Design and technological solutions for technical systems based on the example of a sowing complex for grain crops

To cite this article: K Nemtinov et al 2018 J. Phys.: Conf. Ser. 1084 012004

View the article online for updates and enhancements.
Design and technological solutions for technical systems based on the example of a sowing complex for grain crops

K Nemtinov¹, A Eruslanov¹ and Y Nemtinova*¹,²

¹Department of «Computer-integrated systems in mechanical engineering», Tambov State Technical University, 106 Sovetskaya Street, Tambov 392000, Russian Federation
²Department of «Management, marketing and advertising», Tambov State University named after G.R. Derzhavin, 33, Internatsionalnaya Street, Tambov 392000, Russian Federation

*E-mail: jnemtinova@hotmail.com

Abstract. In this paper, we have developed a formalized problem statement for automated design of a technical system (TS) on the example of a sowing complex (SC) and improved the methodology of decision-making information support for its design by creating a virtual model of the TS. An information-logical model, which unifies sets of data on the external environment and data processing technologies, is used for selecting the structural scheme of the TS. A procedural decision-making model allows optimal selection of standard units and mechanisms of the TS taking into account uncertainty and discrepancies in the data. The virtual model of the SC is presented in the form of a hierarchical frame structure, including parametric three-dimensional geometric models and drawings of individual units, devices, mechanisms and details, as well as attributive data. A new design of a SC for grain crops uses both standard units and non-standard devices, which provides reduction of the sowing time and energy consumption together with the possibility of using the SC as a cultivator and a disk harrow.

1. Introduction

Development of decision-making control systems for design of technical systems (TS) is determined by intensive development of methodological foundations of design, mathematical models and algorithms, software and hardware. This problem is essential for making decisions concerning the structure of TS and its specific design parameters, in particular for the agro-industrial complex (AIC) of the Russian Federation [1-5].

The analysis of literature sources on the technology of automated TS design (using the example of sowing complexes (SC)) showed that much attention is paid to structural design of individual TSs or their nodes, and to a lesser degree to optimal selection of TS’s structural scheme from the standpoint of different criteria (economic criterion, reliability, manufacturability, etc.) tied to specific initial data defined by technical specification and consumers: type of grain crops, soil type and moisture, soil tillage technology, drawbar category of the tractor, etc. [6-12]. As a result, it is not possible to consider all available variants of TS’s structural scheme and to choose an optimal one from the standpoint of different criteria.

By investigating the technologies of computer-aided design of complex TS, it was concluded that the whole set of problems solved at all stages of TS design should be considered using the theory of
complex or large systems [1, 8, 13]. Such systems consist of many separate subsystems, each of which solves its own tasks, in particular: obtaining information about the object, transforming it into appropriate control law and transferring it to the object. The breakdown of a complex control system into separate subsystems is stipulated by large dimension of such systems and difficulties associated with gathering and processing of information about their state, and also selecting control actions. In most cases connection between individual subsystems is hierarchical.

Hierarchical systems are generally characterized by:
- location of subsystems with characteristic local properties in accordance with the levels of adopted hierarchy (in the overall structure of the system) corresponding to significance of decisions they make;
- implementation of connections from subsystems of lower levels to subsystems of higher levels by transferring generalized information;
- implementation of connections from subsystems of higher levels to subsystems of lower level through control actions.

In solving a number of problems of technical objects’ design it is expedient to use expert systems that are used for hard-to-formalize and unformalized tasks, which are characterized by the following features [7-8]: incompleteness and inconsistency of initial data and knowledge about the research domain; large dimension of the problem.

In this regard, we have proposed an improvement of decision-making system for design and technological solutions for TSs the ultimate goal of which is to reduce the cost of design and to improve the quality of TS projects as well as to increase the efficiency of their operation on the example of a SC. To achieve this goal it is necessary to solve the following tasks:
- carry out a formalized statement of the decision-making problem for the system of automated TS design using the SC (sowing complex) example;
- improve the methodology of information support for making decisions on TS design;
- develop models for decision-making support in selecting of TS’s structural scheme, as well as its typical operating bodies, devices and mechanisms;
- develop an original design of a SC for grain crops, including a seeder and a disk harrow, using special software;
- carry out experimental studies of the developed SC and evaluate its effectiveness.

The obtained results are based on the achievements of various scientific schools in the field of systems analysis, management, data processing, and technological design for the agro-industrial complex [6-12].

2. Purposes and objectives of research

The purpose of this work is to reduce the cost of development and to improve the quality of TS’s projects, as well as to increase the efficiency of their operation on the example of a SC.

In order to meet these goals it is necessary to solve the following research tasks:
- perform the analysis of existing methods of decision-making information support for the structural design of TSs;
- develop a formalized problem statement of the automated TS’s design on the example of a SC;
- improve the methodology of information support for making TS’s design decisions;
- develop mathematical models of decision support for selection of a structural scheme, as well as its standard operating units, devices and mechanisms;
- develop a virtual model of TS with the reference to the SC;
- develop the structure of information support and software for the system of automated TS design on the SC example;
- develop the original design of a SC for grain crops, including a seeder and a disk harrow;
- carry out experimental studies of the developed SC and estimate its economic efficiency.
3. Problem statement of technical system design and decision support model

In general, the problem of automated TS design for a set of specific initial data (with the reference to the SC it includes the type of grain crops, soil type and moisture, soil tillage technology, drawbar category of the tractor and criteria set by the consumer) provides: development of its structural scheme, selection of typical elements, and design of original units, devices and mechanisms.

In a formalized form, the problem of TS design is to find an optimal value (minimum) of a function:

\[ I_{\text{opt}} = \min_{w \in W} F_w, \]  

under the constraints:

\[ tx_{i}^{\min} \leq tx_i \leq tx_{i}^{\max}, \quad i = 1, 2, ..., N_k, \quad tx_i \in Tx, \]

and operators representing mathematical models of decision support for selecting:

- structural scheme of a TS:
  \[ \Psi: Pu \times Va \times Zb \times Rm \times Du \times Tu \rightarrow K, \]

- typical elements of a complex (units, devices and mechanisms):
  \[ \Phi: Tx \times R \times G \times k_{opt} \rightarrow Kt, \quad k_{opt} \in K, \]

- design solutions for TS as a whole:
  \[ \Omega: k_{tx_{opt}} \times k_{opt} \times P^3 \rightarrow Ku, \quad k_{tx_{opt}} \in Kt, \quad k_{opt} \in K, \]

- design values and operating conditions of individual elements of TS as a whole:
  \[ \Lambda: k_{tx_{opt}} \times k_{opt} \times k_{tx_{opt}} \rightarrow Tx, \quad k_{tx_{opt}} \in Kt, \quad k_{opt} \in K, \quad k_{tx_{opt}} \in Ku, \]

where: \( F_w \) - generalized criterion for the w-th version of the TS; \( K, Kt, Ku \) - sets of variants for TS’s structural schemes, typical units, devices and mechanisms, and design solutions, respectively; \( k_{opt}, kt_{opt}, ku_{opt}, tx_{opt} \) - optimal choice of a structural diagram; typical units, devices and mechanisms; TS’s design; design values and operating parameters of individual elements, respectively; \( N_k \) - number of technological parameters; \( tx_{i}^{\min}, tx_{i}^{\max} \) - the minimum and maximum values of the i-th technological parameter, \( tx_i \in Tx \); \( Tx \) - set of parameters; \( P^3 \) - three-dimensional space for placement of units and mechanisms; \( Pu, Va, Zb, Rm, Lu, Tu \) - sets of main nodes types; \( W = K \times Kt \times Ku \times Tx \) - set of TS variants;

\[ w_{opt} = \{ k_{opt}, kt_{opt}, ku_{opt}, tx_{opt} \mid k_{opt} \in Kt, \quad k_{opt} \in K, \quad k_{tx_{opt}} \in Ku, \quad tx_{opt} \in Tx \} \]

- an optimal version of TS’s project; \( \Psi, \Phi, \Omega, \Lambda \) - functional operators.

It is almost impossible to obtain the solution to this problem due to high dimensions of variables sets, complexity of mathematical models for design decision-making, complexity of formalizing individual problems, specific design features of individual units, devices and mechanisms of the complex. In this regard, the proposed decision-making method for TS design consists of a sequential solution of 4 sub-tasks of smaller dimension, interconnected by information flows, and possessing independent significance in the design process. In Figure 1 it is shown a conceptual model of the decision-making process for TS design on the example of a SC.

The problem \( A \) of automated formation of admissible TS structural schemes in accordance with the project specifications and selection of an optimal one based on a vector criterion is rarely solved. This is due to various difficulties, e.g. formalization of the problem. In order to solve such problems expert systems are most often used.

In order to solve this problem a structured database was created. Data structure for our subject area is presented in the form of its virtual model.
Figure 1. Conceptual model of decision-making process for TS design on an example of SC.

Data structure in the TS’s virtual model - $TS_{em}$, describing the whole data set:

$$TS_{em} = \{Sc_{em}, P_{em}, Ms_{em}, Ma_{em}, Mg_{em}, D_{em}\},$$

where $Sc_{em}$ - a frame describing the structural composition of a TS; $P_{em}$ - a frame describing the properties of a TS as a whole; $Ms_{em}$ - set of ways to determine the properties of a TS; $Ma_{em}$ - set of attributive characteristics of a TS; $Mg_{em}$ - set of parametric graphic models of a TS; $D_{em}$ - a set of two-dimensional drawings of a TS.

In order to form the functional structure of TS we used production rules of the following type: if ... (fulfillment of a condition), then ... (implementation of a sequence). Below there is an example of such rules applied to the SC design problem:

- if (frame = “solid” and tanker type = “combined”), than dispenser type = “roller, quantity =1”;  
- if (frame = “solid” and tanker type = “separated for four dispensers”), than dispenser type = “roller, quantity = 4”;
- if (frame = “solid” and tanker type = “combined” and dispenser type = “roller, quantity =1”), than transportation unit = “screw conveyer”;
- if (frame = “solid” and tanker type = “combined” and dispenser type = “roller, quantity =1”), than transportation unit = “bucket elevator”;

At present, the dimension of the set of SC structural schemes does not exceed a thousand, thus the method of full enumeration can be applied to find an optimal solution. The next problem in making TS’s design decisions on the example of a SC for grain crops is selection of typical elements (units, devices, mechanisms, etc.) from the assortment manufactured by the industry - $A_i$. In most cases, a significant part of them have a standardized size (hoe and chisel colters, bearings, disc knives, etc.). On the other hand, grain tankers, packing and transporting devices are manufactured according to individual orders.

Due to a wide variety of parts, mechanisms and units of agricultural machinery which have the same basic parameters, it becomes necessary for designers to select the one (unit or mechanism) with characteristics corresponding to a separate subset $R_{\text{cad}}$ of specific customer requirements [13-16].
The authors propose a decision-making model for the selection of a typical part (unit, device or mechanism) of TS that ensures selection of the best one from the standpoint of the accepted criterion, that is characterized by the best technical characteristics and consumer properties obtained on the basis of quantitative (not always accurate) or qualitative information.

The decision support model for the selection of typical units, devices and mechanisms of the TS includes the process of forming a set of types of parts (units, devices or mechanisms) for the required used satisfying the values of technical characteristics. Further, based on the full enumeration method an optimal type is chosen.

4. Implementation of mathematical models of decisions support for design of a technical system

Implementation of the information support methodology for decision-making in design of technological complexes was carried out at LLC CB “ERUSLAN” (Russia) on the example of SC for grain crops. The initial data for design: soil tillage technology = “zero”; sowing material = “grain crops, wheat”; drawbar category of the tractor <= 1.4; soil type = “chernozem (humus content 5-9%, acidity ~ 7 pH).

As a result of solving the $A_1$ problem a technological scheme of the SC was chosen, including the following main operating units, devices and mechanisms: frame = “solid”, tanker type = “combined”, packing device = “pneumatic tires”, sowing mechanism = “disk knives”, dispenser type = “roller”, transportation unit = “bucket elevator”.

As result of solving the $A_1$ problem for the SC the following industry-standard typical nodes were chosen: pneumatic tires brand = “disks from the UAZ452 vehicle, tires 235/65 / R16” quantity of 15 pcs.; disk knives = “BDT smooth disk with a diameter of 560 mm” quantity of 42 pcs.; dosing unit brand “SZP”.

The results of virtual models development for non-standard units and mechanisms (solutions of the problem $A_0$): frames of the grain tanker and bucket elevator are shown in Figure 2.

Visualization of the virtual model and a photo of the prototype are shown in Figure 3 and Figure 4.

5. Analysis of experimental results for the developed technical system

Based on design features of the developed SC we have done the adjustment of the optimal values of its design parameters for a disk knife. In the course of experimental studies the angle of inclination of the disk varied from 10 degrees to 20 degrees. As a result of the experiment required data was obtained and correlation dependences between the value of specific traction resistance $R$ ($R_{cc}$ - on the stubble background, $R_{cn}$ - on the fallow background) and the studied parameter were represented by the second degree polynomials.

As a result of experimental data approximation done with the least squares method we have obtained the regressions of specific traction resistance on the disk inclination angle $l$.

Optimal (minimal) values of these functions are achieved at the disc angle of 15 degrees, while the specific traction resistance of the SC on the stubble background does not exceed 3.44 kN/m, and on the fallow background does not exceed 3.19 kN/m. This angle of inclination and was adopted in the final version of the SC design.
Figure 2. Visualization of virtual models: a - roller dispenser; b - roller of the dispenser.

Figure 3. Visualization of the virtual model of the SC.
Figure 4. Photo of the SC prototype.

The optimal number of plants of grain crops per unit area of planting is largely related to the functioning of the bucket elevator and is provided by varying the following parameters: the volume of the buckets, the distance between the buckets and the speed of the bucket elevator.

The optimal values of these parameters were determined as a result of a computational experiment using the orthogonal central composition plan of the experiment. The bucket capacity ($x_1$) varied in the range from 3.0 dm$^3$ to 9.5 dm$^3$; the distance between the buckets ($x_2$) was in the range from 0.1 m to 0.25 m; and the speed of the elevator ($x_3$) - in the range from 0.047 m/s to 0.16 m/s.

As a response function, we used the function: $f(x_1, x_2, x_3) = |N_v - N_{exp,i}|$, where: $N_v$ - sowing rate per 1 m$^2$, $N_{exp,i}$ - number of seeds during the $i$-th experiment, $i = 1, 2, ..., 15$. Variation levels of selected factors are given in Table 1. For three factors, correction of their squares $a = 0.73$, "star shoulder" $\alpha = 1.215$. Experimental results are given in Table 2.

Optimal quantity of plants of grain crops per unit area of sowing is provided with the following parameters: bucket volume - 7.2 dm$^3$, distance between the buckets - 0.21 m; the speed of the bucket elevator - 0.12 m/s. As the degree of polynomial increases, their values remain unchanged.

Table 1. Variation levels of selected factors.

| Factor | $-\alpha$ | -1 | 0     | +1     | +\alpha |
|--------|----------|----|-------|--------|--------|
| $x_1$  | 3.0      | 3.48| 6.25  | 8.83   | 9.5    |
| $x_2$  | 0.1      | 0.11| 0.175 | 0.236  | 0.25   |
| $x_3$  | 0.047    | 0.057| 0.104 | 0.15   | 0.16   |
Table 2. Experimental results.

| Level of factor $x_1$ | Level of factor $x_2$ | Level of factor $x_3$ | $|N_v - N_{exp}|$ |
|-----------------------|-----------------------|-----------------------|------------------|
| -1                    | -1                    | -1                    | 152              |
| 1                     | -1                    | -1                    | 141              |
| -1                    | 1                     | -1                    | 145              |
| 1                     | 1                     | -1                    | 96               |
| -1                    | -1                    | 1                     | 76               |
| 1                     | -1                    | 1                     | 56               |
| -1                    | 1                     | 1                     | 24               |
| 1                     | 1                     | 1                     | 15               |
| -α                    | 0                     | 0                     | 56               |
| α                     | 0                     | 0                     | 89               |
| 0                     | -α                    | 0                     | 66               |
| 0                     | α                     | 0                     | 97               |
| 0                     | 0                     | -α                    | 98               |
| 0                     | 0                     | α                     | 102              |
| 0                     | 0                     | 0                     | 29               |

In assessing the performance of the SC, the following values were determined: specific traction resistance; the proportion of seeds in the soil layer; uniformity of distribution of wheat seeds in the area of sowing.

Experiments in laboratory conditions and field studies allowed compiling a list of advantages of the developed design of a sowing complex presented in Table 3.

Table 3. Results of structural analysis.

| Indicator                          | Type of seeder |
|------------------------------------|----------------|
|                                    | Base | Designed SC |
| Number of plants per 1 m, pcs      | 329  | 372         |
| Number of productive plants, pcs   | 302  | 347         |
| Plant height, cm                   | 40.3 | 43.9        |
| Length of a spike, cm              | 4.4  | 5.1         |
| Number of grains in a spike, pcs   | 14.1 | 15.5        |
| Grains weight of 1000 pcs          | 42.2 | 44.1        |
| Grain weight from 100 plants, g    | 59.8 | 64.8        |
| Biological yield, centner/ha       | 39.6 | 43.8        |

As an example, the results are given below: the depth of sowing (see Figure 5) and the distribution of seeds along the width of the sown band (see Figure 6).

6. Results and discussion
As a result of the presented research work the authors have solved an important scientific and practical problem of developing a decision management system for structural design of TS, implemented on the
example of the original SC, which provides a cost reduction of up to ~ 15% and an increase in operating efficiency of ~ 17% in comparison with analogs.

![Graph](image)

**Figure 5.** Results of sowing depth evaluation.

![Graph](image)

**Figure 6.** Results of evaluation of seeds distribution over the width of the sown band.

Other notable results include:
- reduction of sowing works duration as there is no gap between soil preparation and sowing;
- reduction of energy consumption by combining the operations of soil preparation, processing, sowing and packing of soil in one device (the use of diesel fuel for the whole cycle of sowing works is no more than 4 l/ha compared to the cost of performing these operations separately ~ 5-7 l/ha);
- optimal depth of sowing at the level of dew point, preserving the initial states of the capillaries, which ensure the natural supply of moisture from the ground;
- the possibility of using the SC as a cultivator and a disk harrow.
7. Conclusion

Based on the research results the following conclusions are made:

- a formalized statement of decision-making problem for computer-aided design of TSs on the example a SC was performed and the methodology of decision-making information support was improved taking into account TS’s construction characterized by complexity of its structure, which includes standard and customized components and mechanisms; in addition a thorough analysis of computational and field experiments was conducted in order to clarify the values of individual structural elements of the TS;

- it was developed an information-logical model, which represents a combination of data sets containing information about external environment, technologies of its processing, and is crucial for making decisions about TS’s structural scheme. A distinctive feature of the decision support model is its structure, which accumulates the set of relationships between all the main operating units and mechanisms of the TS with the help of production rules;

- a virtual model of the TS with the application to the SC is presented in the form of hierarchical frame structure, including parametric three-dimensional geometric models and drawings of individual operating units, devices, mechanisms and parts, as well as related attributive data.

References

[1] Nemtinov V A and Nemtinova Y V 2005 Journal of Computer and Systems Sciences International 44(3) 389-398
[2] Mokrozub V G, Nemtinov V A and Mokrozub A V 2017 Chemical and Petroleum Engineering 53(5-6) 326-331
[3] Lijing L 2015 Transactions of the Chinese Society of Agricultural Engineering 31(11) 40-45
[4] Mokrozub V G and Nemtinov V A 2015 Chemical and petroleum engineering 51(7-8) 31-35
[5] Lin J, Qian Wei, Li Baofa and Liu Yanfen 2015 Transactions of the Chinese Society of Agricultural Engineering 31(9) 19-24
[6] Prasanna Kumar G V, Srivastava B and Nagesh D S 2009 Computers and Electronics in Agriculture 65(1) 26-35
[7] Wang J M, Zhang L, Liu Y B, Mo X N and. Ren G Q 2010 Computer Integrated Manufacturing Systems 16(10) 2017-2023
[8] Mokrozub V G, Manuilov K D, Gorshkov V V and Gorshkova T S 2016 Chemical and Petroleum Engineering 51(9-10) 613-617
[9] Ivannikov A, Kulagin V, Romanov A and Pozdneev B 2016 Proceedings of IEEE EAST-WEST DESIGN & TEST SYMPOSIUM (EWDTS'2016) (Yerevan, October, 14-17, 2016) 248-251
[10] Pappalardo C M and Guida D 2018 Machines 6(2) 19
[11] Pappalardo C M and Guida D 2017 Meccanica 52(11-12) 2503-2526
[12] Pappalardo C M and Guida D 2017 Journal of Dynamic Systems, Measurement, and Control 139(8) 081010
[13] Malygin E N, Mokrozub V G and Nemtinov V A 2017 MATEC Web of Conferences 129 01009
[14] Vamerali V, Bertocco M and Sartori L 2006 Soil & Tillage Research 89(2) 196-209
[15] Yang L, He X T, Cui T, Zhang D X, Shi S, Zhang R and Mantao W 2015 International Journal of Agricultural and Biological Engineering 4 1-9
[16] Zhao T, Zhao Y, Higashi T and Komatsuzaki M 2012 Engineering in Agriculture, Environment and Food 5(2) 50-56