Application of a structural-topological model in the optimization of the working elements of a combine harvester

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Abstract. A structural-topological model is developed, which is presented in the form of connected graphs of the technological flows of grain and spike. Taking into account this model, the use of the main and additional formal features when searching for a non-optimal working element of a combine harvester is justified. For the reaping part, the search for a non-optimal working element is performed on the main formal basis, which characterizes the implementation of the main component of the principle of harmony of the structure. Due to the presence of common arcs of controlled and uncontrolled flows along simple chains, cuts in which two or more working elements, as well as the presence of circulating flows in the threshing machine of the combine, it is necessary to exclude the influence of circulating flows on the process when searching for a non-optimal working element. The search for a non-optimal working element of the thresher is performed on the basis of an additional formal feature, which is characterized by a decrease in the amount of flow along the controlled flow or an increase in the flow through the uncontrolled flow from the circulation flow.

1. Introduction
Grain production is one of the important criteria for assessing the state of the country's food security. One of the ways to increase grain production is the highly efficient use of a combine harvester. Therefore, research is aimed at optimizing the working elements, which reduce the effectiveness of combine harvesting. Quantitative information to assess the effectiveness of the use of harvesters can be obtained experimentally under operating conditions (Comparative tests of agricultural equipment: scientific publication) or by calculation, using the mathematical model [1-3]. Approximate, regression and probabilistic mathematical models are used to optimize the working element [4-6]. However, these models are difficult to use to search for a non-optimal working element of a combine harvester.

2. Methodology and purpose
The purpose of the study is to justify the use of a structural-topological model of a combine harvester to search for a suboptimal working element.

The search for a non-optimal working element will be performed using a structural-topological model, which is presented in the form of graphs [7, 8].

Let's make the connected graphs of the technological flow of grain and the ear of a combine harvester, since grain is a component of productivity, and spike is taken into account when determining the total loss of grain by the combine. The grain in the uncleaned area is designated $P_{s1}$ (Figure 1) and is called
the input of the graph and, and the output is the grain in the bunker of the combine harvester and we
denote $P_1$ ($P_{24}$). On the non-cleaned part of the field of the spike on the stem, let us designate $P_2$ (Figure 2) and call it the network input, and the threshed ear that came from the breeder will be the output of $P_{22}$. Solid green lines (▬▬▬) denote controlled flows on the working elements $P_i$ of the combine harvester, and dash-dotted lines with two points red lines (• • ▬ • • ▬) uncontrolled flows denoted by arcs $Li$. The cuts are shown in dashed blue lines (▬ ▬ ▬). The parameter of the controlled and uncontrolled flow is the flow of grain and spike, and the indicator of the $i$-th working element is the productivity, which we denote by the process flow: grain $\omega_i^1$ and spike $\omega_i^2$.

Figure 1. Associated graph $R_1 = (P, L)$ of the process flow of grain on the working elements of the combine PCM-152 “ACROS-595 Plus”.
Figure 2. Connected graph $R_2 = (P, L)$ of the spike process flow on the working elements of the combine PCM-152 “ACROS-595 Plus”.

Based on the study of the direct process of combining the combine harvester RSM-152 “ACROS-595 Plus” (Combine grain harvester self-propelled RSM-152 «ACROS Plus»). Instructions for use and maintenance) with a shredder-spreader, the associated graphs of the process flow are compiled: grain $R_1 = (P, L)$ and spike $R_2 = (P, L)$.

When the combine moves in the field, the working elements of the header perform the following technological operations. The reel ram 1 (Figures 1 and 2) captures the stems that are cut by the cutting unit 2, and then they are sent to the header auger 3. The spirals of the auger 3 capture the cut stems and direct them to the center of the header. In this case, the finger mechanism of the screw 4 delivers the cut
mass into the inclined chamber of the header. Next, the chain conveyor 5 and the beater top 6 stems are fed into the threshing drum 7 combine harvester.

The working elements of the threshing apparatus and straw walkers perform the following technological operations. Under the action of the threshing drum 7, the bread mass is threshed. On the trellised deck 8 stands out the main part of the grain and fine fractions of coins. Next, the straw fraction with a bumer beater 9 is reflected on the straw walker 10. On the straw walker 10, the straw fraction is divided into parts: straw and a grain pile. After that, the straw enters the hopper-combination 11 for grinding and scattering.

The working elements of the cleaning system perform the following technological operations. From the threshing drum 7, the grain pile is sent to the grading board 12. Next, the pile enters the additional sieve 13, the upper cleaning sieve 14 and the extension 15. During the movement of the grain pile on these working elements, the fan and the spikelets are separated from the seed. After the extension cord is sent to the field. On the bottom sieve of cleaning 16, the grain is separated from the spikelets.

Transporting devices perform the following technological operations. The grain auger 17 directs the cleaned grain to the grain elevator 18. Next, the grain is transported by the screw auger 19 to the bunker 24. Unmilted spikelets, which fell through the upper sieve 14 and the extension of the upper sieve 15 to the lower sieve 16, are transported to the tailings screw conveyor 20 and the grain elevator 21. Next, the spikelet comes in domlama device 22.

In the brewing device 22 is re-threshing. After the threshed heap auger 23 is distributed across the width of the shaker plate 12.

3. Research results and discussion

On the connected graph of the process flow, the grain $R_1 = (P, L)$ of the PCM-152 "ACROS-595 Plus" combine (Figure 1) will denote the cuts by dashed lines, and also divide the adjacent cuts into zones, which take into account the nodes and systems of the combine harvester.

Zone I includes the harvesting section and cuts are included: $(A, \overline{A}) = \{L_{251}\}, (B, \overline{B}) = \{L_{12}\}, (C, \overline{C}) = \{L_{23}\}, (D, \overline{D}) = \{L_{34}\}, (E, \overline{E}) = \{L_{45}\}, (F, \overline{F}) = \{L_{66}\}, (G, \overline{G}) = \{L_{67}\}.

Zone II includes the threshing apparatus and the straw separator, and cuts are also included: $(H, \overline{H}) = \{L_{78}\}, (J, \overline{J}) = \{L_{8912}, L_{912}\}, (JLK, \overline{JLK}) = \{L_{812}, L_{912}, L_{910}\}, (JLN, \overline{JLN}) = \{L_{912}, L_{912}, L_{9012}\}.

Zone III includes the cleaning system and cuts are included: $(P, \overline{P}) = \{L_{213}\}, (RQ, \overline{RQ}) = \{L_{316}, L_{314}\}, (RTS, \overline{RTS}) = \{L_{316}, L_{4146}, L_{415}\}, (RTU, \overline{RTU}) = \{L_{316}, L_{4146}, L_{4516}\}, (U, \overline{U}) = \{L_{5017}\}.

Zone IV includes transporting devices and incisions are included: $(W, \overline{W}) = \{L_{7718}\}, (X, \overline{X}) = \{L_{818}\}, (Y, \overline{Y}) = \{L_{9y1}\}.

On the linked graph $R_2 = (P, L)$ of the process flow of the ear of the PCM-152 "ACROS-595 Plus" combine (Figure 2), we denote the cuts by dashed lines and divide into zones the adjacent cuts that take into account the components and systems of the combine harvester.

Zone I includes the harvesting section and cuts are included: $(A, \overline{A}) = \{L_{251}\}, (B, \overline{B}) = \{L_{42}\}, (C, \overline{C}) = \{L_{23}\}, (D, \overline{D}) = \{L_{24}\}, (E, \overline{E}) = \{L_{43}\}, (F, \overline{F}) = \{L_{26}\}, (G, \overline{G}) = \{L_{67}\}.

Zone II includes the threshing apparatus and the straw separator, and cuts are also included: $(H, \overline{H}) = \{L_{78}\}, (J, \overline{J}) = \{L_{812}, L_{912}\}, (JLK, \overline{JLK}) = \{L_{812}, L_{912}, L_{910}\}, (JLN, \overline{JLN}) = \{L_{912}, L_{912}, L_{9012}\}.
Zone III includes the cleaning system and cuts are included: \( (P, \overrightarrow{P}) = \{L_{1213}\} \), \( (RQ, \overrightarrow{RQ}) = \{L_{316}, L_{314}\} \), \( (RTS, \overrightarrow{RTS}) = \{L_{316}, L_{416}, L_{415}\} \), \( (RTU, \overrightarrow{RTU}) = \{L_{316}, L_{416}, L_{516}\} \).

Zone IV includes transporting devices and incisions are included: \( (BB, \overrightarrow{BB}) = \{L_{201}\} \), \( (CC, \overrightarrow{CC}) = \{L_{212}\} \).

Zone V consists of a brewing device and a distribution auger, and cuts are also included: \( (DD, \overrightarrow{DD}) = \{L_{222}\} \), \( (EE, \overrightarrow{EE}) = \{L_{231}\} \).

On the linked graph \( R_1 = (P, L) \) of the technological flow of grain (Figure 1) we denote the simple chains \( C_i \) of the controlled flow:

\[
\begin{align*}
C_{1}^{1} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1316}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}]; \\
C_{1}^{2} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1316}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}]; \\
C_{1}^{3} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1316}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}]; \\
C_{1}^{4} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1416}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}]; \\
C_{1}^{5} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1416}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}]; \\
C_{1}^{6} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1416}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}]; \\
C_{1}^{7} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}]; \\
C_{1}^{8} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}]; \\
C_{1}^{9} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1617}, L_{1718}, L_{1819}, L_{19v1}].
\end{align*}
\]

On the linked graph \( R_1 = (P, L) \) of the process flow of grain (Figure 1), we denote the simple chains \( C_i \) of the uncontrolled flow:

\[
\begin{align*}
C_{1}^{10} &= [L_{811}, L_{11v1}]; \\
C_{1}^{11} &= [L_{811}, L_{12}, L_{2v1}]; \\
C_{1}^{12} &= [L_{811}, L_{12}, L_{23}, L_{3v1}]; \\
C_{1}^{13} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1011}, L_{11v1}]; \\
C_{1}^{14} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{15v1}]; \\
C_{1}^{15} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{15v1}]; \\
C_{1}^{16} &= [L_{811}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{812}, L_{1012}, L_{1213}, L_{1314}, L_{1415}, L_{15v1}].
\end{align*}
\]

On the linked graph \( G_1 = (N, A) \) of the technological flow of grain (Figure 1) we denote the simple cycles \( S_i \) :

\[
\begin{align*}
S_{1}^{1} &= [L_{1213}, L_{1316}, L_{1620}, L_{2011}, L_{2122}, L_{2223}, L_{2312}]; \\
S_{2}^{1} &= [L_{1213}, L_{1314}, L_{1416}, L_{1620}, L_{2012}, L_{2122}, L_{2223}, L_{2312}]; \\
S_{3}^{1} &= [L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2011}, L_{2122}, L_{2223}, L_{2312}].
\end{align*}
\]
On the linked graph $R_2 = (P, L)$ of the spike process flow (Figure 2), we denote the simple chains $C_i^l$ of the controlled flow:

$C_1^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1316}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_2^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1012}, L_{1114}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_3^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1012}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_4^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_5^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{912}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_6^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1012}, L_{1114}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_7^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_8^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{912}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_9^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1012}, L_{1114}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_{10}^2 = [L_{521}, L_{12}, L_{1v2}];$

$C_{11}^2 = [L_{521}, L_{12}, L_{2v2}];$

$C_{12}^2 = [L_{521}, L_{12}, L_{23}, L_{3v2}];$

$C_{13}^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1011}, L_{11v2}];$

$C_{14}^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_{15}^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{912}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_{16}^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1012}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

On the connected graph $R_2 = (P, L)$ (the technological flow of the spike Figure 2) the simple chains $C_i^l$ of uncontrolled flow denote:

$C_{110}^2 = [L_{521}, L_{12}, L_{1v2}];$

$C_{111}^2 = [L_{521}, L_{12}, L_{2v2}];$

$C_{112}^2 = [L_{521}, L_{12}, L_{23}, L_{3v2}];$

$C_{113}^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1011}, L_{11v2}];$

$C_{114}^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{812}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_{115}^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{912}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}];$

$C_{116}^2 = [L_{521}, L_{12}, L_{23}, L_{34}, L_{45}, L_{56}, L_{67}, L_{78}, L_{89}, L_{910}, L_{1012}, L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{23v2}].$

On the linked graph $R_2 = (P, L)$ of the spike process flow (Figure 2), we denote simple cycles $S_i^2$:

$S_1^2 = [L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{2312}];$

$S_2^2 = [L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{2312}];$

$S_3^2 = [L_{1213}, L_{1314}, L_{1415}, L_{1516}, L_{1620}, L_{2021}, L_{2122}, L_{2223}, L_{2312}];$

The algorithm for solving the structural-topological model is based on the conservation equation for the process flow.

Since the optimization of the working element leads to an increase in the efficiency of the combine harvester, the main component of the principle of the harmony of the machine design must be implemented. In this case, the parameters of all elements of the machine should be proportionally combined with the given performance, as well as the quality of work [9]. Therefore, to determine the state of the working element, we use the main formal feature that characterizes the implementation of the principle of harmonious construction. If the flow on the controlled flow is equal to the theoretical productivity of the working element, then such a working element is taken as the optimal one. If the
flow on a controlled flow value differs from the theoretical performance of the working element, then such a working element is taken as non-optimal.

From Figures 1 and 2, which represent the graphs of the grain and spike process streams, it follows that the main formal feature can only be used to search for the non-optimal working element of the harvest part of the PCM-152 “ACROS-595 Plus” combine. When searching for a non-optimal working element of the thresher, it is necessary to take into account the presence of the following conditions: simple chains of controlled technological flows of grain and spike have common arcs with uncontrolled technological flows; sections include two or more workers element; on simple circuits of controlled process flows of grain and spike there are circulation flows through simple cycles. Therefore, when determining the flow of controlled flow, it is necessary to exclude the influence of the circulating flow on the technological process in the thresher and use the theory of graph theory on the maximum flow and minimum cut [7, 8 and 10].

Due to the absence of the value of supplying the circulating flow to the working parts of the thresher, an additional formal indication of determining the state of the working element is used, which is based on the condition of preserving the flow. If on the working part of the threshing machine the productivity value is equal to the sum of the feeds over the controlled and circulation flows, then a zero flow passes along the arc of the uncontrolled flow. This working part of the thresher is optimal, as it will keep the flow through the controlled flow from the effects of the circulation flow. If on the working element of the thresher the productivity value is less than the sum of innings on the controlled and circulation flows, then on this working body the flow along the uncontrolled flow arc increases. The non-optimal working unit of the thresher contributes to the reduction of the flow through the controlled flow from the circulation flow.

4. Conclusion
The structural-topological model of a combine harvester, which is presented in the form of connected graphs of the technological flows of grain and spike, allows one to substantiate the use of the main and additional formal features when searching for a non-optimal working element of the combine harvester. The search for a non-optimal working element of the reaping part of the combine harvester will be carried out on the basis of the main formal characteristic, which characterizes the implementation of the main component of the principle of harmonious design. Due to the presence of common arcs of controlled and uncontrolled flows along simple chains, cuts in which two or more working elements, as well as the presence of circulating flows in the threshing machine of the combine, it is necessary to exclude the influence of circulating flows on the process when searching for a non-optimal working element of a combine harvester. The search for a non-optimal working element of the thresher is performed on the basis of an additional formal feature, which is characterized by a decrease in the amount of flow along the controlled flow or an increase in the flow through the uncontrolled flow from the circulation flow.

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