ON A NEW PLANETARY SPEED INCREASER WITH DEFORMABLE ELEMENT USED IN R.E.S.

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Abstract: *A new variant of planetary speed increaser with deformable element is presented in the paper. This variant is obtained by applying a conceptual design algorithm proposed by the authors. Therefore, the algorithm contains several steps, including the establishing of the requirements list, the development of the solving structures and, finally, the identification of the planetary transmission to be used as speed increaser in renewable energy systems.*

Key words: *conceptual design, solving structure, product concept, speed increaser with deformable element, renewable energy systems R.E.S.*

1. Introduction

As known from the technical literature, the hydro turbines used in small hydropower plants function at a much lower speed than required by most electric generators. A speed increaser is required to obtain the needed speed of the generator. This multiplication in speed can range from 3 to 5 times [4], [5]. But using a transmission to obtain the necessary speed multiplication involves some disadvantages, related to the system efficiency, overall dimensions and cost. Therefore, objectives of requirement type (compulsory objectives) and of wish type are set in the concept development. These objectives form the requirements list, on which the conceptual design [2] is based.

The following step in the design algorithm consists in the development of the structural variants. But only those structural variants whose technical characteristics meet the requirements in quantitative terms are considered as solving structures. In order to select the solving structures, the synthesis of the sprocket-tooth number for all the structural variants is performed and their efficiency is calculated. Then, their evaluation is made taking into account the technical-economic criteria (the wish type objectives); thus, the optimal solution that fulfils the requirements list (the principle solution) is found. The principle solution is an innovative concept of the chain speed increaser and represents input data for the embodiment design phase.

2. The Requirements List

The first step in the design process is to establish the requirements list, which contains two types of requisites: compulsory objectives (main objectives) that are needed in the elimination of inadequate solutions, and objectives of wish type (secondary objectives) that are needed in ordering the solving structures and selection of the concept. Thus, from the requirements list of the hydropower station [5], [7], the following requirements

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(main objectives) for the speed increaser can be identified:

1) the input and output power should be coaxial;
2) the multiplication ratio should range from 3 to 5 times;
3) it should have an over 60% efficiency;
4) it should not require a particular manufacturing process;
5) the transmission should contain a deformable element (chain, cog belt).

The following secondary objectives, listed in the order of importance, are associated with the five main requirements:

A) minimization of radial overall dimension;
B) minimization of friction losses;
C) minimization of complexity degree;
D) minimization of manufacturing costs.

These secondary objectives are the technical-economic evaluation criteria that are needed in the identification of the principle solution.

3. The Development of the Solving Structures

The speed increaser function is illustrated in Figure 1.

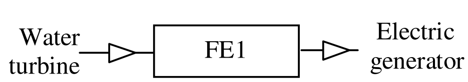


Fig. 1. *The structure of sub-functions in symbolic variant* [8]

FE1 - transmission of mechanical energy with modification of mechanical energy parameters (speed multiplication).

Based on the structure in Figure 1, the speed increaser solving structures will be generated; this stage contains [3]: 1) the generation of the solving structural variants and 2) the establishing of the solving structures, by means of kinematical configuration (synthesis) of the obtained variants and elimination of the variants whose technical characteristics do not fulfill the requirements list in quantitative terms.

3.1. The Development (Synthesis) of the Solving Structures

The solutions found in the technical literature [3], [5-7] for solving the sub-functions in Figure 1 are graphically systematized in the morphological matrix in Figure 2. The following notations have been used (Figure 2): *def* - the deformable element, H - the carrier, 1 - the satellite gear and 2 - the sun gear. Only the variants with deformable element were considered in the morphological matrix to develop the speed increaser.

By means of the morphological matrix, several solving structural variants can be generated, through a compatible composition of the potential solutions in Figure 3; obviously, from these variants, only those whose technical characteristics fulfill quantitatively the main objectives in

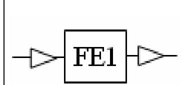
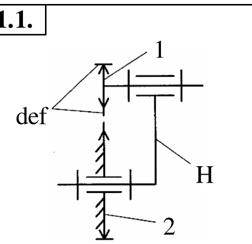
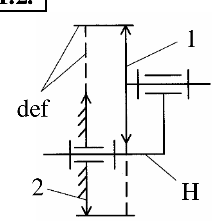
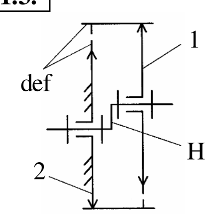
Sub-function	Potential principle solutions		
	**1.1.** 	**1.2.** 	**1.3.** 

Fig. 2. *The morphological matrix for the development of the solving structures variants*

the list will be considered as solving structures (for the speed increaser function).

Solving variant	Speed increaser solution
SR1	1.1+1.1
SR2	1.1+1.2
SR3	1.1+1.3
SR4	1.2+1.1
SR5	1.2+1.2
SR6	1.2+1.3
SR7	1.3+1.1
SR8	1.3+1.2
SR9	1.3+1.3

Fig. 3. *Examples of structural solving variants*

The qualitative schemes of the structural solving variants are represented in Figure 4, while in Figure 5 the qualitative schemes are illustrated, derived from the previous ones by eliminating the tangential over-twist of the deformable element. The solving variants developed by means of the morphological matrix only fulfill in qualitative terms the main objectives set in the requirements list. The technical characteristics of the developed solutions are established in the next phase, in order to check the quantitative accomplishment of the requirements. Obviously, the solving structures of function FE1 will consist in the variants that meet the requirements in quantitative terms.

3.2. The Establishing of the Solving Structures

In order to establish the solving structures (from the obtained variants), it is first made the synthesis of the number of teeth, on condition that i = 3…5. Then, on the basis of the known values of transmission efficiency, the values of efficiency for the proposed speed increasers are calculated. For this purpose, the block diagram with the notations in Figure 6 is used, as a simplification of all the speed increaser variants:

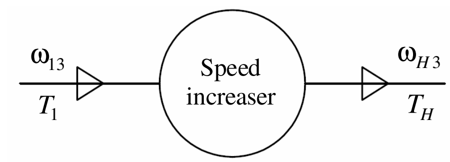


Fig. 6. *Block diagram of the speed increaser*

The following steps are performed in the synthesis of various tooth numbers:

• determination of the relation for the internal transmission ratio (i_0):

$$i_0 = i_{13}^H = i_{12}^H \cdot i_{23}^H ,\ i_{12}^H = \frac{z_2}{z_1} ,\ i_{2'3}^H = \frac{z_3}{z_{2'}} ; \quad (1)$$

• determination of the relation for the transmission ratio (i):

$$i = \frac{1}{i_{1H}^3} = \frac{1}{1 - i_0} ; \quad (2)$$

• determination of tooth numbers from relations (1) and (2):

$$i_0 = \frac{i-1}{i} , \quad (3)$$

$$\frac{z_2}{z_1}\frac{z_3}{z_{2'}} = \frac{i-1}{i} . \quad (4)$$

By imposing a correlation between tooth numbers, the function of the transmission ratio can be obtained (see Figure 7): $i = i(z_1)$. This diagram is drawn for a multiplication ratio $i = 4$.

Thus, according to Figure 7, eight solutions are found that meet the requirement $i = 4$ (see Table 1).

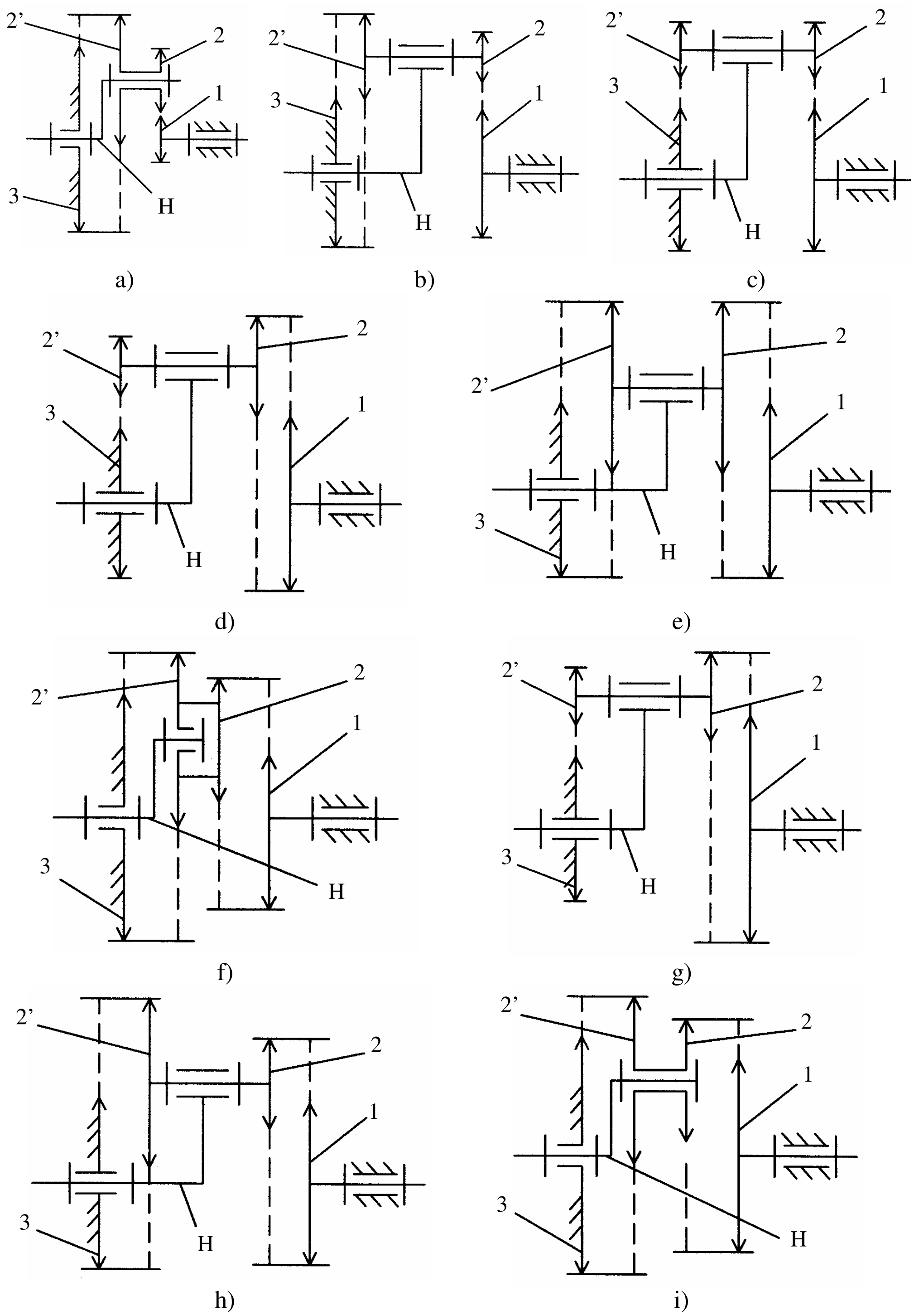


Fig. 4. *Qualitative schemes of the structural solving variants*

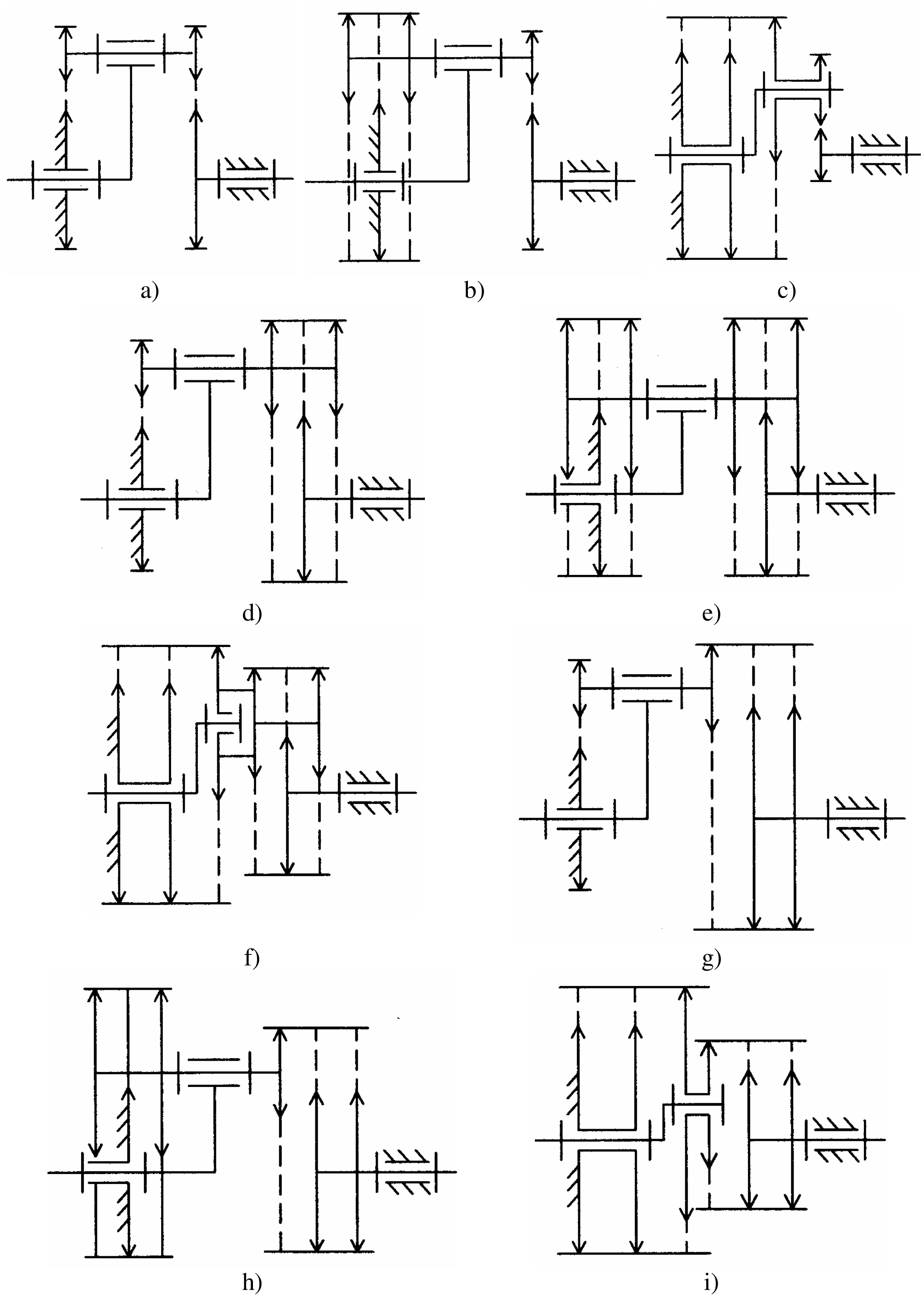


Fig. 5. *Qualitative schemes derived from Fig. 4*

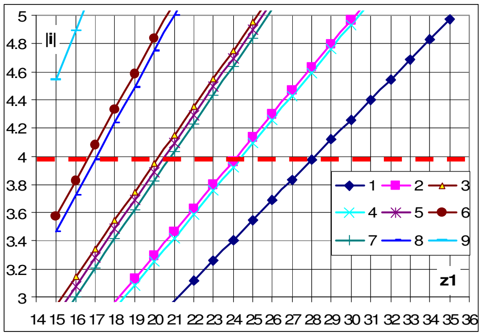


Fig. 7. *The synthesis of tooth numbers*

Knowing from the technical literature the efficiencies of each component mechanism ($\eta_{12} = \eta_{2'3} = 95\%$) [1], [3], [5], the internal efficiency of the speed increaser (η_0) can be obtained according to relation (5):

$$\eta_0 = \eta_{13}^H = \eta_{12}^H \cdot \eta_{2'3}^H. \quad (5)$$

Table 1

Solutions fulfilling the requirement i = 4

Sol.	z_1	z_2	$z_{2'}$	z_3	i	η
1	28	20	21	22	3.97	0.67
2	24	17	18	19	3.96	0.67
3	20	14	15	16	3.94	0.68
4	24	16	17	19	3.92	0.68
5	21	14	15	17	4.09	0.66
6	17	11	12	14	4.08	0.66
7	21	13	14	17	4.02	0.67
8	17	10	11	14	3.97	0.67

The speed increaser efficiency η is established based on relation (6):

$$\eta = \eta_{1H}^3 = \frac{-\omega_{H3} T_H}{\omega_{13} T_1} = \frac{-T_H / T_1}{\omega_{13}/\omega_{H3}} = \frac{\overline{i_{1H}^3}}{i_{1H}^3} \quad \Rightarrow \quad \eta = \eta_{1H}^3 = \frac{1 - i_0 \eta_0^w}{1 - i_0}, \quad (6)$$

$$w = \operatorname{sgn}(\omega_{1H} T_1) = \operatorname{sgn}\left(\frac{\omega_{1H} T_1}{\omega_{13} T_1}\right) = \operatorname{sgn}\left(\frac{i_0}{i_0 - 1}\right). \quad (7)$$

Table 2

Establishment of the absolute (W_k) and relative (w_k) weight coefficients by means of FRISCO formula x

k	**Crit. \ Crit.**	**A**	**B**	**C**	**E**	P_k	L_k	S_k	W_k	w_k
1	A	0.5	1	1	1	3.5	1	3	5	0.58
2	B	0	0.5	1	1	2.5	2	2	2.33	0.27
3	C	0	0	0.5	1	1.5	3	1	1	0.12
4	D	0	0	0	0.5	0.5	4	0	0.2	0.03
								Sum	8.53	1.00

FRISCO formula:

$$W_k = \frac{2 \cdot P_k - P_{\min} + S_k + 0.5}{0.5 \cdot n + P_{\max} - P_k}, \qquad w_k = \frac{W_k}{\sum W_k},$$

where A > B > C > D (the notation > means: more important than)

$k = 1, \ldots, n$ - the order number of the current criterion

P_k - the global grade of the criterion k = the sum of grades from row k of the matrix n x n = 4 x 4

L_k - the place of the current criterion k

S_k - number of criteria whose global grades are inferior to the global grade of the current criterion k

Ordering of the solving structures Table 3

		SR4		SR5		SR6		SR7		SR8		SR9	
Crit.	w_K	N_k	$w_k \cdot N_k$	N_k	$w_k \cdot N_k$	N_k	$w_k \cdot N_k$	N_k	$w_k \cdot N_k$	N_k	$w_k \cdot N_k$	N_k	$w_k \cdot N_k$
A	0.58	7	4.10	8	4.69	9	5.27	7	4.1	9	5.27	10	5.86
B	0.27	9	2.46	9	2.46	8	2.19	8	2.19	8	2.19	8	2.19
C	0.12	10	1.17	8	0.94	8	0.94	9	1.05	7	0.82	9	1.05
D	0.03	10	0.23	8	0.19	7	0.16	9	0.21	6	0.14	7	0.16
Sum		36	7.96	33	8.27	32	8.56	33	7.55	30	8.42	34	9.27
Place			5		4		2		6		3		1

4. The Evaluation of the Solving Structures

The secondary objectives are considered in the evaluation of the solving structures. Therefore, the solutions SR1, SR2 and SR3 are eliminated due to their large radial dimension.

The rest of the solving structures are systematized in Table 2, together with the four secondary objectives. These objectives are used as technical and economical evaluation criteria for ordering the obtained solving structures; the first structure (with the maximum score) represents the product concept. Thus, the absolute (W_k) and relative weight coefficients (w_k) are calculated for the remaining solving structures, based on FRISCO formula.

From these evaluations and based on Table 2, it obviously results that the principle solution of the speed increaser is designated by the structure SR9.

In order to eliminate the tangential over-twisting of the deformable element, the authors propose variants derived from the qualitative schemes of the structural solving variants. Therefore, the principle solution based on the structure SR9 is illustrated in Figure 8.

The efficiency of the principle solution (see Figure 9) is computed taking into account the values of the transmission ratio (Table 1).

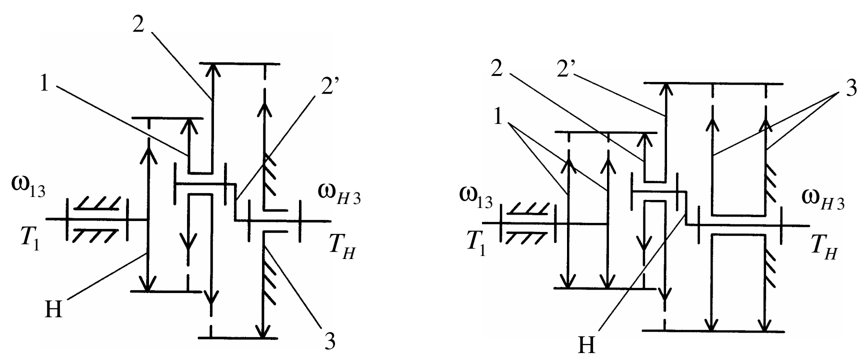


Fig. 8. *The principle solution of the speed increaser: a) the developed variant; b) the variant solving the over-twisting*

5. Conclusions

- An algorithm for conceptual design is presented in the paper, based on the requirements list and the global function of the small hydropower station. The algorithm is applied with the aim to develop a transmission to be used as speed increaser.
- The structure of the algorithm contains:

a) The establishing of requirements list;

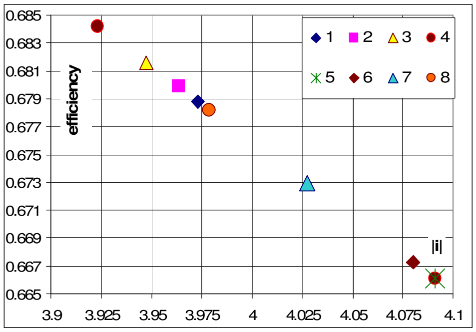


Fig. 9. *Numerical simulations of the efficiency for SR9*

b) The determination of global function;

c) The generation of solving structures by: solving sub-functions, composing sub-solutions and eliminating inadequate solutions;

d) The selection of the best solving structure by means of evaluation.

• The solving structures development phase contains: 1) generation of the solving structural variants and 2) determination of the solving structures, by kinematical configuration (synthesis) of the obtained variants and elimination of the variants whose technical characteristics do not fulfill the requirements list in quantitative terms.

• The requirements list contains two types of requisites: a) compulsory objectives (main objectives) that are needed in the elimination of inadequate solutions and determination of the solving structures, and b) objectives of wish type (secondary objectives) that are needed in ordering the solving structures and selection of the concept.

• In order to establish the solving structures by using the main objectives in the requirements list, the synthesis of the sprocket-tooth numbers and the transmission efficiency are presented in the paper. The numerical simulations made for the nine solving variants form a data base that can be used in choosing the proper solution for given values of the multiplication ratio, efficiency and overall dimensions.

• The concept of speed increaser with deformable element is found according to the weight coefficients of the technical-economic criteria (the secondary objectives). Its structure is obtained combining the potential solutions 1.3 + 1.3 in Figure 2. The result of the conceptual design algorithm is an innovative solution of speed increaser, which is subject to patenting.

• The developed principle solution of the speed increaser represents input data for the embodiment design phase.

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