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Verifying module heuristics for large scale products

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VERIFYING MODULE HEURISTICS FOR LARGE SCALE PRODUCTS

by

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Ming Leu

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This thesis has been prepared in the style utilized by the Design Engineering Technical Conferences and the Journal of Mechanical Design. Pages 1-21 have been submitted for publication in that conference and 24-46 will be submitted for publication in that journal. Appendices has been added for purposes normal to thesis/dissertation writing.

ABSTRACT

Decreasing time and costs is a major objective in many businesses today. Including modularity in the early design phases can effectively decrease time spent on and costs associated with a project. The task of identifying modules within a product early in the design process (when decisions are less expensive) is made less daunting by using the techniques of functional modeling and module heuristics. The two papers that form this thesis discuss the results of the efforts to verify the module heuristics on large products. Observations on needed modifications to the functional modeling technique and original module heuristics are reported along with an investigation of using potential risk statements to formulate modules.

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1. VALIDATING MODULE HEURISTICS ON LARGE SCALE PRODUCTS

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ABSTRACT

Decreasing time and costs is a major objective in many businesses today. Including modularity in the early design phases can effectively decrease time spent on and costs associated with a project. The task of identifying modules within a product early in the design process (when decisions are less expensive) is made less daunting by using the techniques of functional modeling and module heuristics. This paper discusses the results of the initial efforts to verify the module heuristics on large products. Observations on needed modifications to the functional modeling technique and original module heuristics are reported along with an investigation of using potential risk statements to formulate modules.

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1 INTRODUCTION

Product design today focuses heavily on being better, cheaper, and faster. That means beating rival companies in getting products to market. This is crucial in competition. If one company does not produce a product in time and gain the respective market share another company will [2]. If decisions can be made earlier in the design process, thus increasing the process' efficiency, time and money can be saved. McGrath estimates design inefficiency to cost between $5 billion and $10 billion a year [3].

One way to decrease production time and cost in a product family is to increase commonality [4]. Modularity is one of the suggestions made by Kota and Sethuraman to help increase commonality [5]. This has helped Volkswagen save $1.7 billion annually on development and production costs [6, 7]. When production costs and time are decreased, market share often increases. In 1987, Fuji introduced a single use camera known as the Quick Snap. Fuji already had a second model developed a year later when Kodak produced its first single use camera. By 1994, however, Kodak captured 70% of the market back from Fuji. Kodak successfully redesigned their single use camera base and produced three more models between 1989 and 1990. Common components amongst Kodak's single use cameras enabled Kodak to produce more models in a shorter amount of time. This allowed them to dominate the market [8]. Common components were used by Black and Decker as well. Across hundreds of Black and Decker's power tools in 1970, more than 30 different motors, 60 different motor housings, and dozens of unique operating controls and armatures existed. Production cost was reduced by 50% and market share was increased by 20% after a decision was made to share common parts and subsystems [9]. Taking modularity to more of an extreme, Boeing and Airbus create new aircraft using common wings, noses, and tail components. This allows the companies to generate aircraft of differing lengths and capacities relatively easily [10].

If modules play a key role in reducing production time and cost, then the identification of those modules is crucial. Using the technique of functional modeling and applying heuristics techniques such as the module heuristics [1] help identify modules early in the design process. The heuristics are easily and rapidly applied to smaller products, such as an electric toothbrush. The modules themselves are also more distinct and one can choose what the final modules should be without too much effort. When a large scale product is being designed, however, module identification can become overwhelming and messy. Billions of dollars could be saved every year if the module heuristics could be applied to large scale products more efficiently and clearly.

2 BACKGROUND

The state of the art in three thematic areas are reviewed as underlying theories and techniques for this research work. Specific functional modeling, risk analysis (based on product or system function) and modularity identification methods are highlighted in the following sub-sections that inspire the module validation activities.

2.1 Functional Modeling:

A functional model is a description of a product or process in terms of the elementary operations or functions that are required to transform its input flows of material, energy, or signal into desired output flows [11]. This type of model is a form-independent blueprint of a product that can be derived early in the conceptual design phase. Function-flow pairs make up a functional model. A flow is a material, energy, or signal that is used by or affects the product. A function is the operation the product performs on a flow or a set of flows to transform it from its input state to its output state.

Customer needs must be gathered before a functional model can be generated [1]. A black box model is generated next. This is an overall view of the product with its inputs and outputs expressed by a single function-flow pair. Function chains are created for each input and output in the black box model. These function chains are then combined to create the functional model of a product. All function-flow pairs are expressed in a common language, known as the functional basis [12, 13].

2.2 Risk in Early Design:

Risk is defined as the chance an undesirable event will occur and the consequences of all its possible outcomes [14]. Risk in Early Design (RED) was created as a tool to minimize project risks occurring in the conceptual design phase and that utilizes failure analysis to estimate project risk in the early design phase [11]. A computer-based version of RED was developed based on archived data containing largely NASA and other aerospace systems failure reports. This program performs mathematical calculations based on its archived data to report to the user unbiased consequence and likelihood rankings for each function-flow pair in any given functional model. A fever chart and extensive text document containing failures are the RED program's outputs.

2.3 Modules:

One must first have a thorough realization of what a module is to fully understand the module heuristics. Modules are defined as physical structures that have a one-to-one correspondence with functional structures by Ulrich and Tung [15]. Sosale et al. says modules are commonly described as groups of 'functionally' or 'structurally' independent components [16]. A module, according to Dictionary.com, is a separable component, frequently one that is interchangeable with others, for assembly into units of differing size, complexity, or function [17]. Foreshadowing the next section, a module identification method known as the module heuristics is based on functional modeling. Thus, we present the definition used in this paper for a module with its basis in functional modeling: a clustering of functions that as a group are solved by a component or tightly integrated set of components to perform tasks that are easily associated together.

2.4 Module Heuristics:

The module heuristics developed but Stone et al. in 2000 are a method of examination in which the designer uses a set of steps, empirical in nature, yet proven scientifically valid, to identify modules in a design problem [1]. They go on to define the phrase 'proven scientifically valid' as referring to a hypothesis, formulated after systematic, objective data collection that has successfully passed its empirical tests.

Groups of sub-functions related by flows were observed to form subsystems or modules of the device during the conceptual design phase of a large-scale maintenance device [1]. The module heuristics grew out of this simple observation and were broken down into three different possibilities a flow can experience: 1) a flow may pass through a product unchanged, 2) a flow may branch, forming independent function chains, or 3) a flow may be converted to another type. These different possibilities are now known as the dominant flow, branching flow, and conversion-transmission heuristics, respectively.

2.4.1 Dominant Flow Heuristic:

Concisely defined, the dominant flow heuristic is the set of sub-functions which a flow passes through, from entry to initiation of the flow in the system to exit from the system or conversion of the flow within the system [1]. This forms a module. A generic dominant flow module schematic can be seen in Figure 1.

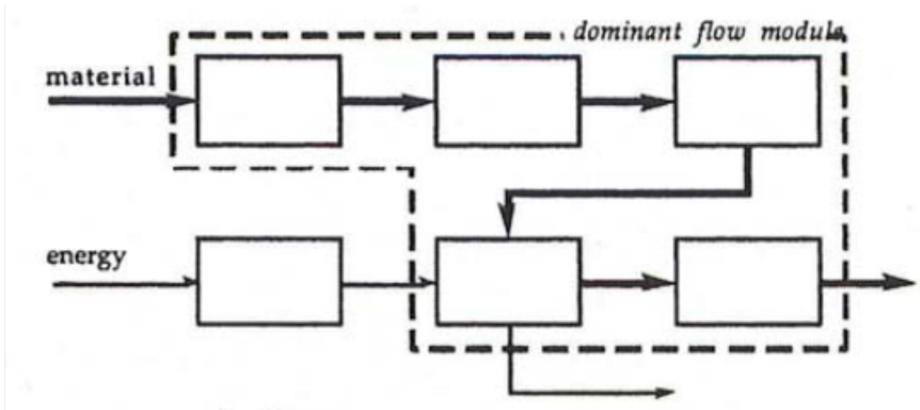

Figure 1. Generic Dominant Flow Module [1].

2.4.2 Branching Flow Heuristic:

The formal definition of the branching flow heuristic is the limbs of a parallel function chain constitute modules. Each of the modules interface with the remainder of the product through the flow at the branch point [1]. A generic branching flow module schematic can be seen in Figure 2.

2.4.3 Conversion-Transmission Heuristic:

Stated simply, the definition of the conversion-transmission heuristic is a conversion sub-function or a conversion-transmission pair or proper chain of sub-functions [1]. This forms a module. A generic conversion-transmission module schematic can be seen in Figure 3.

2.4.4 Application of Module Heuristics:

One must select which modules to implement once all three heuristics have been performed, because the modules identified from each heuristic often overlap. This requires some engineering judgment unfortunately. It is noted by Stone et al., however, that the more ways a module is identified (in terms of heuristics and flows), the more important it is to implement (since it must be associated with more customer needs) [1].

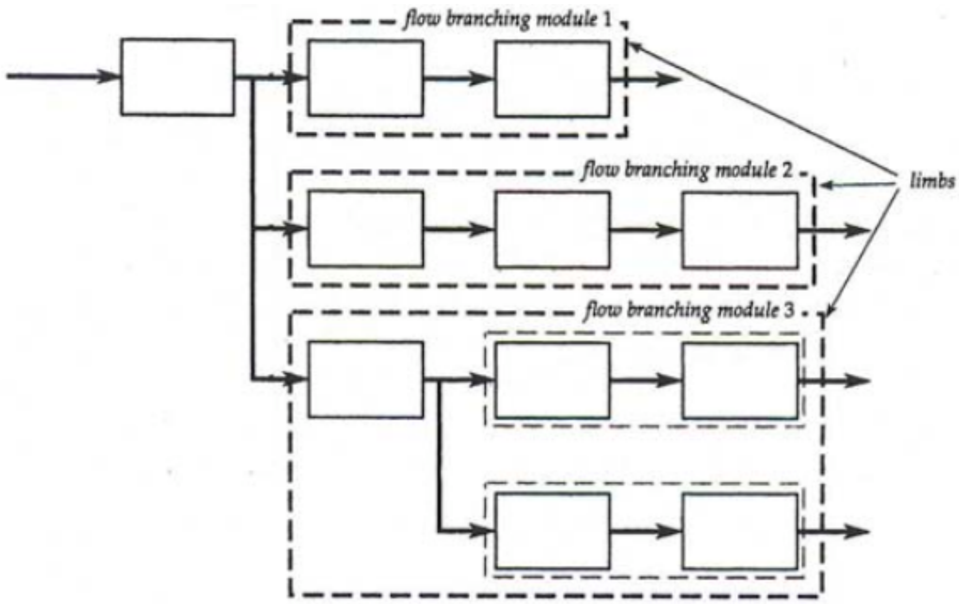

Figure 2. Generic Branching Flow Module [1].

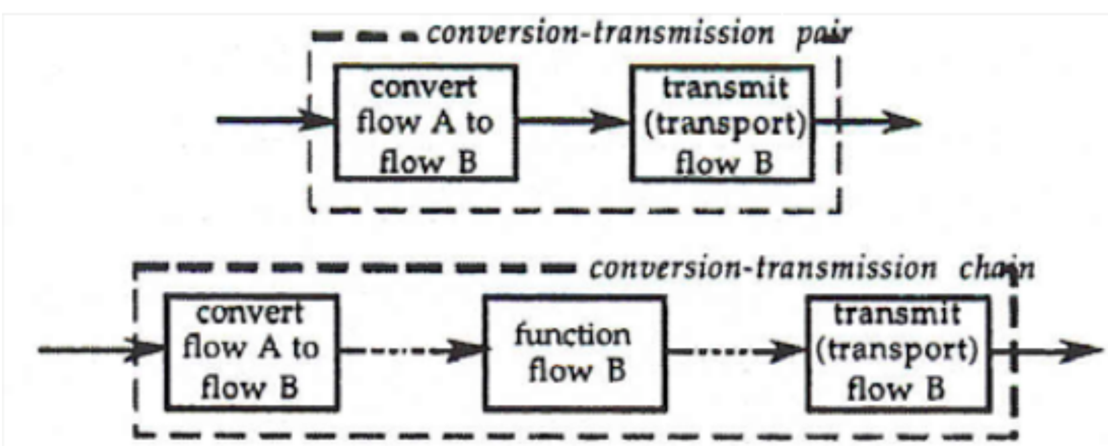

Figure 3. Generic Conversion-Transmission Modules [1].

3 RESEARCH APPROACH: VERIFY THE MODULE HEURISTICS ON LARGE SCALE PRODUCTS

The module heuristics were originally tested and verified on approximately 70 consumer products. Only one of these products was a large product (a lignite removal system for the power generation industry). It was assumed by Stone et al. that since the module heuristics worked for this single large product, they were likely applicable for all large products. In practice, however, the heuristic method quickly becomes overwhelming and confusing as the size of a system's functional model grows large (e.g., > 30 functions). It has since been hypothesized that the module heuristics will need to be modified for large products.

Many guidelines were made for this particular project in an attempt to keep subjectivity to a minimum and create a standard that could apply to all functional models. The guidelines are as follows:

1) the current module heuristics still apply;
2) at least two function-flow pairs are needed to constitute a module;
3) the dominant flow heuristic does not include branching or conversion function-flow pairs;
4) the branching flow heuristic consists of at least two function-flow pairs, one of which is the function-flow pair the flow is branching from;
5) the conversion-transmission heuristic starts one function-flow pair before conversion and ends one function-flow pair past conversion or at a transfer function-flow pair; and
6) all of these assumptions are universal to all functional models.

Guideline 1 was made because it is the main point of this study. Guideline 2 was made to support the other guidelines. Guideline 3 attempts to prevent the heuristics from overlapping. It is hypothesized the final modules will be easier to choose by having clearer divisions while applying the heuristics. Guideline 4 was made to prevent the branching heuristic from completely overlapping with the dominant flow heuristic. The modules include the function-flow pair the flow branches from to show how the branches are linked together and where the branches originated. This gets increasingly important the larger the functional model. Guideline 5 is different from the original way the conversion-transmission heuristic was applied because when a flow is converted it seems one would want to include not only what it is converted to, but also what it was converted from. Limiting the conversion-transmission heuristic also helps prevent it from overlapping too much with the other two heuristics. Guideline 6 just states all the previous guidelines apply to all functional models to keep the module heuristics universal. The module heuristics would not be nearly as useful if there were certain kinds of functional models they could not be applied to.

3.1 Product Scope of Functional Models:

Eleven functional models of “large” scale products were collected or generated for this study. The definition for “large” scale product for this study is a product that is described functionally with 30 or more functions at the secondary level of the Functional Basis [18]. While this is somewhat arbitrary, this is the approximate dividing line where products transition out of the small consumer product realm based on the author’s experience. Functional models of a Felt mountain bike, non-rigid blimp, car, combine, Kenmore clothes dryer, helicopter, HVAC system, Brother sewing machine, side-by-side

Whirlpool refrigerator, top-bottom Whirlpool refrigerator, and flat screen TV were used and their attributes are summarized in Table 1. The functional models were created by various authors and thus had a wide variety in modeling style. Figure 4 shows part of a functional model for the Felt mountain bike.

Table 1. Summary of Large Scale Products Investigated.

Product	Domain	# of sub-functions	# input/ output flows
Felt Mountain Bike	Consumer: Recreational	38	6 / 6
Combine	Agricultural	142	8 / 8
HVAC system	Consumer: Major Appliance	31	5 / 6
Helicopter	Transportation: Aerospace	66	4 / 9
Flat Screen TV	Consumer: Entertainment	34	4 / 5
Kenmore Clothes Dryer	Consumer: Household Appliance	32	4 / 7
Brother Sewing Machine	Consumer: Household Appliance	45	4 / 3
Top-Bottom Whirlpool Refrigerator	Consumer: Household Appliance	39	6 / 8
Side-by-Side Whirlpool Refrigerator	Consumer: Household Appliance	44	6 / 9
Non-rigid Blimp	Transportation: Aerospace	35	7 / 7
Car	Transportation: Automotive	261	27 / 17

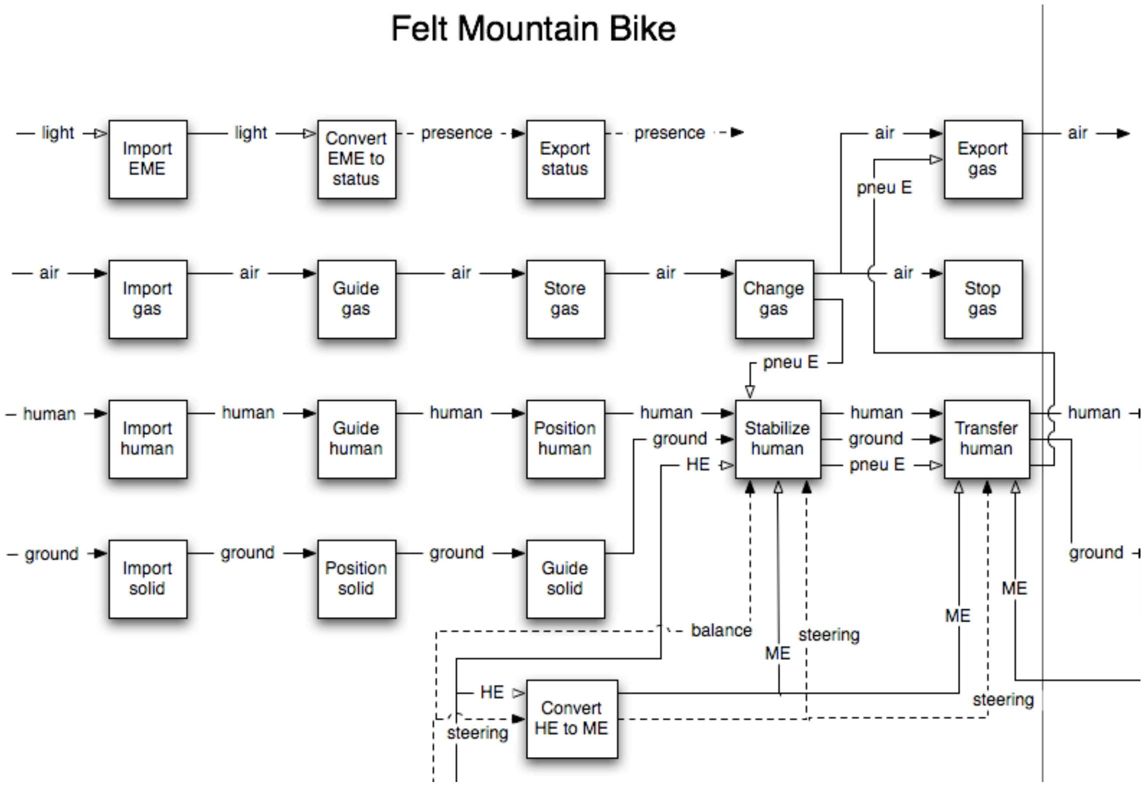

Figure 4. Part of the Mountain Bike Functional Model.

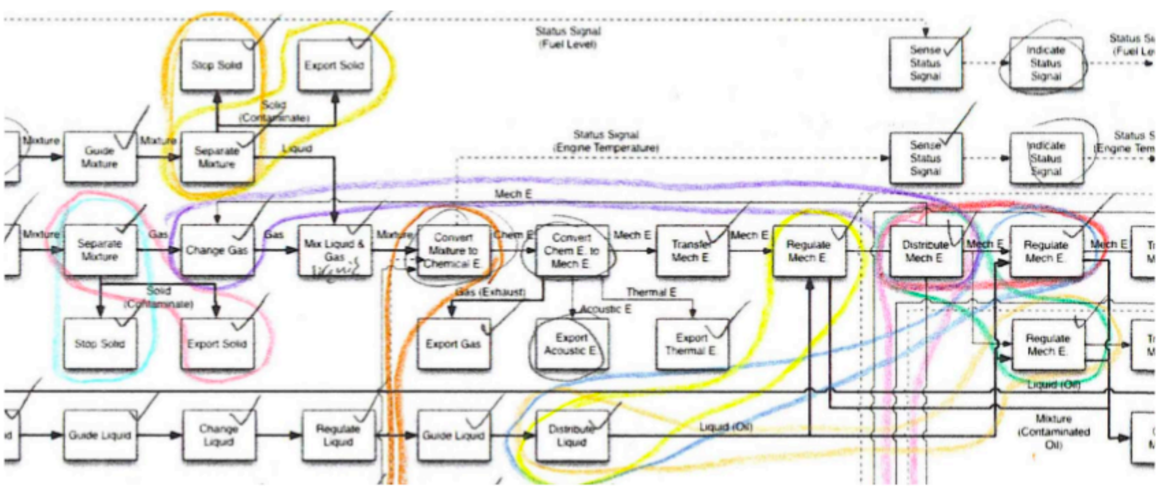

Figure 5. Part of the Application of the Branching Flow Heuristic on the Helicopter.

3.2 Performing Module Heuristics:

Copies were made of each functional model and the module heuristics were applied by hand. Color pencils were used to distinguish between different modules and each heuristic was applied to a fresh copy of the plain functional model for each product. A new copy of the functional model was used every time in an effort to not bias any of the heuristics and to decrease confusion. An example showing the branching flow heuristic applied to the helicopter functional model can be seen in Figure 5.

3.3 Aggregating the Module Heuristics:

Once all three module heuristics were applied to a product, they were aggregated to generate a final version of the modules of the product. The final modules were selected by engineering judgment. Every attempt was made to include as many functions in the functional model as reasonably possible. Figure 6 shows the final modules (denoted by the large boxes) of the flat screen TV.

3.4 Risk in Early Design Program:

In addition to the original three module heuristics, potential product risk was investigated as a predictor of product modularity. The RED method associates historical failure likelihood and consequence with product function. Since functional models are the starting point of the module identification method, it was hypothesized that clusters of similar failures or similar risk rankings could point to modules. That is, the functions that experience similar failures (or risk) may be solved by the same component or integrated set of components. Knowledge of the potential failures could then be used in the design analysis phase to dictate the appropriate types of failure prevention analyses to be performed by the designer.

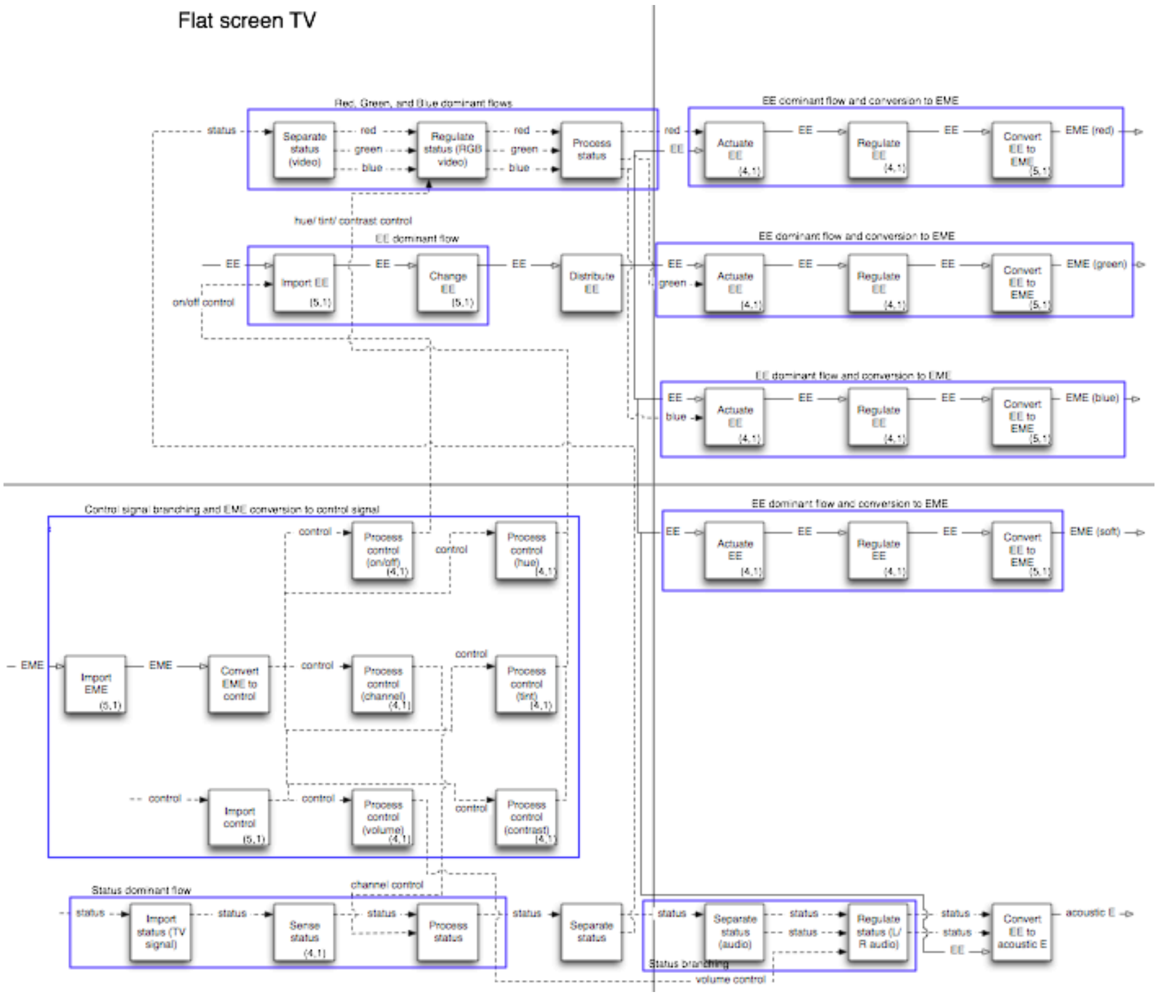

Figure 6. Final Modules of the Flat Screen TV.

The Risk in Early Design (RED) computer program was utilized to generate consequence and likelihood rankings for each function-flow pairing in five of the functional models. Using the RED program decreased subjectivity and generated good risk numbers in an efficient manner. The output of the program for the combine can be seen in Figure 7.

3.5 Incorporating Risk in Early Design Results:

A plethora of risks was generated by the RED program for each product. The consequence and likelihood rankings, and thus, overall risk level, that were the most severe for each function-flow pair were incorporated into each functional model. In the lower right-hand corner of each function-flow pair is where the consequence and likelihood rankings can be found. Color coding of the text in each function-flow block helped risk level identification. Figure 8 shows an example from the combine functional model.

	1	2	3	4	5
5	0	0	0	0	5
4	0	0	0	0	4
3	0	0	0	9	5
2	0	0	0	3	54
1	0	11	129	286	198

Figure 7. RED Output for the Combine.

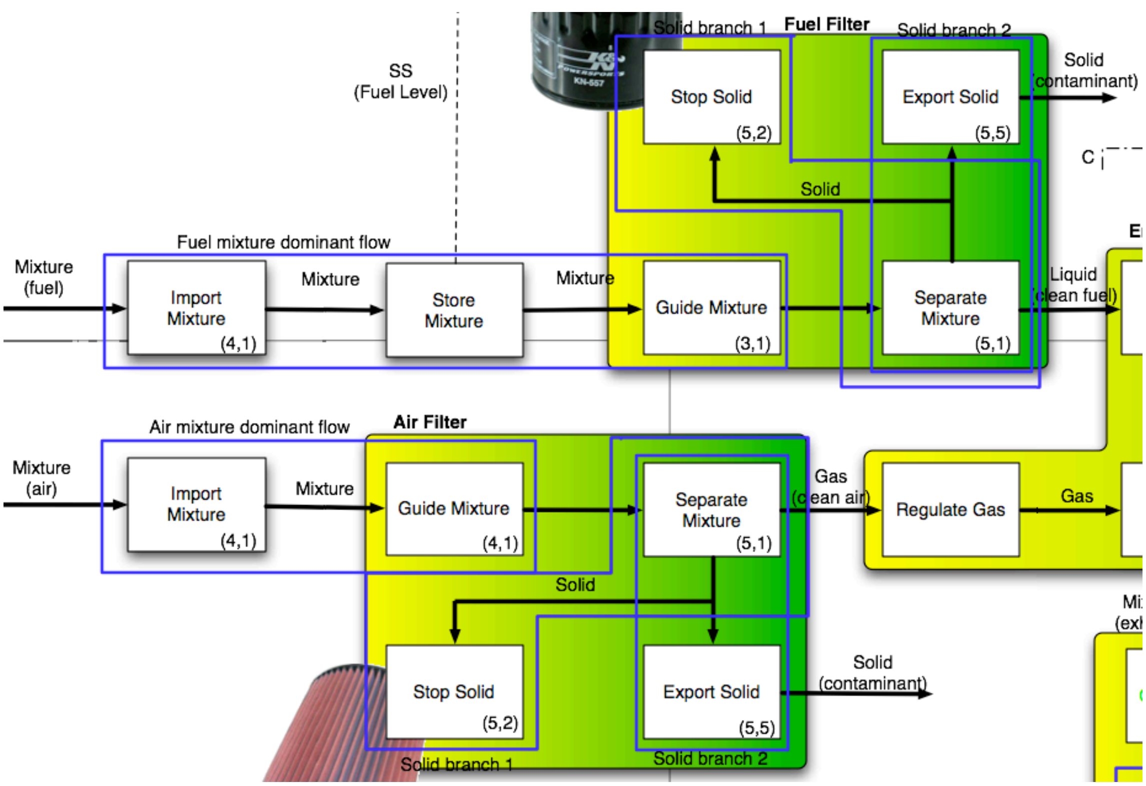

Figure 8. Snippet of Combine Functional Model with Risk.

4 OBSERVATIONS

4.1 Functional Models:

Using functional models generated at various points in time and by vastly different authors brought many problems to light. These problems make applying the module heuristics difficult. There were several functional models where some flows were not exported from the system or did not have their own flow-specific export function. This leaves the module heuristic applier wondering what is happening to that particular flow. All flows leaving a system should be exported. One functional model made applying the conversion-transmission and branching flow heuristics near impossible because the flows coming out of conversion functions branched at the same time they were converted. Not having a distribution function also made the functional model itself harder to understand and follow. Adding a distribution function after a conversion function would greatly help in applying the module heuristics.

4.2 Risk as a Module Heuristic:

Investigation of each product's functional model with modules and risks proceeded after all the functional models were color-coded. It appeared at the onset of incorporating the risk numbers into the functional models the higher risk functions would be at the beginnings and ends of the modules (termed a 'risk sandwich' and depicted in Figure 9). This was disproved the further the risk incorporation continued. It was also thought perhaps patterns such as 'sandwiches' would be blatantly evident. While cases of one level of risk surrounded another level of risk (creating a 'sandwich') existed, it was not commonplace (Figure 9).

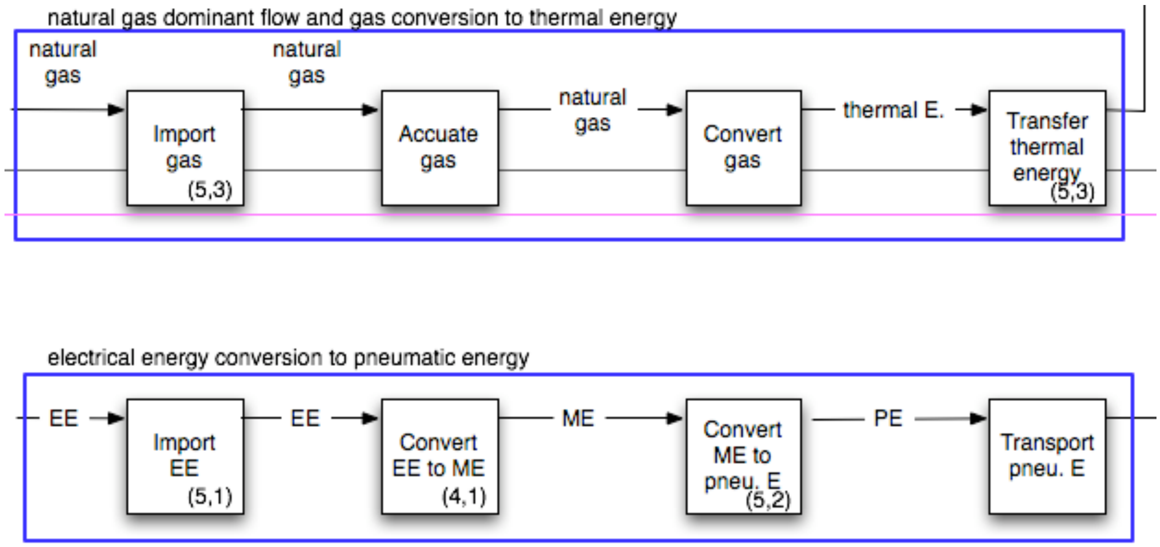

Figure 9. Pattern Examples from the HVAC Functional Model.

4.3 Module Heuristics:

Many interesting occurrences were noticed after having performed the original module heuristics on eleven extremely different, large scale products.

- Flow convergence: There is a heuristic for when flows branch, but there is no heuristic for when flows converge. An example of this would be the flow of the thread in the sewing machine functional model (Figure 10).
- Conversion-transmission: The larger a product is the more conversion functions it seems to have in series (Figure 11). This creates large conversion-transmission modules as the modules for each conversion function significantly overlap.
- Import-export: Import and export functions have a tendency to be left out in the final version of modules. All eleven functional models with the module heuristics applied had this problem.
- Change functions: There is a heuristic for conversion-transmission, but none for change. Change was used several times in the refrigerator functional models for

changing a flow such as ice to crushed ice. Like the import and export functions, change was often left out in the final version of modules.

- Super conversion-transmission: As seen in the Kenmore clothes dryer functional model, ‘super’ conversion-transmission modules emerge when distribute functions are not used and flows branch directly from a conversion function.
- Super branching modules: It might be better to create ‘super’ modules with the branching flow heuristic than several little modules that are all connected (Figure 12).
- Redundant dominant flow modules: Also from the Kenmore clothes dryer, sometimes one module may accommodate more than one flow. In this case, one dominant flow module covers two material flows and two energy flows. There is no rule for this.
- Flow loops: Looping flows can be seen but currently there is no way to accommodate this phenomenon heuristically. While it appears these looping flows are often signals (as in the altitude, pitch, yaw, and tilt in the blimp functional model) they are not limited to only signals. The refrigerator functional models contain looping flows of refrigerant, which is a material flow. An example of a looping flow can be seen in Figure 13.

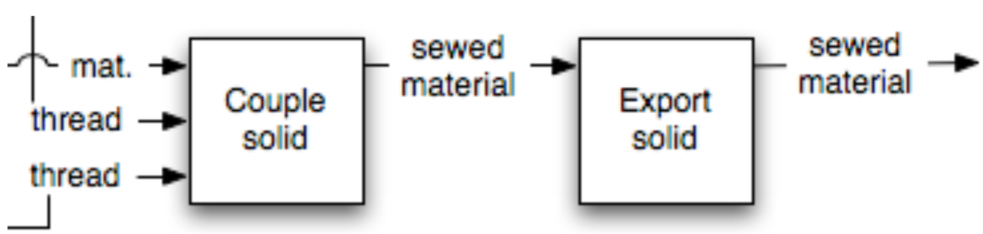

Figure 10. Thread Flow Convergence in Sewing Machine Functional Model.

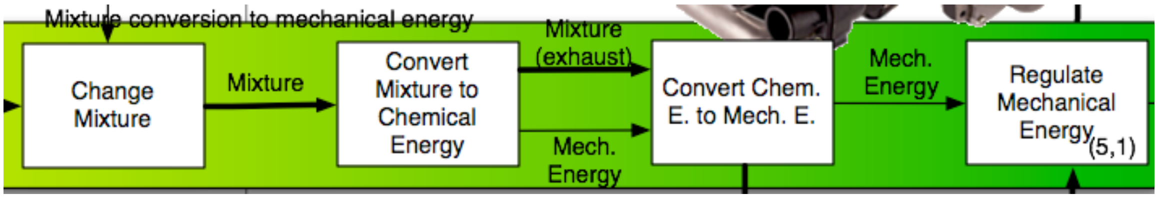

Figure 11. Convert Functions in Series in Combine Functional Model.

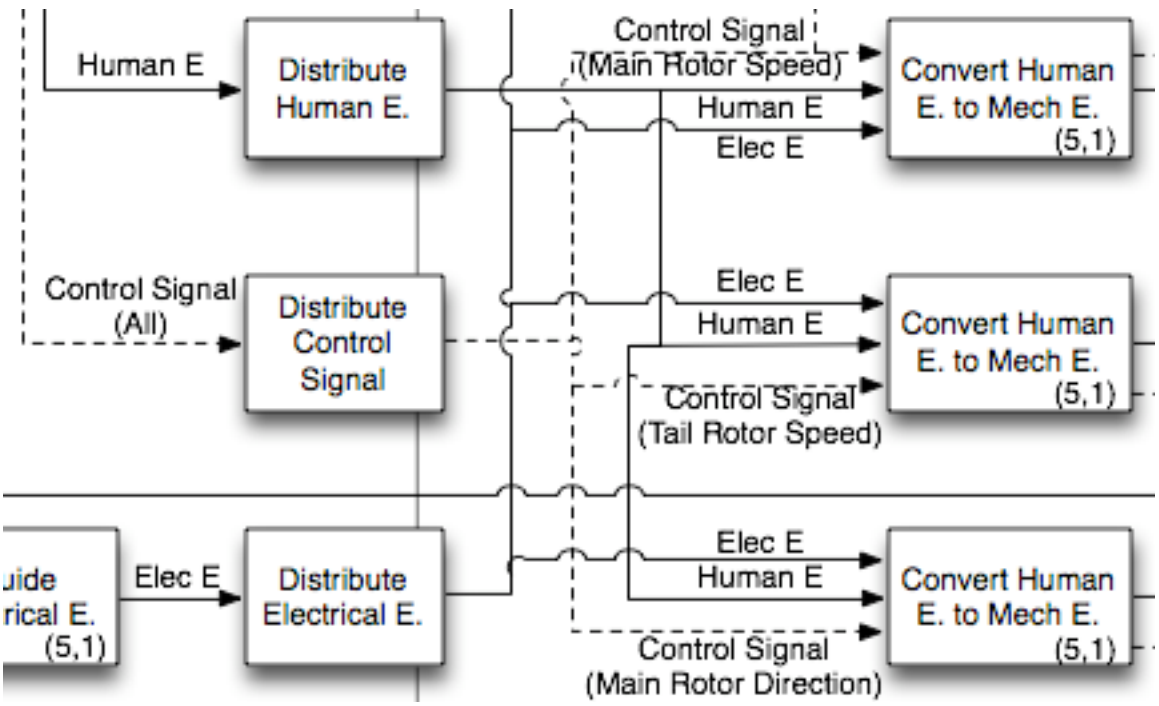

Figure 12. Super Branching Module from Helicopter Functional Model.

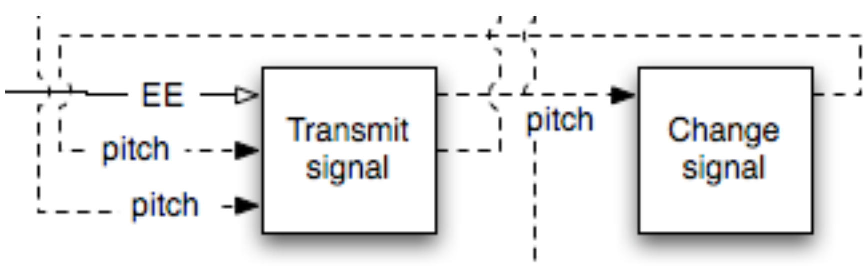

Figure 13. Looping Pitch Signal Flow from Blimp Functional Model.

5 VALIDATION AND CONCLUSIONS

Unfortunately, the risk and module heuristics could only be checked on the combine functional model. This product's functional model already had the actual modules incorporated into it when it was acquired. No obvious patterns were evident looking at the actual modules and risk color-coding. It should be noted, however, due to the lack of data generated by the RED program that patterns were difficult or near impossible to be identified. Only function-flow pairs that already exist in the RED program's database can be checked for consequence and likelihood rankings. This was severely debilitating in some cases, such as the HVAC functional model where half of the function-flow pairs could not have consequence and likelihood numbers associated with them. It was thus determined that risk could not be used as a module heuristic as it stands now. Perhaps in the future the results of a study similar to this will be different when the RED program is more complete.

Other possibilities for new heuristics do exist however. The looping flow and converging flow observations are currently the most intriguing. Looping flows would probably be considered a special case of the dominant flow heuristic. So far it has been seen in signal flows and refrigerant cycles. If converging flows were to be a heuristic, they could possibly be considered a counterpart to the branching flow heuristic. This needs more analysis. 'Super' modules need to be investigated further as well. This peculiarity is usually a result of the branching flow heuristic. 'Super' modules would decrease the number of modules in a product while still allowing the designer to break it down into smaller, more specialized modules. Not only is this advantageous from a module perspective, but it could aid the design process by making the project easier to split up amongst different design teams while still maintaining some cohesiveness.

It should be noted for all the module heuristics to be most useful, the functional models might have to adhere to certain format requirements. Such requirements would be nothing new. They would be more of a checklist of items to ensure the functional model is prepared for the application of the module heuristics.

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APPENDIX

FUNCTIONAL MODELS ON CD-ROM

1. INTRODUCTION

Included with this thesis is a CD-ROM, which contains the functional models for ten of the eleven products mentioned in this conference paper. One functional model is proprietary and cannot be published. Each functional model was developed using OmniGraffle for Macintosh. All documents have been prepared as Adobe Acrobat pdf files. An outline of the contents of the CD-ROM is as follows.

2. CONTENTS

Plain Functional Models:

Bike.PDF

Blimp.PDF

Combine.PDF

Dishwasher.PDF

Helicopter.PDF

HVAC.PDF

KenmoreDryer.PDF

SewingMachine.PDF

SideSideRefrigerator.PDF

TopBottomRefrigerator.PDF

TV.PDF

Functional Models with Original Module Heuristics:

BikeModules.PDF

BlimpModules.PDF

CombineModules.PDF

DishwasherModules.PDF

HelicopterModules.PDF

HVACModules.PDF

KenmoreDryerModules.PDF

SewingMachineModules.PDF

SideSideRefrigeratorModules.PDF

TopBottomRefrigeratorModules.PDF

TVModules.PDF

2. VERIFICATION OF MODULE HEURISTICS FOR LARGE PRODUCTS

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ABSTRACT

Decreasing time and costs is a major objective in many businesses today. Including modularity in the early design phases can effectively decrease time spent on and costs associated with a project. The task of identifying modules within a product early in the design process (when decisions are less expensive) is made less daunting by using the techniques of functional modeling and module heuristics. This paper discusses the results of the efforts to verify the module heuristics on large products. Observations on needed modifications to the functional modeling technique and original module heuristics are reported.

1 INTRODUCTION

Product design today focuses heavily on being better, cheaper, and faster. That means beating rival companies in getting products to market. This is crucial in competition. If one company does not produce a product in time and gain the respective market share another company will [2]. If decisions can be made earlier in the design process, thus increasing the process' efficiency, time and money can be saved. McGrath estimates design inefficiency to cost between $5 billion and $10 billion a year [3].

One way to decrease production time and cost in a product family is to increase commonality [4]. Modularity is one of the suggestions made by Kota and Sethuraman to help increase commonality [5]. This has helped Volkswagen save $1.7 billion annually on development and production costs [6, 7]. When production costs and time are decreased, market share often increases. In 1987, Fuji introduced a single use camera known as the Quick Snap. Fuji already had a second model developed a year later when Kodak produced its first single use camera. By 1994, however, Kodak captured 70% of the market back from Fuji. Kodak successfully redesigned their single use camera base and produced three more models between 1989 and 1990. Common components amongst Kodak's single use cameras enabled Kodak to produce more models in a shorter amount of time. This allowed them to dominate the market [8]. Common components were used by Black and Decker as well. Across hundreds of Black and Decker's power tools in 1970, more than 30 different motors, 60 different motor housings, and dozens of unique operating controls and armatures existed. Production cost was reduced by 50% and market share was increased by 20% after a decision was made to share common parts and subsystems [9]. Taking modularity to more of an extreme, Boeing and Airbus create new aircraft using common wings, noses, and tail components. This allows the companies to generate aircraft of differing lengths and capacities relatively easily [10].

If modules play a key role in reducing production time and cost, then the identification of those modules is crucial. Using the technique of functional modeling and applying heuristic techniques such as the module heuristics [1] help identify modules early in the design process. The heuristics are easily and rapidly applied to smaller products, such as an electric toothbrush. The modules themselves are also more distinct and one can choose what the final modules should be without too much effort. When a large scale product is being designed, however, module identification can become overwhelming and messy. Potentially billions of dollars could be saved every year if the module heuristics could be applied to large scale products more efficiently and clearly.

2 BACKGROUND

The state of the art in three thematic areas are reviewed as underlying theories and techniques for this research work. Specific functional modeling and modularity identification methods are highlighted in the following sub-sections that inspire the module validation activities.

2.1 Functional Modeling:

A functional model is a description of a product or process in terms of the elementary operations or functions that are required to transform its input flows of material, energy, or signal into desired output flows [11]. This type of model is a form-independent blueprint of a product that can be derived early in the conceptual design phase. Function-flow pairs make up a functional model. A flow is a material, energy, or signal that is used by or affects the product. A function is the operation the product performs on a flow or a set of flows to transform it from its input state to its output state.

Customer needs must be gathered before a functional model can be generated [1]. A black box model is generated next. This is an overall view of the product with its inputs and outputs expressed by a single function-flow pair. Function chains are created for each input and output in the black box model. These function chains are then combined to create the functional model of a product. All function-flow pairs are expressed in a common language, known as the functional basis [12, 13].

2.2 Modules:

One must first have a thorough realization of what a module is to fully understand the module heuristics. Modules are defined as physical structures that have a one-to-one correspondence with functional structures by Ulrich and Tung [15]. Sosale et al. says modules are commonly described as groups of ‘functionally’ or ‘structurally’ independent components [16]. A module, according to Dictionary.com, is a separable component, frequently one that is interchangeable with others, for assembly into units of differing size, complexity, or function [17]. Foreshadowing the next section, a module identification method known as the module heuristics is based on functional modeling. Thus, we present the definition used in this paper for a module with its basis in functional modeling: a clustering of functions that as a group are solved by a component or tightly integrated set of components to perform tasks that are easily associated together.

2.3 Module Heuristics:

The module heuristics developed but Stone et al. in 2000 are a method of examination in which the designer uses a set of steps, empirical in nature, yet proven scientifically valid, to identify modules in a design problem [1]. They go on to define the phrase ‘proven scientifically valid’ as referring to a hypothesis, formulated after systematic, objective data collection that has successfully passed its empirical tests.

Groups of sub-functions related by flows were observed to form subsystems or modules of the device during the conceptual design phase of a large-scale maintenance device [1]. The module heuristics grew out of this simple observation and were broken down into three different possibilities a flow can experience: 1) a flow may pass through a product unchanged, 2) a flow may branch, forming independent function chains, or 3) a flow may be converted to another type. These different possibilities are now known as the dominant flow, branching flow, and conversion-transmission heuristics, respectively.

2.3.1 Dominant Flow Heuristic:

Concisely defined, the dominant flow heuristic is the set of sub-functions which a flow passes through, from entry to initiation of the flow in the system to exit from the system or conversion of the flow within the system [1]. This forms a module. A generic dominant flow module schematic can be seen in Figure 1.

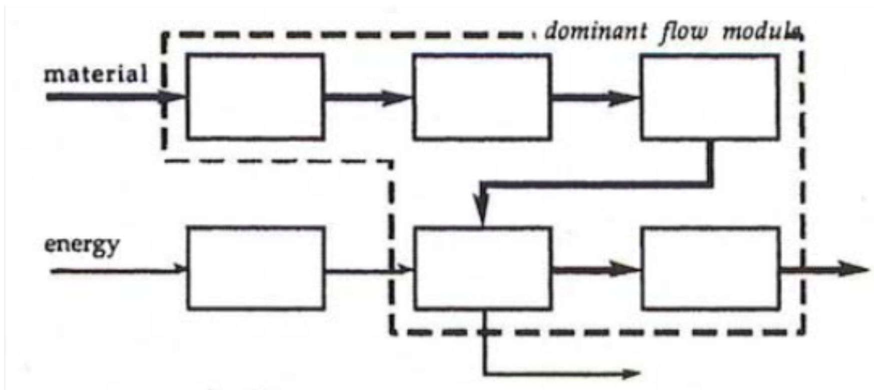

Figure 1. Generic Dominant Flow Module [1].

2.3.2 Branching Flow Heuristic:

The formal definition of the branching flow heuristic is the limbs of a parallel function chain constitute modules. Each of the modules interface with the remainder of the product through the flow at the branch point [1]. A generic branching flow module schematic can be seen in Figure 2.

2.3.3 Conversion-Transmission Heuristic:

Stated simply, the definition of the conversion-transmission heuristic is a conversion sub-function or a conversion-transmission pair or proper chain of sub-functions [1]. This forms a module. A generic conversion-transmission module schematic can be seen in Figure 3.

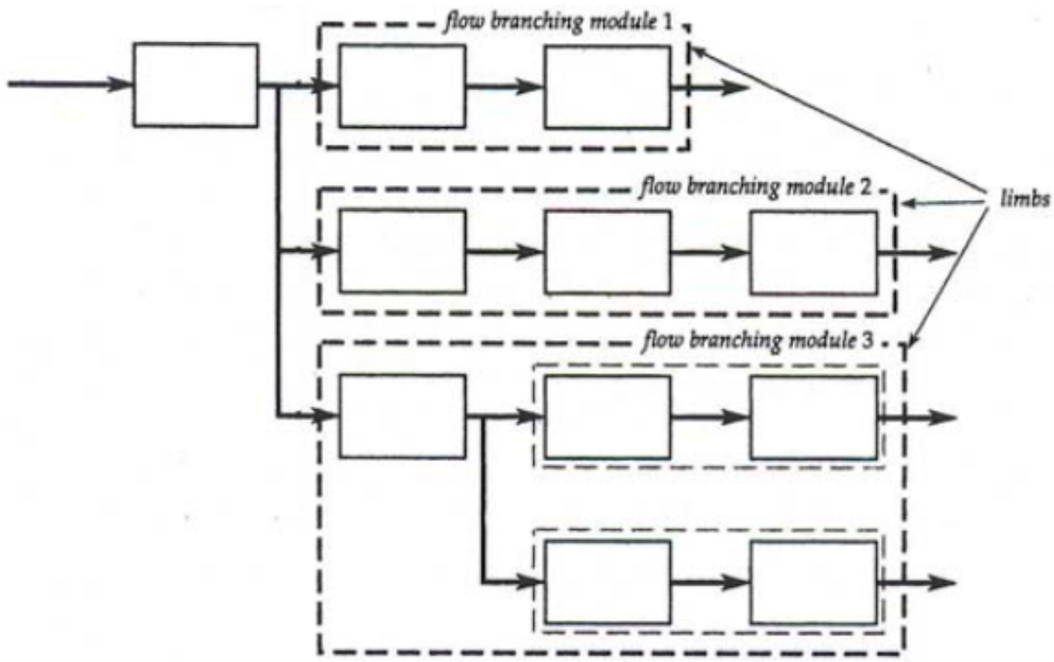

Figure 2. Generic Branching Flow Module [1].

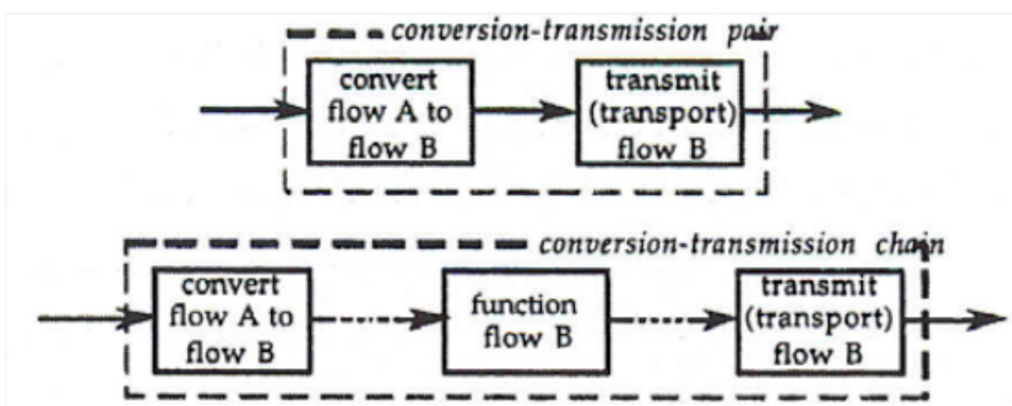

Figure 3. Generic Conversion-Transmission Modules [1].

2.3.4 Application of Module Heuristics:

One must select which modules to implement once all three heuristics have been performed, because the modules identified from each heuristic often overlap. This requires some engineering judgment unfortunately. It is noted by Stone et al., however, that the more ways a module is identified (in terms of heuristics and flows), the more important it is to implement (since it must be associated with more customer needs) [1].

3 RESEARCH APPROACH: VERIFY THE MODULE HEURISTICS ON LARGE SCALE PRODUCTS

The module heuristics were originally tested and verified on approximately 70 consumer products. Only one of these products was a large product (a lignite removal system for the power generation industry). It was assumed by Stone et al. that since the module heuristics worked for this single large product, they were likely applicable for all large products. In practice, however, the heuristic method quickly becomes overwhelming and confusing as the size of a system's functional model grows large (e.g., > 30 functions). It has since been hypothesized that the module heuristics will need to be modified for large products.

Many guidelines were made for this particular project in an attempt to keep subjectivity to a minimum and create a standard that could apply to all functional models. The guidelines are as follows:

1) the current module heuristics still apply;
2) at least two function-flow pairs are needed to constitute a module;
3) the dominant flow heuristic does not include branching or conversion function-flow pairs;
4) the branching flow heuristic consists of at least two function-flow pairs, one of which is the function-flow pair the flow is branching from;
5) the conversion-transmission heuristic starts one function-flow pair before conversion and ends one function-flow pair past conversion or at a transfer function-flow pair; and

6) all of these assumptions are universal to all functional models.

Guideline 1 was made because it is the main point of this study. Guideline 2 was made to support the other guidelines. Guideline 3 attempts to prevent the heuristics from overlapping. It is hypothesized the final modules will be easier to choose by having clearer divisions while applying the heuristics. Guideline 4 was made to prevent the branching heuristic from completely overlapping with the dominant flow heuristic. The modules include the function-flow pair the flow branches from to show how the branches are linked together and where the branches originated. This gets increasingly important the larger the functional model. Guideline 5 is different from the original way the conversion-transmission heuristic was applied because when a flow is converted it seems one would want to include not only what it is converted to, but also what it was converted from. Limiting the conversion-transmission heuristic also helps prevent it from overlapping too much with the other two heuristics. Guideline 6 just states all the previous guidelines apply to all functional models to keep the module heuristics universal. If there were certain kinds of functional models the module heuristics could not be applied to they would not be nearly as useful.

3.1 Product Scope of Functional Models:

Fourteen functional models of "large" scale products were collected or generated for this study. The definition for "large" scale product for this study is a product that is described functionally with 30 or more functions at the secondary level of the Functional Basis [18]. While this is somewhat arbitrary, this is the approximate dividing line where products transition out of the small consumer product realm based on the author's experience. Functional models of a Felt mountain bike, non-rigid blimp, car, combine, Kenmore clothes dryer, helicopter, HVAC system, hydropower plant, Brother sewing machine, side-by-side Whirlpool refrigerator, top-bottom Whirlpool refrigerator, tunnel boring machine (TBM), flat screen TV, and Zamboni were used and their attributes are summarized in Table 1. The functional models were created by various authors and thus had a wide variety in modeling style. Figure 4 shows part of a functional model for the Felt mountain bike.

3.2 Performing Module Heuristics:

Copies were made of each functional model and the module heuristics were applied by hand. Color pencils were used to distinguish between different modules and each heuristic was applied to a fresh copy of the plain functional model for each product. A new copy of the functional model was used every time in an effort to not bias any of the heuristics and to decrease confusion. An example showing the branching flow heuristic applied to the helicopter functional model can be seen in Figure 5.

3.3 Aggregating the Module Heuristics:

Once all three module heuristics were applied to a product, they were aggregated to generate a final version of the modules of the product. The final modules were selected by engineering judgment. Every attempt was made to include as many functions in the functional model as reasonably possible. Figure 6 shows the final modules (denoted by the large boxes) of the flat screen TV.

Table 1. Summary of Large Scale Products Investigated.

Product	Domain	# of sub-functions	# input flows	# output flows
Felt Mountain Bike	Consumer: Recreational	38	6	6
Non-rigid Blimp	Transportation: Aerospace	35	7	7
Car	Transportation: Automotive	261	27	17
Combine	Agricultural	142	8	8
Kenmore Clothes Dryer	Consumer: Household Appliance	32	4	7
Helicopter	Transportation: Aerospace	66	4	9
HVAC system	Consumer: Major Appliance	31	5	6
Hydropower plant	Industrial: Power Generation	49	4	8
Brother Sewing Machine	Consumer: Household Appliance	45	4	3
Side-by-Side Whirlpool Refrigerator	Consumer: Household Appliance	44	6	9
Top-Bottom Whirlpool Refrigerator	Consumer: Household Appliance	39	6	8
Tunnel Boring Machine	Industrial: Construction Equipment	495	24	67
Flat Screen TV	Consumer: Entertainment	34	4	5
Zamboni	Industrial: Maintenance Equipment	70	6	7

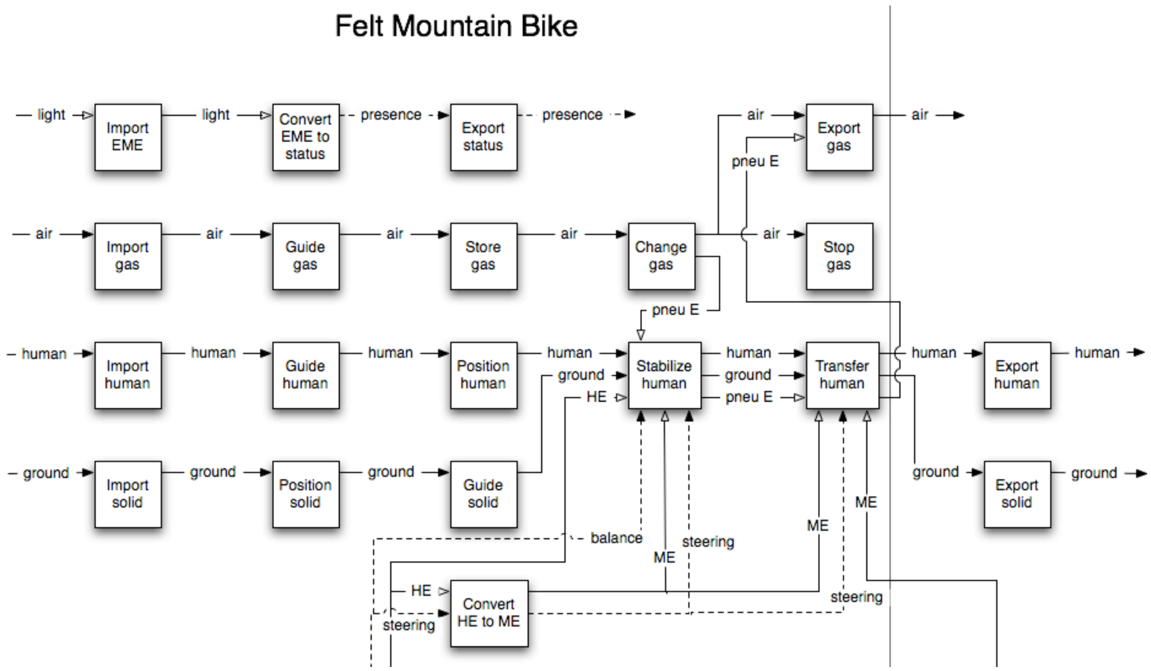

Figure 4. Part of the Mountain Bike Functional Model.

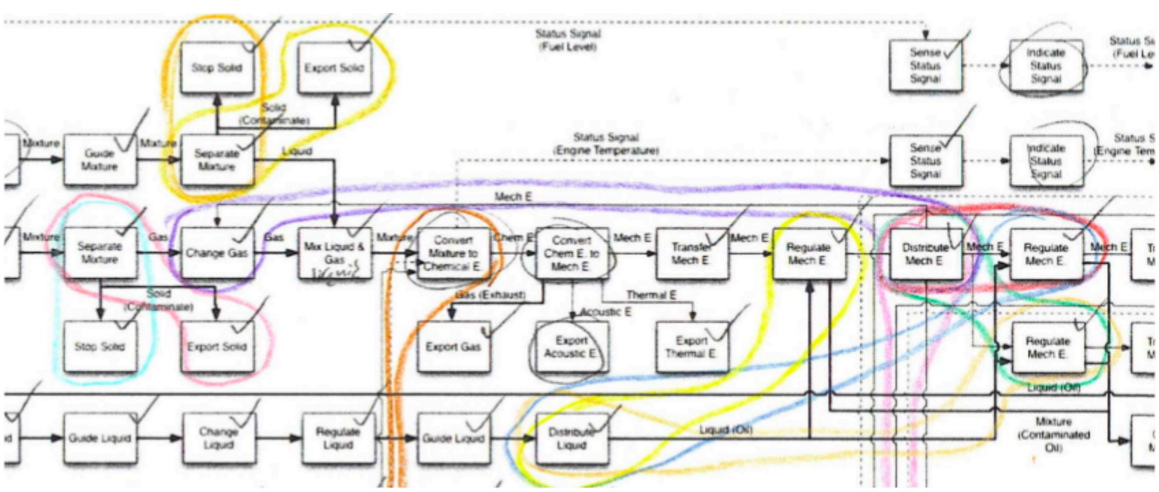

Figure 5. Part of the Application of the Branching Flow Heuristic on the Helicopter.

4 OBSERVATIONS

Observations and theories were made after the original module heuristics had been applied to all the functional models. A second pass through the functional models validated these observations and theories.

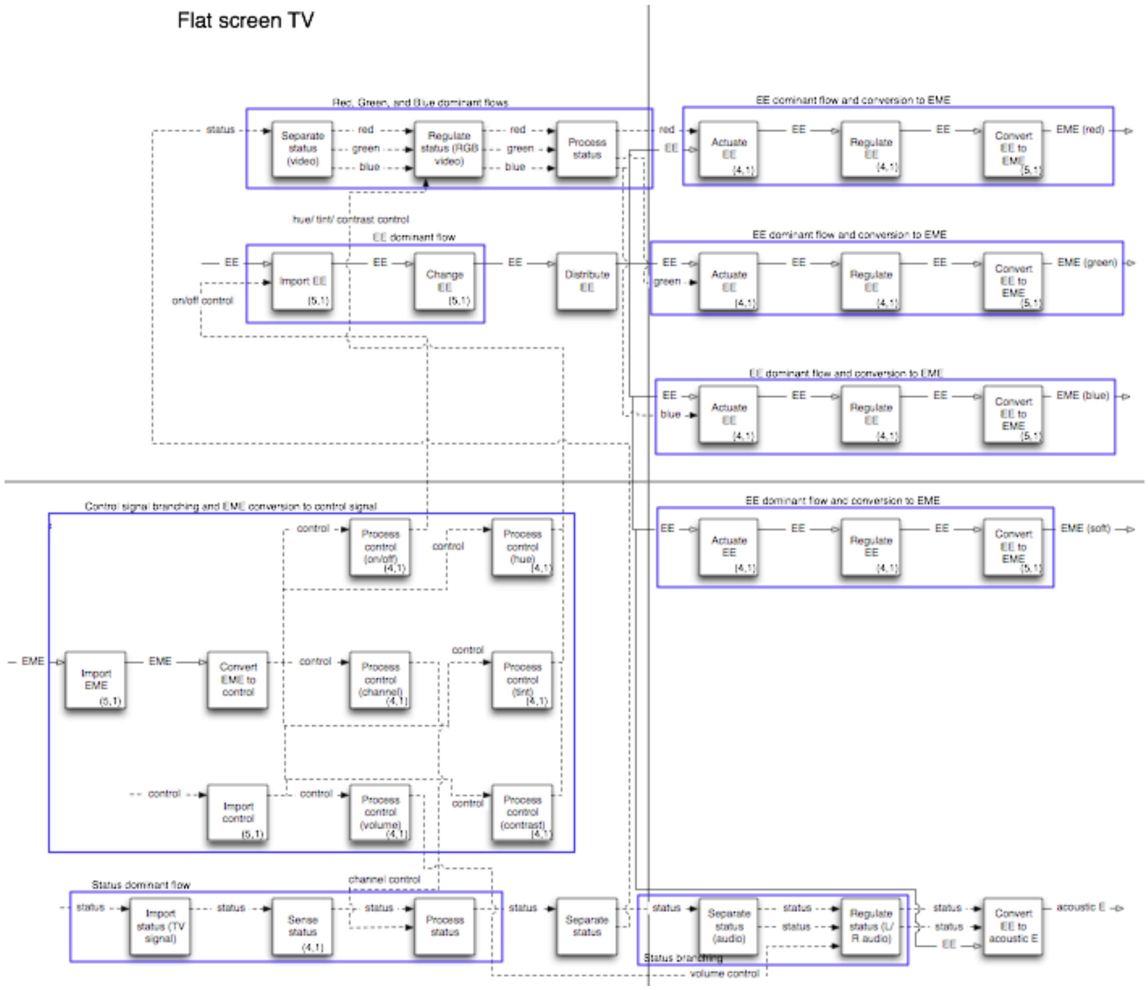

Figure 6. Final Modules of the Flat Screen TV.

4.1 Functional Models:

Using functional models generated at various points in time and by vastly different authors brought many problems to light. These problems make applying the module heuristics difficult. There were several functional models where some flows were not exported from the system or did not have their own flow-specific export function. This leaves the module heuristic applier wondering what is happening to that particular flow. All flows leaving a system should be exported. One functional model made applying the conversion-transmission and branching flow heuristics near impossible because the flows coming out of conversion functions branched at the same time they were converted. Not having a distribution function also made the functional model itself harder to understand and follow.

4.2 Module Heuristics:

Many interesting occurrences were noticed after having performed the original module heuristics on fourteen extremely different, large scale products.

- Flow convergence: There is a heuristic for when flows branch, but there is no heuristic for when flows converge. An example of this would be the flow of the thread in the sewing machine functional model (Figure 7).
- Conversion-transmission: The larger a product is the more conversion functions it seems to have in series (Figure 8). This creates large conversion-transmission modules as the modules for each conversion function significantly overlap.

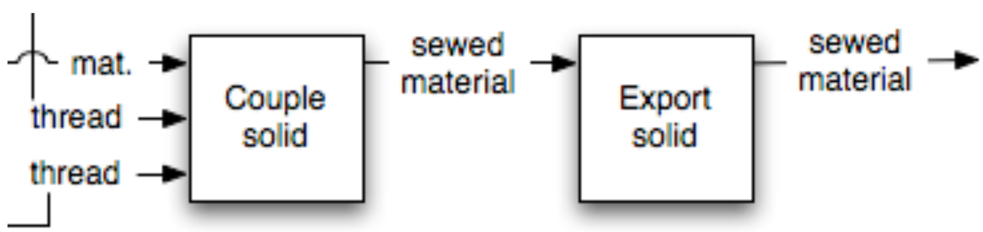

Figure 7. Thread Flow Convergence in Sewing Machine Functional Model.

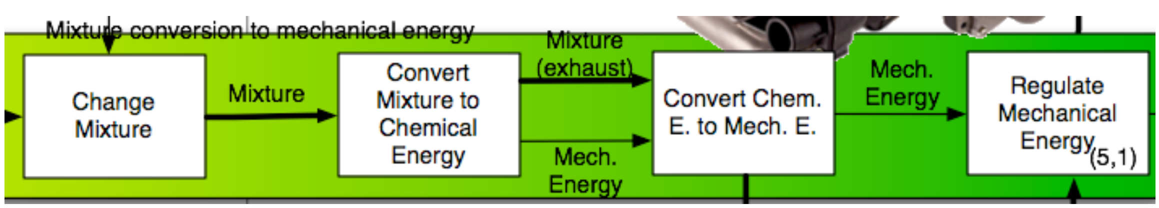

Figure 8. Convert Functions in Series in Combine Functional Model.

- Import-export: Import and export functions have a tendency to be left out in the final version of modules. All eleven functional models with the module heuristics applied had this problem.

- Change functions: There is a heuristic for conversion-transmission, but none for change. Change was used several times in the refrigerator functional models for changing a flow such as ice to crushed ice. Like the import and export functions, change was often left out in the final version of modules.
- Super conversion-transmission: As seen in the Kenmore clothes dryer functional model, 'super' conversion-transmission modules emerge when distribute functions are not used and flows branch directly from a conversion function.
- Super branching modules: It might be better to create 'super' modules with the branching flow heuristic than several little modules that are all connected (Figure 9).

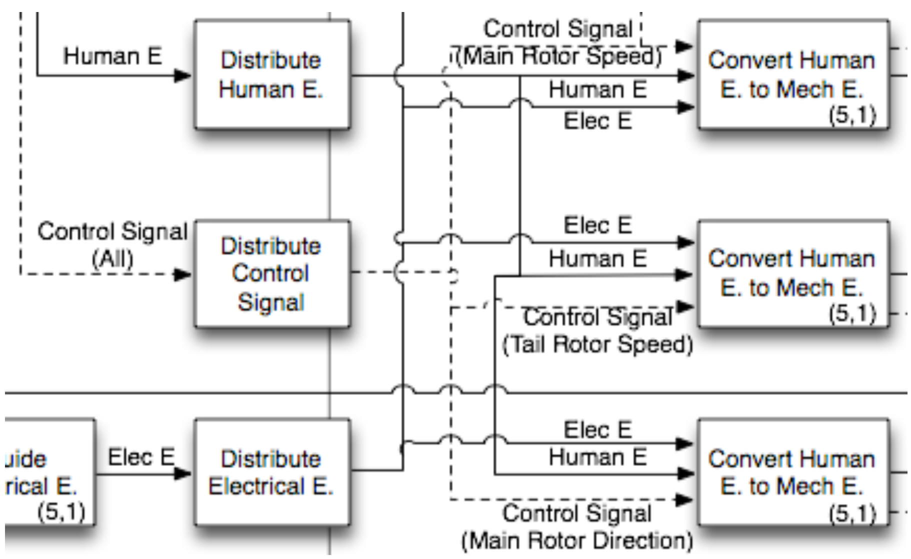

Figure 9. Super Branching Module from Helicopter Functional Model.

- Redundant dominant flow modules: Also from the Kenmore clothes dryer, sometimes one module may accommodate more than one flow. In this case, one dominant flow module covers two material flows and two energy flows. There is no rule for this.
- Flow loops: Looping flows can be seen but currently there is no way to accommodate this phenomenon heuristically. While it appears these looping flows are often signals

(as in the altitude, pitch, yaw, and tilt in the blimp functional model) they are not limited to only signals. The refrigerator functional models contain looping flows of refrigerant, which is a material flow. An example of a looping flow can be seen in Figure 10.

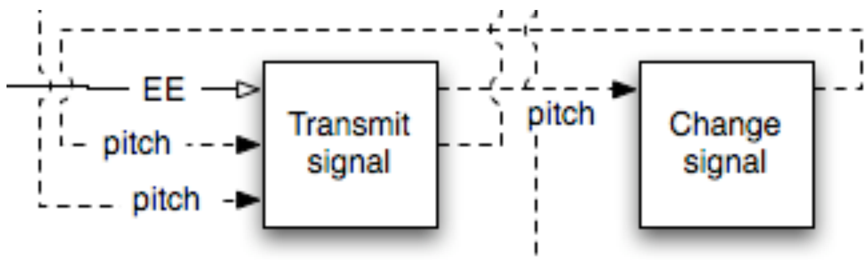

Figure 10. Looping Pitch Signal Flow from Blimp Functional Model.

These observations were all considered in more detail during a second pass over the functional models with the original module heuristics applied. The following are the outcomes.

- Flow convergence: While it exists, it does not seem to have that large of an impact on functional models and would complicate the module heuristics, especially if every flow had its own export function.
- Conversion-transmission: Since conversion modules do have a tendency to overlap in large products, how the heuristic is applied can easily be changed to accommodate conversion functions in series. These have become known as 'super conversion modules' (Figure 11) and decrease confusion and the number of functions not in a module.

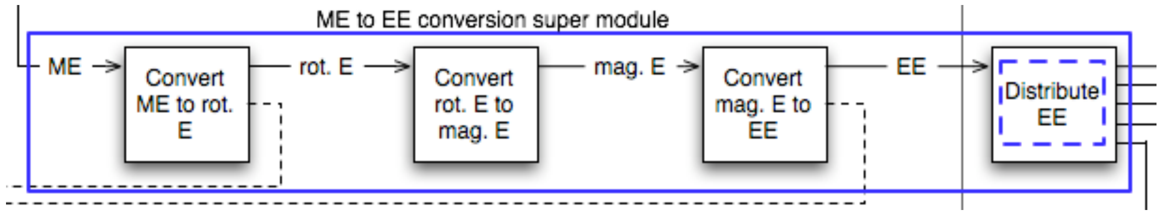

Figure 11. Conversion Super Module and Key Function from Hydropower Plant Functional Model.

- Import-export: After the module heuristics were altered, some import and export functions were still not in modules. Several could be incorporated into modules, however.
- Change functions: In looking closer at how the change function was used, it was noted that many authors used it incorrectly or could have used a different function to perform the same task. The problems generated by this function in regards to the module heuristics depend greatly on how the functional model author chose to use it. Thus, the change function was left alone.
- Super branching modules: While these are called ‘super branching modules’, the heuristic application method is all that was altered. Instead of having several individual modules overlapping at the same function, they are combined to create one large module. This ‘super branching module’ (Figure 12) can easily be broken down later into smaller, more individual branches if necessary.
- Redundant dominant flow modules: Having multiple modules including the same functions is redundant and unnecessary. Such modules are combined and have become known as ‘super dominant flow modules’ (Figure 13). Now one module simply accommodates more than one flow and the flows can be of various types.

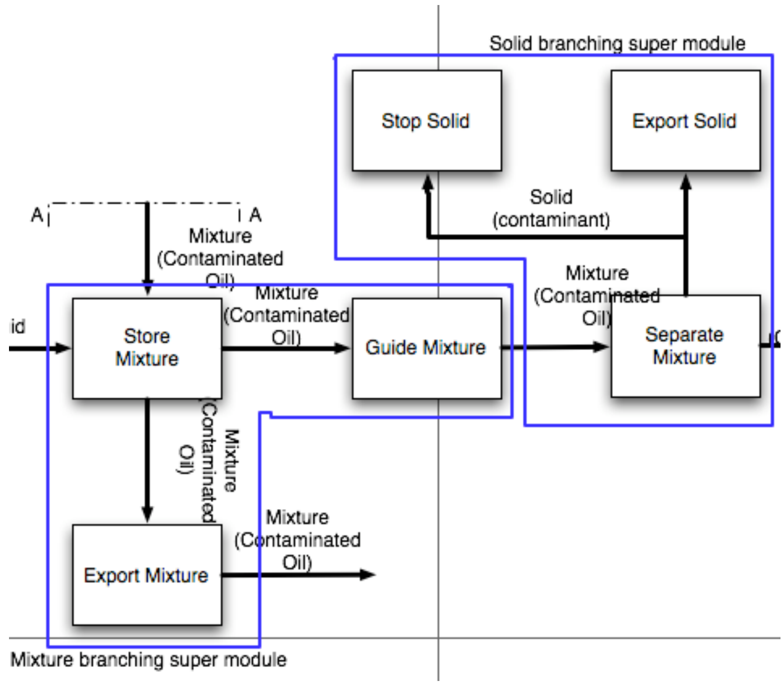

Figure 12. Branching Super Module from Combine Functional Model.

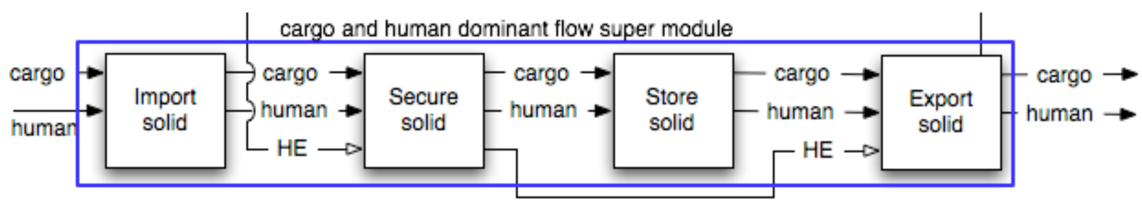

Figure 13. Dominant Flow Super Module from Blimp Functional Model.

- Flow loops: This is a new case of the dominant flow heuristic. A ‘loop module’ (Figure 14) can contain just one flow and a single loop or multiple flows with multiple loops. These loops seem to appear most often with functions related to a sensor component. They are certainly not limited to such cases though.

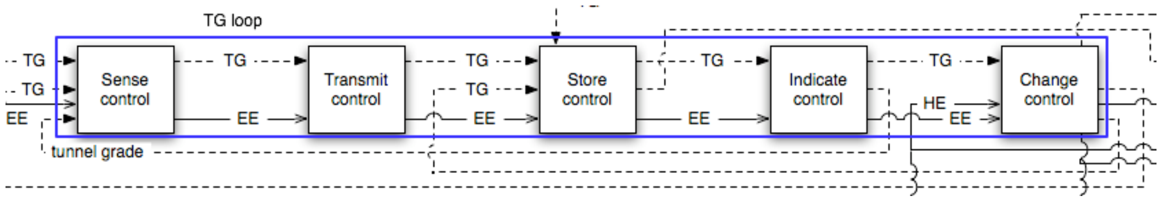

Figure 14. Loop Module from Tunnel Boring Machine Functional Model.

- Conversion-transmission and other heuristics: It was observed conversion modules were often directly tied to branching modules and they could not be separated. In such cases the two heuristics were combined to generate ‘branching-conversion super modules’ (Figure 15). These can take the form of the branching coming first and then the conversion, or the conversion and then branching. Both patterns were prevalent. Conversion modules could also be extended in several cases to include a nearby function that was not in a module to combine what would have been overlapping dominant flow and conversion-transmission modules. This is called a ‘dominant flow conversion super module’ (Figure 16) and helps include import and export functions that often get left out of modules. The dominant flow part of the module can occur before or after the conversion.
- Key functions: While it seems the original branching heuristic disappears in large products, it was noticed to still be somewhat helpful. The branching heuristic easily identifies functions that affect several different modules. These ‘key functions’ are typically distribute functions and while they do not have any direct effect on the module heuristics they could be an extremely helpful by-product. ‘Key functions’ (Figure 14, denoted by dashed box) could help in product design and architecture and could influence the final selection of modules for a product after the module heuristics have been performed.

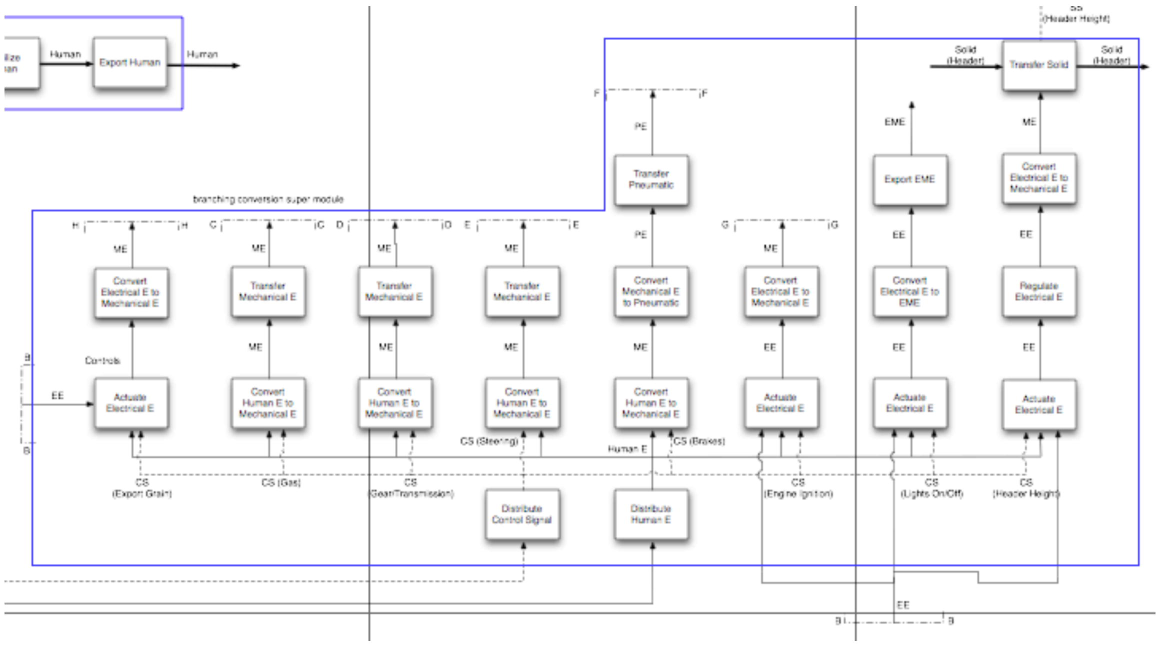

Figure 15. Branching Conversion Super Module from Combine Functional Model.

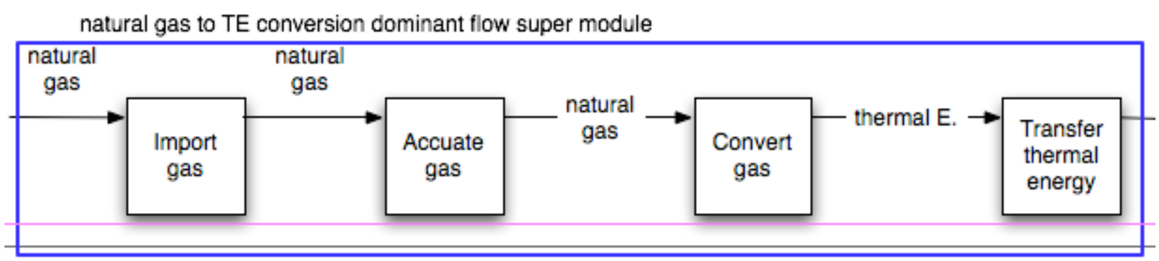

Figure 16. Dominant Flow Conversion Super Module from HVAC Functional Model.

5 VALIDATION

These observations and theories are supported by data presented in Appendix A. On average, the number of modules for each product was reduced by 17% after the new module heuristics were applied. There were four (out of fourteen) cases where the number of modules increased, but this may not be a bad thing. In many cases several modules were labeled 'electric energy dominant flow,' but after the new module heuristic were applied, these modules got broken up into more specific modules. It depends on the level of modularity and definition needed in the functional model. The number of functions not in modules was reduced on average by 22% after the application of the new module heuristics. Ideally, all functions would be in a module. ‘Key functions’ were identified in 86% of the functional models. ‘Loop modules’ were present in 50% of the functional models. The TBM functional model contained 52 loop modules. Ninety-three percent of functional models contained at least one ‘super’ module. ‘Branching super modules’ occurred in 57% of functional models, ‘conversion super modules’ occurred in 50% of functional models, and ‘dominant flow super modules’ occurred in 36% of functional models. ‘Branching-conversion super modules’ occurred in 64% of the functional models and ‘dominant flow conversion super modules’ occurred in 21% of the functional models. While 21% is not very high, this ‘super’ module helps decrease the number of functions not in modules and is thus still important.

6 CONCLUSIONS

The following are the recommended alterations to the module heuristics for large products:

- Dominant flow heuristic: This heuristic can still be applied in the original way, but can become a ‘super dominant flow module’ when the same module accommodates more than one dominant flow through the same functions. It can also be combined with a conversion-transmission module to form a ‘dominant flow conversion super module.’ The dominant flow module can occur before or after the conversion-transmission module. A special case of this heuristic is when a dominant flow continuously loops. This creates ‘loop modules.’

- Branching flow heuristic: It would be more advantageous for large products if the branching flow heuristic application was altered. Instead of making several modules, one for each branch, they can all be combined along with the original function they branch from to form a 'branching super module.' This effectively eliminates all appearance of the original branching heuristic. If a person wanted to break down a 'branching super module' later, however, the original branching flow heuristic application could still be useful. The original branching flow heuristic also helps identify functions that affect a large number of modules. These are called 'key functions' and are helpful by-products of the module heuristics.
- Conversion-transmission heuristic: Just as the dominant flow heuristic, this heuristic can still be applied in the original way, but can become a 'super conversion module' when conversion modules overlap due to several convert functions appearing in series. Conversion modules can be combined with branching modules to form 'branching-conversion super modules'. It does not matter if the conversion occurs before or after the branching.

It is the finding of this research that the original module heuristics do still apply to large products. These module heuristics can be combined with themselves or other heuristics to create 'super' modules. This increases the heuristics' efficiency and usefulness in regards to large products.

7 FUTURE WORK

While this study has opened the module heuristics to large products there are still other intriguing areas where the module heuristics could be applied. It would be interesting to test the revised module heuristics on non-electromechanical devices. One such example would be a living organism, such as the common house fly. Testing the revised module heuristics on small consumer products could also be worth pursuing. After performing the module heuristics on extremely large functional models, it has become apparent a more efficient method of applying them would greatly increase their worth and usefulness.

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APPENDIX A

MODULE HEURISTIC DATA

Table 1. Basic Functional Model Data.

	# of sub-functions	# input flows	# output flows
Bike	38	6	6
Bike 2	38	6	6
Blimp	35	7	7
Blimp 2	35	7	7
Car	261	27	17
Car 2	261	27	17
Combine	142	8	8
Combine 2	142	8	8
Dryer	32	4	7
Dryer 2	32	4	7
Helicopter	66	4	9
Helicopter 2	66	4	9
HVAC	31	5	6
HVAC 2	31	5	6
Hydropower plant	49	4	8
Hydropower plant 2	49	4	8
Sewing machine	45	4	3
Sewing machine 2	45	4	3
Side-by-side refrigerator	44	6	9
Side-by-side refrigerator 2	44	6	9
Top-bottom refrigerator	39	6	8
Top-bottom refrigerator 2	39	6	8
Tunnel Boring Machine	495	24	67
Tunnel Boring Machine 2	495	24	67
Flatscreen TV	34	4	5
Flatscreen TV 2	34	4	5
Zamboni	70	6	7
Zamboni 2	70	6	7
min	31	4	3
max	495	27	67
avg	99	8	12

Table 2. Reduction Data.

	# of modules	% modules reduced by	# sub-functions not in modules	% sub-functions not in modules reduced
Bike Bike 2	13 10	0.23	1 2	-1.00
Blimp Blimp 2	11 5	0.55	6 6	0.00
Car Car 2	62 52	0.16	36 25	0.31
Combine Combine 2	55 29	0.47	18 18	0.00
Dryer Dryer 2	12 8	0.33	12 5	0.58
Helicopter Helicopter 2	27 16	0.41	14 6	0.57
HVAC HVAC 2	7 9	-0.29	10 4	0.60
Hydropower plant Hydropower plant 2	7 9	-0.29	7 9	-0.29
Sewing machine Sewing machine 2	12 10	0.17	8 6	0.25
Side-by-side refrigerator Side-by-side refrigerator 2	12 11	0.08	14 8	0.43
Top-bottom refrigerator Top-bottom refrigerator 2	12 9	0.25	5 5	0.00
Tunnel Boring Machine Tunnel Boring Machine 2	94 135	-0.44	34 26	0.24
Flatscreen TV Flatscreen TV 2	23 5	0.78	8 0	1.00
Zamboni Zamboni 2	15 16	-0.07	5 3	0.40
increased decreased same	4 10 0		2 9 3	
increased % decreased % same %	0.29 0.71 0.00		0.14 0.64 0.21	
min max avg		-0.44 0.78 0.17		-1.00 1.00 0.22

Table 3. Original Module Heuristics Data.

	# dominant flow modules	# branching modules	# conversion modules
Bike	5	4	4
Bike 2	5	0	1
Blimp	5	5	1
Blimp 2	1	0	0
Car	40	5	17
Car 2	28	0	1
Combine	20	27	8
Combine 2	20	0	1
Dryer	8	0	4
Dryer 2	4	0	1
Helicopter	12	15	0
Helicopter 2	10	0	0
HVAC	6	0	1
HVAC 2	6	0	0
Hydropower plant	2	5	0
Hydropower plant 2	3	0	1
Sewing machine	7	2	3
Sewing machine 2	7	0	0
Side-by-side refrigerator	8	3	1
Side-by-side refrigerator 2	6	1	1
Top-bottom refrigerator	6	1	5
Top-bottom refrigerator 2	4	0	0
Tunnel Boring Machine	85	6	3
Tunnel Boring Machine 2	30	0	47
Flatscreen TV	5	18	0
Flatscreen TV 2	2	0	0
Zamboni	6	8	1
Zamboni 2	7	0	1
increased	1	0	2
decreased	10	14	8
same	3	0	4
increased %	0.07	0.00	0.14
decreased %	0.71	1.00	0.57
same %	0.21	0.00	0.29

Table 4a. Modified Module Heuristics Data.

	# key sub-functions	# loop modules	# super modules	# branching super modules
Bike	0	0	0	0
Bike 2	3	0	4	1
Blimp	0	0	0	0
Blimp 2	1	0	4	1
Car	0	0	0	0
Car 2	4	3	20	3
Combine	0	0	0	0
Combine 2	2	0	8	6
Dryer	0	0	0	0
Dryer 2	4	0	3	0
Helicopter	0	0	0	0
Helicopter 2	4	0	6	3
HVAC	0	0	0	0
HVAC 2	0	1	2	0
Hydropower plant	0	0	0	0
Hydropower plant 2	1	4	1	0
Sewing machine	0	0	0	0
Sewing machine 2	0	0	3	1
Side-by-side refrigerator	0	0	0	0
Side-by-side refrigerator 2	3	1	2	1
Top-bottom refrigerator	0	0	0	0
Top-bottom refrigerator 2	1	1	3	0
Tunnel Boring Machine	0	0	0	0
Tunnel Boring Machine 2	4	52	6	2
Flatscreen TV	0	0	0	0
Flatscreen TV 2	1	0	3	1
Zamboni	0	0	0	0
Zamboni 2	1	8	0	0
had at least one	12	7	13	8
had at least one %	0.86	0.50	0.93	0.57

Table 4b. Modified Module Heuristics Data Continued.

	# branching conversion super modules	# conversion super modules	# dominant flow super modules	# dominant flow conversion super modules
Bike	0	0	0	0
Bike 2	3	0	0	0
Blimp	0	0	0	0
Blimp 2	0	1	2	0
Car	0	0	0	0
Car 2	5	2	3	7
Combine	0	0	0	0
Combine 2	1	1	0	0
Dryer	0	0	0	0
Dryer 2	2	0	1	0
Helicopter	0	0	0	0
Helicopter 2	1	1	0	1
HVAC	0	0	0	0
HVAC 2	0	1	0	1
Hydropower plant	0	0	0	0
Hydropower plant 2	0	0	1	0
Sewing machine	0	0	0	0
Sewing machine 2	2	0	0	0
Side-by-side refrigerator	0	0	0	0
Side-by-side refrigerator 2	0	1	0	0
Top-bottom refrigerator	0	0	0	0
Top-bottom refrigerator 2	3	0	0	0
Tunnel Boring Machine	0	0	0	0
Tunnel Boring Machine 2	1	1	2	0
Flatscreen TV	0	0	0	0
Flatscreen TV 2	1	0	0	0
Zamboni	0	0	0	0
Zamboni 2	0	0	0	0
had at least one	9	7	5	3
had at least one %	0.64	0.50	0.36	0.21

APPENDIX B

FUNCTIONAL MODELS ON CD-ROM

1. INTRODUCTION

Included with this thesis is a CD-ROM, which contains the functional models for thirteen of the fourteen products mentioned in this conference paper. One functional model is proprietary and cannot be published. Each functional model was developed using OmniGraffle for Macintosh. All documents have been prepared as Adobe Acrobat pdf files. An outline of the contents of the CD-ROM is as follows.

2. CONTENTS

<u>Plain Functional Models</u>:

Bike.PDF

Blimp.PDF

Combine.PDF

Dishwasher.PDF

Helicopter.PDF

HVAC.PDF

HydropowerPlant.PDF

KenmoreDryer.PDF

SewingMachine.PDF

SideSideRefrigerator.PDF

TopBottomRefrigerator.PDF

TunnelBoringMachine.PDF

TV.PDF

Zamboni.PDF

Functional Models with Original Module Heuristics:

BikeModules.PDF

BlimpModules.PDF

CombineModules.PDF

DishwasherModules.PDF

HelicopterModules.PDF

HVACModules.PDF

HydropowerPlantModules.PDF

KenmoreDryerModules.PDF

SewingMachineModules.PDF

SideSideRefrigeratorModules.PDF

TopBottomRefrigeratorModules.PDF

TunnelBoringMachineModules.PDF

TVModules.PDF

ZamboniModules.PDF

Functional Models with Modified Module Heuristics:

BikeModifiedModules.PDF

BlimpModifiedModules.PDF

CombineModifiedModules.PDF

DishwasherModifiedModules.PDF

HelicopterModifiedModules.PDF

HVACModifiedModules.PDF

HydropowerPlantModifiedModules.PDF

KenmoreDryerModifiedModules.PDF

SewingMachineModifiedModules.PDF

SideSideRefrigeratorModifiedModules.PDF

TopBottomRefrigeratorModifiedModules.PDF

TunnelBoringMachineModifiedModules.PDF

TVModifiedModules.PDF

ZamboniModifiedModules.PDF

CONCLUSIONS

It is the finding of this research that the original module heuristics do still apply to large products. These module heuristics can be combined with themselves or other heuristics to create ‘super’ modules. This increases the heuristics’ efficiency and usefulness in regards to large products.

VITA

Rachel Marie Day was born in West Plains, Missouri on March 18, 1986 and grew up in Bloomington, Indiana. In May 2008, she earned a Batchelor of Science in Mechanical Engineering from the Missouri University of Science and Technology with high honors. She also earned a Master of Science in Mechanical Engineering from the Missouri University of Science and Technology in May 2009. Rachel has been a member of Pi Tau Sigma since 2006 and the Order of the Engineer since 2007.