Benjamin W. Caldwell
Clemson Engineering Design Applications and
Research (CEDAR) Lab,
Department of Mechanical Engineering,
136 Fluor Daniel Building,
Clemson University,
Clemson, SC 29634-0921

Jonathan E. Thomas
Lexmark International, Inc.,
740 W. New Circle Road,
Lexington, KY 40550

Chiradeep Sen
School of Mechanical, Industrial,
and Manufacturing Engineering,
204 Rogers Hall,
Oregon State University,
Corvallis, OR 97331

Gregory M. Mocko[1]
e-mail: gmocko@clemson.edu

Joshua D. Summers

Clemson Engineering Design Applications and
Research (CEDAR) Lab,
Department of Mechanical Engineering,
243 Fluor Daniel Building,
Clemson University,
Clemson, SC 29634-0921

The Effects of Language and Pruning on Function Structure Interpretability

In this research, the interpretability of function structures is evaluated through a user study in which participants are given function structures and asked to identify the product that is modeled. Two abstraction factors are controlled in the experiment: the type of functions and the specificity of the terms, thus resulting in functional models are four level of abstraction. The user study shows that free language significantly improves the accuracy and speed of human interpretability over the functional basis vocabulary. Further, pruned function structures significantly improve the speed of interpretability over reverse-engineered function structures without a loss of accuracy. It is concluded that the levels of each factor are useful for different activities and stages of design. Recommendations are made for the appropriate combinations of factor levels for various design activities. [DOI: 10.1115/1.4006442]

Keywords: function structure, product modeling, design cognition, engineering design, communication

1 Introduction

The overall goal of this research is to understand the limitations of current function modeling methods and to improve the usefulness of function models for conceptual design and reverse engineering. As a first step in this overall goal, the level of understanding of reverse engineered function models is assessed by studying the interpretability of models of existing products. The interpretability of reverse engineered function models will provide insights into the use of these models for communication and archival of functional information. The principles of communication learned through studying the interpretability of reverse engineered function models can then be extended to new design problems, where communication is also essential within design teams and extend current design repositories to better support the usage of archived functional models by human designers.

Function-based approaches to conceptual design are prescribed by many design texts [1–4], and one focus of recent design research is the area of function modeling. Views and definitions of function vary among researchers [5], but many focuses on what a product does rather than how it does it. Designers use various representations to describe "what" a product must do as opposed to "how" a product must complete a task during the conceptual design phase [2]. Function modeling formalization is important for repeatable and meaningful results [6], and current design research has assisted the formalization of functional modeling, such as the development of a functional basis [6], a design repository [7], and pruning rules for function structures [8]. However, much of this research focuses on the reverse engineering and modeling of existing products. Models of existing products can be useful for information archival and a function-based search for solutions to a new design problem. Further, the modeling process can also be useful to the modeler by forcing him or her to understand how the product functions and communicate it clearly. Function models can also be created for new products that do not yet exist. The modeling process for forward design may help the designer decompose the problem functionally, understand the problem better, and identify several ways to solve the problem. When creating a function model for a new product, the designer must make decisions about the new design as he or she creates the model, resulting in a model or several models that are not unique for the given design problem. The information gained through modeling a new product is different from that gained by modeling an existing product. Likewise, the value, or usefulness, of the model of a new product is different from the value of a model of an existing product.

In either a forward design setting or a reverse engineering setting, it is important for a modeler to be able to communicate his or her ideas clearly using the model. New design problems are often addressed by team of designers, so the function models developed and used within a design task must be understood by an entire design team. Reverse engineered models may be used for information archival and reuse, so these models must be understood by not only the original author(s) of the model but also by other design teams not initially involved in creating and storing the models. Thus, for any use of a function model, it is important that the ideas in the model are clearly communicated. Finally, multiple functional models of a product may exist, but each model should clearly communicate the functions that the product performs.

2 Frame of Reference

2.1 Function Structures. The definition of function used in this research is a transformation of a set of inputs to a set of

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[1] Corresponding author.

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outputs [1]. Using this view, designers can model systems using function structures, which show the transformation of material, energy, and signals through a system. For example, a vacuum cleaner function structure, shown in Fig. 1, models the conversion of electricity to rotational energy and pneumatic energy to guide gas through the vacuum cleaner as well as many other functions. The purpose of function modeling in conceptual design is to describe a system or product in a manner that is independent of the product's final form, allowing designers to focus their attention on higher level purposes of a system rather than its form [1]. Function modeling has also been used in reverse engineering to understand how a system works [2] and to capture functional information for archival and retrieval [7].

2.2 Interpretability.

2.2 Interpretability. Recent research in function structures has focused on consumer, electromechanical products, such as handheld power tools and household appliances. The function structures developed for these products are relatively small and can be created by a single person, so the intent of each element in the model is fully understood by the modeler. However, when someone unfamiliar with the model uses it, he or she may not understand what the modeler intended. For example, in the vacuum cleaner function structure (see Fig. 1), the functions import human force and guide translational motion could be interpreted as movement of the whole system or movement of a component of the system, such as a switch. It is important to note that the function structure modeling approach has been augmented from that originally proposed by Pahl et al. [1] to include transformations of and interactions with the system of interest. This is often captured in function structures using the *import* and *couple* notations. The authors recognize this problem with function structures but it is not addressed in this research. The goal of this research is to understand the interpretability of function structures, or how well designers unfamiliar with a model can understand what is modeled. A commonly accepted definition of interpretability is *capable of being understood.* Specifically in this research, interpretability is defined as the human designer's ability to understand the product that is described by the functional model. In this research function structure interpretability is defined on two levels. The first level is the ability to identify the exact product for which the function structure was originally created. The second level is represented by the ability to identify products that accomplish a similar high-level purpose.

2.3 Ambiguity. A primary goal of function modeling in conceptual design is to identify what the product should do independent of its final form to aid in concept development. Since the final form is not known, a function model can support uncertainty and flexibility in the design. However, this uncertainty should be clearly identified and communicated by the function model, rather than containing ambiguity that can be misinterpreted by users of the function models [9]. In conceptual design, it is important to explore as much of the available design space as possible, and an abstract model such as a function structure can support this exploration. However, an abstract model should not be ambiguous, but it should clearly outline the design space that is available for exploration. An ambiguous model may seem to be abstract, but it may allow a designer to misinterpret the model and explore areas that are outside the design space. If ambiguity exists in function models of reverse engineered products, then similar models used in forward design may also be ambiguous. This research uses the interpretability of function models to understand if ambiguity exists within function models and, if so, to identify ways to reduce

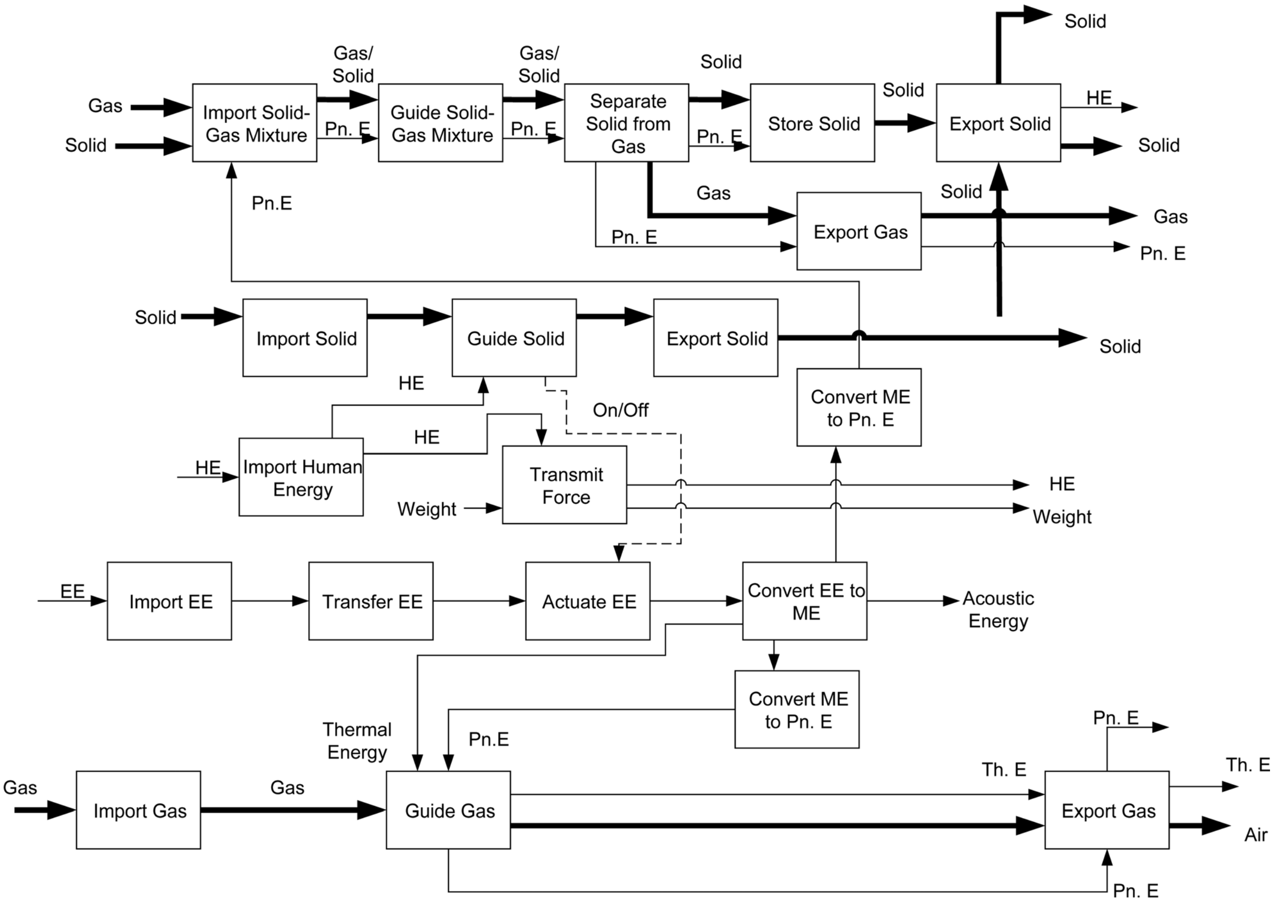

Fig. 1 Vacuum cleaner function structure

this ambiguity, improving function-based communication and information archival in engineering design.

2.4 Functional Basis and Design Repository. The functional basis is a vocabulary developed to describe the functionality of mechanical devices [6]. The functional basis consists of a 53 functions and 45 flows and their definitions, which help designers to model product functionality in a consistent manner [6]. The functional basis provides a common language for communication and archival of design knowledge. The functional basis is used in design research to create function structures and other functional descriptions of products. Functional information of approximately 160 mechanical products is stored in a web-based design repository[2] using the functional basis [7]. The information in the design repository is used within design tools such as failure analysis [10–12], similarity [13,14], concept generation [15–17], process modeling [18], behavior modeling [19,20], and biomimicry [21–23]. Function models obtained for this research from the design repository have been created through reverse engineering and contain both free language and functional basis terms.

2.5 Function Structure Pruning Rules. In order to reduce the level of detail, eliminate solution-specific functions, and decrease inconsistencies in the modeling of human-product interactions within reverse engineered function structures, researchers from Clemson University developed nine functional pruning rules [8]. These rules were developed by examining 18 consumer electromechanical products from the Missouri University of Science and Technology (MUST) design repository. These rules are aimed at reverse engineering a function structure appropriate for the early stages in the product design process, where designers could potentially benefit more by focusing on the core functionality of the product rather than solution-specific details. For example, the function "*Transfer Electrical Energy*" refers to a wire within an existing product. While the wire is essential for the product to function, such details about a product are not important considerations on the early stage of design. The functional pruning rules developed in Ref. [8] are summarized as:

(1) Remove all import and export functions.
(2) Remove all channel, transfer, guide, transport, transmit, translate, rotate, and allow DOF functions referring to any type of energy, signals, or human material.
(3) Remove all couple, join, and link functions referring to any type of solid.
(4) Remove all support, stabilize, secure, and position functions.
(5) Remove all control magnitude, actuate, change, stop, increase, decrease, increment, decrement, shape, condition, prevent, and inhibit functions.
(6) Remove all provision, store, supply, contain, and collect functions referring to any type of energy or signal.
(7) Remove all distribute functions referring to any type of energy.
(8) Remove all signal, sense, indicate, process, detect, measure, track, and display functions.
(9) Combine adjacent convert functions if the output flows of the first function block are identical to the inputs of the second function block.

An example of applying the pruning rules to the vacuum cleaner function structure in Fig. 1 is shown in Fig. 2. The number of functions is reduced from 15 to 5, the essential flows remain within the model, and solution and assembly specific detail are eliminated from the model.

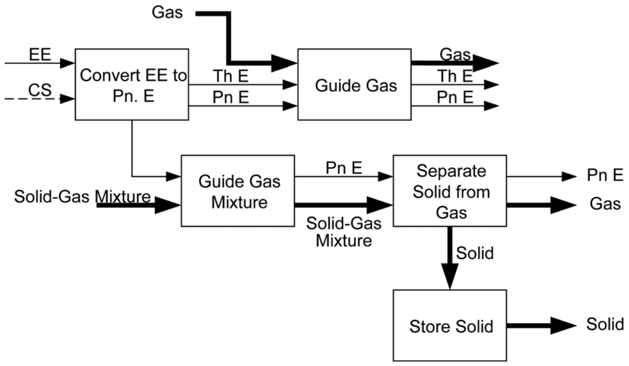

Fig. 2 Vacuum cleaner function structure after applying pruning rules

3 Research Approach

A previous study conducted by the authors tested the interpretability of three levels of abstraction of function structures [24]. The previous study led to the identification of two dimensions of abstraction and further refinement of the experiment [24]. The study has been revised and repeated with a larger sample size and an additional level of abstraction that was discovered through the initial study. The primary difference in this refined study is the testing of two independent factors of abstraction. Secondary improvements include testing the speed of interpretation and identifying key elements in models that aid in interpretation.

The refined user study was completed to ascertain the interpretability of functional representations at various levels of abstraction. The function models vary in abstraction in two dimensions: (1) the type of functions within the model and (2) the specificity of the terms used within the functional models. In the study, participants are asked to identify the product modeled based solely on its function structure. Additionally, participants are asked to denote what aspects of the function structures aided them in their decision-making. This information provides an in depth look at what information in the model is meaningful and should be included within the function models.

3.1 Function Structure Abstraction Levels. In this study, four levels of abstraction are tested in each of the two dimensions. The function level is tested at the reverse engineered level (RE) and at the pruned level (Pruned). The language specificity is tested at the free language level (Free) and using the secondary level of the functional basis (FB). Thus, the following four levels of abstraction are obtained: RE-Free, RE-FB, Pruned-Free, and Pruned-FB.

In order to analyze these abstraction levels, four products were chosen from the design repository and translated into the additional levels of abstraction. The products chosen from the repository were the Black and Decker rice cooker, Dewalt sander, Shopvac vacuum cleaner, and the Black and Decker electric screwdriver. The four products were chosen because they are all electromechanical products that the user study participants should be familiar with.

3.2 Translation of Function Structures Between Four Levels of Abstraction. The four levels of abstraction used in this study are the result of combining the two levels of each of the two factors. The RE-Free level of abstraction is obtained from the design repository and used in the study without modification. The free language terms in the RE-Free model are translated to the secondary level of the functional basis using corresponding terms in the vocabulary [6] and knowledge about the product, resulting in the RE-FB level of abstraction. The pruning rules are then applied to the RE-FB model, resulting in the Pruned-FB level of abstraction. The final level of abstraction, Pruned-Free, is

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[2] http://repository.designengineeringlab.org

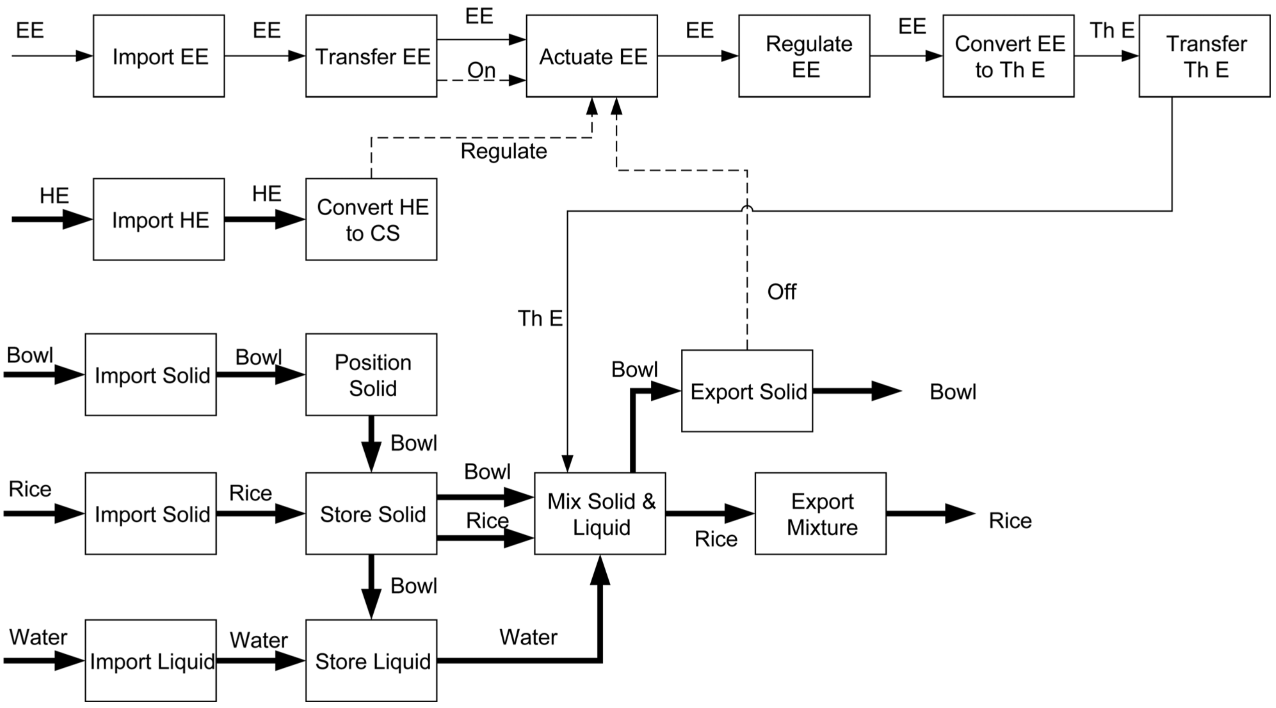

Fig. 3 Rice cooker function structure at the RE-Free abstraction level

obtained by converting the functional basis terms in the Pruned-FB model back to free language terms used in the RE-Free level of abstraction. These four levels of abstraction are discussed in further detail in Secs. 3.2.1–3.2.4.

3.2.1 RE-Free Abstraction Level. The RE-Free models are downloaded directly from the design repository and used in this study. Approximately 25% of the flows and 9% of the nouns in these models are free language terms [25], while all functions are functional basis terms. An example of the RE-Free level is shown in Fig. 3, which is the model of the Black and Decker rice cooker used in this study.

The key features of this model relative to the FB level of language abstraction are the inclusion of context-specific free language terms, such as *bowl*, *rice*, *water*, *on*, and *off*. In the function dimension, this model contains auxiliary functions and interactions such as *import electrical energy*, *transfer thermal energy*, and *import solid*, which can be identified through reverse engineering but may not be specified in conceptual design.

3.2.2 RE-FB Abstraction Level. The RE-FB level of abstraction is obtained by translating the free language terms in the RE-Free model to functional basis terms using guidelines provided with the functional basis vocabulary as well as knowledge about the product. The number of functions and flows and the relationships among these are identical between the RE-Free and RE-FB levels of abstraction. The RE-FB level of abstraction of the rice cooker is shown in Fig. 4. In this model, terms such as *bowl* and *rice* have been translated to *solid*, *on* and *off* to *control signal*, and *water* to *liquid*. The auxiliary functions and interactions remain in the model, as in the RE-Free level of abstraction.

3.2.3 Pruned-FB Abstraction Level. The Pruned-FB level of abstraction is obtained by applying a set of previously developed pruning rules to the RE-FB model. The pruning rules remove auxiliary functions and interactions from the models, resulting in a more conceptual-level model compared to the reverse engineered models in the repository. The pruning process reduces the number of functions and flows in the models but does not change the language. In the Pruned-FB rice cooker model, shown in Fig. 5, functions such as *import human energy*, *transfer electrical energy*, and *export solid* have been removed.

3.2.4 Pruned-Free Abstraction Level. The Pruned-Free level of abstraction is constructed by converting the functional basis flow terms in the Pruned-FB models back to the free language originally used in their RE-Free function structure. Hence, the terms *solid* and *liquid* from the rice cooker function structure shown in Fig. 5 are replaced with the free language terms *rice* and *water* and is shown in Fig. 6. The idea behind this Pruned-Free abstraction level is to restore some information back to each products function structure, which was lost in the translation of the RE-Free level to the RE-FB level. In the case of the rice cooker, the terms *on*, *off*, *bowl*, *rice*, and *water* are added back into the structure, since they were used in the original RE-Free function structure.

4 Experimental Setup

4.1 Research Hypotheses. The two factors in this study, language specificity and type of function, are tested to determine if either factor or a combination of the two factors have an effect on the interpretability of function structures and the amount of time required to interpret the function structures. The mean interpretability and time for each factor are compared, with the primary research hypotheses shown in Table 1.

The secondary research hypotheses test the combined effects of each factor on interpretability and time:

- $I_{\text{Pruned-Free}} > I_{\text{Pruned-FB}}$
- $I_{\text{RE-Free}} > I_{\text{RE-FB}}$
- $I_{\text{Pruned-Free}} > I_{\text{RE-Free}}$
- $I_{\text{Pruned-FB}} > I_{\text{RE-FB}}$
- $t_{\text{Pruned-Free}} < t_{\text{Pruned-FB}}$
- $t_{\text{RE-Free}} < t_{\text{RE-FB}}$
- $t_{\text{Pruned-Free}} < t_{\text{RE-Free}}$
- $t_{\text{Pruned-FB}} < t_{\text{RE-FB}}$

The interpretability hypotheses are tested using two scoring approaches: (1) an exact response is given a score of 1, and a

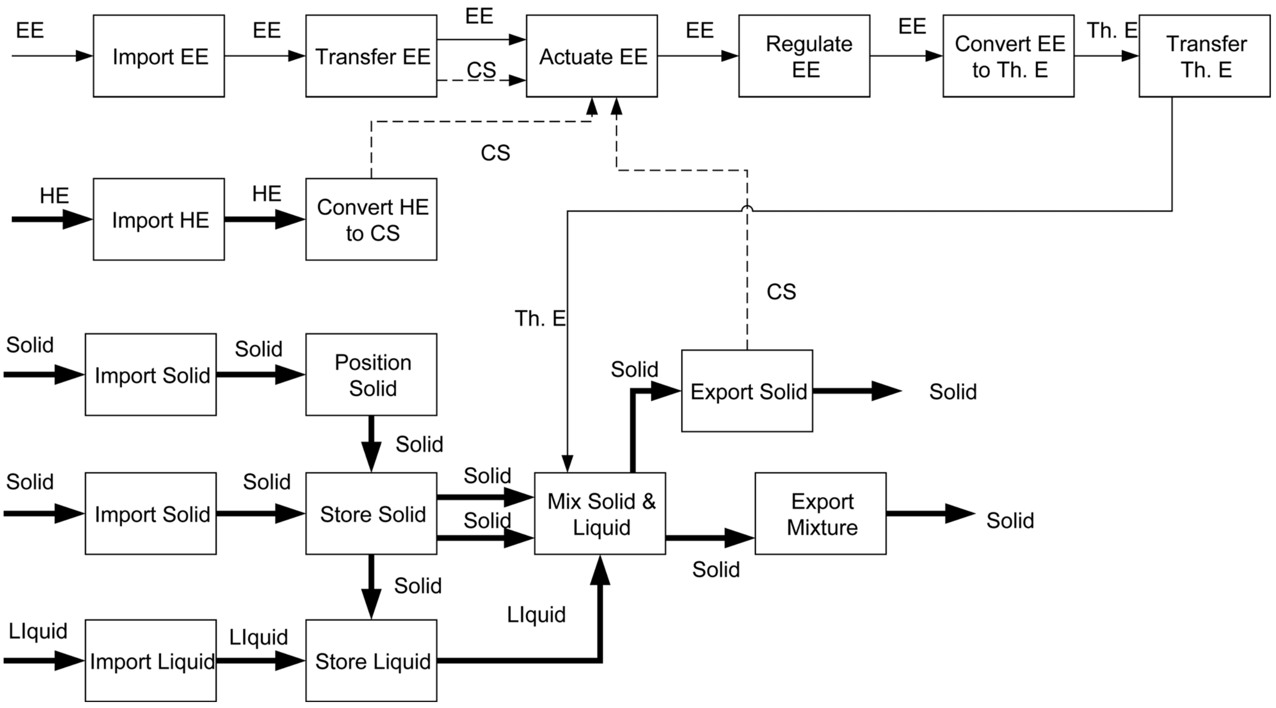

Fig. 4 Rice cooker function structure at the RE-FB abstraction level

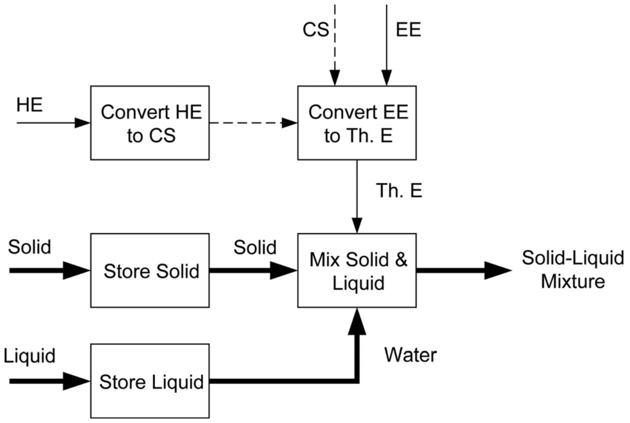

Fig. 5 Rice cooker function structure at the Pruned-FB abstraction level

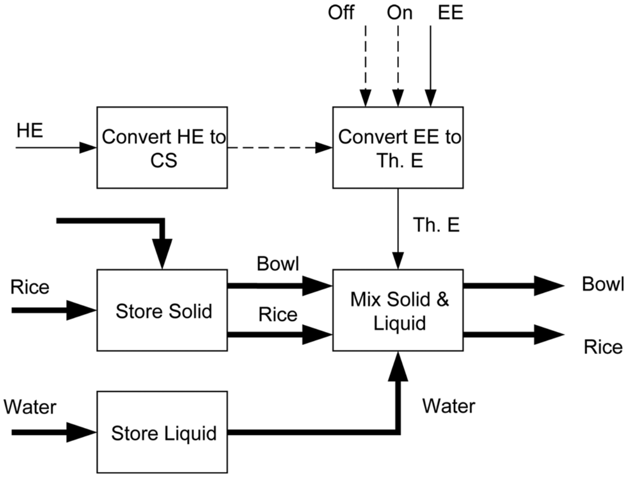

Fig. 6 Rice cooker function structure at the Pruned-Free abstraction level

Table 1 Primary interpretability research hypotheses

Research hypothesis	
The interpretability of function structures using free language is greater than the interpretability of function structures using the secondary level of the functional basis.	$I_{Free} > I_{FB}$
The interpretability of pruned function structures is greater than the interpretability of reverse-engineered function structures.	$I_{Pruned} > I_{RE}$
The time required to interpret a free-language function structure is less than the time required to interpret a functional basis function structure.	$t_{Free} < t_{FB}$
The time required to interpret a pruned function structure is less than the time required to interpret a reverse-engineered function structure.	$t_{Pruned} < t_{RE}$

Notes: I—interpretability; t—time; Free—free language; FB—functional basis; RE—reverse engineered.

nonexact response is given a score of 0; and (2) an exact or similar response is given a score of 1, and a dissimilar response is given a score of 0. The definition of exact, nonexact, similar, and dissimilar responses is discussed in Sec. 4.6. The time hypotheses are tested using three approaches: (1) all times are considered, (2) only times of exact responses are considered, and (3) the times of exact and similar responses are considered.

4.2 Participants. Participants were chosen based on the enrollment and attendance of students in a graduate mechanical engineering design course taught at Clemson University. The students in this course had prior exposure to design theories, design methods, and design research, including function modeling. To ensure environmental familiarity, the participants completed the study in their engineering design course classroom.

Table 2 Products included in picture packet

	1	2	3	4
A	Stapler	Microwave	Electric toothbrush	Dremel
B	Electric screwdriver	Electric shaver	Printer	Handheld vacuum cleaner
C	Disposable camera	Sander	Hair dryer	Lawn mower
D	Toy gun	Electric knife	Salad shooter	Engine
E	Coffee maker	Weed trimmer	Paintball gun	Pogo stick
F	Circular saw	Flashlight	Nail gun	Vacuum cleaner
G	Wok	Sewing machine	Gaming console	Rice cooker
H	Electric drill	Can opener	Juicer	Blower
I	Shop vacuum cleaner	Toaster	Lighter	Bench grinder
J	Band saw	Can opener	Electric pencil sharpener	Popcorn popper
K	Fan	Breathalyzer	Portable CD player	Ironing machine
L	Kettle	Curling iron	Electric jar opener	Cotton candy machine

4.3 Training and Normalization of Participants.

A 10 min presentation about function modeling was given to all user study participants immediately before the study was conducted. The presentation defined function in engineering design, outlined the benefits of functional modeling, and provided a function structure example (Proctor Silex iron) from the design repository for discussion. After the presentation, the participants were given an opportunity to ask any questions pertaining to the presentation and function modeling. Participants were then introduced to the user study and told that they would be identifying products based on the function models of the products.

4.4 Experiment Packets.

Participants were given a two-page picture packet containing 48 electromechanical consumer products, which served as the answer choices for the study. Pictures of products were used rather than names of the products as answer choices because some of the product names include the functionality of the product (e.g., rice cooker, hair dryer, lawn mower) and others do not (e.g., kettle, wok). Students were given a few minutes to ask any questions about the pictures to ensure familiarity. The picture packets were printed in color for the user study, and few questions arose regarding what was being illustrated in the packets. The products included in the picture packet and their layout is shown in Table 2.

The alphanumeric labels on the columns and rows are provided for ease of participant identification and do not imply a grouping of the products. For example, the *Curling Iron*, is identifies as *L3*. This coding scheme is only used to aid in post experiment analysis.

4.5 Participant Worksheet Packets.

Four worksheet packets were developed, each containing function structures for a shop vacuum, rice cooker, sander, and electric screwdriver, with each product modeled at a different level of abstraction (see Secs. 3.2.1–3.2.4). The type of information collected for each product at each level of abstraction includes the product selected from the answer choices, the amount of time taken to identify the product (start and finish), and what information from the function structure served as a primary aid in their decision. To assist with time keeping an online digital clock was projected on a screen visible to all participants. Students were given 12 min to complete the contents of each of the four worksheet packets. The time limit was fixed by the need to conduct the experiment without exceeding the time scheduled for the class. Time evidence from the previous user study suggested that this is a sufficient amount of time for participants to complete the worksheets.

The products and abstraction levels were mixed between worksheet pages in each of the four packets in attempt to eliminate the opportunity for participants to develop any type of correlation between the function structures within each packet. Each packet contained one model of each product and one of each of the four combinations of abstraction levels. In addition, the participants were randomly divided into two different groups with each group receiving the packets in reverse sequence from each other. Table 3 shows the contents of each packet.

Table 3 Contents of experimental packets

	Product	Abstraction level
Packet 1	Rice cooker	Pruned-FB
	Sander	RE-Free
	Electric screwdriver	Pruned-Free
	Shop vacuum	RE-FB
Packet 2	Rice cooker	RE-Free
	Shop vacuum	Pruned-Free
	Sander	Pruned-FB
	Electric screwdriver	RE-FB
Packet 3	Shop vacuum	Pruned-FB
	Rice cooker	RE-FB
	Electric screwdriver	RE-Free
	Sander	Pruned-Free
Packet 4	Shop vacuum	RE-Free
	Electric screwdriver	Pruned-FB
	Sander	RE-FB
	Rice cooker	Pruned-Free

4.6 Classification of Responses.

Participants were presented with an unidentified function structure and asked to identify what product was modeled. The participants were not told that only four products were used and that answers would be repeated. The participants' responses were classified as exact, nonexact, similar, and dissimilar. Exact responses are those that exactly identify the product being modeled, while nonexact responses are the remaining 47 incorrect answer choices. The nonexact responses are further broken down into similar and dissimilar responses. Similar responses are identified as products in the answer packets are functionally similar to the exact answer, while dissimilar products are those that are not functionally similar.

A product is considered functionally similar to another, in this research, if it achieves the same high-level purpose. This high-level purpose was determined by consensus of a panel of design researchers before the results were analyzed. The panel determined that products similar to the Black & Decker rice cooker include the microwave (A2), wok (G4), coffee maker (E1), and kettle (L1) since all of these products are food processing devices that accept water and food as inputs and produce heated food as the output. Products similar to the Dewalt sander include the Dremel (A4), lawn mower (C4), drill (H1), grinder (I4), and pencil sharpener (J3). The Dremel and grinder are similar as they are abrasive surface-polishing devices. The lawn mower is similar to the sander since it is a device that removes part of the surface (grass) exposed to it and removes the debris (cut grass) with air flow. The drill and pencil sharpener are similar devices since their primary purpose is to remove material. The products similar to the

Table 4 Products similar to the four products tested in the user study

Product	Similar products
Rice cooker	Coffee maker Kettle Microwave Wok
Sander	Dremel Lawn mower Grinder Pencil-sharpener
Shopvac vacuum	Handvac Vacuum cleaner Lawn mower Blower
Electric screwdriver	Dremel Drill

Shopvac vacuum cleaner include the hand vac (B4), lawn mower (C4), vacuum cleaner (F4), and blower (H4). The hand vac and upright vacuum cleaner are considered similar since they are both vacuum cleaners. The blower is similar based on the fact that it works by creating a pressure difference to move air through the system. The lawn mower is included since it also moves air and debris through the system and filters the air. Finally, products similar to the electric screwdriver are the Dremel (A4) and drill (H1). These products are considered similar to the electric screwdriver since they are all mechanisms that apply torque by rotating the tip. All products similar to the four products used in this user study are shown in Table 4.

4.7 Data Collection. Each worksheet packet was collected at the end of the 12 min interval to ensure that participants did not refer to alternate function structures of a product during the experiment. Sample date from the study is illustrated in Table 5. The table contains (1) the participant's ID, (2) the product they believe was being modeled in the function structure, (3) the time taken to identify the product, and (4) any aspects or keywords from the structure which aided them in their decision. As seen in Table 5 some students did not complete the worksheets in their entirety denoted by dashes in the table. Examples can be found with student 1 who do not denote the amount of time taken to identify the fourth product in his or her packet, which he or she recognized as a carpet vacuum and rated his confidence as a two. Another example is seen with student 3 who left the final model in his or her packet completely blank.

5 Experimental Data

5.1 Exact and Nonexact Responses. The number of participants who identified the function structures exactly, according to each abstraction level is presented in Table 6. The RE-Free abstraction level yielded the highest success rate, in regards to indentifying the products exactly from their function structures, compared to the other three levels. This claim is based on the fact that out of the 71 responses for all four products at one level, 43 of those responses, or approximately 61%, were exact identifications as to what the product was being modeled at the RE-Free level. Responses from the Pruned-Free level for each product were fairly close to the results of the RE-Free level at 58%. At the Pruned-FB level, approximately 14% of responses were exact. Products modeled at the RE-FB level had the lowest success rate at indentifying the exact product at roughly 7%.

5.2 Exact and Similar Product Responses Combined. As mentioned in Sec. 4.6, function structure interpretability is defined on two levels. The first level is an individual's ability to identify the exact product for which a function structure was originally

Table 5 User study sample data

Participant ID	Correct product	Function level	Language l evel	Participant's response	Time (seconds)	Comments
1	Rice cooker	Pruned	FB	Coffee maker (E1)	57	Only one machine mixed solid. Heat applied. Solid is grounds, understood as coffee.
	Sander	RE	Free	Sander (C2)	85	Sander paper is used. Wood is involved.
	Electric screwdriver	Pruned	Free	Screwdriver (B1)	33	Screw, electric energy used to guide solid
	Shopvac	RE	FB	Carpet vacuum (F4)	—	Solid plus gas. Solid is separated. Pneumatic energy is used.
2	Rice cooker	Pruned	FB	Coffee maker (E1)	71	Solid liquid mixture
	Sander	RE	Free	Circular saw (F1)	39	Output wood. Hand movements
	Electric screwdriver	Pruned	Free	Screwdriver (B1)	19	Input EE. Output screw and mechanical energy
	Shopvac	RE	FB	Sander (C2)	344	Vague guess
3	Rice cooker	Pruned	FB	Coffee maker (E1)	38	EE to Th.E. Store/Mix. Liquid/solid. Made less confident because thermal energy is not shown added to the liquid as expected. Also do not expect solid/liquid mixture leaving
	Sander	RE	Free	Sander (C2)	128	"Hand" used to manipulate solid. "wood" and "sandpaper" gave it away.
	Electric screwdriver	Pruned	Free	Electric screwdriver (B1)	48	"screw"
	Shopvac	RE	FB	—	—	—

Table 6 Number of exact and nonexact identifications of products at each level of abstraction

	Exact	Nonexact
RE-Free	43	28
Pruned-Free	41	23
RE-FB	5	53
Pruned-FB	10	59
Total	99	163

Table 7 Number of similar and dissimilar identifications of products at each level of abstraction

	Exact or Similar	Dissimilar
RE-Free	59	12
Pruned-Free	54	10
RE-FB	23	35
Pruned-FB	31	38
Total	167	95

created. The second level is an individual's ability to identify products that accomplish the same high level purpose as the product being modeled. Since the product being modeled is similar to itself, the exact and similar responses are combined in this approach and compared to dissimilar responses. The results of the study using this approach are shown in Table 7.

5.3 Variation of Products Identified Based on Abstraction Level.

The participants' responses and the number of participants selecting the response at each level of abstraction are presented in Table 8. For example, for the sander function structure at the RE-Free abstraction level, eleven students identified a sander, two identified a circular saw, two identified a band saw, and one identified a vacuum cleaner, pencil sharpener, and grinder.

The results of the rice cooker suggest that the rice cooker's function structure at RE-FB was more abstract compared with the other three levels due to the fact participants identified eight different products at this level. The Pruned-Free level was more abstract when compared to the RE-Free, Pruned-Free, and RE-FB level for both the sander and electric screwdriver seeing that 12 products were identified for the sander and 14 for the electric screwdriver.

5.4 Participants' Notes on Enabling Features.

In order to gain additional insight regarding the interpretability of the function structures analyzed in the study, participants indicated what aspects of each function structure aided them in their decision making on their experiment worksheets. For the rice cooker function structure at the RE-Free abstraction level, all eighteen participants indicated that the use of the word *rice* was a key contributor toward identifying the product. The same is true for the twelve out of eighteen participants who identified the rice cooker exactly at the Pruned-Free abstraction level. The remaining six students' responses were blank and the participants did not provide comments at all. At the RE-FB level for the rice cooker, students relied primarily on the functions within the model to identify

Table 8 Unique student responses for each product and abstraction level

	Rice cooker	Sander	Shopvac vacuum	Electric screwdriver
RE-Free	Rice cooker (18)	Sander (11) Circular saw (2) Band saw (2) Vacuum cleaner (1) Pencil sharpener (1) Grinder (1)	Hand vac (6) Vacuum cleaner (5) Shopvac vacuum (3) Sander (3) Coffee maker (1)	Electric screwdriver (11) Drill (3) Nail gun (2) Toaster (1) No response (1)
Pruned-Free	Rice cooker (12) No response (6)	Sander (12) Circular saw (3) Band saw (2) No response (1)	Shopvac vacuum (6) Vacuum cleaner (5) Hand vac (5) Sander (1) Lawn mower (1)	Electric screwdriver (11) Drill (3) Nail gun (2) Paintball gun (1) No response (1)
RE-FB	Rice cooker (5) Coffee maker (5) Wok (2) No response (2) Microwave oven (1) Popcorn popper (1) Cotton candy machine (1) Washing machine (1)	No response (6) Band saw (2) Coffee maker (2) Nail gun (2) Vacuum cleaner (2) Dryer (1) Pencil sharpener (1) Blower (1) Hand vac (1)	Vacuum cleaner (6) No response (4) Dryer (2) Hand vac (2) Juicer (1) Lawn mower (1) Sander (1) Grinder (1)	Salad shooter (4) No response (3) Jar opener (1) Sewing machine (1) Toaster (1) Nail gun (1) Band saw (1) Camera (1) Pencil sharpener (1) Popcorn popper (1) Can opener (1) Paintball gun (1) Candy machine (1)
Pruned-FB	Coffee maker (12) Rice cooker (4) Juicer (1) Wok (1)	Sander (2) Nail gun (2) Coffee maker (2) No response (2) Jar opener (2) Pencil sharpener (1) Hair curler (1) Weed whacker (1) Breathalyzer (1) Juicer (1) Candy machine (1) Blower (1) Shopvac (1)	Vacuum cleaner (8) Shopvac (3) Hand vac (2) Popcorn popper (1) Blower (1) No response (1) Salad shooter (1) Candy machine (1)	Nail gun (2) Circular saw (2) Pencil sharpener (2) Electric screwdriver (1) Jar opener (1) Toaster (1) Band saw (1) CD player (1) Salad shooter (1) No response (1) Candy machine (1) Lawn mower (1) Can opener (1) Microwave (1)Motor (1)

Table 9 Results of statistical tests of interpretability

Research hypothesis	Exact = 1 Nonexact = 0 ($n = 262$)	Exact = 1 Similar = 1 Dissimilar = 0 ($n = 262$)	Result of research hypothesis
(1) $I_{Free} > I_{FB}$	$0.68 > 0.066$ $p < 0.0001$	$0.91 > 0.37$ $p < .0001$	Accept
(2) $I_{Pruned} > I_{RE}$	$0.33 > 0.22$ $p = 0.0629$	$0.75 > 0.68$ $p = 0.1467$	Fail to accept
(3) $I_{Pruned\text{-}Free} > I_{Pruned\text{-}FB}$	$0.72 > 0.088$ $p < 0.0001$	$0.92 > 0.43$ $p < 0.0001$	Accept
(4) $I_{RE\text{-}Free} > I_{RE\text{-}FB}$	$0.64 > 0.041$ $p < 0.0001$	$0.91 > 0.31$ $p < 0.0001$	Accept
(5) $I_{Pruned\text{-}Free} > I_{RE\text{-}Free}$	$0.72 > 0.64$ $p = 0.2068$	$0.92 > 0.91$ $p = 0.3274$	Fail to accept
(6) $I_{Pruned\text{-}FB} > I_{RE\text{-}FB}$	$0.088 > 0.041$ $p = 0.0964$	$0.43 > 0.31$ $p = 0.1415$	Fail to accept

products. One participant's comments read "Import solid, storing, and mixing with liquid to get a solid output using EE and HE" and this participant identified a microwave. A majority of participants, 15 out of 18, indicated that the mixing portion of the rice cooker function structure at the Pruned-FB level aided them in their decision making.

In the case of the sander at the RE-Free level, all participants noted that the use of either sandpaper or wood aided them in their decision making. Even though the all students alluded to the specificity of terms, six different products were identified from the function structure at the RE-Free level. One participant who identified a band saw wrote the following comments: "(1) Processing wood and separating debris. (2) EE input, guiding with hand. (3) Using Pn.E to separate debris." At the Pruned-Free level a similar trend is observed; 17 out of 18 students stated that the free language terms such as *sandpaper*, *wood*, and *debris* from the function structure aided them in their decision. Seven out of 18 participants did not leave select a product or leave comments for the sander function structure at the RE-FB level. For those participants who did leave comments, the term *solid* was the primary focus and participants attempted to understand what was being represented by this term. Students alluded to the *solid* being an article of clothing, a blade, wood, dirt, and even a pencil. At the Pruned-Free level, is seems as though participants regained their confidence, seeing that only two students did not identify a product. One of the students who did not answer commented, "The function model has too few details making it ambiguous." However, those who did respond seemed to focus on the *separating* and *storing* of the *solid*, which ultimately led to 12 unique responses from the participants.

As for the Shopvac function structure at the RE-Free level, 15 of the participants indicated that the use of the *debris* provided the most help toward identifying a product. In addition, many participants pointed out that the usage of the word *hand* or *human energy* contributed to their responses. One participant wrote on his worksheet that the terms *debris*, *air*, and *hand* led him to identifying a hand vacuum. Another participant specified that, "air and debris as input giving debris as output and using of the hand to guide solid" motivated his decision in choosing the sander as the product being modeled. The comments from the Pruned-Free abstraction level are similar to that of the RE-Free in that the usage of free language motivated most decisions. At the RE-FB level, many students referred to the *solid–gas mixture* within the model as the key factor in their decision. In addition, two students interpreted this mixture to be articles of clothing in a dryer. At the Pruned-Free level, more vacuuming devices were identified and a common comment among participants was the storing of a solid and the input of *solid–gas mixture* motivated their decision.

In the case of the electric screwdriver at the RE-Free level, the majority of participants claimed that the usage of the word *screw* aided them in their decision. In addition, *guiding of the hand* within the structures motivated many students as well. The human interaction, *guiding of the hand*, was so influential that 17 out of the 18 of the function structure identifications provided by students were handheld devices: the electric screwdriver, a hand drill, and a nail shooter. Comments at Pruned-Free level were similar to the RE-Free. At the RE-FB and Pruned-Free levels, participants seemed to have focused much of their attention on the *solid* and the *guiding of the solid*. Ultimately, since the term *solid* is ambiguous, 12 and 14 different responses were provided by students at the RE-FB and Pruned-Free levels, respectively.

6 Statistical Analysis

6.1 Interpretability. As discussed in Sec. 4.1, the data collected were used to determine if the function level (Pruned or RE), the language level (Free or DR), or a combination of these levels has an effect on interpretability of function structures. For the interpretability statistical tests, each of the two scoring approaches discussed in Sec. 4.6 were analyzed assuming a binomial distribution of the responses. Students and products were both modeled as random effects. The GLIMMIX procedure within SAS/STAT® software was used to analyzed the data and compare the means of interpretability. The interpretability hypotheses and results are shown in Table 9, where the values in the table represent the mean interpretability on a scale from 0 to 1.

The interpretability of free language models, using both scoring methods, is significantly better than the interpretability of functional basis models ($p < 0.0001$). Using the exact/nonexact scoring, free language models had an average interpretability of 0.68 on a scale from 0 to 1, while functional basis models had an average interpretability of 0.066. Using the exact/similar/dissimilar approach, the free language models had an average interpretability of 0.91, while the functional basis models had an average interpretability of 0.37. Therefore, the use of free language significantly improves the interpretability of function structures.

The average interpretability of pruned and reverse-engineered function structures using the exact/nonexact scoring method is 0.33 and 0.22, respectively. When using the exact/similar/dissimilar scoring system, the averages are 0.75 and 0.68, respectively. The comparison of these values results in p-values of 0.06 and 0.15, respectively. The hypothesis test was also performed using additional scoring approaches, such as exact responses receiving a score of 2, similar responses a score of 1, and dissimilar responses a score of 0; or nonresponses scored as nonexact. In each variation of the analysis, the p-value for this hypothesis test was approximately 0.15. Since the level of significance in this research is 0.05, the second interpretability research hypothesis is not accepted.

The third through sixth hypotheses test for mixed effects of the two factors. The results of these hypotheses are consistent with

Table 10 Results of statistical tests for time

Time research hypothesis	Time from all responses ($n = 262$)	Times from exact responses only ($n = 96$)	Times from exact and similar responses only ($n = 162$)	Result of research hypothesis
(1) $t_{Free} < t_{FB}$	$70.0 < 127.6$ $p < 0.0001$	$70.4 < 106.7$ $p = 0.0069$	$67.7 < 103.2$ $p = 0.0001$	Accept
(2) $t_{Pruned} < t_{RE}$	$79.9 < 117.6$ $p < 0.0001$	$81.7 < 95.4$ $p = 0.1726$	$70.9 < 100.0$ $p = 0.0005$	Accept
(3) $t_{Pruned\text{-}Free} < t_{Pruned\text{-}FB}$	$48.7 < 111.1$ $p < 0.0001$	$54.1 < 109.3$ $p = 0.0008$	$48.7 < 93.1$ $p = 0.0002$	Accept
(4) $t_{RE\text{-}Free} < t_{RE\text{-}FB}$	$91.3 < 144.0$ $p < 0.0001$	$86.7 < 104.0$ $p = 0.2256$	$86.8 < 113.2$ $p = 0.0253$	Accept
(5) $t_{Pruned\text{-}Free} < t_{RE\text{-}Free}$	$48.7 < 91.3$ $p < 0.0001$	$54.1 < 86.7$ $p = 0.0012$	$48.7 < 86.8$ $p = 0.0001$	Accept
(6) $t_{Pruned\text{-}FB} < t_{RE\text{-}FB}$	$111.1 < 144.0$ $p = 0.0013$	$109.3 < 104.0$ $p = 0.4201$	$93.1 < 113.2$ $p = 0.0820$	Accept

the results of the first two hypotheses, and there are no significant mixed effects.

6.2 Time. The time required to interpret each function structure was analyzed using three approaches: (1) all times are considered, (2) only times of exact responses are considered, and (3) only times of exact and similar responses are considered. The procedure GLIMMIX within SAS was also used in the time data analysis. The interpretability times were assumed to be normally distributed, and students and products were modeled as random effects. The time hypotheses and results are shown in Table 10, where the values in the table represent the mean time, in seconds, taken to interpret a function structure.

When the times from all responses or exact and similar responses are considered, all of the hypothesis tests are accepted with a significance level of 0.05. Free language models are interpreted significantly faster than functional basis models, and pruned models are interpreted significantly faster than reverse-engineered models. Hypotheses 3–6, which test for mixed effects, are consistent with the first two hypotheses, so there are no mixed effects. The fastest level of abstraction, therefore, is the Pruned-Free level, which took approximately 49 s to interpret.

When the times from only exact responses are considered, the trends in time required to interpret the models are similar but not always significant. The sample size is much smaller in this approach because the times from nonexact responses are not considered. Therefore, the results of the other two approaches are used to accept all of the time research hypotheses.

7 Conclusions

The interpretability of function structures has been studied to determine how well human users of function structures understand a model. Additionally, the experiment has shed light on what aspects of a functional model enable a designer to identify specific design concepts. A user study was conducted in which participants were given a function structure and asked to identify what product is represented by the model. Function structures varied in terms of language specificity and the level of abstraction of functions to better understand the aspects of a function structure that aid in interpretation. A limitation of the study is that all free language terms in the models were used to describe flows, not functions. Therefore, all conclusions drawn on the functional basis are relevant for the flow vocabulary and not necessarily for the function vocabulary. Additionally, it is important to note the primary focus of this research is understanding how human designers use functional representations in design. The authors do recognize that computational support and reasoning in design, is important [26–29], but it is not the focus of this research study. Two major conclusions are drawn from this study.

7.1 The Use of Free Language Increases the Accuracy and Speed of Interpretability Compared to a Controlled Vocabulary. The statistical analysis shows that a free language function structures had a much greater interpretability than functional basis function structures, and the participants' notes further support this conclusion, since many comments focused on free language terms in the models. The high specificity of flow terms in free language models provides additional context in the model that helps the user to interpret it. In the functional basis models, less-specific terms create more ambiguity in the model, and students are not able to understand the content of the model. One purpose of the functional basis is to improve the communication of function models through the use of a controlled vocabulary and specific definitions of terms. This interpretability study, however, shows that functional basis terms, specifically flow terms, cause ambiguity in a model rather than clarity. Even though definitions of each term have been provided, the specificity of the terms is not adequate for human communication and interpretability. Thus, either free language should be used in function structures or a more specific flow vocabulary should be developed that enables contextual information to be included in the models.

The speed of interpretation of free language models is significantly higher than functional basis models. Participants identified these contextually rich free-language terms and used them to quickly understand the model. In functional basis models, the terms were less clear, so they required more time to interpret. The use of free language in communication between human designers, therefore, is enhanced in terms of speed and accuracy when free language is used in the model.

7.2 Removing Auxiliary Functions and Interactions From a Reverse-Engineered Function Structure Increases the Speed of Interpretation Without Decreasing Interpretability. Pruning rules specify the removal of auxiliary functions and interactions in a function model. When this specific set of functions is removed, the average interpretability does not significantly change. Although there is no increase in interpretability, there is also no reduction in interpretability caused by the removal of these functions. Therefore, for human interpretation, auxiliary functions and interactions do not add value to the model. Further, the time required to interpret pruned function structures is significantly lower than that of reverse-engineered functions structures, indicating that the auxiliary functions and interactions divert the interpreter's attention to less important elements in the model. Overall, pruned models are a more efficient representation of function since they are faster to interpret without a sacrifice in accuracy, so pruned models should be used when humans are reading function structures.

The results and conclusions of this study can be used to improve our understanding of and ability to model and use product functionality in engineering design. The following three applications of this study have been identified:

7.2.1 Model Communication. When designers use function models to communicate their ideas to other designers, such as in a design report, they should use the Pruned-Free abstraction level. Free language will provide context to those reading the model that will increase the speed and accuracy of their interpretations, reducing the potential for misinterpretation. Further, pruned function structures are more efficient in communication and do not increase the risk of misinterpretation by a reader. If a designer desires to communicate auxiliary functions or interactions, he or she can include these in a function structure without significantly reducing the ability of the receiver to interpret the model. However, the designer could instead use a separate, complementary model, such as an assembly diagram or a model of interactions, maintaining the efficiency of a pruned function structure while communicating the additional information captured in a reverse-engineered model.

7.2.2 Model Creation. When creating models in conceptual design, the use of free language and the exclusion of auxiliary functions and interactions from a function structure will support faster identification and increased understanding of critical product functionality. Therefore, the pruning rules can be used as guidelines for identifying the types of functions that should be identified first as a problem is decomposed. After a pruned function model is created, auxiliary functions and interactions can be added to the model if desired.

7.2.3 Information Archival. If functional information describing products is captured in a design repository and retrieved by human users, free language should be used in addition to a controlled vocabulary. In other words, authors of functional model should commit to a standard language for describing functionality, but add additional product solution specific "labels" to increase the knowledge content of the functional description. The advantage of a controlled vocabulary is increased computational reasoning on the design knowledge, but when the functional representation should include both the controlled language and free language to increase the human interpretability of the mode while not sacrificing computational aspects of the representation. The disadvantage of capturing both free language and controlled vocabulary descriptions of functional models is increased effort on model creation. A database should also have the ability to provide pruned models to a human user to further increase the ease of interpretation of models. If free language is captured and pruning rules are implemented within a database management system, all four levels of abstraction investigated in this research can be supported, each of which have different applications. Programmatically, this can be accomplished in several different ways including (1) developing external rule-based systems for translating between different level of abstraction, (2) tagging specific function verbs *pruneable* and developing standard queries to return functional models at the varying levels of abstraction, and (3) using views within relational database systems to generate different abstraction levels. The Pruned-Free level supports quick, accurate communication of functional descriptions between humans, while the RE-Free level supports a more complete but less efficient description of a product. In related research, it has been shown that the Pruned-FB level of abstraction supports design-by-analogy at the conceptual level [14], which is enabled by the use of the functional basis and conceptual-level functions. Therefore, it is hypothesized that the RE-FB level best supports computer-based reasoning in detailed design of mechanical devices.

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