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Knowledge-based configuration design of a train bogie †

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Abstract

The configuration design of a mechanical product can be performed efficiently when it is based on a functional model. There are some function-based design methodologies that decompose functions from the abstract level to the concrete level by matching the functions to physical parts. However, executing innovative design is difficult when the function is matched only to pre-defined parts. This paper describes the configuration design process of a train bogie with a design expert system that uses function taxonomy and TRIZ. The design expert system can propose a functional model of a new part that is not on the existing parts list of train bogies. Levels of design knowledge which describe the operations of the mechanical product at different levels of abstraction are introduced. This is the theoretical basis for using TRIZ with the function taxonomy for configuration design. The design expert system is adequate for controlling the design knowledge, which is expressed as knowledge of parts, functional modeling, mapping rules between functions and parts, and TRIZ. The functional model of a new brake system in the bogie is introduced with the design expert system.

Keywords: Configuration design; Design expert system; Function decomposition; Functional modeling; Function taxonomy; Levels of design knowledge; TRIZ

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1. Introduction

Configuration design is performed in the early stages of conceptual design. It can be defined as "a process of generating artifacts by assembling pre-defined components" [1]. In the configuration design of a mechanical product, function is used to describe the design target. "Function plays a key role in the conceptual design process, just as geometry does for the detailed design stage" [2]. Function decomposition and the creation of functional structures may be essential processes in a function-based design.

This paper describes a design expert system with the following features: (1) functional modeling of a mechanical product by Kirschman and Fadel's [3] 'function taxonomy', (2) configuration design of a train bogie (bogie) according to the functional model, and (3) functional modeling of a new part which is not on the existing parts list of the bogie using TRIZ's 30 function groups [4], which represent a portion of the 'physical phenomenon and effects' database in TRIZ.

The main purpose of a design methodology is to provide an effective way to accomplish design targets and prevent design failure without hampering creativity. There have been many function-based design methodologies, of which the main concerns are (1) simplifying the design problem by function decomposition, and (2) performing the decision problem efficiently in the design process.

Altshuller [4, 5] analyzed patents filed from the former Soviet Union and proposed several methodologies which he called the 'theory of inventive problem solving'. TRIZ is intended to provide a systematic way to solve problems in many engineering fields. Among the databases proposed by TRIZ is the 'physical phenomenon and effects' (PP&E) database, which is a classified collection of physical theory that is growing as new scientific discoveries occur. The 30 function groups which describe mechanical design functions represent a small portion of the function groups in TRIZ, [4]. Each function group has elements of physical theory selected from PP&E. It is possible that TRIZ's 30 function groups could provide fundamental physical knowledge for the design of mechanical parts if they are combined with a functional modeling strategy.

Collins et al. [6] presented functions inferred from helicopter part failures. They propose 46 key words and 40 antecedent adjectives to form 105 elemental functions. After analyzing

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Table 1. Four basic function groups [3, 7, 8].

Basic Function Groups	Specific Functions
Motion	Create, Convert, Modify, Dissipate, Transmit Rotary, Linear, Oscillatory, Other Flexible, Rigid
Control	Power, Motion, Information Continuous, Discrete Modification, Indication User-supplied, Internal Feedback
Power/Matter	Store, Intake, Expel, Modify, Transmit, Dissipate Electrical, Mechanical, Other
Enclosure	Support, Attach, Connect, Guide, Limit Cover, View, Protect Removable, Permanent

Collins' work and considering consumer products, Kirschman and Fadel [3] described the function of mechanical products as four basic function groups – Motion, Power/Matter, Control, and Enclosure. They break down each function group into more detailed descriptions as shown in Table 1. Each detailed description forms verb-adjective relations.

When function decomposition is performed, there will be a point at which primitive functions are found. At this point the decomposition process should be stopped to maintain a reasonable level of complexity of the function hierarchy. Function-based taxonomy usually has a list of parts for matching functions at the completion of decomposition. Even a novice designer can select parts from the list to fulfill the given function.

There have been many expert systems that perform configuration design based on the function hierarchy of mechanical products. Myung and Han [9] developed an expert system that parametrically models a machine tool assembly with a commercial CAD system. They introduce the concept of the 'design unit', which is a unit of function used to describe the function hierarchy.

Function-based design makes it possible to formalize the design process used by the experienced designer in a given domain. However, it is difficult to design a new part to satisfy a given function in most function-based design methodologies and design expert systems because a pre-defined part must be selected for the function. To solve this problem, this paper uses TRIZ's 30 function groups with Kirschman and Fadel's [3] function taxonomy because the function taxonomy is applicable to general mechanical products. This paper attempts to create a design expert system that can be used as a tool for various product design rather than one that is limited to a specific field.

2. Function taxonomy and abstraction levels of design knowledge

There are several abstraction levels of knowledge available to describe the components and operations of a computer system [10]. Similarly, it is possible to express the design knowledge of a mechanical product through hierarchical levels of

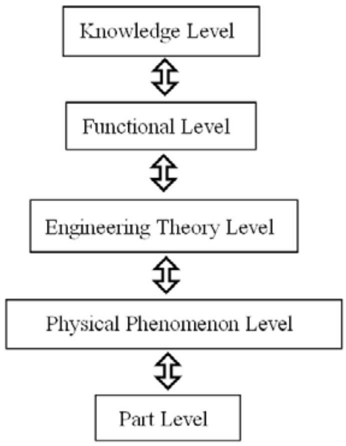

Fig. 1. Abstraction levels of design knowledge [7].

knowledge, as shown in Fig. . Each level describes the behavior of the mechanical product at a different level of abstraction. The highest knowledge level includes the design methodologies, which use any available knowledge to accomplish the design target. The functional level is concerned with the knowledge of functional modeling, e.g. function decomposition strategies and function hierarchy.

The engineering theory level includes the knowledge of analytical theories about the mechanical product or its parts. The physical phenomenon level includes basic physical theory and supplies fundamental knowledge to the next higher level of abstraction, the engineering theory level. It is likely that each level of knowledge is an abstraction of the preceding lower level. The part level describes physical components or mechanical parts fulfilling various. The types of connections between parts in the hierarchical structure of parts are also described at this level.

Each knowledge level has its own characteristics. The design methodologies in the knowledge level may include TRIZ, axiomatic design [11] and other A.I. theories. The main role of the knowledge levels is to interconnect other design knowledge in an attempt to accomplish the design target. In this paper, TRIZ is used to show possibilities as a design method in concept design with a design expert system. Consider the design knowledge that one design company might possess for a bogie. The knowledge about the bogie's function belongs to the functional level, while the mechanical parts performing the functions are subject to the part level. The engineering theory level may include technical constraints such as strength, durability and dynamic properties of parts, and the physical phenomenon level would describe the superconductivity phenomenon that can be used to levitate the vehicle.

The core idea of this paper was generated after pursuing ways to use this knowledge structure to create new design concepts. If there are four knowledge categories in each abstraction level shown in Fig. 1 excepting the knowledge level, it will be helpful to fully use the four categories to make a creative design. The strategy for creative design might belong to the knowledge level in Fig. 1. This paper suggests that it is

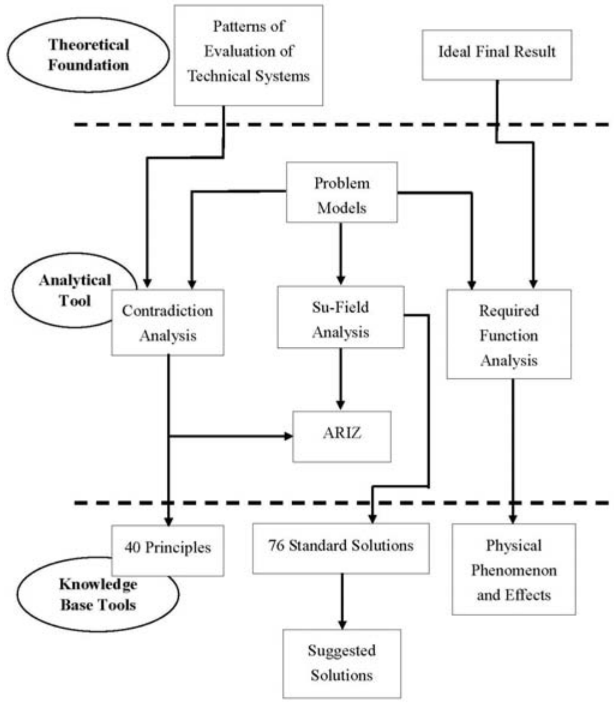

Fig. 2. Structure of TRIZ methodology [5, 7, 8, 12].

necessary to classify five levels of knowledge in order to use relevant knowledge in a systematic way, especially for creative design. This task will be more successful if an expert system is applied to the classified knowledge as it can be successfully used to correlate the knowledge of each level to its knowledge bases, rules and inference engine.

The more complex the design information is, the more difficult it is to manage efficiently without an expert system. After a design is completed, the knowledge base of the expert system can be supplemented by designers through classifying and adding newly acquired design knowledge, making it more reliable and useful for future design. This additional merit of the expert system shows how it serves as a tool to manage design knowledge. It does not simply store information but sorts it by knowledge level and interconnects the design knowledge for efficient storage, modification and use.

Every level of design knowledge can be used for conceptual design. For instance, a designer can make and analyze the functional hierarchy of a train bogie on a functional level and try to find parts for the function in the part level (Fig. 1). Then the designer can examine the physical phenomenon or engineering theory the part must satisfy to fulfill the required function. Selecting parts according to the function taxonomy can be described as making a connection between the two design knowledge levels – the functional level and the part level. The advantage of the function taxonomy is to provide "a common language for designers to refer to the same function" [3]. It standardizes the decomposition process by providing a set of standard functions and makes it easier to configure physical components.

Table 2. Selected examples of TRIZ's function groups and its elements [4, 7, 8].

TRIZ's 30 Function Group	Physical Phenomenon and Effects
Stabilizing object position	Applied electric or magnetic field Holding a liquid by hardening through the influence of an electric or magnetic field Gyroscope effect Reactive force
Moving an object	Magnetic field applied to influence an object or magnet attached to the object Magnetic field applied to influence a conductor with direct current passing through it Electric field applied to influence an electrically charged object Pressure transfer in a liquid or gas Mechanical oscillations Centrifugal force Thermal expansion Pressure of light
Influencing moving object	Applied or magnetic fields, with no influence through physical contact

3. The application of TRIZ

Altshuller, the inventor of TRIZ, has studied many creative patents and has categorized the manners by which the patents settled problems. As a result, he sets up a general problem solving methodology [4, 5], the structure of which is depicted in Fig. 2 [12]. TRIZ methodology is classified into three groups: theoretical foundation, analytical tool, and knowledge base tool.

In axiomatic design [11] theory, function decomposition is generated from the condition that each design parameter of functional requirements should not be coupled. This theory focuses on the independence and minimum complexity of functional requirements. This approach increases the possibility of producing simple and elegant design. However, it is not helpful to follow this method when inventing new products because innovation does not result from predefined relations between functions and parts as the axiomatic design theory suggests.

To work out this problem, it is reasonable to explore and find a physical theory to satisfy the given function when designing a new part. This process can be described and systematized in terms of the knowledge levels shown in Fig. 1. The physical phenomenon level shown in Fig. 1 offers fundamental physical descriptions for the development of new parts. Innovative designs often result from adopting different physical principles for an existing function. This research uses TRIZ's knowledge base of PP&E to find the necessary physical theory for a function and also suggests that this will substantially aid the designer to formalize the creative design process using the knowledge base and levels of design knowledge. It can also help experienced designers who design without the help of any standardized design method. Table 2 shows the selected examples of TRIZ's 30 function groups

Table 3. Analogy between function taxonomy and TRIZ's 30 function groups [7, 8].

Function taxonomy	TRIZ's 30 function groups
Motion	Moving an object, Moving a liquid of gas, Moving an aerosol, Influencing moving object
Control	Reducing temperature, Increasing temperature, …, Controlling electromagnetic fields, Controlling light, light modulation
Power / Matter	Generating and / or manipulating force, Accumulating mechanical and thermal energy, …, Generating electromagnetic radiation, Initiating and intensification of chemical reactions
Enclosure	Stabilizing object position, Developing certain structures, structure stabilization

and its elements of 'physical phenomenon and effects' selected from TRIZ's function groups.

The strong associations between function taxonomy [3] and the grouping of TRIZ's 30 function groups are investigated and categorized in this paper as shown in Table 3. The functional analogy between them is employed to make a connection between the decomposed function by function taxonomy and physical theory. This is one reason to use function taxonomy as a tool for functional modeling. Because the physical theory database increases continuously, the contents of the 30 function groups should be supplemented. In this paper, we use a restricted amount of functions which are assumed to be sufficient to show its availability.

Designers need to demonstrate creativity when choosing a physical theory to satisfy the decomposed function, then develop a new part based on the theory. If two different parts have similar functional models at the functional level shown in Fig. 1 but have different physical theories at the physical phenomenon level, the two parts can differ greatly in their overall shape. Therefore, applying a different physical theory to a function may result in a completely different configuration of parts.

4. Building an expert system for configuration design of a bogie

The use of expert systems in mechanical product design has increased, most of which are rule-based systems [9, 13]. Expert systems for engineering design may have many knowledge bases, which are separated but accessed and modified from the problem solving algorithm [14]. An expert system named 'BODES' (BOgie Design Expert System) has been developed for the configuration design of a bogie. The expert system consists of an inference engine and three knowledge bases – functional modeling, parts list, and PP&E of TRIZ as shown in Fig. 3. These knowledge bases contain the design knowledge of the three levels shown in Fig. 1 – the functional level, part level, and physical phenomenon level. The design rules of the knowledge level (shown in Fig. 1) interconnect the functional modeling knowledge base with the parts and TRIZ

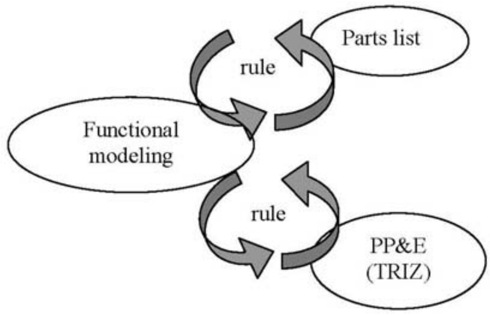

Fig. 3. Knowledge bases in the bogie design expert system (BODES) [7, 8].

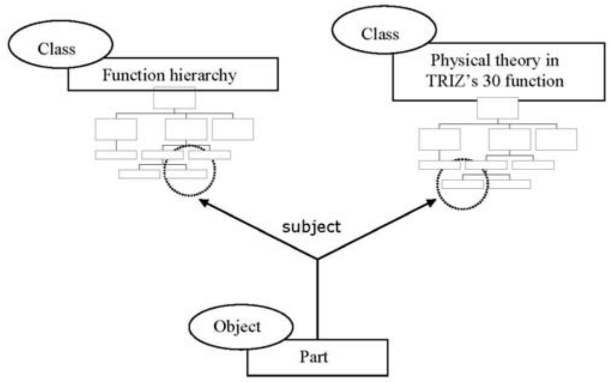

Fig. 4. Relation of design knowledge in BODES [7, 8].

knowledge bases.

Intelligent Rules Elements (IRE) V 4.0 of Neuron Data [15] is used as the expert system shell for the development of BODES. IRE uses object-oriented software architecture [16]. It supports "organization and use of knowledge in the form of objects of different kinds, and makes it possible to treat knowledge and data structures in a unified way" [17]. This feature of IRE is suitable for treating the design knowledge of different abstraction levels.

Class and property, the components of IRE, are appropriate for describing functions of mechanical products and TRIZ's 30 function groups. Objects of IRE are used to express parts of a bogie, while rules and methods can have the role of linking functions to parts. Fig. 4 shows the relation of the design knowledge in BODES after performed part is configured using TRIZ's 30 function groups. In Fig. 4, an object that represents a physical part is subject to two classes of functions and physical theory.

Fig. 5 shows the procedure for the configuration design of a bogie by BODES. The decomposition process by function taxonomy [3] is performed with inputs from the user. The decomposed function is to be linked to part in the function-based design process. The expert system asks designers whether they use an existing part for each decomposed function. If the designer decides to use an existing part, the object that represents the part is subject to the class that represents the decomposed function.

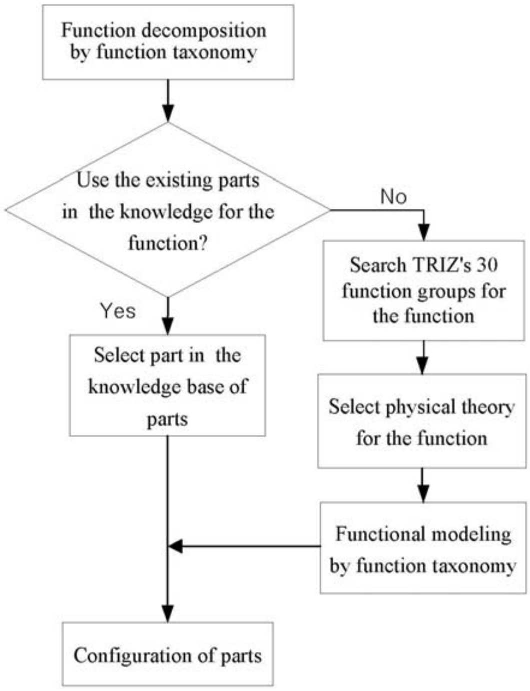

Fig. 5. Flowchart of the configuration design procedure in BODES [7].

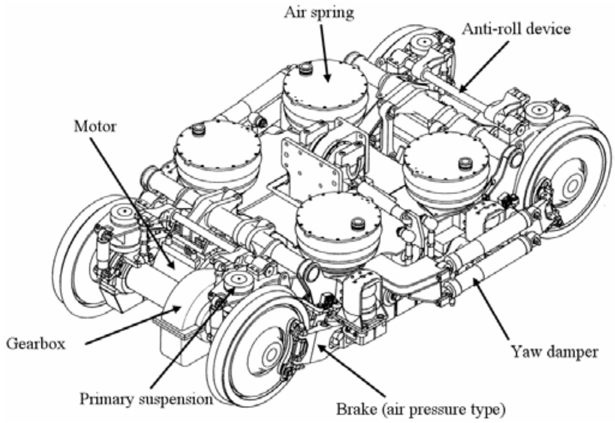

Fig. 6. Components of a bogie [7, 8].

If the designer tries to devise a new part that is not on the bogie parts list, the expert system, BODES, suggests physical theories for the functions of new part using the analogy described in Table 3 and corresponding elements shown in Table 2. After the designer chooses a physical theory, functional decomposition of the new part is performed with the function taxonomy, in which a process functional hierarchy may be built to actualize the new physical theory. The shapes and dimensions of parts will be fixed in the detailed design stage based on the configuration design results in BODES.

5. Configuration design of a bogie

The bogie is an essential piece of a train as it is in direct contact with the rails and supports the weight of the train. When the train moves, the bogie undertakes traction and braking

Fig. 7. Rule network of BODES.

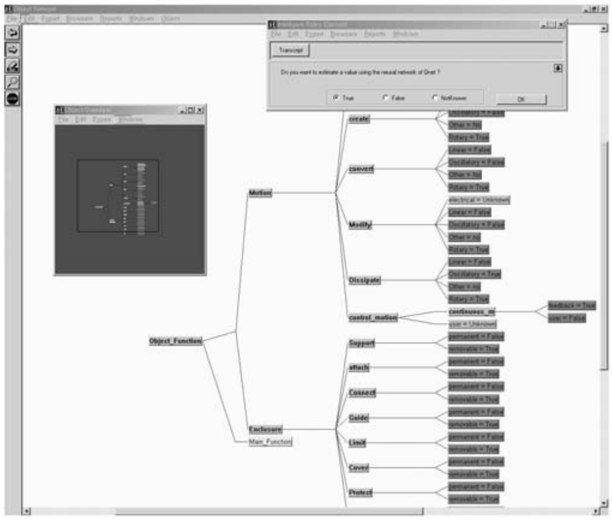

Fig. 8. Accepting data from the user during inference by BODES.

action, providing comfort and safety to the passengers [18]. The components of a bogie are shown in Fig. 6. Amongst the components of a bogie are the traction system, the brake system, suspensions, and the bogie frame. Most of the bogie components are mechanical parts [19].

The configuration design starts with a function decomposition of a bogie by the design expert system BODES as shown in Fig. 5. The four basic functions (Motion, Power, Control, and Enclosure) are subdivided into more specific functions according to inputs from BODES' GUI. Fig. 7 shows the rule network for BODES. According to the input given by the user, the inference engine selects and triggers rules in the reasoning process. Forward chaining is the most commonly used reasoning method of BODES because it makes new inferences possible according to accepted data from the user. This enables the inference engine to be better suited to dynamic situations.

The rules for function decomposition mainly consist of antecedent (If clause) and consequent (Then clause). The 'If clause' receives information through GUI, in that the user can choose functions for bogie parts according to the function taxonomy shown in Table 1. The 'Then clause' of the expert system builds the functional structure of a bogie by adding functions hierarchically. The inference process of the expert system showing the GUI frame and ongoing function decom-

Table 4. Decomposed functions and related parts of bogie [7, 8].

Function Decomposition		Parts of Bogie
Motion	Create rotary motion Modify rotary motion Convert rotary motion Dissipate rotary motion Dissipate oscillatory motion	Motor Gearbox Wheel set Brake system Yaw resistance system, Anti roll device
Control	Continuous modification and Internal feedback of motion	Tilting Device
Enclosure	Connect removal Enclosure	King pin
	Guide removal Enclosure	Lemniscate
	Support permanent and removal Enclosure	Bogie Frame

position is presented in Fig. 8.

After functional modeling is completed, BODES matches decomposed functions to parts. Table 4 shows the relation between the decomposed functions of the bogie and parts which are currently used in an existing bogie. This relation is embodied as rules in BODES to configure bogie parts after the function decomposition process.

Designers can make decisions on whether or not to use existing parts during the matching process between functions and parts after looking at the parts presented by BODES, such as those in a typical brake system of a bogie shown in Fig. 9. The function hierarchy and corresponding parts of the bogie after the matching process is completed are shown in Fig. 10.

The brake system of a bogie is an example of how to develop a new part with BODES. Contact-type brake systems operated by air pressure have been widely used. A non-contact type brake system, which uses the eddy current effect, has also recently been used. This paper shows that BODES can infer the functional model of the non-contact type brake system using the function taxonomy and TRIZ's 30 function groups.

The brake system is a part that is chosen to satisfy the decomposed function, 'dissipate rotary motion', as shown in Table 4. Contact-type brakes use friction between the disk and caliper to decrease the speed of a bogie as shown in Fig. 9. In terms of energy efficiency, it converts kinetic energy to heat and emits it to the air without doing any purposeful work. It also creates noise and scatters dust during braking. Therefore, an eco-friendly brake system must be developed which reduces noise and dust while allowing the brake system to reuse the decreased kinetic energy. This brake may need to be developed based on different physical phenomenon, as is the case for many technical innovations. For this purpose, BODES searches appropriate physical theories that fulfill the braking action. The function of the brake system, 'dissipate rotary motion', is matched to the function group, 'influencing a moving object' as shown in Table 3. After completing the inference process, BODES suggests the 'eddy current effect' from the function group. This paper assumes that the designer

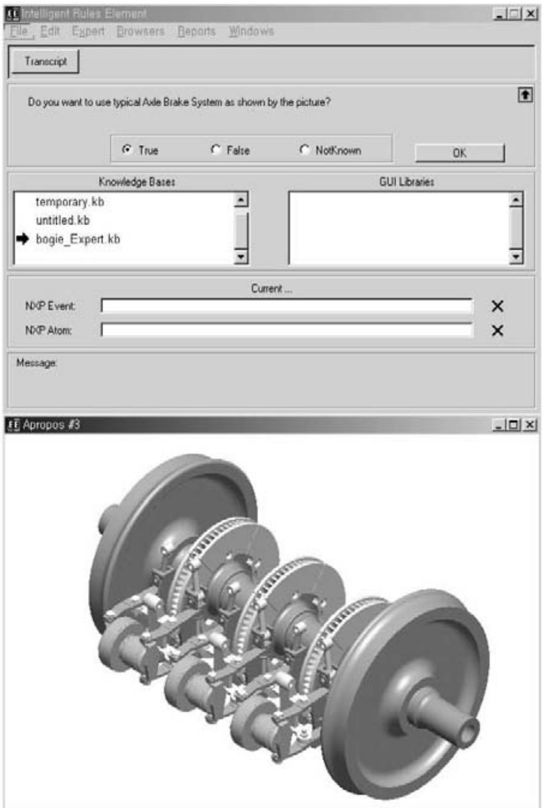

Fig. 9. Inference process of BODES for selecting existing parts [7].

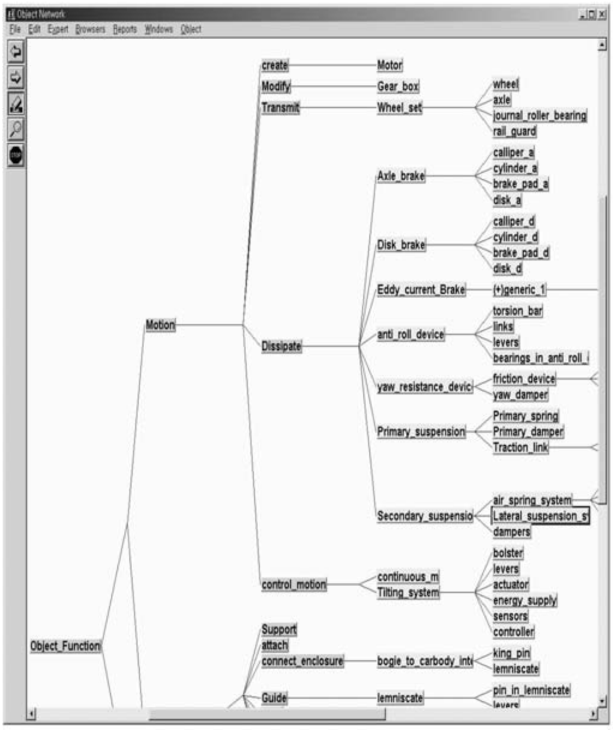

Fig. 10. Mapping structure between functions and parts of bogie [7, 8].

selects the eddy current effect as a physical phenomenon for the development of the new brake system.

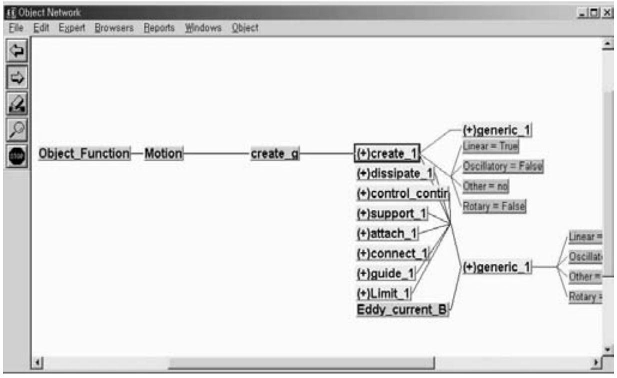

Fig. 11. A functional model of a new brake system [7].

Based on the chosen working principle of the brake, functional modeling of the new brake system is performed. It is possible to make several functional models for one selected physical theory since designers try many possibilities, and these models are expressed by objects named generic_1, generic_2, … , and generic_n in BODES. After functional modeling of the new brake system, BODES matches the decomposed functions of the brake system to parts. A functional model of the new brake system, named 'generic_1' and composed of eight functions, is shown in Fig. 11. In case of 'Creat_1', a sub function of 'generic_1', the function hierarchy is displayed with the following components: linear, oscillatory, rotary and other.

6. Conclusions

This paper proposes a configuration design methodology using an expert system that guides the designer toward innovative design by integrating function taxonomy and TRIZ. The concept of design knowledge levels is also introduced, providing the theoretical background for creating new parts with physical theory. This concept also plays an important role in organizing the expert system with knowledge bases of each knowledge level.

A design expert system, BODES, has been developed for the configuration design of a bogie. The expert system decomposes the function of a bogie and matches decomposed functions to existing parts. BODES can also produce functional models for a new part not in the existing knowledge base. With BODES, it is also possible to easily decompose the function of a mechanical product according to the function taxonomy that is in use or under development.

BODES contains the knowledge bases of functional modeling strategy, parts of a bogie, and TRIZ's 30 function groups for mechanical design—all of which belong to the design knowledge levels respectively. For further research, it is desirable to make a knowledge base of the engineering theory level by adding relevant knowledge of engineering facts and analysis. This will offer the designer important information about the engineering tasks that will be required at later stages of design.

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