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Variant Design of Modular Products Using Functional Modelling and Multi-Criteria Evaluation Method

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Abstract: In this work, the function structure of a mobile machine for corn peeling was developed using the functional decomposition method. The function structure obtained by functional decomposition served as the basis for the definition of working principles, i.e. initial modules (function carriers) by which partial functions were solved. A multi-criteria evaluation of the working principles was used to select those working principles that received the highest rating. A technical and economic evaluation was carried out in accordance with VDI2225. This evaluation method was chosen because it allows working principles to be analysed and evaluated by applying different criteria and sub-criteria. The results of the overall quality of the compared working principles are presented graphically. This shows which working principle received the highest or lowest rating. By combining working principles with different physical effects and design forms, five conceptual variants were generated. In the further analysis through the other phases of the design process, the first conceptual variant was selected as the final product with a modular structure.

Keywords: conceptual design; functional decomposition; modular design; multi-criteria evaluation; technical systems; variant design

1 INTRODUCTION

The systematization of design knowledge [1-3] is extremely important in the early stages of the design process, such as the phase of the task clarification and definition and the conceptual phase. In the design process, these two phases have a decisive influence on the future product because it is necessary to make decisions during their implementation, for which not all information and data about the future product are still known [4]. It is therefore important that such decisions are correctly made and systematically written down. Other phases of the design process do not have such a problem because the technical description of the product is recorded in prescribed formal documents such as structural title blocks, technical drawings, computerized CAD models, control and service documentation. Therefore, it is necessary to apply different design tools that would enable the design team to make reliable and traceable decisions in the conceptual phase and the clarification task phase.

Application of functional modelling is an important tool that enables creation of product function models in the conceptual phase, creating connections between functions at different levels of the function structure [5]. By applying the functional decomposition method, the overall function is broken down into functions of less complexity of components and sub - assemblies, which enables a better understanding of the relationship between functions [6, 7]. The authors in [8] develop a method of hierarchical functional modelling for the analysis of complex systems. Since the function structure is limited to identifying auxiliary systems of individual components, the authors in [9] propose an integrated function structure and object-oriented design framework method. Papers [5, 7, 10], use graphic models of function flow diagrams. These models connect partial functions into function structures by monitoring the flow of energy, material and signal. Very often, such models can be very complex, and tracking the connections between functions is complicated and unclear. Also, the mentioned function models can hardly help the designer in analysing the functionality of technical systems in the conceptual phase [11]. Papers [12, 13] develop a model of the function and functionality matrix (MFF), which enables the connection of partial functions into function structures through the matrix form. Also, the MFF model enables searching for the principle of solutions for individual partial functions, which is not possible to achieve through the function flow diagram models. Such research is based on the application of the morphological matrix [14] in the generation of the conceptual variants in the process of the product design.

Modular design can be a good initial point for a design of variant products, whose modules form independent and connectable units [15]. Functional analysis of products with different or equal functions precedes to the design of function modules [16]. Different market requirements have influence on the product design that are created by combining and connecting modules with precisely defined functionalities into a unique structure of a new product. Certain specific user requirements, the need for mass production, shorter production time, assembly forms, improvement of production quality, increase of innovative products, costs reduction and simple maintenance, influenced on the development and application of modular design methods [16, 17]. In the paper [18], by applying a modular design method in the conceptual phase, the modular structure of the refrigerators was determined. The importance of the modular structure determination in the early stage of design, i.e. on the conceptual stage, was observed. Authors in [19] using Design Structure Matrix (DSM) and Modular Function Deployment (MFD), optimized product designs for automation. The products had a modular structure, which enabled them to increase the variety of a new products and higher degree of automation in the assembly line.

Modularity does not only represent products whose structure consists of exchangeable modules that form product variants, but also contains some other aspects of application [20]. The application of modular design methods is significant in the development of the interface modules of the mobile APP [21], in the new design approach of the housing market [22] and in the design of smart furniture [16]. The connection between mechatronic solutions as the fulfilment of the functions of modular design structures in wheelchair construction is shown in [23]. The authors in [24] base modularity on the life - cycle processes such as manufacture, assembly, service, and recycling. By grouping components into modules, according to the way they are recycled, it has the effect of reducing the cost of withdrawing the product from use. According to research conducted on smartphones [25], it is necessary to take into account the economic and technological feasibility of modularization when designing new products. The authors introduce an ecological efficiency index that analyzes the environmental impact of upgradeable components such as batteries and motherboards. The proposed index can be helpful in determining the appropriate modular design of product variants. Also, multi - objective modular design methods are increasingly being developed. These methods include multiple objectives related to functionality, environmental and economic constraints. The authors in [26] develop a multi-objective green modular design method. This method uses atomic theory and fuzzy clustering to create module configurations.

It is extremely important to make the right decisions when choosing working principles and connecting them into the structure of the conceptual variant. It is also important, after several conceptual variants have been defined, to select those variants that make the most sense for further development in the other phases of the design process. The knowledge and experience of the designer is important here, but often the choice of the best working principle or conceptual variant differs from designer to designer [4]. Therefore, in the design process, as well as in the conceptual phase, different methods and tools are used that enable the designer to be reliable and repeatable in making decisions [27, 28]. Bad decisions in the conceptual phase affect costly rework and the demand for resources that could have been spent on innovative and new products [27]. Some of the more significant evaluation methods that use defined multi - criteria systems in the decision - making process in the conceptual phase are: Promethee method [29], technical and economic evaluation method according to VDI 2225 [30, 31], Analytic Hierarchy Process (AHP) [32, 33] and Quality Function Deployment (QFD) [34]. Regardless of the development of new methods and tools, and the desire to minimize the designer's subjective approach in decision - making, the need for his knowledge and experience is still an important part of the decision - making process in the conceptual phase [29].

2 METHODS AND METHODOLOGY

In the paper, a function model of a mobile machine for corn peeling was developed using the functional decomposition method. By the function flow diagrams, the overall function is decomposed into partial functions, which form the function structure at five functional levels. The connection between the functions is achieved through monitoring the flow of energy, material and signal. It is presented how the function model can serve as a basis for the generation of a modular structure, that is, the functional modelling of five independent modules (function carriers). For their interconnection, it is important to use the experience and knowledge of the designer as well as precisely defined interfaces. In the design phases of embodiment design and detailed design, the function carriers are formed into the following modules: stand with wheels, drive reducer, peeling table, fan and corn cob pressers. The function model did not prove to be sufficient for determining the carrier of functions. Therefore, this model is connected to the morphological matrix. The morphological matrix enabled the connection of partial functions from the function model with working principles, i.e. function solutions. The working principles served as a basis for determining the modules (function carriers). The selection of the best modules was achieved using the evaluation of working principles using the method of technical and economic evaluation according to VDI 2225 [30]. For this purpose, a system of criteria was determined. From this system, a set of goals was determined. For each goal, the goal importance, the goal importance factor and the goal rating were determined. After the evaluation process, the working principles that had the best values of overall goodness were connected in the structure of the first conceptual variant. Also, through further analysis, the remaining working principles are interconnected in next four conceptual variants. After further analysis, through the other stages of the design process, the first conceptual variant was selected as the final product, whose modular structure consists of five modules.

3 FUNCTIONAL DECOMPOSITION OF THE MOBILE MACHINE FOR CORN PEELING

The design task that resulted from the market research aims to design a prototype of a new mobile machine for corn peeling. The market survey was conducted on a sample of 30 family farms that harvest corn on the cob. The basic purpose of the machine would be the domestication of mercantile and seed cobs of corn after it has been harvested by corn pickers, and before the corn is stored. A detailed description of the requirements, resulting from the market analysis, is categorized into five categories listed in [4]. The more important design requirements, according to which the function structure was generated by the functional decomposition method, are extracted from [4] and listed below: the purity level of corn after passing through the machine should be 95 – 100 %, the possibility of driving with a tractor or an electric motor, ensure the mobility of machine with two or four wheels, two or more inputs for feeding the machine with the corn cob, one output for the exit of the peeled corn cob, easy use, modular structure, easy maintenance, satisfy the necessary safety regulations at work and reduce production costs.

Conceptual design, in the first step, aims to generate the function structure of the product. The overall function of a mobile machine for corn peeling is the carrier of the highest level of abstraction and is described at the first level of the function structure through the input - output flow of energy, material and signal (Fig. 1).

By analysing the requirements from the requirement list [4], the main function "*Completed corn cob peeling*", using the functional decomposition method, was divided into five levels. Thus, the level of its abstraction was reduced, that is, partial functions of lower complexity were determined. For partial functions, the carriers of these functions, i.e. the working principles, will be seeked later. By connecting the working principles, conceptual variants and modules of the mobile machine for corn peeling will be formed.

The function flow diagram of the second level of the function structure of the mobile machine for corn peeling (Fig. 2) was formed by decomposing the overall function from the first level of the function structure.

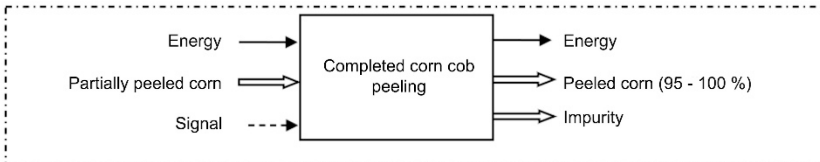

Figure 1 The first level of the function structure of the mobile machine for corn peeling

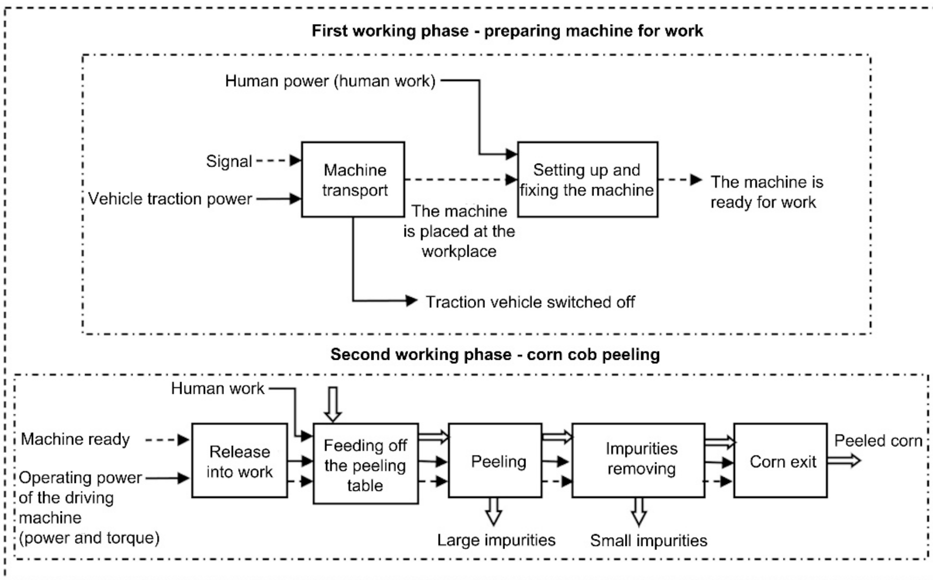

Figure 2 The second level of the function structure of the mobile machine for corn peeling

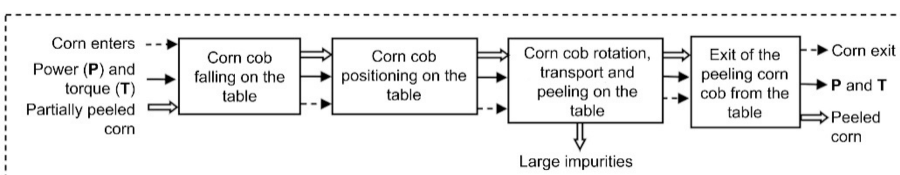

Figure 3 The third level of the function structure of the mobile machine for corn peeling

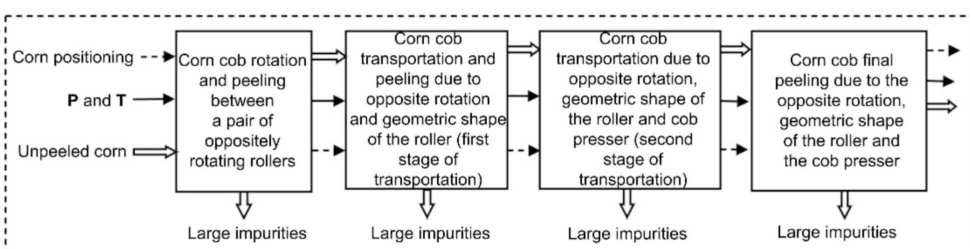

Figure 4 The fourth level of the function structure of the mobile machine for corn peeling

The second level of functional decomposition includes two phases of manipulating the machine. The first phase consists of preparing machine for work. To realize this phase, two functions "Machine transport" and "Setting up and fixing the machine" are required. After the first phase has been realized, the second phase follows. Five functions are needed to realize the second phase (Fig. 2).

Due to its complexity, the function "Peeling" is divided into four partial functions that form the third level of the function structure (Fig. 3).

Due to its complexity, the function "Corn cob rotation, transport and peeling on the table" was divided into four new functions that form the fourth level of the function structure (Fig. 4).

This complexity is also evident from its name, since it is necessary to functionally solve rotation, transport and peeling.

The function "*Corn cob final peeling due to the opposite rotation, geometric shape of the roller and the cob presser*" is also a complex function. Therefore, it is divided into two functions of less complexity. These two functions form the fifth level of the function structure of the mobile machine for corn peeling (Fig. 5).

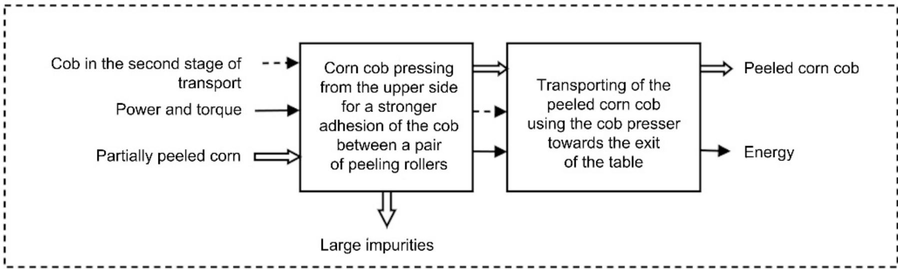

Figure 5 The fifth level of the function structure of the mobile machine for corn peeling

3.1 Function Carriers of the Mobile Machine for Corn Peeling

From the function structure, it follows that the mobile machine for corn peeling will have a modular structure, i.e. the machine itself will consist of several independent modules that will be interconnected via precisely defined interfaces.

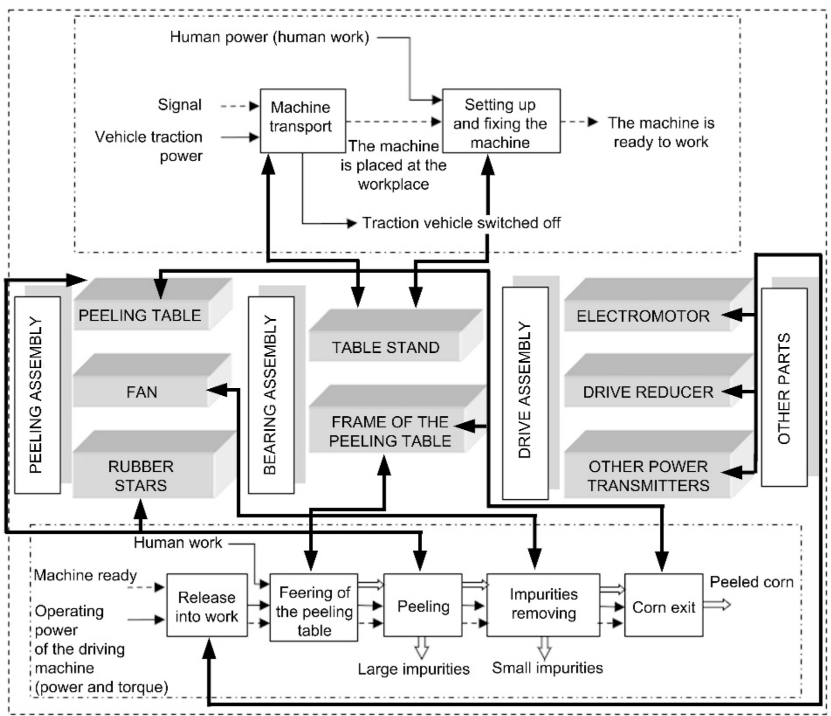

Figure 6 Integrated scheme of relations of partial functions and their carriers

Modules are functionally independent units, i.e. carriers of one or more functions, which have a minimum number of previously precisely defined connections with other modules, components and parts. From the function structure developed on five levels and shown in Fig. 1 to Fig. 5, the mobile machine for corn peeling can potentially have the following modules: stand with wheels, drive reducer, peeling table, fan and corn cob pressers. Connections between partial functions and their carriers are shown in Fig. 6. It follows from the above that with the mentioned modules the machine would be almost complete, if the equipping of the machine with electrical signalling is excluded. According to traffic laws, the machine, as a trailer, must have electric signalling, but it is not functionally analysed in this paper.

3.2 Determination of the Working Principles of the Partial Functions

The working principles represent technical systems of varying complexity that are possible solutions for partial functions determined by the function structure of a mobile machine for corn peeling. They represent the function carriers and by their subsequent connection in the further course of the design process, they will form the structures of the construction variants (conceptual variants) and modules of the mobile machine for corn peeling. At the searching for a solution, priority is given to those partial functions that determine the principles of the overall solution, and the sequence is derived from the identification connections between the flow of energy, material and signal.

Partial functions and the principles of their solutions (working principles) are presented using the morphological matrix method (Fig. 7). The concretization of working solutions (principles of the solutions) is represented by solution sketches, solution schemes and geometric forms of potential modules of the mobile machine for corn peeling.

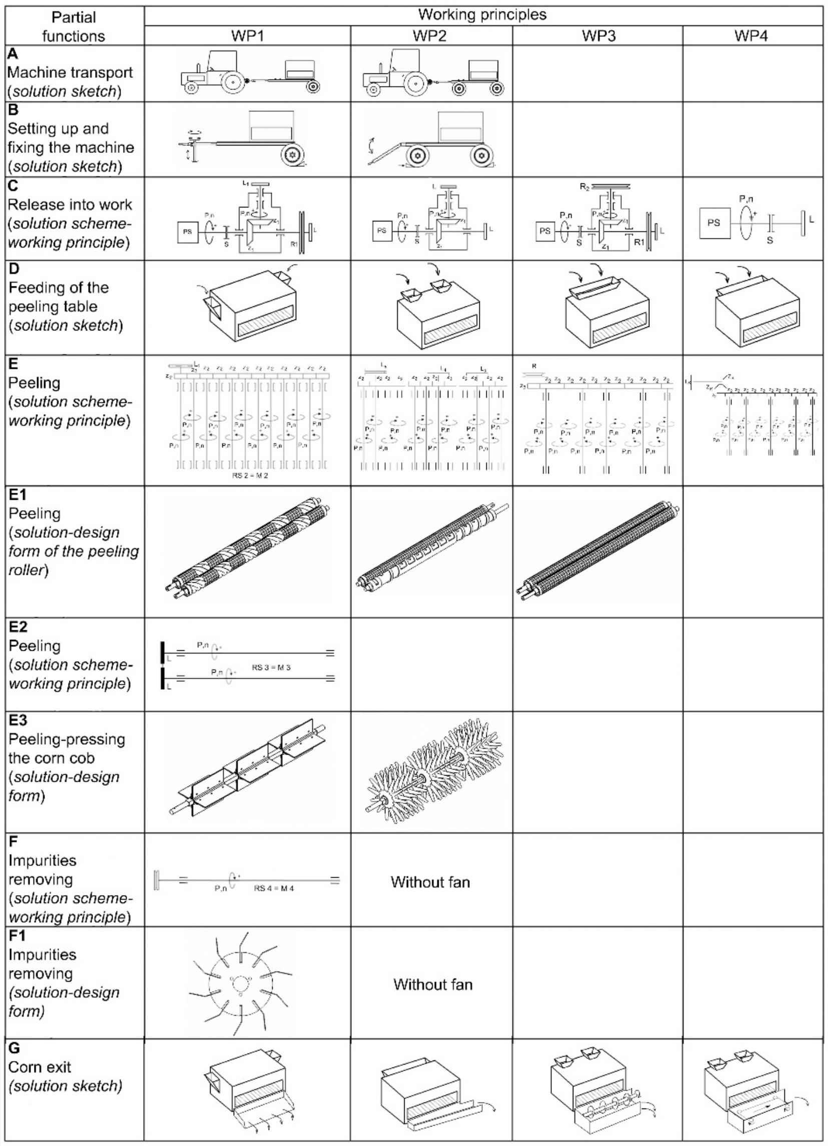

Figure 7 Morphological matrix of possible working principles of partial functions obtained from function structure

4 EVALUATION BY THE METHOD OF TECHNICAL AND ECONOMIC GOODNESS ACCORDING TO VDI 2225

4.1 Determination of the Criteria System and the Goal System

By analysing the working principles shown in the morphological matrix (Fig. 7) and combining them into working structures (conceptual variants), the basis for designing product variants was achieved. In order to select the best solution principles, a technical and economic evaluation was carried out according to VDI 2225. According to the evaluation, the best solutions were selected, which were then connected into working structures (conceptual variants).

The evaluation represents the phase in which all the proposed working principles of the solution (Fig. 7), in relation to the set of goals, are assigned appropriate ratings. The goals system is determined from the criteria system. It should be pointed out that during the evaluation in the conceptual phase, a lot of information about the product is still missing. Therefore, after evaluation process, it is useful to reduce the choice of possible variant solutions (combination of working principles) to those variants that are the most promising. Then only they need to be further developed in the following design phases.

The criteria according to which the evaluation of working principles was carried out were defined based on the analysis of the most important requirements from the requirement list and the function structure of the mobile machine for corn peeling. The criteria system is divided into three levels (Tab. 1). On the first level there are three basic criteria, which on the second level are described by six sub-criteria. Finally, at the third level there are fourteen sub-criteria that describe the criteria from the second level.

Table 1 Evaluation criteria of working principles

First level	Second level	Third level
Safe function execution	Mechanical safety	Working principle reliability
		Working principle complexity level
	Basic function efficiency	Traffic operability
		Work operability
Technological design	Design complexity level	Parts complexity level
		Parts number
	Manufacturing and assembly complexity level	Machining share
		Casting technology share
		Welding device
		Assembly complexity level
Good exploitation properties	Adjustment and maintenance	Simple adjustment
		Simple maintenance
	Maintenance costs	Regular costs
		Extraordinary costs

According to the criteria from Tab. 1, a system of goals is determined, which for each evaluation cycle is divided into four hierarchical levels (Fig. 8). Two quantitative indicators are attached to each partial goal. The first indicator is goal importance at the associated level (G_{ijk}), and the second indicator is the goal importance factor relative to the ultimate goal (g_{ijk}). In this way, the advantage of certain partial goals is clearly suggested in relation to other goals that are on the same level. At the same time, the importance of individual partial goals is analyzed according to the degree of realization of the ideal solution (ultimate goal).

Due to the comprehensiveness of the evaluation of the working principles in the morphological matrix (Fig. 7), this paper presents the evaluation of the working principles WP1 and WP2, which solve the partial function A (*"Machine transport"*). Since they solve the function A, in the evaluation process they are marked with A WP1 and A WP2, that is, the working principle WP1 (two-wheel machine drive) which solves function A and the working principle WP2 (four-wheel machine drive) which also solves function A. For all other working principles from the morphological matrix (Fig. 7), the evaluation procedure is presented in [4].

For the evaluation process of all working principles, the same system of goals was used (Fig. 8). Different values are assigned only to individual goals for the indicators G_{ijk} and g_{ijk}. The assignment of the numerical values to quantitative indicators was achieved on the basis of the experience and knowledge of the designer. The final structure of the goal system with associated system elements and features, for the evaluation of working principles A WP1 and A WP2, is shown in Fig. 8.

According to the principle of consistency of the value of the importance of goals, the total value of the goal importance at the second hierarchical level (Fig. 8) corresponds to the value of the factor of the overall goal (ideal goal):

$$\mathrm{G}_i = \sum_{j=1}^{3} G_{ijk} = \mathrm{G}_{11} + \mathrm{G}_{12} + \mathrm{G}_{13}, \tag{1}$$

where $i = 1$ and $k = 0$.

The total value of the partial goal importance factor at the second hierarchical level, in the system of goals, must correspond to the value of the associated goal importance factor of the higher level, i.e. the value of the importance factor of the ideal goal:

$$g_i = \sum_{j=1}^{3} g_{ijk} = \mathrm{g}_{11} + \mathrm{g}_{12} + \mathrm{g}_{13}, \tag{2}$$

where $i = 1$ and $k = 0$.

The third hierarchical level of the system of partial goals with its goal importance values is determined by the expression:

$$\mathrm{G}_i = \sum_{j=1}^{3} \sum_{k=1}^{2} G_{ijk}, \tag{3}$$

where $i = 1$.

The third hierarchical level of the system of partial goals with its values of the goal importance factor is determined using the expression:

$$g_{ij} = \sum_{j=1}^{3} \sum_{k=1}^{2} g_{ijk}, \tag{4}$$

where $i = 1$.

The fourth hierarchical level of the system of partial goals with its goal importance values is determined by the expression:

$$\mathrm{G}_i = \sum_{j=1}^{3} \sum_{k=1}^{2} \sum_{l=1}^{4} G_{ijkl}, \tag{5}$$

where $i = 1$.

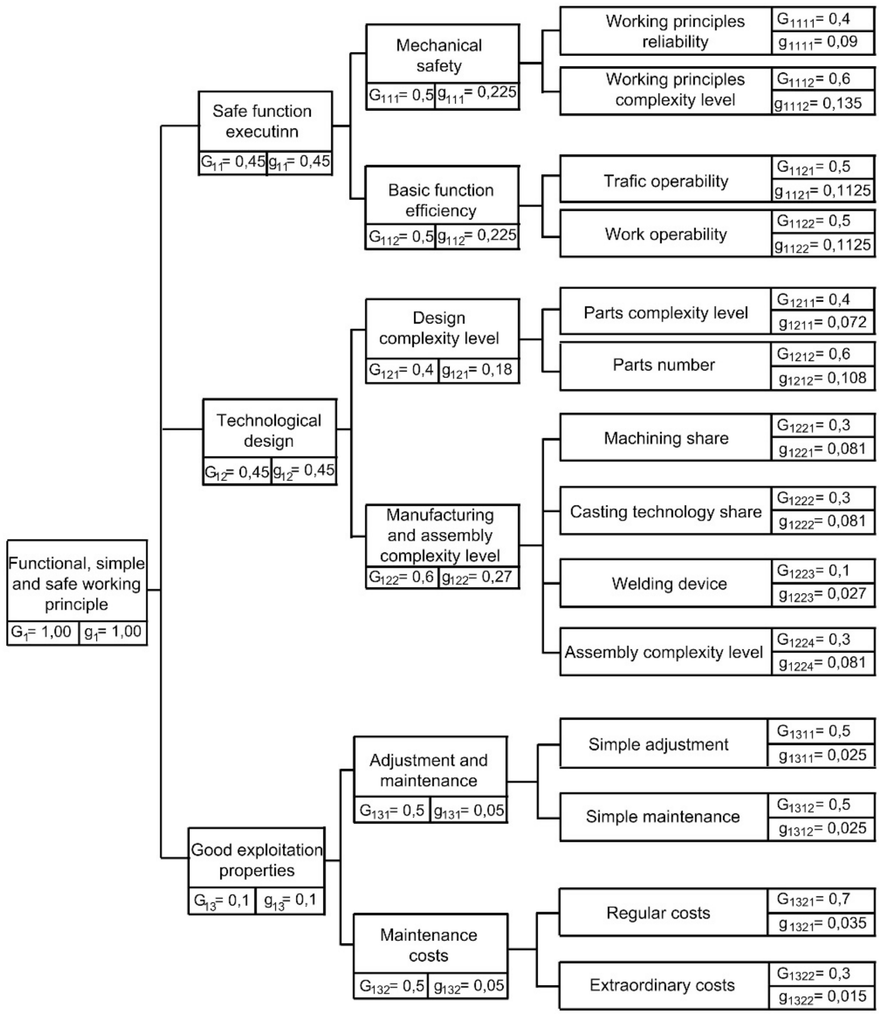

Figure 8 Goals system for working principles A WP1 and A WP2

Table 2 Calculated values of the goals system for working principles A WP1 and A WP2

Evaluation criterion	Goal mark	Goal description	Goal level	G_{ijk}	g_{ijk}
	C_1	Functional, simple and safe working principle	1	1,0	1,0
1	C_{11}	Safe function execution	2	0,45	0,45
2	C_{111}	Mechanical safety	3	0,5	0,225
3	C_{112}	Basic function efficiency	3	0,5	0,225
4	C_{1111}	Working principle reliability	4	0,4	0,09
5	C_{1112}	Working principle complexity level	4	0,6	0,135
6	C_{1121}	Traffic operability	4	0,5	0,1125
7	C_{1122}	Working operability	4	0,5	0,1125
8	C_{12}	Technological design	2	0,45	0,45
9	C_{121}	Design complexity level	3	0,4	0,18
10	C_{122}	Manufacturing and assembly complexity level	3	0,6	0,27
11	C_{1211}	Parts complexity level	4	0,4	0,072
12	C_{1212}	Parts number	4	0,6	0,108
13	C_{1221}	Machining share	4	0,3	0,081
14	C_{1222}	Casting technology share	4	0,3	0,081
15	C_{1223}	Welding devices	4	0,1	0,027
16	C_{1224}	Assembly complexity level	4	0,3	0,081
17	C_{13}	Good exploitation properties	2	0,1	0,1
18	C_{131}	Adjustment and maintenance	3	0,5	0,05
19	C_{132}	Maintenance costs	3	0,5	0,05
20	C_{1311}	Simple adjustment	4	0,5	0,025
21	C_{1312}	Simple maintenance	4	0,5	0,025
22	C_{1321}	Regular costs	4	0,7	0,035
23	C_{1322}	Extraordinary costs	4	0,3	0,015

The fourth hierarchical level of the system of partial goals with its values of the goal importance factor is determined using the expression:

$$g_{ijk} = \sum_{j=1}^{3}\sum_{k=1}^{2}\sum_{l=1}^{4} g_{ijkl} \,, \tag{6}$$

where $i = 1$.

Quantitative values of the partial goals importance factors (g_{111}, g_{112}, g_{121}, g_{122}, g_{131}, and g_{132}) of the third hierarchical level, are determined according to the rule of the product of all goals importance of higher level, following the descending index of the order of partial goals of the higher level:

$$g_{ijk} = \mathrm{G}_{ijk} \cdot G_{ij} \cdot G_i \,, \tag{7}$$

where $i = 1$, $j = 1, 2, 3$ and $k = 1, 2$.

Quantitative values of the partial goals importance factors of the fourth hierarchical level are calculated in the same way.

Calculated values of the goals importance and importance factors for working principles A WP1 and A WP2 are presented in Tab. 2

In this way, the distribution of the elements of the goals system with the corresponding values of the features of the partial goals at individual levels was prepared for the evaluation process.

4.2 Technical and Economic Evaluation of Working Principles

Each solution of the working principle of the mobile machine for corn peeling, after the evaluation process, will be ranked according to the relative rating of the degree of fulfilment of the goal. In this way, the advantage of a better solution compared to another less good solution is suggested.

The product is acceptable for further design and production if it meets the technical and economic criteria. The fulfilment of technical criteria enables the product to be suitable from a technical aspect, while the fulfilment of economic criteria ensures the product's economic justification. Therefore, during the evaluating process of the working principles A WP1 and A WP2, a technical and economic evaluation was carried out. According to [30, 35], the following rating scale was defined (Tab. 3).

Table 3 Rating scale for the implementation of the evaluation process

Solution quality	Rating
Unsatisfying	1
Partially satisfying	2
Satisfying	3
Very good	4
Excellent	5

Ratings were then added to each goal based on the designer's knowledge and experience (Tab. 4). Insufficient experience and knowledge of the designer can significantly reduce the implementation of the evaluation procedure and lead to unreliable evaluation results.

The total value of the criterion evaluation factor for working principles A WP1 and A WP2 (Tab. 4) is determined according to the expression:

$$Gw_k = \sum_{j=1}^{14} w_{jk} \,, \tag{8}$$

where w is the grade that is added to an individual goal from the system of goals and $k = 1, 2$ for two working principles A WP1 and A WP2 (Tab. 4).

The total value of the factor of real significance of the criteria for the working principles A WP1 and A WP2 (Tab. 4) is determined according to the expression:

$$Gwg_k = \sum_{j=1}^{14} wg_{jk} \,, \tag{9}$$

where $k = 1, 2$ for two working principles A WP1 and A WP2 (Tab. 4).

The utility factor of the evaluated solution for the working principles A WP1 and A WP2 (Tab. 4) is determined according to the expression:

$$W_k = \frac{Gw_k}{w_{\max} \cdot n} \,, \tag{10}$$

where $w_{\max}$ is the highest amount of the goal ratting from the set of selected goals that are evaluated for a particular working principle (Tab. 4), n is the number of selected criteria (Tab. 4) from the total set of criteria (Tab. 2) which are evaluated and $k = 1, 2$ for two working principles A WP1 and A WP2.

The technical goodness factor for the working principles A WP1 and A WP2 is determined according to the expression:

$$Wg_k = X_k = \frac{Gwg_k}{w_{\max} \cdot \sum_{j=1}^{14} g_{ijk}} = \frac{Gwg_k}{w_{\max} \cdot 1} \,, \tag{11}$$

where X_k is the overall technical goodness of a particular working principle and $k = 1, 2$ for two working principles A WP1 and A WP2.

In the economic evaluation of the goodness of the solution, only the manufacturing and assembly costs were used. Manufacturing costs consist of the costs of materials and their processing. Since the working principles of A WP1 and A WP2 are in the conceptual phase, the exact costs of the material and its processing cannot be determined at this stage of design. These costs can only be defined when the entire design process is completed and the optimal batch size is determined. For budget purposes, the authors of the paper estimated these costs based on many years of experience in the development and design of machines for corn peeling. Therefore, when conducting an economic evaluation in the conceptual phase, according to [35], the cost of the ideal solution is introduced, whose amount is $K_{\text{ideal}} = 1$. If the rating of the cost of manufacturing and assembly indicates how much this cost is above the cost of the ideal solution, then the value of the overall economic goodness of the solution can be determined using the expression [35]:

$$Y_k = \frac{K_{\text{ideal}}}{K_{\text{real}}} = \frac{1}{K_{\text{real}}} < 1 \,, \tag{12}$$

where K_{real} is the real cost of production and assembly.

Table 4 List of technical and economic evaluation of working principles A WP1 and A WP2

Evaluation criterion	g_{ijk}	Evaluated goal	Variant 1 – A WP1		Variant 2 – A WP2	
			w_{j1}	wg_{j1}	w_{j2}	wg_{j2}
4	0,09	Working principle reliability	4,9	0,441	4,9	0,441
5	0,135	Working principle complexity level	4,9	0,662	4,0	0,54
6	0,1125	Traffic operability	4,0	0,45	4,2	0,473
7	0,1125	Working operability	4,5	0,506	4,2	0,473
11	0,072	Parts complexity level	4,0	0,288	4,0	0,288
12	0,108	Parts number	4,9	0,529	3,5	0,378
13	0,081	Machining share	4,2	0,340	3,8	0,308
14	0,081	Casting technology share	4,2	0,340	3,8	0,308
15	0,027	Welding devices	4,0	0,108	4,0	0,108
16	0,081	Assembly complexity level	4,6	0,373	3,5	0,284
20	0,025	Simple adjustment	4,2	0,105	3,8	0,095
21	0,025	Simple maintenance	4,4	0,11	4,0	0,1
22	0,035	Regular costs	4,8	0,168	4,4	0,154
23	0,015	Extraordinary costs	4,9	0,074	4,4	0,066
$\sum$	1	Total values	Gw_1	Gwg_1	Gw_2	Gwg_2
		Numerical amount of the total value	62,5	4,493	56,5	4,014
		Total value regarding the ideal solution	W_1	Wg_1	W_2	Wg_2
		Numerical amount	0,911	0,917	0,824	0,819
		Technical goodness X_k	$X_1 = 0{,}917$		$X_2 = 0{,}819$	
		Relative costs regarding the ideal solution	$K_1 = 1{,}4$		$K_2 = 1{,}8$	
		Economic goodness Y_k	$Y_1 = 0{,}714$		$Y_2 = 0{,}555$	

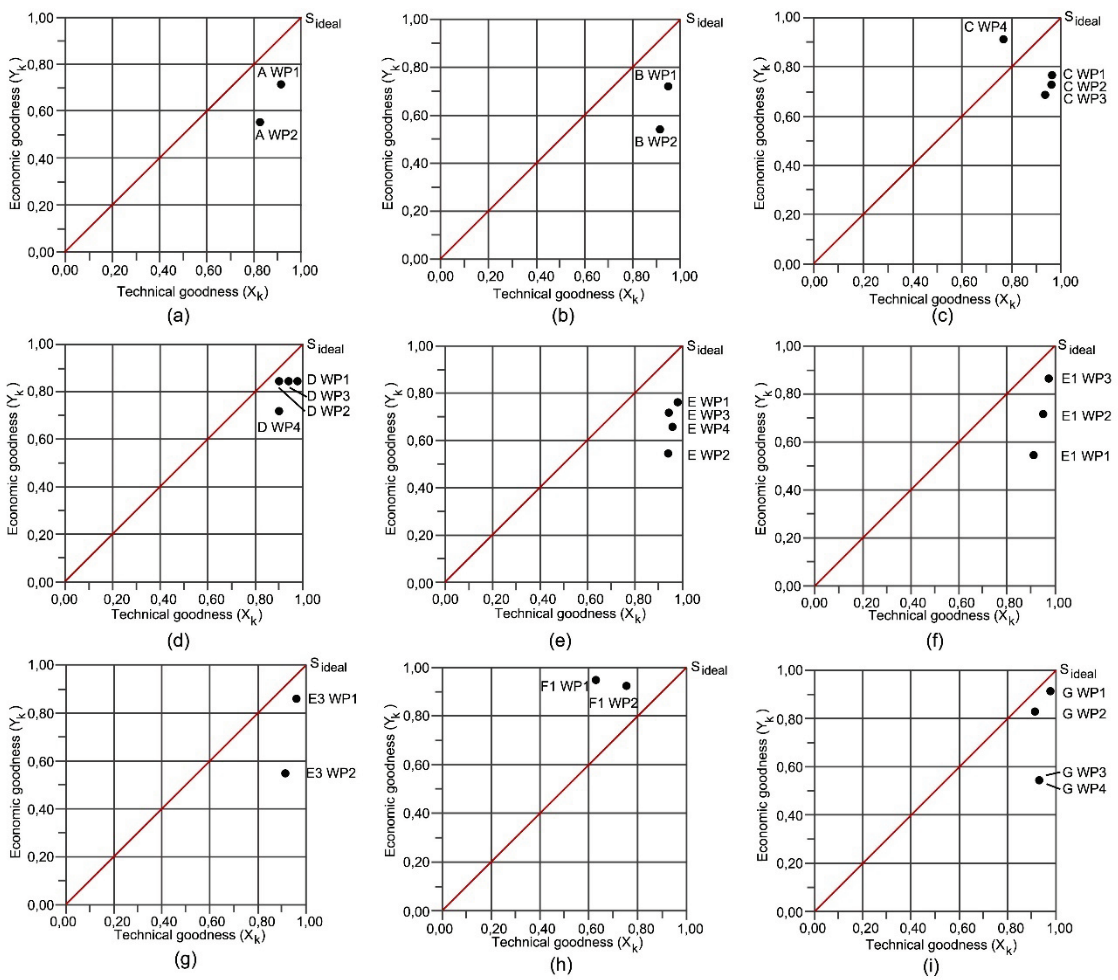

Figure 9 The overall technical and economic goodness of the working principles of the partial functions of the mobile machine for corn peeling

Solutions of technical and economic goodness for working principles A WP1 and A WP2 are presented in Tab. 4. For all other working principles shown in the morphological matrix (Fig. 7), solutions of technical and economic goodness are presented in [4].

The graphic representation of the solution of the performed technical and economic evaluation is shown in Fig. 9a. It is evident that the working principle of A WP1 has better overall goodness values compared to A WP2. Therefore, the working principle A WP1 represents the choice of the final solution of the partial function A (*"Machine transportation"*). The selection of the ideal solution is determined by the coordinates of the point Sideal with the amount X_{ideal} =1 and Y_{ideal} =1. The graphic representation of the obtained solutions for evaluating the working principles of the other partial functions, listed in the morphological matrix, is shown in Fig. 9b to Fig. 9i.

5 VARIANT DESIGN SOLUTIONS OF THE MOBILE MACHINE FOR CORN PEELING

After the evaluation process, field solutions was generated, i.e. five variant solutions (Fig. 10). The structure of the variant solutions is formed by varying the physical effects and design forms (working geometry, working movement and materials) from the morphological matrix (Fig. 7). In such a way, the synthesis of new technical systems (variant designs) was arranged. By combining the working principle of a partial function with the working principle of the following partial function, possible working structures, or variant designs, are formed. Due to the aforementioned, it is not possible every time to combine the working principles that received the highest rating into a unique variant solution. Therefore, the working principles E1 WP3 and F1 WP2, which received the highest rating in the evaluation process, are not included in the structure of the first variant solution (Fig. 9 and Fig. 10).

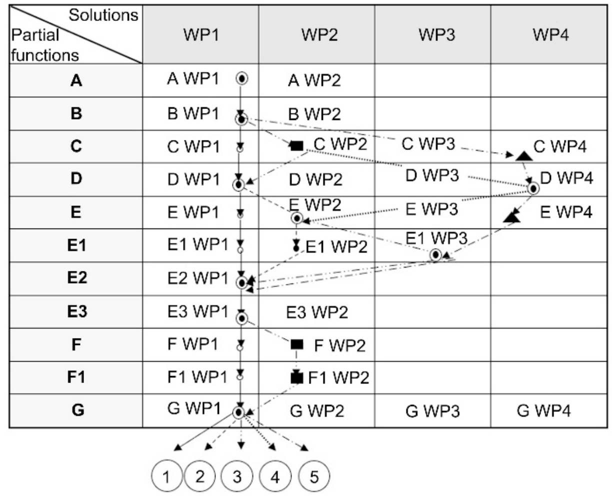

Figure 10 Combinations of working principles that generate variant solutions of a mobile machine for corn peeling

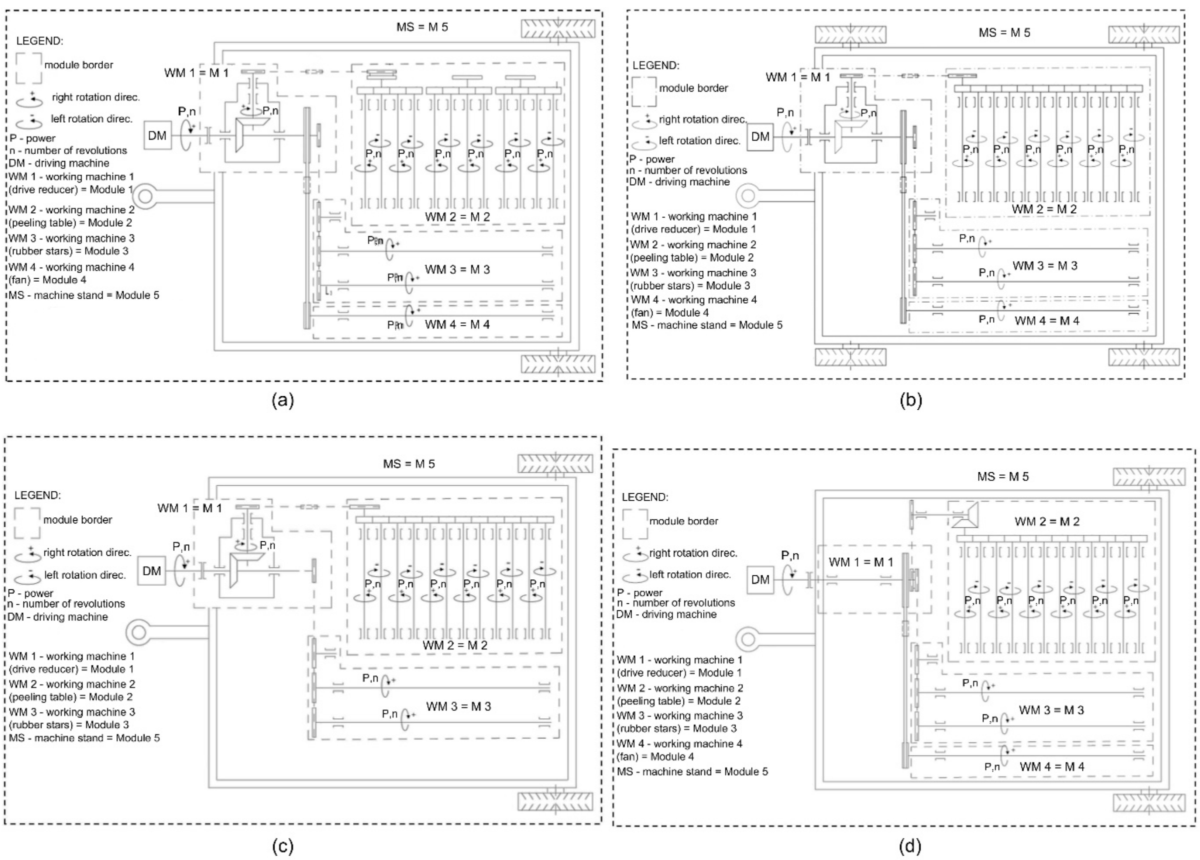

Figure 11 Schematic representation of function carriers and kinematics of design variants

After further elaboration of variant solutions, shown in Fig. 10, through analyses in other phases of the design process, the first variant solution was selected as the final design solution. This solution was further improved and shaped as a final product in the detailed design phase. A schematic representation of the final design solution, its function carriers and kinematics is shown in Fig. 11a. Five modules, i.e. function carriers, form the modular structure of the first variant solution: module 1 represents working machine 1 (WM 1) i.e. drive reducer, module 2 represents working machine 2 (WM 2) i.e. peeling table, module 3 represents working machine 3 (WM 3) i.e. rubber stars, module 4 represents working machine 4 (WM 4) i.e. fan and module 5 represents machine stand (Fig. 11a).

The other four variants of the solution (Fig. 11b – Fig. 11d) were not developed in the other phases of the design process, but depending on the market needs, they leave the possibility of further development. Also, five design modules, defined as five function carriers, were implemented in the structure of these four variant solutions.

At the beginning of the design process (conceptual phase), using functional decomposition and morphological matrix, the initial modules, i.e. function carriers, are defined (Fig. 6). Due to its complexity, the function "*Peeling*" (Fig. 2) is divided into four functions on the third level of the function structure (Fig. 3). At the third level, the function "*Corn cob rotation, transport and peeling on the table*" contains a group of functions in its name. It is also equally possible to see in the names of the functions from the fourth and fifth level of the function structure. This points to the need for modularity, because those multiple functions are grouped into the one function name. By searching for the principle of solutions for functions from the function structure, by applying the morphological matrix, solutions were obtained in the form of more complex technical systems. These systems represent function carriers, or modules. The connection between the functions and their carriers is shown in Fig. 6.

By developing the initial modules, through the other phases of the design process, their final appearance and structure of the first variant solution shown in Fig. 11a. This modular structure, after refinement in the detailed design phase, was developed into the final design solution of the mobile machine for corn peeling shown in Fig. 12.

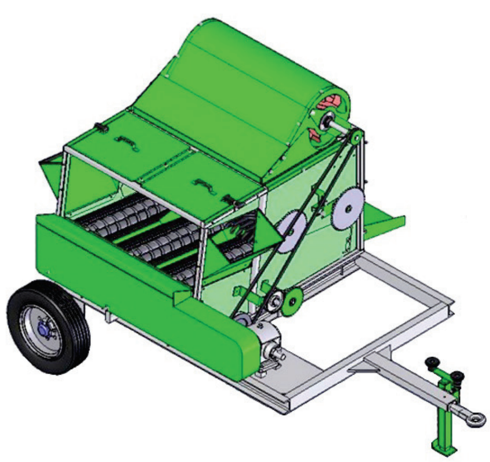

Figure 12 CAD model of the first design variant of the mobile machine for corn peeling

6 RECAPITULATION ANNOTATION

The application of the principles of functional modelling and modularity is extremely important for the development of variant products in the conceptual phase. After the analysis of requirements, using the method of functional decomposition, the function structure of the mobile machine for corn peeling was developed. The function structure proved as an important design tool that enabled the search for working principles that solved the functions who form the function structure. Through the relational relationship between the functions, which was realized by connecting the flows of energy, materials and signals, the connection between the functions was observed. Through the function structure, it is visible how certain functions in their name unite groups of less complexity functions. Therefore, by the function decomposition process, certain functions are broken down into the less complexity functions. Through the function structure, the connection of functions in their name indicates their grouping, that is, the need for modularity. Since the function structure shown by functional flow diagrams does not allow searching for the principle of the solution, i.e. the carrier of the functions, a morphological matrix was used for the solution search.

The function carriers are determined by working principles. Since it is evident from the morphological matrix that the working principles are complex technical systems, which combine multiple functions in their structure, they can represent modules that will be transformed and connected in the remaining stages of the design process into a modular structure of the machine for corn peeling. Five modules are defined through the function structure.

The principles of the solution, shown using sketches and schemes, are related to the partial functions in the morphological matrix. The selection of the best solution principles for each partial function was achieved by applying the method of technical and economic evaluation according to VDI 2225. By further combining them into five conceptual variants (working structures), the product variant was achieved.

The evaluation of working principles was achieved through a system of criteria, divided into three levels. From the system of criteria, a system of 23 goals, structured on four levels, was defined. Thus, each working principle was ranked according to the relative rating of the degree of goal fulfilment. The lack of this method was observed in the determination of the amount of the assessment, which evaluates the importance of a particular goal in the system of goals. The amount of the rating assigned results from the experience and knowledge of the designer, which leads to the conclusion that two different designers, depending on their knowledge and experience, can assign different values for the same goal they are analysing.

After the evaluation process, the following working principles achieved the best results, that is, they came close to the ideal solution: A WP1, B WP1, C WP1, D WP1, E WP1, E1 WP3, E3 WP1, F1 WP2 and G WP1. It is to be expected that these working principles should be connected in a single structure of the best conceptual variant. However, the principles of solutions E1 WP3 and F1 WP2 are not part of the structure of the conceptual variant that offers the most possibilities for further design development (the first conceptual variant). The lack is reflected in the realization that it is not always possible to connect the working principles into a single structure according to the highest ratings achieved by evaluation process, but through precisely defined interfaces and geometric relationships. The experience and knowledge of the designer is crucial for this connection.

Further research aim is to develop a unique algorithm that will enable the application of repeatability of evaluation results, regardless of the level of experience and knowledge of the designer. In order to achieve such a goal, the development of a mathematical model and its implementation in the aforementioned algorithm of technical and economic evaluation would be approached.

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