Defence Science Journal, Vol. 72, No. 2, March 2022, pp. 217-226, DOI : 10.14429/dsj.72.17240

A Tool for Supporting Conceptual Design of Multiple State Mechanical Devices

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ABSTRACT

Research into conceptual design of mechanical systems has been an area of interest for decades. Conceptual design plays a significant role as an early stage of design to produce designs with higher quality by economically exploring a larger solution space. Several attempts been proposed in literature to automate the conceptual design synthesis process using computer support. However, most of this has focused on single state design problems and generating a single solution. This paper deals with multiple state mechanical design problems and proposes a systematic 'prescriptive' process for supporting synthesis of a larger solution space. Further, a set of modification rules has been proposed, and a database of building blocks has been developed, to further support the synthesis process. Finally, a web-based tool has been developed to guide designers through the above 'prescriptive' synthesis process, where they can utilise the database of building blocks and modification rules as well as contribute to the database by adding new building blocks or modification rules.

Keywords: Conceptual design; Multiple state; Mechanical devices; Design synthesis; Design synthesis tool

Nomenclature:

f_n	Elemental functions $(n = 1 to 5)$
θ_j	Orientation of the handle in Fig. 5 $(j = 0,1)$
x_k	Position of the block in Fig. 5 $(k = 0,1)$
$C_i = (\theta_j, x_k)$	Kinematic configuration of door-latch system in Fig. 4 $(i = 1,2,3)$

1. INTRODUCTION

Conceptual design of mechanical devices can be considered as an activity of transforming a perceived need into a solution concept that inhabits mechanical engineering principles to satisfy the need. Multiple such solution concepts can exist for a given problem; thus, a large solution space can be explored during conceptual design. Evidence suggests that exploration of a wider solution space leads to designs of higher quality[1]. Usually, the process of conceptual design depends on the designer's ingenuity, intuition, and experience[2]. However, this approach often leads to bias towards a limited set of solutions and cannot ensure the identification of an adequate set of feasible alternatives within the time constraint[3]. Therefore, development of new support systems or enhancement of existing design synthesis tools is required to help designers in generating a substantial variety of feasible alternative solutions at the conceptual design stage.

Many of the mechanical devices have a single set of input-output relationship associated with its input and output components. However, a substantial set of mechanical devices also have multiple sets of input-output relations where each set of relations are enabled by a set of functions within the relevant operating state of the device[4-6]. Liu *et al.*[7] addressed such devices as 'multi-modal' systems where the word 'mode' referred to a certain functioning arrangement or condition. A distinguishing feature of a multi-state device is that its topological structure and the interactions among its components can change when the device is in different operating states. The definition of 'multiple state' given by Li *et al.*[4] is adopted for this paper, which reports on the development of a computer support that can be used during conceptual design synthesis of multiple state mechanical devices.

2. RELATED WORK

Research in conceptual design synthesis of mechanical devices can be broadly classified into case-based and process-based approaches[8]. The case-based approach[9-13] is a technique where past solutions are reused or adapted to solve new problems. Generally, the method begins with a knowledge base abstracted from design cases and then they are modified to meet the new specifications. In contrast, the process-based approach starts with the desired functionality of the device and synthesises a structure that satisfies it. This approach of synthesis usually

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Received : 25 June 2021, Revised : 27 January 2022
Accepted : 02 March 2022, Online published : 11 May 2022

generates intermediate behavioural specifications and then combines identified kinematic building blocks that generate those behaviours. In the existing literature, different schemes of representing behavioural specifications have been proposed; the two major schemes used by most of researchers are: functional reasoning[14-20] and configuration space approach[1,4,21]. Starling & Shea[15] proposed a synthesis approach based on a parallel grammar methodology for designing mechanical systems. Chiou & Kota[18] adopted a matrix-based functional representation for primitive building blocks and developed a computer program for automated generation of alternative conceptual designs. Chakrabarti & Bligh[14] proposed functional reasoning through a set of input-output vectors with specific characteristics and produced an exhaustive set of solution concepts. Researchers also proposed graph theory-based approaches[16-17] to synthesize solution concepts for planar mechanisms. Behaviours of kinematic pairs can also be represented using configuration space; related work includes Li *et al*.[4], Subramanian & Wang[21], and Todeti & Chakrabarti[1, 19-20].

Most of the work discussed above are restricted to single-state design problems, with the exception of Li *et al*.[4] and, Todeti & Chakrabarti[1,19-20] who have addressed the multiple state mechanical design task. Li *et al*.[4] developed a computation tool called ADCS (Automatic Design by Configuration Space) that can automatically generate conceptual solutions for multiple state design tasks. However, it does not allow one to explore a comprehensive set of alternative design solutions. ADCS uses the method of combinatorial retrieval of building blocks, which is simply a hierarchical search from requirement space to solution space, and the solution generated by ADCS is a network of building blocks. ADCS does not consider the modification of building blocks. If some of the elemental functions of a given design task are not satisfied by a building block, ADCS searches in its database and retrieves another building block and adds to the existing building block(s), instead of modifying the existing building block. There is no guarantee that a compatible building block would exist in the ADCS database, in which case no solution could be generated. To address this issue, empirical studies were carried out by Todeti & Chakrabarti[19] to understand how the synthesis of multi-state devices is currently carried out by designers and an empirical model was proposed. It was observed that the designers tend to start with a semi-working initial solution and try to modify it until it becomes a fully working solution. However, the proposed model is descriptive, and the empirical results show that following this process alone fails to address two problems. The first problem is, designers do not explore a wide range of solutions, often focussing on a single one. The second is, more often than not, the solution proposed by the designer does not fully satisfy the functional specification. does not prescribe a systematic method of exploring a wide range of alternative conceptual solutions. To overcome these problems, in this work, the empirical 'descriptive' model is used as the initial basis to develop and propose a 'prescriptive' design synthesis process. To further support the process, a set of modification rules has been proposed, and a database of building blocks has been developed. Finally, a web-based tool has been developed to computationally support use of the process, modification rules, and building blocks.

3. FUNCTIONAL REPRESENTATION OF MULTI-STATE MECHANICAL DEVICES

3.1. Understanding Multi-state Instances

An existing example of a multiple state mechanical device – a simple door latch system – is taken from[19] and its multiple operating states have been briefly discussed below. Usually, a door latch system has three operating states as shown in Fig. 1; each state has a number of functional attributes. In this case, it has been assumed that the input effort necessary is given to the door handle and the locking feature is achieved by putting a wedge-shaped block into a slot fixed to the wall (see Fig. 2). Thus, the functional attributes of the operating states can be described as following:

Locked state:

- Function 1: An effort is applied on the handle along positive Z_D, but the door does not move.
- Function 2: An effort is applied on the handle along negative Z_D, but the door does not move.

Opening state:

- Function 3: An effort is applied to rotate the handle and thus the block is displaced along negative X_D.
- Function 4: While maintaining the effort of Function 3 on handle, another effort is applied on the handle along positive Z_D and the door opens.
- Function 5: The block returns to its initial position along positive X_D as the effort on the handle is released.

Closing state:

- Function 6: The door is pushed towards the wall and the slot moves along negative X_D because of the wedge action but the handle does not rotate at all.
- Function 7: The block travels into the slot along positive X_D to achieve the locked state.

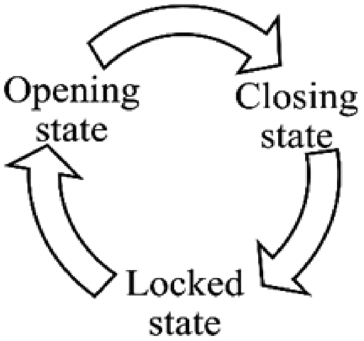


Figure 1. Multiple operating states of a door latch system.

The functional attributes of a design task are usually represented with a function diagram containing subfunctions connected by energy, material, and signal flows[22]. For example, the function diagrams of the door-latch system (for both opening and closing states) are shown in Fig. 3. The purpose is to explain the functional attributes of the design task without implying a specific working principle for the solution concept. However,

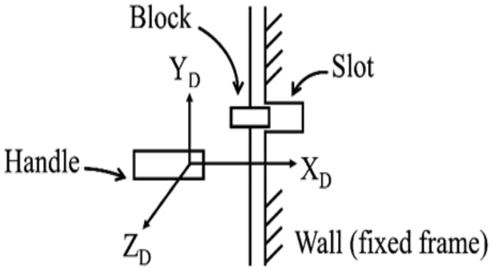


Figure 2. The components of a simple door latch where, the coordinate system (X_D, Y_D, Z_D) is attached to the door.

it is difficult to employ a single function diagram to represent the functionalities of a multi-state system[6] and there is no single correct way of creating a function diagram[22]. As these are static diagrams, it is often difficult for a computer-based tool to identify the elements in the diagram and to reason about the functionalities of the multi-state design task[6]. Therefore, a new functional representation scheme is required to support the synthesis tool development.

3.2. The Elemental Functions

Based on existing literature, a computational representation has been developed by Todeti & Chakrabarti[20] to capture the kinematic changes of the input and output components. For a planar mechanism, the effort-motion relationship of a single component can be presented in the form of a vector with six parameters $(F_x, F_y, F_z, x, y, \theta)$ where, each parameter can take values '$+$' or, '$-$' or, '0'. The first three parameters i.e., (F_x, F_y, F_z) denote the effort applied to the component; the next three parameters i.e., (x, y, θ) denote the change in configuration with respect to a global coordinate system (X, Y, Z). Hence, a vector $(+,0,0,+,0,0)$ specifies that an effort is applied along the positive $X-axis$ on a component, which undergoes a displacement along the same direction. Similarly, a vector $(0,0,+,0,0,+)$ denotes that a clockwise torque is applied on a component, and it rotates clockwise along the $Z-axis$. In the above, simple door-latch example, the handle and the block can be considered input and output components respectively. Therefore, two sets of effort-motion vector representation are required to describe an elemental function associated with an operating state i.e., $\langle (effort-motion\ vector\ of\ input\ component), (effort-motion\ vector\ of\ output\ component)\rangle$. The complete set of elemental functions for the opening and closing states of door latch system is given in Table 1 (here, locked state is eliminated because throughout this operating state, the kinematic configuration for both input and output components remain unaffected).

3.3. The Specifications Graph

The graph shown in Fig. 4 is termed as specifications graph [4]. This graph depicts the changes in the configuration of the door latch system during its opening and closing states.

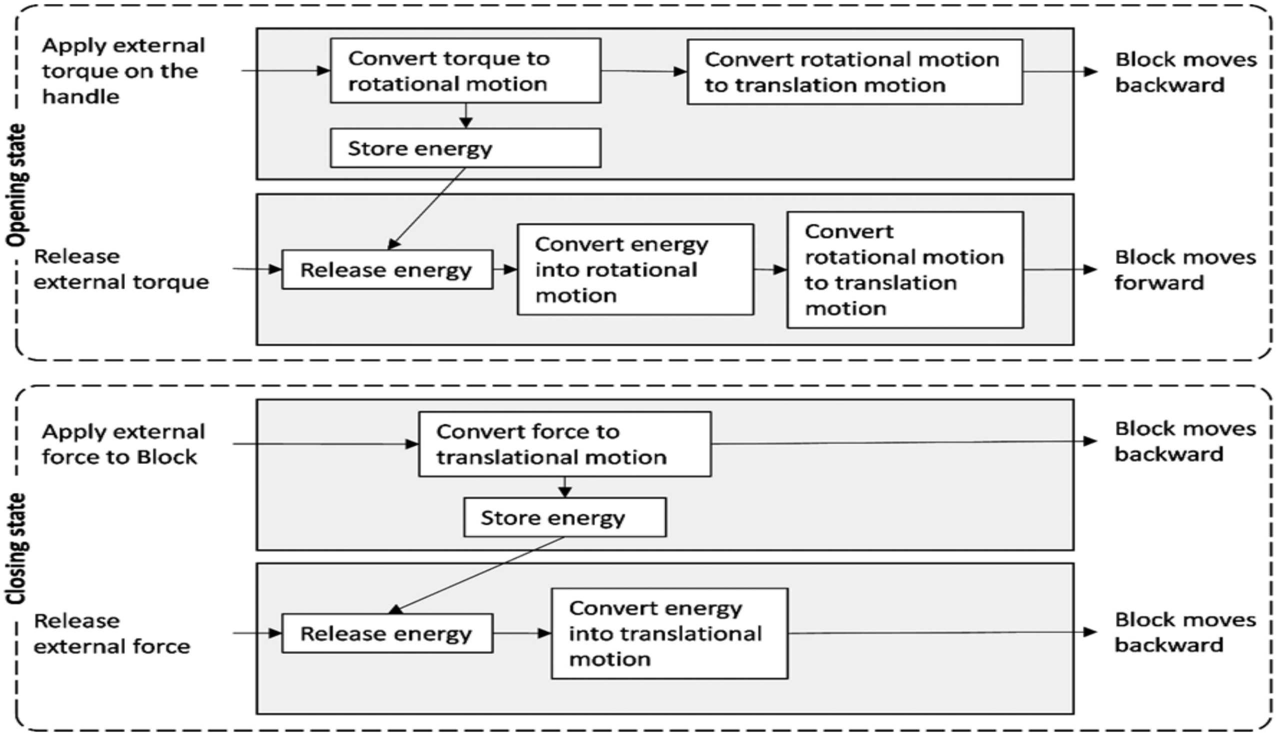


Figure 3. Function diagram of a multi-state door-latch system.

Table 1. The elemental functions of a door latch system

States	Elemental functions
Opening state:	$f_1 = \langle (0,0,-,0,0,-),(0,0,0,-,0,0) \rangle$
	$f_2 = \langle (0,0,-,0,0,0),(0,0,0,0,0,0) \rangle$
	$f_3 = \langle (0,0,0,0,0,+),(0,0,0,+,0,0) \rangle$
Closing State:	$f_4 = \langle (0,0,0,0,0,0),(-,0,0,-,0,0) \rangle$
	$f_5 = \langle (0,0,0,0,0,0),(0,0,0,+,0,0) \rangle$

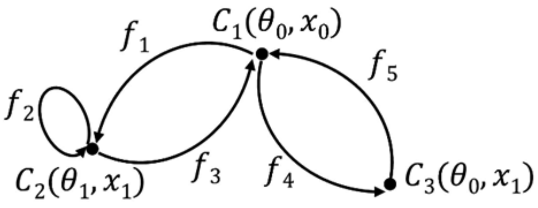


Figure 4. The specifications graph.

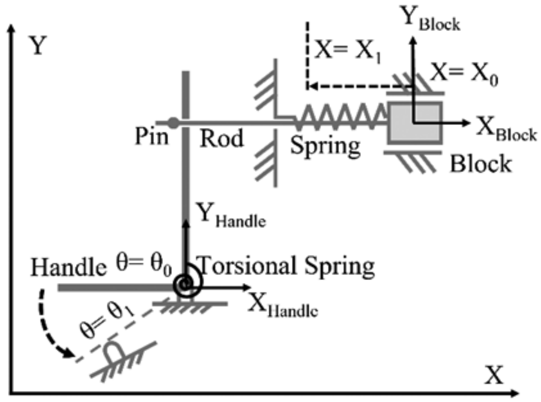


Figure 5. Schematic representation of the door latch.

Each node of the graph signifies a kinematic configuration of the system. Fig. 5 resembles a model of a door latch where the handle and the block have local coordinate systems attached to them. The initial positions of the handle and the block with respect to the global coordinate system (X, Y, Z) can be labelled as $C_1(\theta_0, x_0)$. The elemental function f_1 leads to a change in configuration from $C_1(\theta_0, x_0)$ to $C_2(\theta_1, x_1)$, and during the closing state, arc f_4 ends at another configuration $C_3(\theta_0, x_1)$. However, the arc corresponds to the elemental function f_2, which starts and ends at the same node implying no change in configuration. Hence, the elemental functions of a multiple state mechanical device can be broadly characterized into four categories (see Fig. 6):

(1) Type-1: An effort is applied and the configuration of the kinematic system changes.
(2) Type-2: An effort is applied but the configuration of the kinematic system doesn't change.
(3) Type-3: The configuration of the kinematic system changes without any external effort.
(4) Type-4: No effort is applied and no change in configuration occurs.

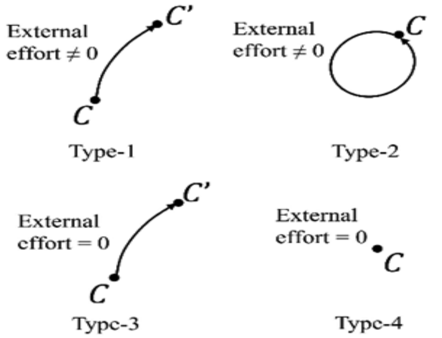


Figure 6. Elemental function characterisations.

4. PROPOSED 'PRESCRIPTIVE' DESIGN SYNTHESIS PROCESS

The functional requirements of a multiple state mechanical device differ across operating states; a new, prescriptive design process has been proposed below for synthesising multiple solutions (as shown in Fig. 7). While the proposed process is based on the empirical studies carried out by[23], it is aimed at addressing two issues faced by designers while following the 'descriptive' design process they naturally followed as found in the empirical studies. One is their focus and fixation to explore only one solution during synthesis; the other is the difficulty they faced in making their solution to fully satisfy the functional specification of the synthesis task.

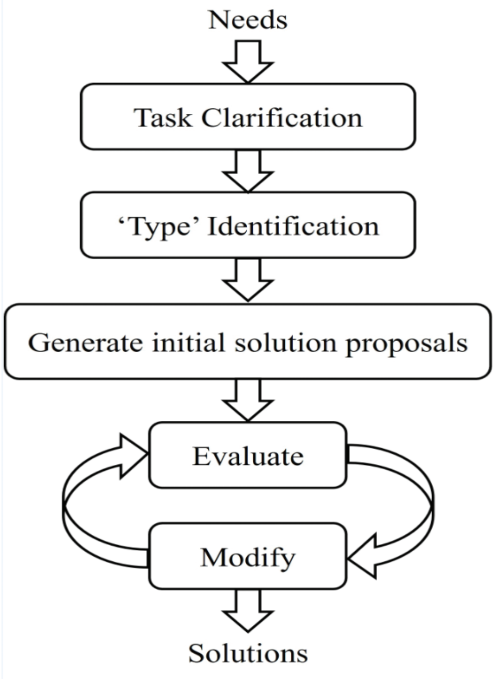


Figure 7. Proposed 'prescriptive' design synthesis process.

4.1 Task Clarification

The objective of the task clarification phase is to convert ‘needs’ into ‘functional requirements’. In case of multiple state devices, the functional requirements can be represented in the form of a specifications graph which consists of both elemental functions and changes in kinematic configurations.

4.2 “Type” Identification

As discussed in Section 3, elemental functions can be classified into four types. The empirical study in[23] suggested that after task clarification, the ‘Types’ of elemental functions be identified so that the designer can start with a ‘Type-1’ elemental function. Hence, at this stage, all the operating states and associated configurations should be analysed in detail to identify all ‘Type-1’ elemental functions that can be used for generating initial solution proposals.

4.3 Generate

Initial solution proposals for ‘Type-1’ elemental functions can be generated as follows: (1) retrieving from memory, which depends on designer’s domain knowledge and experience, (2) retrieving from existing database of mechanisms or books, or (3) using computational tools for searching or retrieving relevant solutions[24]. The solutions can be generated in the form of a kinematic pair or serially connected kinematic pairs or mechanisms and henceforth, abbreviated as ‘building blocks’.

4.4 Evaluate

After generating an initial solution proposal for a ‘Type-1’ elemental function, the next activity is to evaluate the solution against the elemental function. Evaluation is done against two major aspects: (1) The input-output components of the solution should follow the effort-motion relationship of the elemental function and, (2) The solution should support identical configurational changes as portrayed in the specifications graph.

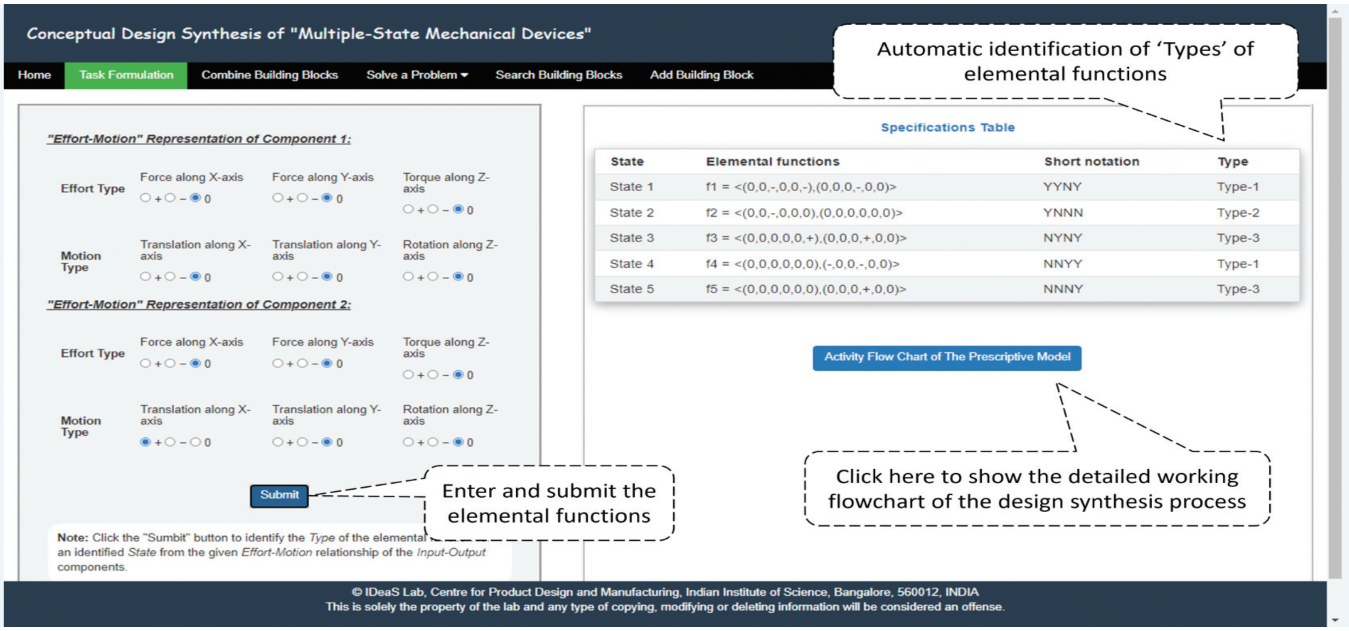
4.5 Modify

The door latch example acknowledges the fact that in a multiple state design task, the component which acts as an input in an operating state, could act as an output in some other operating state. In the design synthesis process, if an initial solution proposal does not satisfy the subsequent elemental function(s), the solution needs to be modified to satisfy the elemental functions while upholding the already satisfied ‘Type-1’ elemental function(s). Modification can be done in the following ways: (1) addition of new building blocks to the system, (2) modification of the interface between input-output components, or (3) by considering both. This activity should continue until the solution proposal satisfies all the desired requirements of the elemental functions. After performing the ‘Generate-Evaluate-Modify’ activities repetitively, a large number of solution space can be generated by considering different initial solution proposals at a time.

In order to further address the two issues that designers faced while following their natural design process, that they did not explore more than one solution, and their solutions often did not fully satisfy the multi-state functional specification, a set of modification rules and a database of building blocks have been developed, see details in Sections 5.2 and 5.3.

5. DEVELOPMENT OF THE TOOL

A web-based interactive platform has been developed for supporting designers to perform the design synthesis process for multiple state design tasks. The objective is to guide designers in a step-by-step manner with which they can search through an existing database of building blocks and modification rules as well as contribute to the database by adding new building blocks or modification rules. The web-based tool has been coded with PHP and JavaScript. MySQL server has been used for maintaining the database. In the following subsections, all features of the tool, as well as the process of using this tool, are demonstrated using an example case study. The door latch



"Effort-Motion" Representation of Component 1:

Effort Type
Force along X-axis ○ + ○ – ● 0
Force along Y-axis ○ + ○ – ● 0
Torque along Z-axis ○ + ○ – ● 0

Motion Type
Translation along X-axis ○ + ○ – ● 0
Translation along Y-axis ○ + ○ – ● 0
Rotation along Z-axis ○ + ○ – ● 0

"Effort-Motion" Representation of Component 2:

Effort Type
Force along X-axis ○ + ○ – ● 0
Force along Y-axis ○ + ○ – ● 0
Torque along Z-axis ○ + ○ – ● 0

Motion Type
Translation along X-axis ● + ○ – ○ 0
Translation along Y-axis ○ + ○ – ● 0
Rotation along Z-axis ○ + ○ – ● 0

Note: Click the "Sumbit" button to identify the *Type* of the elemental an identified *State* from the given *Effort-Motion* relationship of the *Input-Output* components.

Enter and submit the elemental functions

Automatic identification of ‘Types’ of elemental functions

Specifications Table

State	Elemental functions	Short notation	Type
State 1	f1 = <(0,0,-,0,0,-),(0,0,0,-,0,0)>	YYNY	Type-1
State 2	f2 = <(0,0,-,0,0,0),(0,0,0,0,0,0)>	YNNN	Type-2
State 3	f3 = <(0,0,0,0,0,+),(0,0,0,+,0,0)>	NYNY	Type-3
State 4	f4 = <(0,0,0,0,0,0),(-,0,0,-,0,0)>	NNYY	Type-1
State 5	f5 = <(0,0,0,0,0,0),(0,0,0,+,0,0)>	NNNY	Type-3

Click here to show the detailed working flowchart of the design synthesis process

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Figure 8. A screenshot of the ‘Task Formulation’ tab of the web-based tool.

design task with five elemental functions is considered as the example design task and an attempt has been made by the researcher to come up with an alternative conceptual design solution of the door latch system.

5.1 Design Task Representation

Initially, the designer is given a problem statement in which the multiple state design task is stated in the form of a specifications graph and associated elemental functions. For the example case study, Table 1 and Fig. 4 can be referred as the given problem statement. Fig. 8 captures a screenshot of the 'Task Formulation' tab of the web-based tool where all the given elemental functions are needed to be entered. After entering and submitting the functions, the 'Types' of elemental functions (as discussed in section 4) are identified by the tool automatically, as shown in Table 2. The tool further provides a detailed working flowchart of the design synthesis process within the 'Task Formulation' tab. The flowchart shown in Fig. 9 describes the strategy of generating initial solution proposals and guides through the iterative evaluation and modification processes.

Table 2. The 'Type' Identification

Elemental functions	Type
$f_1 = \langle (0,0,-,0,0,-),(0,0,0,-,0,0) \rangle$	Type-1
$f_2 = \langle (0,0,-,0,0,0),(0,0,0,0,0,0) \rangle$	Type-2
$f_3 = \langle (0,0,0,0,0,+),(0,0,0,+,0,0) \rangle$	Type-3
$f_4 = \langle (0,0,0,0,0,0),(-,0,0,-,0,0) \rangle$	Type-1
$f_5 = \langle (0,0,0,0,0,0),(0,0,0,+,0,0) \rangle$	Type-3

5.2. Searching for Building Blocks

After identifying the 'Type' of elemental functions, the designer needs to select a 'Type-1' elemental function to generate initial solution proposals. The 'Search Building Blocks' tab can be used to perform a search by entering the parameters of the elemental function selected. The search results can be retrieved in the form of either 2D schematic representations of planar mechanisms or abstract examples demonstrating possible ways of modifications. For the example design task, multiple initial solutions have been retrieved from the database, each of which satisfies f_1. Out of these, the slider-crank mechanism has been selected as an initial solution, but it has been observed that this solution does not satisfy the rest of the four elemental functions and thus requires further modifications.

5.3 The Modification Rules

Modifications are required when a solution proposal does not satisfy the subsequent elemental functions. After modifying the solution, it should also maintain all the previously satisfied elemental function(s). Three kinds of modification rules are derived from the empirical study done in[23] as described below:

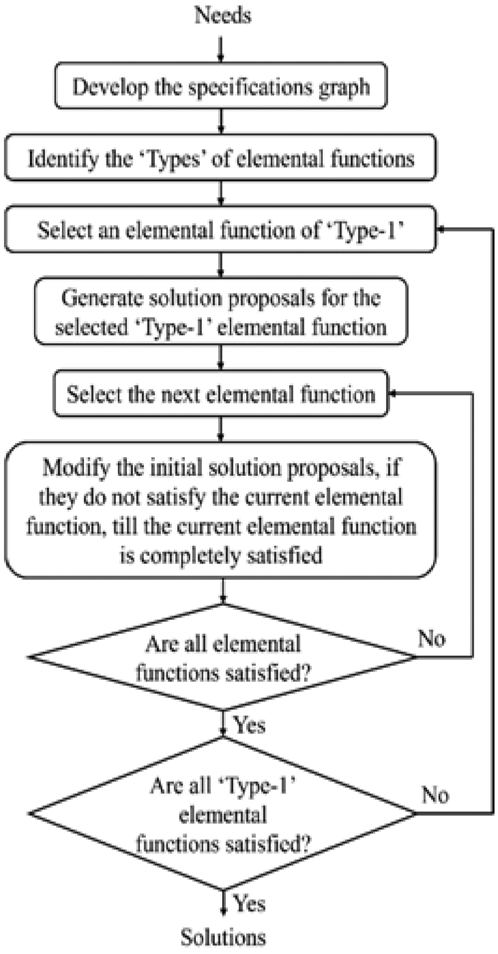


Figure 9. Detailed steps in the prescriptive design process.

- *Rule 1 – Impose constraint:* This rule can be applied when an initial solution exhibits 'Type-1' elemental function but needs to support a subsequent 'Type-2' elemental function. Fig. 10(a) illustrates this modification through an abstract example where it shows one possible way of positioning the constraint.
- *Rule 2 – Modify interface:* This is required when an initial solution satisfies an existing 'Type-1' elemental function but does not fulfil the requirement of another 'Type-1' elemental function. This condition arises when one of the components of the proposed solution remains idle in some different operating state. For example, in the case of the door latch system, the handle remains idle throughout the closing state; hence the first six effort-motion vector parameters of the elemental functions associated with that state i.e., f_4 and f_5, are all '0'. Therefore, the interface which connects the input and output components, can be modified as shown in Fig. 10(b).
- *Rule 3 – Add artificial effort:* This case occurs when the solution proposal needs to satisfy a 'Type-3' elemental function where both input and output components have to move but no effort is applied from any external sources. Thus, the required effort has to be provided by using stored energy, e.g., in the form of spring or in the form of

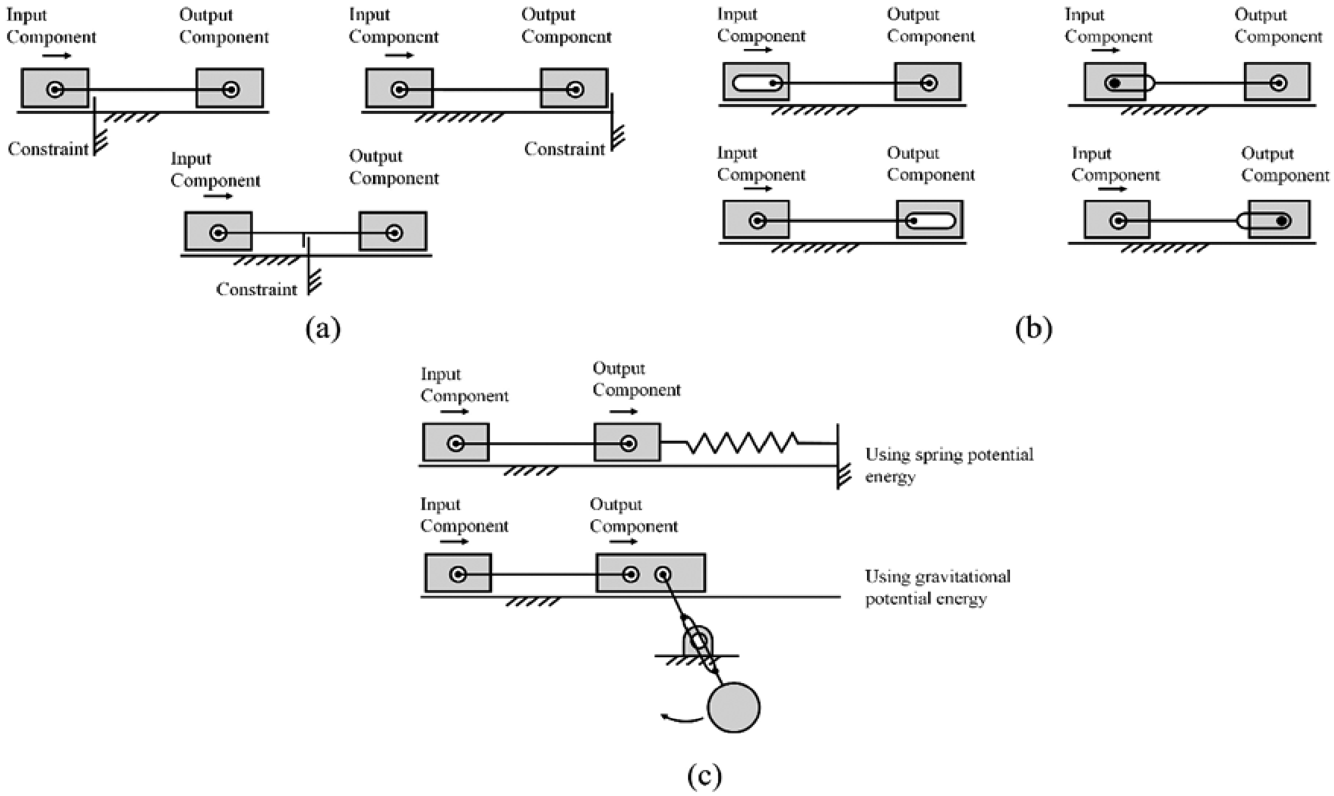


Figure 10. The modification rules are demonstrated through examples: (a) Different ways of imposing constraints, (b) Different ways of modifying interfaces and (c) Different ways of adding an artificial effort.

gravitational potential energy. Possible modifications are shown in Fig. 10(c).

5.4 Modification Examples

Based on the aforementioned modification rules, the selected initial solution for the example case study i.e., the slider crank mechanism is modified considering subsequent elemental functions until the modified solution satisfies all the five elemental functions. The modification rules are retrieved automatically from the tool by performing search actions. The complete modification process is given in Table 3 and described as four distinct steps. Firstly, the initial solution is evaluated with respect to all the elemental functions, and it has been found that except f_1 no other elemental functions are satisfied. Then, first modification rule is applied, and a stopper is added to constrain the motion of crank in the desired direction. At this point, the solution satisfies both f_1 and f_2 but fails to satisfy the rest. Finally, a conceptual solution is arrived at by modifying the current solution using modification rule 2 and rule 3 as described in Table 3.

5.5 Adding New Building Blocks to the Database

The tool also enables users to add new building blocks in the database. The user needs to find an appropriate elemental function for the new building block and enter it in the prescribed format along with an image file of the given format and size which represents the 2D schematic diagram of the new building block. All the data provided by the user will be uploaded to the existing MySQL database and can be used for further data retrieval. Since the tool is web-based, multiple users can use the tool simultaneously, and thus a large number of building blocks can be added to the database in a short period of time.

6. RESULTS AND DISCUSSION

In the previous section, the functioning of the proposed synthesis process, modification rules and database of building blocks using the web-based tool that embody these, using an example case study where a slider-crank mechanism is selected from the tool as an initial solution for a given multi-state door-latch design problem and a final working solution is achieved by applying the modification rules provided by the tool. Exploration of a wider solution space can be achieved by applying the same process can be followed with different initial solution proposals – where the proposals can be supported with the database of building blocks. For example, two such alternative solutions are shown in Fig. 11 where, instead of slider-crank, rack-and-pinion and cam-and-follower mechanisms were selected as initial solutions. In the alternative solution 1 (see Fig. 11(a)), the handle is fixed with the pinion and the block is connected to the rack and similarly in case of alternative solution 2 (see Fig. 11(b)), the handle is fixed with the cam and the block is fixed with the follower. Both initial solutions are further modified by using modification rules 1, 2 & 3 until they satisfy all the elemental functions. As a result of this, multiple potential solutions can be conceptualized for a given multiple state design task, and a wider range of alternative conceptual solutions can be explored before deciding on the most promising for further development.

It is important to note that in the current study, the tool has been evaluated by the researchers only, and not by external designers. In future, further case studies need to be conducted to evaluate the usefulness of the proposed synthesis process, modification rules and the database of building blocks and the associated tool, with controlled experiments involving potential users – designers – in solving different multi-state design tasks.

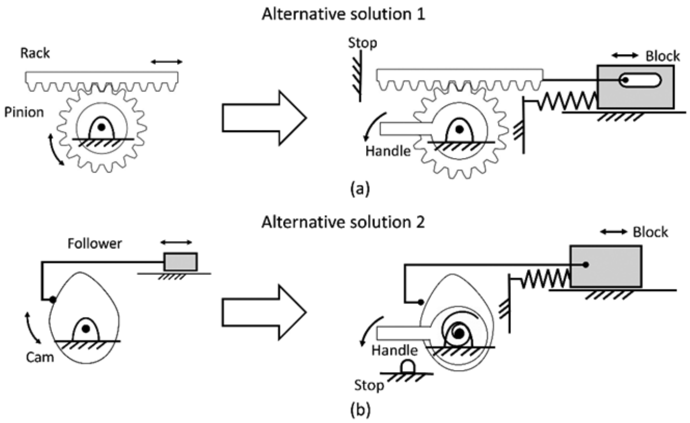


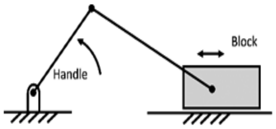
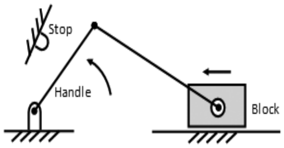
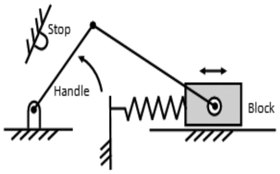
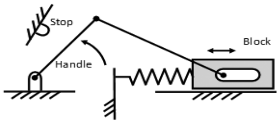
Figure 11. Two more alternative solutions are generated with support from the tool.

7. SUMMARY, CONCLUSIONS AND FUTURE WORK

In summary, this paper proposes a novel, systematic, prescriptive approach for supporting synthesis of a wide range of alternative conceptual solutions that fully satisfy given multiple state functional specifications. It also proposes a set of modification rules and a database of building blocks for supporting the process. The paper also presents a new web-based tool that is developed to computationally support designers in the conceptual design of multiple state mechanical devices, using the process, the modification rules, and the building blocks.

Specifically, the tool encapsulates the following. A simpler way of representing multi-state design tasks is adopted from existing literature for defining elemental functions. The elemental functions can be used in generating initial solution proposals. Evaluation and modification of the initial solutions can be carried out in an iterative manner until all the functional requirements are fulfilled. The tool is provided with a database of a wide range of building blocks and a set of modification rules. In the current version of the tool, the process of finding initial solution proposals is fully automated. However, it does not support automated evaluation and modification, and

Table 3. The step-by-step modification process

Steps	Process Description	Process Outcome	Satisfied Elemental Functions				
			f_1	f_2	f_3	f_4	f_5
1.	The initial solution proposal retrieved from the database of building blocks.		✓	✗	✗	✗	✗
2.	A constraint has been added to restrict the motion of the handle after a certain amount of rotation by using modification rule 1.		✓	✓	✗	✗	✗
3.	A spring has been added between the fixed frame and the block by using modification rule 3 which acts as an artificial effort to fulfil the requirements of elemental function f_3.		✓	✓	✓	✗	✗
4.	The interface which connects the handle and block has been modified by using modification rule 2. After this modification the solution satisfies all elemental functions and thus, the modified solution can be considered as a potential solution for the given multiple state design task.		✓	✓	✓	✓	✓

currently guide designers in modifying initial solutions by offering relevant modification rules.

In conclusion, the work presented in this paper adds to the current state of the art in the area of multiple state design synthesis in the following:

- There are two major gaps in the current state of support: they do not support designers explore a wide range of solutions, and the solutions proposed do not necessarily fully satisfy the functional specification.
- A novel, prescriptive design process has been proposed for addressing these gaps.
- A database of building blocks is developed for supporting exploration of a wider variety of conceptual solution alternatives.
- A set of modification rules has been proposed for supporting systematic modification of the alternatives.
- A web-based tool has been developed to support designers using the process, building blocks and modification rules.
- Preliminary evaluation by researchers indicate that the tool has the potential to support creation of multiple concept alternatives that fully satisfy the functional specification

Future work involves systematic and comprehensive evaluation of the process, modification rules, database of building blocks and the tool with external users and multiple tasks, and further advancement of the tool, including greater automation, in supporting designers.

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