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Task based conceptual design of a testing machine

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Abstract. A novel approach of task based conceptual design(TBCD) has been successfully used as direct guider and efficient developer of unique mechanical structures for many cases of mechanical design. Nearly a decade long efforts of elaboration of efficient every day usage formats for this method have been ended in convenient design pages suitable and applicable for revealing, describing, visualizing and managing the data necessary for organizing the design process from task definition to solutions satisfying original design tasks. The aim of current study is to show steps of a solution generation within frames of a single design cycle and extend this action over consecutive design cycles. Those steps are described from standpoint of general concept design method starting from key model and finished with final aggregation matrice as ultimate step of a single design cycle. Unified mathematical expressions are used for introduction and description of all worked out and developed components of conceptual design. The paper is arranged in a way to show gradual steps of conceptual design(CD) of a power transmission system – a pipe wrench life test machine.

1 Introduction

Conceptual design is considered the most studied and less understood part of mechanical design. In spite of numerous methods and even methodologies present in literature it is still hard to find a common background setting the same common principles of this segment of design. Such matter of things can be particularly explained by specific and individual approaches of authors who are summing up and generalizing their own experience in mechanical design. Viewed from the same point the proposed method of Conceptual design is not an exception and is based on long time author's experience in development of various hand tools and machine tools. One can state that both quantitatively and qualitatively the interest to conceptual design has been grown over the past few decades along with accumulation of huge mechanical engineering knowledge for the past 150 years since industrial revolution and with dawn of digital era. Growing demand on products with novel, useful and facilitating everyday life properties on one hand and necessity of in time satisfaction of this demand keeps vivid the task of creation effective design methods and effective conceptual design methods in particular[1,2,3]. Nowadays the fundamental approach is still valid in building of new concept design methods, according to which the function should be separated from mechanism [4.5] and due to which it is becoming possible application of abstraction and computational procedures. Efficiency of such approach is limited because of necessity of consideration of large number of potential solutions with not direct and participation of such functions in search of novel structure, which could be essential for success of conpet design of a new product. Well known and popularized method of TIPS (Theory on inventive problem solving) implies consideration of limited number of functions and construction of so called VEPOL mechanical-functional models and is from this point an effective designer tool [6,7]. Anyhow limitation of standard set of functions on one hand and necessity of running an exhaustive search by means of contradiction matrix on the other narrows application of this method for cases where direct comparison of features of competing products are to be outlined clearly and guidance is needed for setting the carcass of possible solution. Can be noticed that many researchers completing comprehensive studies on kinematics, force analyzes and dynamics ending with fresh and innovative products are being merely satisfied by intuitive and narrative way for introduction of the conceptual design step of their study [1, 2, 8]. Several studies [9, 10] utilize simplified models and computational schemes for targeted search of novel solutions, however limited functional resource of the proposed model from one point and extremely computerized, hence limited nature of search on the other again are slowing down and narrowing application of the method for synthesis of mechanical devices, which were possible within frame of application of proposed conceptual design method. The proposed method [11] is based on principle of simultaneous consideration and modification of mechanical and functional sets, resulting in possibility of creation of work models containing limited number of

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links and limited number of functions, enabling and facilitating search of solutions as in manual mode of design as well laying a cornerstone for digitizing of conceptual design process. Milestones for successful achievement of this goal are development of appropriate means of abstraction and mathematical description, modelling of decision making process and documenting of the entire CD process in specifically developed formats. Previous studies were devoted to modification of mechanical and functional sets, to creation of models, search of solution, rework, analyzes and usage of database resources accompanied by specific examples of conceptual design from engineering practice. The aim of current study is to separate the planning and solution steps and develop of an aggregating methodic for combining those steps within a frame of one step of conceptual design. The rest of paper is constructed as below. Section 2 reveals key model and basic approach of concept design method. Subsections show modification techniques necessary for conceptual design formation of models leading to search of solution. Subsection 2.5 describes format and procedure of task and solution aggregation process. Section 3 is for a summarizing effort of results of previous sections, it presents a flow chart of a single design cycle of conceptual design.. Section 4 contains an example of conceptual design of a pipe wrench life test machine.

2. Components of conceptual design

2.1 Idea and key model

The mechanism model (1) built according current task based design method mechanism is a set of links and set of relations between them, which are satisfying set of challenged functions. It can be presented as m,n set of numerated by of links which are related to each other in a way, to satisfy a i,j set of numerated functions. Secondly the functions can be related to other functions, particularly explained by other functions, depending on their implementation status and by availability of mechanisms which are able to implement the challenged functions (2). Functions could be given as task, or can be challenged during conceptual design process or can be originated from each other in a way to allow their satisfaction from database sources or from self-synthesizing sources.

$$M = \{m, n / F(m,n)\} \tag{1}$$

$$F = \{i, j / M(i,j)\} \tag{2}$$

$m = n$ - relates to indexation of a link
$m \neq n$ - relates to indication of a relation
$i = j$ - relates to indexation of a function
$i \neq j$ - relates to indication of translation of a function

The aim of proposed conceptual design method is interconnectivity consider two fields of mechanical and functional means in a way to allow composition and decomposition (growth and squeezing) of both fields serving current design tasks. Two assumptions are to be accepted when building different states of mechanical and functional fields. First the mechanical means, links in particular, are related to each other by means of as kinematical joints as well by other types or relations, explaining functional purpose. And secondly the functions can be related to other functions, particularly explained by other functions, depending on their implementation status and by availability of mechanisms which are able to implement the challenged functions.

Based on (1) and (2) two key models can be presented in 2 x 2 square matrices (3) and (4) including main components of task based concept design. Links or other mechanical means L_1 and L_2 are related by relation r_{12} in a way to satisfy challenged function F_{12}. Such model includes important objectives of task based conceptual design: means: L_1 and L_2, purpose and planning: function F_{12}, way of implementation: relation r_{12}. The analogously built functional model includes: functions F_1 and F_2, translation operator t_{12}, mechanical means M_{12}, and ensuring satisfaction of translated function F_2. Both symbols M and F can substitute corresponding lower left cells in (2) and (1) to show combined mechanical-functional character of the model and allow composition of more comprehensive key models.

One can state that as mechanical means L_1 and L_2 as well functions F_1 and $F_2$are parallel connected. In (3) we see connection of links by means of relation r_{12} and challenged function F_{12}, while in (4) functions F_1 and F_2 are connected by the translation operator t_{12} and by mechanical means M_{21}.

In a case of key model introduction by means of 2 x 2 matrix will have: The same idea can show a denoted numbers of links and functions can show a 2 x 2 matrice

$$M = \begin{bmatrix} L_{11} & r_{12} \\ F_{21} & L_{22} \end{bmatrix} \tag{3}$$

$$F = \begin{bmatrix} F_{11} & t_{12} \\ M_{21} & F_{22} \end{bmatrix} \tag{4}$$

L_{12} - relates to numeration of a link
F_{12} - relates to numeration of a function
r_{12} - relates to interaction between links
t_{12} - relates to numeration of a functional operator
M_{21} -relate to mechanical means for F_{12} implementation

2.2 Description of mechanical and functional sets

Square matrices are the best matching for description of mechanical and functional sets. Such matrices provide following features of mechanical and functional sets description:

- Diagonal presentation of mechanical means links and functions: right descending diagonal serves for links and left descending diagonal for function and relations between links.
- Interconnection or combined presentation of mechanical means and functions: matrix

includes all necessary components for concept design organization and development.

- A function planning feature: before satisfaction of a function it could be planned as virtual relation between links of mechanism.
- Composition and decomposition feature; number of links can be added or reduced by changing the size of square matrix.

Structurally similar features are specific for square matrix presenting the functional set.

An example of 5 x 5 matrices for both mechanism set and functional set are shown in set format (5) and (6) and in matrix format (7) and (8).

$$M = \{m, n / F(m,n)\},\ m = n = 5 \tag{5}$$

$$F = \{i, j / M(i,j)\},\ i = j = 5 \tag{6}$$

$$M = \begin{bmatrix} L_{11} & - & - & - & r_{15} \\ - & L_{22} & - & r_{24} & - \\ - & - & L_{33} & - & - \\ - & F_{42} & - & L_{44} & - \\ F_{51} & - & - & - & L_{55} \end{bmatrix} \tag{7}$$

$$F = \begin{bmatrix} F_{11} & - & - & - & t_{15} \\ - & F_{22} & - & t_{24} & - \\ - & - & F_{33} & - & - \\ - & M_{42} & - & F_{44} & - \\ M_{51} & - & - & - & F_{55} \end{bmatrix} \tag{8}$$

Meaning and numeration of components in above (5), (6), (7) and (8) are the same as in key models (1), (2), (3) and (4)

2.3 Modification and properties of mechanical and functional sets

2.3.1. Growth and squeezing of mechanical set

Growth of mechanical set is demanded by necessity and possibility of function satisfaction by getting satisfactory number of links and setting necessary relations between them.

Such modification of mechanical and functional sets provide and ensure the following possibilities for concept design:

- Self-synthesizing feature by originating new links
- Application of parallel chains
- Application of design primitives (cam, screw, lever, wedge)
- Simulation and consideration of any type of physical-mechanical contacts between links
- Methodical convenience: add a link, put a relation between them

Growth of mechanical set is measured by number of links Δm added to original number of links m . The mechanical entity can be squeezed down as well as opposite procedure to growth. Combined description of both procedures are given in (9):

$$\begin{aligned} & M\{m, n / F(m,n)\} \rightarrow \\ & \rightarrow M\{m \pm \Delta m, n \pm \Delta n / F(m \pm \Delta m, n \pm \Delta n)\} \end{aligned} \tag{9}$$

2.3.2 Growth and squeezing of functional set

Growth of functional entity is demanded by necessity and possibility of translation function into an "understandable" one that could be implemented by mechanical means. Growth is measured by number of functions Δi consecutively translated from original function i . Analogously to mechanical entity the functional entity also can be squeezed down. Combined description of both growth/squeezing action is:

$$\begin{aligned} & F\{i, j / M(i,j)\} \rightarrow \\ & \rightarrow F\{i \pm \Delta i, j \pm \Delta j / F(i \pm \Delta i, j \pm \Delta j)\} \end{aligned} \tag{10}$$

An example of growth squeezing action for both sets is visualizing this process for the case of changing the matric size from 3 x 3 to 2 x 2(squeezing down) and to 5 x 5(growing up)(11) and (12)

$$\begin{bmatrix} F_{33} & t_{34} \\ M_{43} & F_{44} \end{bmatrix} \leftarrow \begin{bmatrix} F_{22} & - & t_{24} \\ - & F_{33} & - \\ M_{42} & - & F_{44} \end{bmatrix} \rightarrow \begin{bmatrix} F_{11} & - & - & - & t_{15} \\ - & F_{22} & - & t_{24} & - \\ - & - & F_{33} & - & - \\ - & M_{42} & - & F_{44} & - \\ M_{51} & - & - & - & F_{55} \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} L_{33} & r_{34} \\ F_{43} & L_{44} \end{bmatrix} \leftarrow \begin{bmatrix} L_{22} & - & r_{24} \\ - & L_{33} & - \\ F_{42} & - & L_{44} \end{bmatrix} \rightarrow \begin{bmatrix} L_{11} & - & - & - & r_{15} \\ - & L_{22} & - & r_{24} & - \\ - & - & L_{33} & - & - \\ - & F_{42} & - & L_{44} & - \\ F_{51} & - & - & - & L_{55} \end{bmatrix} \tag{12}$$

2.3.3. Search of Solutions

Besides introducing the main idea of conceptual design the key models (1) and (2) carry twain meaning. Firstly they store the composition/decomposition resource necessary for conceptual design (CD) and secondly they serve as formats as for CD development per challenged tasks. They also serve for comparing of ongoing and final results with existing solutions. Denoting symbols S for solution to mechanical and functional sets we may use all described above procedures for modelling and modification for mechanical and functional entities of solutions

$$M_S = \{m, n / F_S(m,n)\} \tag{13}$$

$$F_S = \{i, j / M_S(i,j)\} \tag{14}$$

2.4 Mechanical and functional models

Methodical value of choice of a subset $\langle M \rangle$ (15) from mechanical set M is in isolation of best suitable model for planning and implementation of current set of functions:

$$M\{m, n / F(m,n)\} \rightarrow \langle M \rangle \{\langle m, n \rangle / F(\langle m, n \rangle)\} \tag{15}$$

Analogously a functional model $\langle F \rangle$ can be composed from functional set F (16) best matching requirements of the search of mechanical means for satisfying subset $\langle F \rangle$:

$$F\{i,j/M(i,j)\} \rightarrow \langle F \rangle \{\langle i,j \rangle / M(\langle i,j \rangle)\} \quad (16)$$

Obviously $\langle M \rangle$ belongs to M (17) and $\langle F \rangle$ belongs to F (18):

$$\langle M \rangle \{\langle m,n \rangle / F(\langle m,n \rangle)\} \subseteq M\{m,n/F(m,n)\} \quad (17)$$

$$\langle F \rangle = \{\langle i,j \rangle / M(\langle i,j \rangle)\} \subseteq F\{i,j/M(i,j)\} \quad (18)$$

Two sets (17) and (18) can be called mechanical-functional model of conceptual design. Modification of both sets is described in actions above this paper.

2.5 Aggregation of planning and solution matrices

Once preliminary matrices of original links from mechanical set (function planning state) and rough solution from database or from other synthesizing source (solution state) are developed, they can be combined in an aggregation matrix insuring a concept design solution at first step of concept design cycle.

$$M_E\{m,n/F_E(m,n)\} \rightarrow \langle M_E \rangle \{\langle m,n \rangle / F_E(\langle m,n \rangle)\} \quad (19)$$

$E = S$: (19) is for solution components (mechanism and function)

$E = P$: (19) is for planning components (mechanism and function)

Action of aggregation is shown as a sum of planned and solution states of mechanical means(20):

$$M = M_P + M_S = \begin{bmatrix} L_{1P} & a_{12P} & C & . \\ F_{12P} & L_{2P} & . & C \\ F_{12} & . & L_{1S} & a_{12S} \\ . & F_{12} & F_{12S} & L_{2S} \end{bmatrix} = \quad (20)$$

$$= M + M_S = \begin{bmatrix} M_P & M_P & C & . \\ M_P & M_P & . & C \\ F & . & M_S & M_S \\ . & F & M_S & M_S \end{bmatrix} = \begin{bmatrix} M_P & C \\ F & M_S \end{bmatrix}$$

This procedure is then repeated for modified status of both original set of links and modified status of preliminary solution. In next step this action is completed in final aggregation matrix and a single cycle of concept design procedure is finished.

2.6 Evaluation of conceptual solutions

Functional $F_{i,j}$ entity stores capability for qualitative evaluation of conceptual design solutions at as at a single step as well for final solution. Summarizing indicator (21) depends on presence or absence of a challenged function and its weight :

$$E_{i,j} = \sum_{i.j=1}^{I,J} W_{i,j} F_{i,j} \quad (21)$$

$F_{i,j} = 1$, if function is satisfied

$F_{i,j} = 0$, if function is not satisfied

$0 \le W_{i,j} \le 1$, function weight and its range

Two conceptual solutions can be compared and evaluated by summarizing indicators:

$$E_{i,j} = \sum_{i.j=1}^{I,J} W_{i,j} F_{i,j} \Leftrightarrow \bar{E}_{i,j} = \sum_{i.j=1}^{I,J} \bar{W}_{i,j} \bar{F}_{i,j} \quad (22)$$

3 Flow chart of task based conceptual design

Flow chart of consecutive steps of task based conceptual design process is shown in Fig.1.

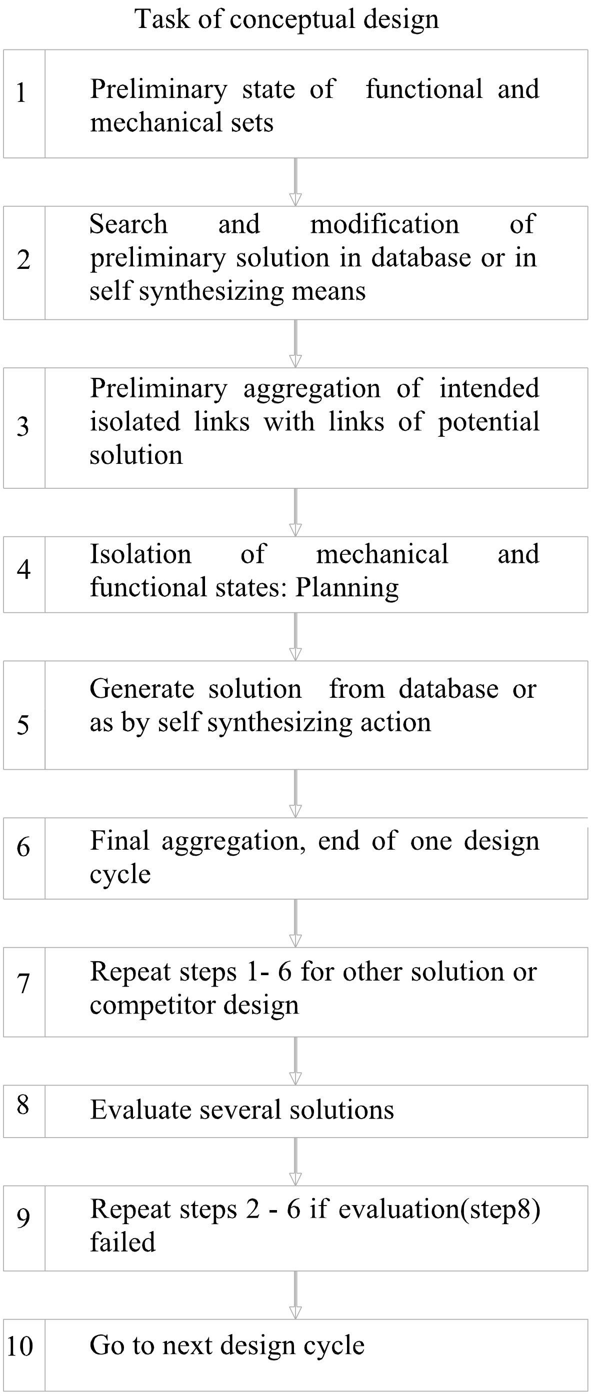

Fig. 1. General flow chart of task based conceptual design.

Idea of flow chart is clear from contents of its cells. Two aggregations steps are the milestones leading to preliminary solution (3) and final solution (6). Flow chart discloses actions for a single cycle of CD process. Another combination of cells of Fig.2 are grouped in a way to separate preliminary blocks (1,2,3) from solution block (4,5,6) and planning block (1,4) from implementation block(2,5).

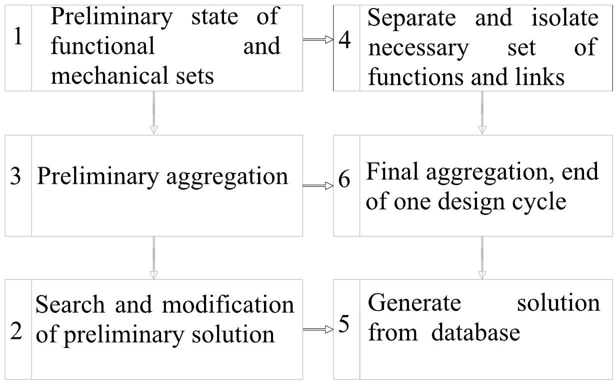

Fig. 2. CD procedure grouped in two sets of blocks

4 Example of conceptual design for pipe wrench test machine

4.1 Task of conceptual design

Task of this concept design is to develop structural and kinematical diagram of a pipe wrench life test machine. A regular pipe wrench normally needs to have resource of several thousand cycles of usage and its manual implementation is an exhaustive task, so actuality of designing of such machine is obvious. Solution of this task is shown in Fig.3.

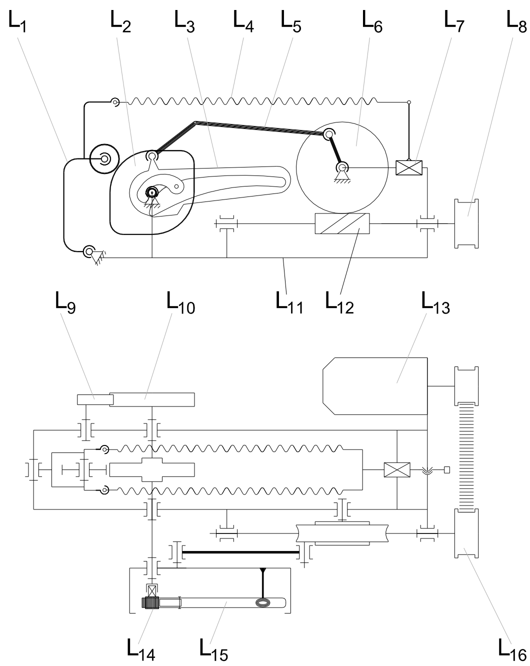

Fig. 3. Solution of pipe wrench test machine conceptual design.

4.2 Set of design cycles

Main functions serving as a task for pipe wrench life test machine are listed below. Based on concept design method described in sections above 6 concept design cycles are presented on Fig.4 and Fig.5 each guided by a specific functional task.

Set of links involved in conceptual design process is counted below.

Set of Links

L_1.Arm, L_2.Cam, L_3.Trough, L_4.Spring, L_5.Rocking arm, L_6.Worm wheel, L_7.Slider, L_8.Pulley, L_9.Dog, L_{10}.Ratchet wheel, L_{11}.Ground link, L_{12}.Worm, L_{13}.Motor, L_{14}.Pipe mandrel, L_{15}.Pipe wrench, L_{18}.User, L_{16}.Pipe in nut, L_{17}.Nut fixed to ground.

Set of Functions

F_1.Safe action, F_2.Easy operate, F_3.Easy maintenance, F_4.Load resistant, F_5.Take limited footprint, F_6.Imitate, F_7.Simple structure, F_8.Low weight, F_9.Convenient, F_{10}.Easy assemble, F_{11} Adjustable, F12.Compact, F_{13}.Load adjustment, F_{14}.Record and digitize data, F_{14}.High torque load, F_{16}.Simulate, F_{20}.Rotate pipe mandrel, F_{21}.Pure rotate pipe wrench, F_{17}.Real usage of pipe wrench, F_{18}.Rotate on thread, F_{19}.Swing rotate, F_{20}.Touch and clamp round pipe, F_{21}.Simulate pipe wrench usage

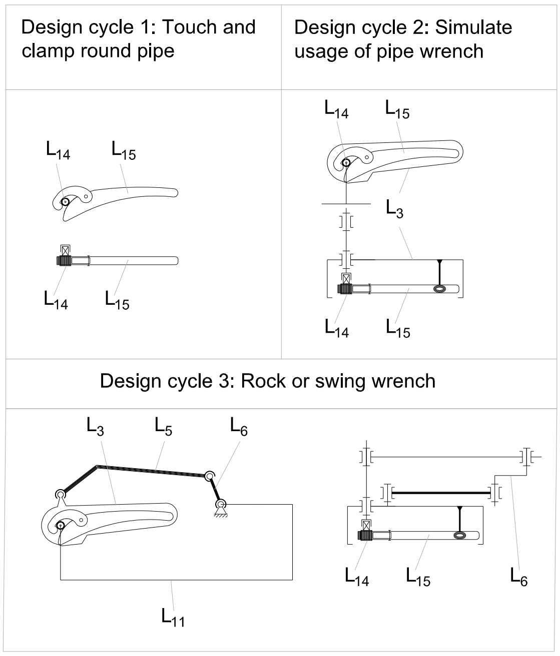

Fig. 4. First two steps of design cycles.

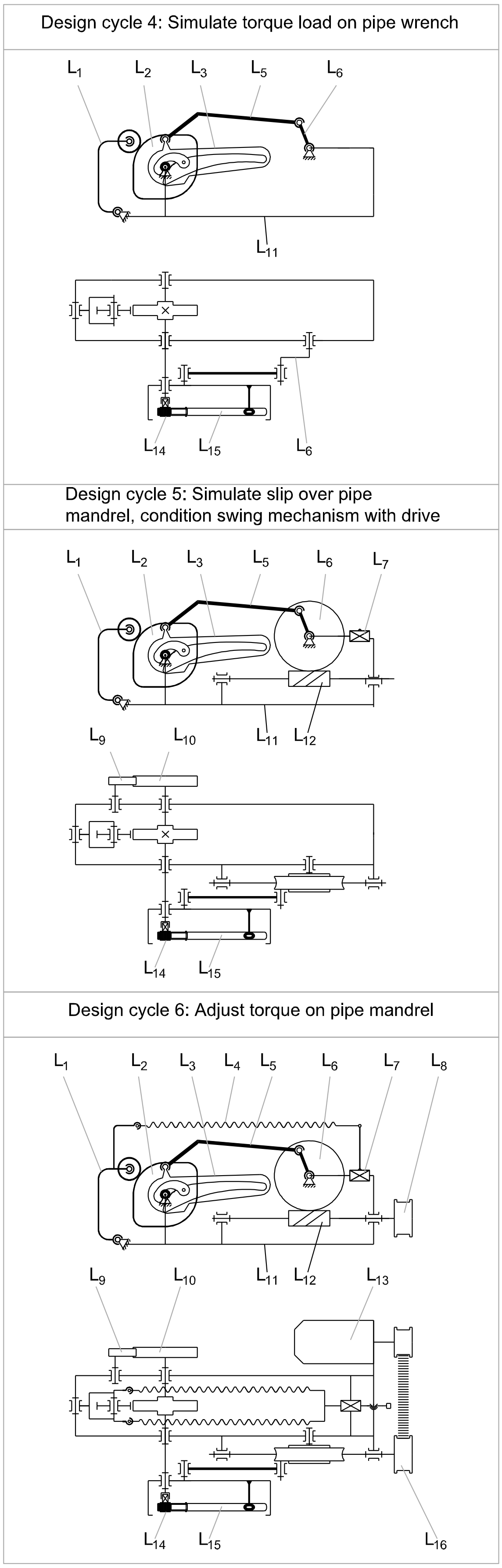

Fig. 5. Last four steps of design cycles.

4.3 Aggregation step for design cycle 2

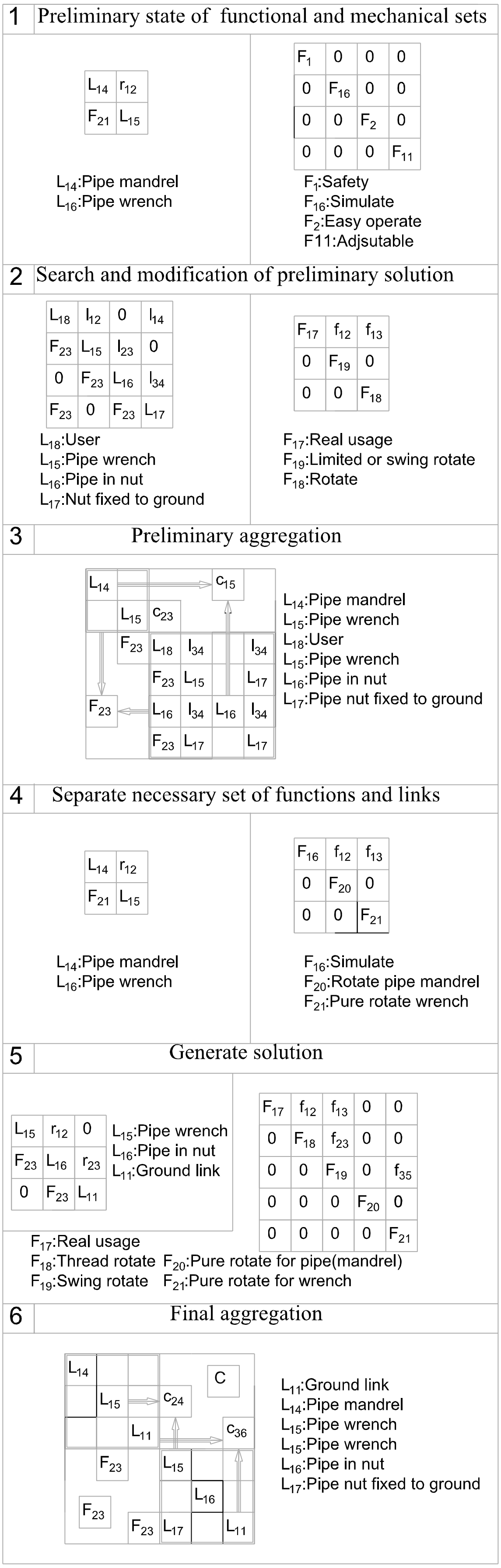

Fig. 6. Aggregation steps for design cycle2.

One design cycle 2 is considered in more detail. Here the task of simulating the user's action while using the wrench is simulated by appropriate mechanical solutions guaranteeing maximum similarity of pipe wrench usage during real life application and machine testing. The procedure duplicating method disclosed in section 3 is presented on Fig.6.

5 Conclusion

1. The novel method of task based conceptual design have been tested and verified for conceptual and engineering design of a specific hand tool testing machine.
2. Both general and local approaches for getting novel solution have confirmed their workability and efficiency in search of an optimal solution of design of test machine in terms of compact sizes, scope of useful functions and features.
3. Have been developed compact and universal expressions describing components and actions of proposed task based concept design method.
4. Developed mathematical models for description of the main components of conceptual design process, are making another step toward setting standards and developing a computerized program supporting the designer in concept design process.

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