| 1  | Span of a rod \( (L_P) \), m | 32.18 | 0.20 | 0.252 |
| 2  | Engine power \( (W_M) \), HP | 220.1 | 0.18 | 0.271 |
| 3  | Maximum height of the rod \( (H_M) \), m | 2.50 | 0.09 | 0.206 |
| 4  | Maximum gauge width \( (S_M) \), m | 2.95 | 0.05 | 0.014 |
| 5  | Ground clearance \( (H_T) \), m | 1.45 | 0.07 | 0.052 |
| 6  | Tank volume with solution \( (Q_P) \), m³ | 3.72 | 0.16 | 0.213 |
| 7  | Operating speed \( (V_P) \), km/h | 22.9 | 0.14 | 0.106 |
| 8  | Transport speed \( (V_T) \), km/h | 43.9 | 0.11 | 0.097 |
Calculated K_T values for all machines are recorded in Table 7.

Using Excel and Statistica software, a correlation regression analysis of the U_E indicator was performed.

The multiple regression equation for the U_E index of the specification complex is as follows:

\[ U_E = 46.362 + 0.267L_P + 0.647W_M + 0.127H_M + 0.187S_M + 0.108H_T + 0.254Q_P + 0.175V_P + 0.166V_T \]  

(5)

Based on the obtained regression, it is possible to determine the forecast value of the U_E indicator of the new brand of self-propelled sprayer at the early stages of the life cycle without conducting an expert survey.

As a result of the calculations, the maximum modules of Pearson's paired correlation coefficient with the U_E index are obtained for the complex K_T index, for the ecological rank R_E, as well as for the span of the L_P rod and the power of the W_M engine:

\[ \text{corr} (U_E, R_E) = -0.407. \]
\[ \text{corr} (U_E, K_T) = 0.296. \]
\[ \text{corr} (U_E, L_P) = 0.252. \]
\[ \text{corr} (U_E, W_M) = 0.271. \]

The correlation coefficient values for the remaining specifications are shown in Table 9.

The higher values of the correlation coefficients R_E with L_P and W_M compared to the rest of the specifications can be explained as follows.

Increasing of the span of the rod L_P reduces the number of passes through the field, thereby reducing the negative compaction of the soil by the wheels of the machine. High-performance wide-range sprayers reduce the time of field work and increase the possibility of chemical treatment of plants in the optimal agricultural period.

The high power of the W_M engine increases the pressure in the solution supply system, which improves the quality of its spraying. Fine-dispersed disintegration promotes better adhesion of solution droplets to plant leaves and stems, reduces drop deposition into soil during treatment of crops.

The results of the calculations allow constructing three-dimensional quadratic response surfaces for the U_E indicator from the change of R_E and K_T (Figure 4), as well as from the change of L_P and W_M (Figure 5). The response surfaces in Figures 4 and 5 are derived from the processing of expert survey data in Statistica 10.

![Figure 4. Response surface for U_E indicator from R_E and K_T change.](image-url)
The analysis of the first surface (Figure 4) allows saying the following:

The direct dependence of the ecological indicator of \( U_E \) products on the ecological rank of the producing country \( R_E \) is more clearly expressed for machines with low technical characteristics.

In countries with low \( R_E \) ecological rank, the main factors of market success are the performance and economic performance of machines, such as productivity, resource costs per hectare, the cost of a ton of produced products, etc.

In countries with high \( R_E \) rank, there are strict environmental laws, high intra-firm standards, and the role of environmental social organizations is great. Manufacturers do not chase unique quantitative characteristics, but develop and produce machines that use innovative technical solutions of environmental orientation. This is especially true for machines handling hazardous and harmful substances (crop sprayers, etc.).

In general, the relationship of the \( U_E \) indicator to the \( R_E \) rank can be characterized as a "correlation slightly lower than the average" and it is higher than the relationship of the \( U_E \) to the \( K_T \), which can be considered a "weak correlation."

With respect to the second response surface (Figure 5), the following can be noted.

For sprayers with span of the rod \( L_P \) less than 30 m, there is a more significant dependence of \( U_E \) index on engine power \( W_M \) than for wide-grip machines. This is due to the greater sensitivity of the quality of the chemical spraying from the power of the engine \( W_M \) in machines with a smaller span of the \( L_P \) rod. In addition, the low power of the engine forces it to operate at reduced gears and high speed, resulting in increased exhaust emissions.

In general, sprayers with span of the rod \( L_P \) of more than 30 m are characterized by the presence of engines with high power \( W_{DM} \) (from 200 to 300 hp). Therefore, either of these engines provides both high quality spraying and reduction of emissions to the atmosphere.

4. Conclusions

The expert indicator "level of environmental impact" has been developed and justified, allowing carrying out quantitative assessment of ecological properties of knowledge-intensive machine-building products through the degree of impact on the environment of processes of its production, use and disposal.

The competitiveness of 22 brands of self-propelled sprayers was evaluated according to the developed indicator.
An analysis of the international Environmental Performance Index EPI for the last 12 years has been carried out for the producing countries of the selected sprayers, on the basis of which the weighted average environmental rank of the countries is calculated.

The indicator of competitiveness of selected sprayers according to the set of technical characteristics is calculated.

A correlation-regression analysis of the indicator "level of environmental impact" was carried out, the results of which show that there is a sufficiently high correlation of the values of this indicator with the rank of the producing country on the EPI index.

There is a smaller correlation of the indicator "level of environmental impact" with the technical characteristics of the product compared to EPI.

The proposed indicator and its analysis methodology can be used to assess the environmental competitiveness of any type of innovative machine-building products at all stages of the life cycle.

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