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FUNCTION-BASED SYSTEMS ENGINEERING (FUSE)

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ABSTRACT
Function-based Systems Engineering (FuSE) is a design method that uses functional modeling throughout the first three phases of engineering design: product planning, conceptual design and embodiment design. The objective of the method is to implement existing and newly developed functional modeling based tools throughout the design of systems. Specific improvements over current design methods include: A standardized functional modeling method that is applicable throughout the design process, conceptual functional models that limit form-specific assumptions and are used for identifying potential solutions to product functionality, form-specific functional models that assist detailed behavioral model identification, behavioral model development based on functional models, well defined methods for identifying, modeling and evaluating solutions and improved identification and representation of auxiliary functions. The design method is introduced along with a motivating example based on an automotive powertrain.

Keywords: Functional modeling, behavioral modeling, systems engineering, requirements flowdown

1. INTRODUCTION
FuSE, or function-based systems engineering, represents the application of formal functional modeling techniques to the functional design, behavioral modeling, requirements identification and flowdown and solution identification process of a product.

This paper introduces the methodology and is organized into three major sections. Current systems engineering methodologies are reviewed and opportunities to improve upon current practices are identified in the following section. Next, a function-based system engineering methodology is proposed with an outline of the specific activities that are included during various stages in the design process along with a summary example based on an automotive powertrain. Finally, conclusions from the work are presented along with a discussion about limitations of the method and future work. It should be noted that this paper is an introduction and definition of the method. A complete example of the method that includes the powertrain system along with details of the model assembly and solution appears in [1].

2. DESIGN METHODOLOGIES
Pahl and Beitz define a design methodology as "a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology, and from practical experience in different domains." [2]. To this end, they have established a set of criteria that a design methodology must exhibit. These criteria include:
- A problem-directed approach that is directed to every type of design activity
- Compatibility with concepts, methods and findings of other disciplines
- Application of known solutions to similar tasks
- Compatibility with electronic processing systems

To date, a number of design methodologies have been proposed. Pahl and Beitz's methodology consists of four steps: product planning and clarification, conceptual design, embodiment design and detailed design. A summary of the activities that are included in each phase is included in Table 1 [2].

Table 1. Activities During Design

Design Phase	Example Activities
Product Planning	• Market analysis • Finding and selecting product ideas • Defining the product's intended functionality and requirements
Conceptual Design	• Establishing detailed functionality • Identifying solutions to functions • Combining solutions into working structures • Selecting combinations of solutions • Developing principal solution variants • Evaluating variants
Embodiment Design	• Identifying product layouts and form • Finding solutions to auxiliary functions • Developing detailed and compatible layouts for main and auxiliary functionality • Evaluating and optimizing the design
Detailed Design	• Finalizing layout and creating drawings • Developing assembly drawings • Completing production documents • Checking documents for compliance, completeness and correctness

Other researchers in the field of design methodology propose similar design processes. Suh's design domains closely correspond to the four design phases established by Pahl and Beitz. These domains include the customer, functional, physical and process domains [3] which correspond to Pahl and Beitz's product planning, conceptual design, embodiment design and detailed design phases respectively. Additionally, modern design textbooks present similar design methods. Ullman presents a five step process including [4]:

1. Identification of needs
2. Planning for the design process
3. Developing engineering specifications
4. Developing concepts
5. Developing products

The first three steps of Ullman's method correspond to Pahl and Beitz's product planning phase. Step 4 corresponds to conceptual design and Step 5 is a combination of the embodiment design and detailed design phases. Otto and Wood identify three steps in the design process including understanding the opportunity, developing a concept and implementing a concept [5]. The first step, understanding the opportunity, corresponds to Pahl and Beitz's product planning phase of design. Developing a concept corresponds to conceptual design and implementing a concept corresponds to a combination of the embodiment design and detailed design phases similar to Ullman's developing products (5th) step.

2.1 Functional Modeling During Design

A functional model is a graphical representation of the transformation of energy, material or information flows as they pass through a system. Functional models are frequently used during the design of systems under the guise of schematics, flow-charts and process diagrams (all of which are graphical representations of the flows through a system along with the operations that are performed on them). For example, if you told an engineer with some experience in the field of hydraulics to design an open reservoir system that extends a single piston (with an external return force) and is actuated by a single manual control input, they would probably start by creating a schematic like the one in Figure 1. Such a schematic would be developed early in the design of a system to be used as a tool for identifying the basic functionality of the system and to drive specific component selection. The problem with using diagrams such as this early in the design of systems is that their creation requires too many assumptions about the form of the solution. Rather than indicating, in general, what the system should do, such a diagram represents what basic component families will be used to solve the problem (potentially before the problem has been fully understood). Instead, a less form-specific representation should be used during the early stages of design. Formal functional modeling techniques such as those proposed in [6; 7] allow such a representation. The same basic functionality of the system, represented with minimal assumptions about form appears in the functional model in Figure 2.

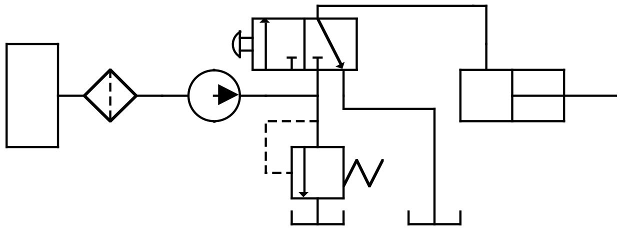

Figure 1. Hydraulic System Schematic

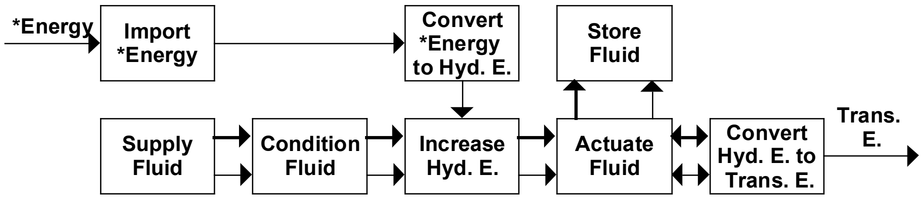

Figure 2. Hydraulic System Conceptual Functional Model

A model such as the one in Figure 2 should be used as the driver for component selection. Rather than assume a form when specifying the functionality of the system (as in the typical schematic approach), a generic representation of functionality should serve as the starting point for identifying solutions to the desired functionality. This approach increases the solution space and enables engineers to investigate potential solutions to desired functionality that would not have been considered if a form had already been selected. Once initial component identification has been completed, schematics such as the one in Figure 1 should be developed.

The functional model in Figure 2 uses Functional Basis names for the functions and flows. The Functional Basis (FB) is a standard set of function and flow names (verbs and nouns respectively) that can be used to model electromechanical systems [6]. There are FB terms for energy (with associated flow and effort components), material and signal flows as well as a hierarchical set of function terms. The functional models presented in this paper are all modeled using these FB terms. The use of such a standard taxonomy is necessary in formalizing the functional modeling process.

The intent of this work is to use such a formalized functional modeling process to drive design from start to finish. Such an approach increases the potential solution space, models assumptions about the form of the system as they are made and enables the use of a multitude of design tools that have been developed based on formal functional modeling techniques [8; 9; 10]. An additional goal of this work is to use functional modeling to drive the behavioral modeling process during the design of systems.

Existing work in this area includes [11; 12] . Roth [11] proposes that the design process be conducted by the selection of components from design catalogs based on the desired functionality of a system. The component-based models used by Roth are generally low-level models of specific existing components. The functional models used to specify these components are low-level as well and generally consist of the transformations of a single energy, material or signal state. During design, it is often the case that a functional element has multiple energy, material and signal transformations but is represented in a functional model as a single function. An example is an internal combustion engine. The internal combustion engine satisfies the convert chemical energy to rotational energy function and as a result has a chemical energy input along with a rotational energy output. However, this function also includes multiple auxiliary inputs and outputs such as the flows of thermal energy, acoustic energy and electrical energy.

Grabowski et al [12] propose that three-layer functional models be used to represent the functionality of a system. The three layers include logic, status and relations. As defined in this paper, these models would be classified as behavioral models rather than functional models. The objective of the models used in Grabowski et al is to capture the mathematical relationship between states rather than the conceptual functionality required to achieve a desired result. What is missing from such a modeling methodology is a high-level representation of the desired functionality along with a mapping to the logic, status and relation models.

2.2 Behavioral Modeling During Design

During all stages of the design process of a system, mathematical models are useful evaluation tools. For example, during the planning phase of a design, energy balance equations are used to identify size and performance requirements, cost models can be used to estimate potential product cost, time-to-market models can be made, etc. During conceptual design, models are used to estimate performance and other aspects of a potential concept such as weight, size and interoperability. These models can in turn be used to compare concepts during the concept selection process. During embodiment design, mathematical models are used for detailed analysis of components (such as a finite element analysis) or entire systems (simulations). Additionally, during embodiment design, performance models for auxiliary functionality can be made.

Currently, the behavioral modeling of systems is considered more an art than a science [13; 14; 15]. Personal experience and expert knowledge form the basis for most modeling practices. To enable the behavioral modeling of systems where this experience and/or knowledge may not exist, significant research has been conducted on linking the functionality of a product to its behavioral models [16; 17; 18; 19]. The goal of this research is to drive the behavioral modeling of systems with functional modeling. Since functionality is known very early in the design of a product and new products often exhibit functionality similar to previous solutions, it is proposed that linking behavioral models from prior product solutions will enable model re-use and assist model development for new systems. The objective of this work is to develop a formal method for conducting this process.

2.3 Specific Contributions to Systems Engineering Practices

In addition to model re-use, several additional contributions to current systems engineering practices have been identified, both in the area of functional modeling and the application of behavioral modeling. Specifically, these contributions include:

1. Limiting form-specific solutions through the use of conceptual functional models
2. Formalizing the role of conceptual and form-specific functional models during design
3. Creating a framework for developing the behavioral models used to evaluate a system
4. Improving identification and flowdown of requirements throughout the design process

3. FUNCTION-BASED SYSTEMS ENGINEERING

These contributions are implemented through a formal design process known as **Fu**nction-based **S**ystems **E**ngineering, or **FuSE**. FuSE complies with the stated criteria for a design method and uses functional modeling techniques to augment the first three phases of design: Product planning, conceptual design and embodiment design. The definitions of the terms used in this method follow:

Product – The object being designed it its entirety
Functional Model – A graphical model of the transformations of energies, materials and signals that occur through use of the product
Solution – A working physical structure that solves a specific function or collection of functions
System – A solution for some part of the product-level functional model
Subsystem – A solution for some part of the system-level functional model
Component – A uniquely identifiable solution for a specific function or collection of related functions
Conceptual Functional Model (CFM) – A functional model that includes minimal information about form-specific solutions; a CFM is used to generate concepts
Form Specific Functional Model (FSFM) – A functional model that includes function structures specific to the form of chosen solutions
Requirement – A specific attribute a solution must exhibit in a certain quantity (assessed by a metric)
Behavioral Model – A mathematical model of a solution's ability to meet certain requirements
Conceptual Behavioral Model (CBM)– A behavioral model that is not based on the specific form of solutions that is used to flow requirements from a higher level to a lower level

The steps included in the FuSE method occur through the first three stages of product design and are used to augment, not replace, the activities performed in a traditional design process. An outline of the steps included in the FuSE method follows. Each step is presented in detail in the following section along with an example based on the powertrain of an automobile.

1. **Product Planning**
   1.1. Create a black box functional model for the product
   1.2. Define product-level requirements based on the black box functional model
   1.3. Create a CFM at the product level based on the flows in the black box model
   1.4. Create system boundaries by grouping related functions in the product-level functional model
   1.5. Use a CBM to flowdown product-level requirements to the system-level

2. **Conceptual Design**
   2.1. Identify potential system solutions
   2.2. Develop behavioral models for systems
      2.2.1. Identify model elements
      2.2.2. Assemble model elements into a complete solvable model
      2.2.3. Solve model
      2.2.4. Evaluate solution based on results of model
   2.3. Update requirements and/or product-level functionality as necessary
   2.4. Repeat until a feasible set of solutions has been obtained
3. **Embodiment Design**
   3.1. Identify auxiliary functionality
   3.2. Create subsystem level CFMs as necessary
   3.3. Identify requirements for auxiliary functions and flow requirements to the subsystem-level
   3.4. Use the concept selection process to select solutions to auxiliary functions and sub-systems

3.1 FuSE During Product Planning

During the Product Planning phase of design, FuSE is applied to five activities: black box functional modeling, product-level requirements definition, conceptual functional model development, system boundary identification and requirements flowdown through the use of conceptual behavioral models. The following section outlines each of these steps along with a short example of each step being applied to the design of an automotive powertrain.

3.1.1 Black Box Functional Modeling

The first step in applying FuSE to the design of a system is to begin modeling the desired functionality of the system by creating a black box functional model. This model represents the overall functionality of the product as well as the energy, material and signal input and outputs and is created by mapping customer needs to overall functionality and product-level flows.

The overall function of an automotive powertrain is to convert stored energy into a rotation of some number of wheels. In this example, it is assumed that the energy being used is stored in the form of *chemical energy* and the powertrain drives two wheels on a common axis. The overall function of such a powertrain is to *convert chemical energy to rotational energy*. The basic inputs to this function include the *chemical energy* flow itself, a *liquid* flow of fuel, a *gas* flow of air and some number of *control signals*. The outputs include *rotational energy*, a *gas* flow of exhaust and some number of *status signals* (at this point, auxiliary flows such as *thermal energy* in the form of waste heat and *acoustic energy* in the form of exhaust noise are not being modeled). The overall function and flows are represented in the functional model that appears in Figure 3.

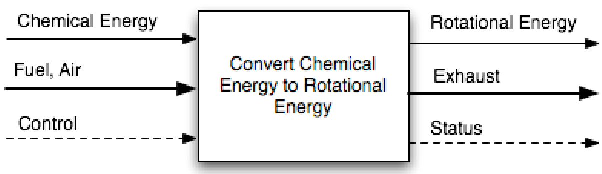

Figure 3. Powertrain Black Box

The next step in the application of FuSE to the powertrain is the identification of product-level requirements. To accomplish this step, the input and output flows are listed and used as a reference for placing requirements. For example, the powertrain has an input of *chemical energy* and as a result of the law of conservation of energy the maximum energy output by the powertrain must be less than the total input. The overall efficiency can be stated as a function of the energy input along with the various outputs. Thus, the *chemical energy* input serves as a good location to place a requirement on maximum energy consumption and overall efficiency of the engine. Similarly, the other input and output flows to the black box can be used to place additional requirements (Table 2).

Table 2. Product-level Requirements Identification

Type	Function/Flow	Requirement
Input	Chemical Energy	Energy input
	Fuel (Liquid)	Fuel flow rate, corrosion resistance
	Air (Gas)	Air inlet speed, mass flow rate
	Control	Throttle control
	Control	On/off/start
Output	Rotational Energy	Peak torque, peak power
	Exhaust (Gas)	Pollution, noise, exhaust temperature
	Status	Engine speed, engine health

3.1.2 Conceptual Functional Model Development

A CFM should then be made to identify the basic individual functions required to accomplish the overall functionality of the product. Any additional required flows that are identified in this step should be added to the black box model. At this point in the design process, form specific solutions should not be chosen (this broadens the solution space for conceptual design).

For the powertrain, four functions are considered in the product-level CFM. These were identified by starting with the *chemical energy* flow and identifying the functions required to turn it into the desired *rotational energy* output. The first function identified is *regulate chemical energy*. This function serves to regulate the amount of energy that is to be converted and needs a *control signal* to determine the amount of regulation. Next, the *chemical energy* needs to be converted into *rotational energy*. There is a *status* output from this function that reports the status of the conversion. The speed and torque produced in the conversion must then be *changed* from their converted values to the values required at the driven wheels. This function includes a *control* and *status* signal. Finally, the *rotational energy* must be *distributed* to the rear wheels. These functions are represented in the CFM that appears in Figure 4.

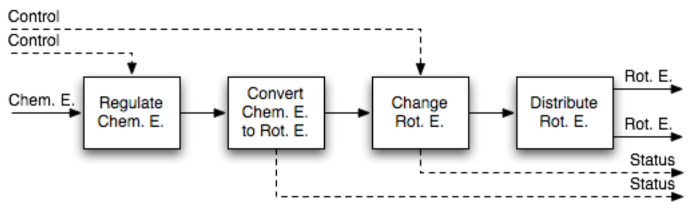

Figure 4. Powertrain CFM

3.1.3 System Boundary Identification

The next step in the FuSE method is to identify system boundaries from the CFM. This is done by identifying groups of related functions in the model based on prior experience or through well-defined methods such as the application of module heuristics [8].

The powertrain CFM was broken down into three systems. The first system, the induction system, includes the *regulate chemical energy* function. The next system, the engine, includes the energy *conversion* function. Finally, the drivetrain system was chosen to include the *changing* and *distribution* of *rotational energy*. This system breakdown corresponds to the typical breakdown structure used in the automotive industry.

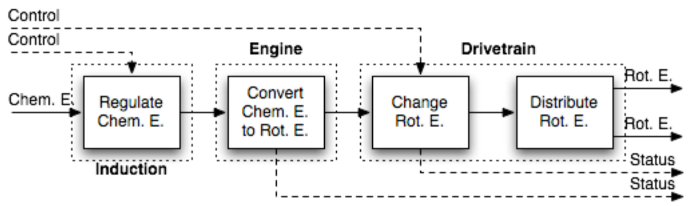

Figure 5. Powertrain System Boundaries

3.1.4 Product-level Requirements Flowdown

The final step during product planning is to use conceptual-level behavioral models to flow requirements from the product level down to the system level. This step involves creating mathematical models for the individual functions in the CFM and assembling them into a solvable model. This model is then used to determine the states of internal flows in the system given a defined set of external states (the external states come from the product level requirements).

To create the conceptual behavioral models for the powertrain, input and output states were first identified for each function. For the *chemical energy* input of the *regulate chemical energy* function the inputs were *chemical energy* and a *control signal*. The *chemical energy* input was mapped to a power flow state labeled P_I. The *control signal* was mapped to a control state labeled C_{RE}. The output of this function was a *rotational energy* flow that was mapped to a power state labeled P_O. The objective of this type of modeling is to establish a relationship between the inputs and outputs with minimal assumptions regarding the form of the system. To this end, a relationship between the power input and output could be found by applying the law of conservation of energy and setting the input energy equal to the output energy (no energy accumulation or additional power losses are considered at this point). Additionally, to accomplish the function of regulating the flow of *chemical energy* through the system, the amount of power out (P_O) was set to be some function of the *control signal* input. Simple models were created for the other three functions (see Figure 6) using the states that appear in Table 3. The format of these behavioral models was chosen as F(x)=0 to assist model assembly and solution (work is currently being done to create a general model format and solution technique for behavioral models created in this method). The result of this modeling step is a series of equations that allow the internal states of the system to be solved for by setting the external states to known values based on the product level requirements. The internal states are then used to establish numerical values for the system-level requirements.

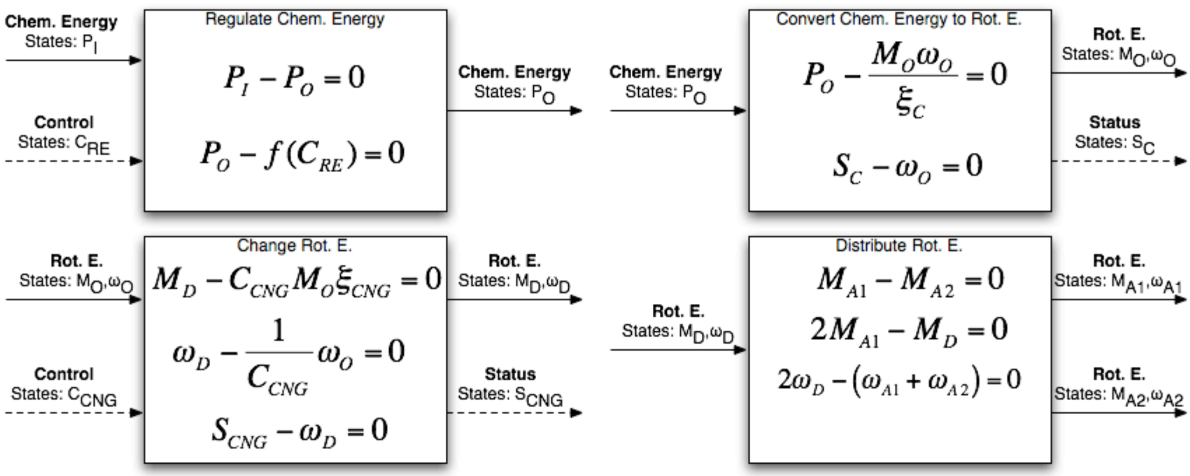

Figure 6. Powertrain Behavioral Models

The system-level requirements are identified in a similar manner to the product-level requirements. Instead of using the external flows of black box model, the internal flows of the CFM are used. Example requirements for the internal flows of the powertrain CFM are shown for the *regulate chemical energy* and *convert chemical energy to rotational energy* functions in Tables 4 and 5 respectively.

Table 3. State Variables

State	Description	State	Description
P_I	Power Input	C_{CNG}	Transmission Ratio
P_O	Regulated Power Input	ξ_{CNG}	Transmission Efficiency
C_{RE}	Regulation Control	ω_D	Transmission Speed
M_O	Engine Moment	S_{CNG}	Transmission Control
ω_O	Engine Speed	M_{A1}	Axle 1 Moment
ξ_C	Engine Efficiency	M_{A2}	Axle 2 Moment
S_C	Engine Status	ω_{A1}	Axle 1 Speed
M_D	Transmission Moment	ω_{A2}	Axle 2 Speed

Table 4. Regulate Chemical Energy Requirements

Type	Flow	Requirement
Input	Chemical Energy	Energy input
Output	Chemical Energy	Min/max power
Input	Control	Control type, linear, progressive, etc.

Table 5. Convert Chemical Energy to Rotational Energy Requirements

Type	Flow	Requirement
Input	Chemical Energy	Peak power input
Output	Rotation Energy	Torque and speed
Output	Status	Engine speed, health

3.2 FuSE During Conceptual Design

During the conceptual design of a system, FuSE is applied to four activities: identifying potential system solutions, developing behavioral models for these solutions, updating requirements and functionality and finally iterating this process until feasible solutions have been found.

3.2.1 Identifying Potential System Solutions

The first step in applying FuSE to the conceptual design of a product is to identify potential solutions for the systems in the CFM. This step involves finding components or collections of components that solve the desired functionality of the system. This step can be performed using a designer's experience with existing physical solutions or can be assisted with formal methods such as morphological matrices or design repositories [20].

For the powertrain, one set of potential solutions includes using a natural induction system that consists of a throttle, manifold and runners for the *regulate chemical energy* function, a conventional piston/cylinder internal combustion engine to solve the *convert chemical energy to rotational energy function*, a continuously variable transmission for the *change rotational energy* function and finally an open style differential to *distribute* the *rotational energy*. These solutions appear in Table 6.

Table 6. Powertrain Function Solutions

System	Function	Solution
Induction	Regulate Chem. E.	Natural
Engine	Convert Chem. E. to Rot. E.	Piston/cylinder ICE
Drivetrain	Change Rot. E.	CVT
Drivetrain	Distribute Rot. E.	Open diff., 2WD

3.2.2 Developing Behavioral Models

Once potential solutions have been found, behavioral models should be developed for the identified solution elements. These behavioral models allow the performance of concepts to be evaluated and compared to the product and system-level requirements are created using the following four steps:

- Identify model elements
- Assemble model elements into a complete solvable model
- Solve the model
- Evaluate solutions based on results of model

The first step is to identify model elements for the functions in the system-level CFM. These model elements may be derived from first principles or may be reused from existing model knowledge bases if available. The next step is to assemble these model elements into a complete and solvable mathematical model. This step involves associating the various inputs and outputs of the model elements based on the connectivity established in the CFM. The model should then be solved and used to evaluate the performance of a concept relative to the product and system-level requirements. Examples of behavioral model types for the powertrain functions appear in Table 7.

Table 7. Powertrain Behavioral Model Types

Solution	Model
Natural	CFD model of intake
Piston/Cylinder ICE	Commercial IC simulation package
CVT	First-principle based simulation
Open Diff, 2WD	Algebraic equations

As previously mentioned, a modeling format and integration method is currently being developed to automatically assemble and evaluate behavioral model elements based on the connectivity in the functional model. Once assembled, such a model enables the evaluation of the complete performance of concepts relative to product and system-level requirements.

3.2.3 Updating Requirements and Functionality

Once potential solutions have been identified, the functional model of the system should be updated to reflect changes in functionality that have occurred as a result of these choices. At this point, the functional model begins to become a form-specific functional model (FSFM) instead of a conceptual functional model (CFM). The role of the CFM is to help identify requirements and potential solutions early in the design of a system. An FSFM is used to further refine the design for the remainder of the design process. After the functional model has been updated to represent the functionality of the chosen solutions, additional requirements should be generated and existing requirements modified to reflect the new functionality and flows.

An example of creating an FSFM for the *regulate chemical energy* function of the powertrain follows. In this example, a natural induction system is assumed. To create the FSFM, the functions specific to the solution are found starting with the input flows into the system. For the natural induction system, air is *imported* into the system, *regulated* with a throttle, *distributed* through a manifold and *actuated* with a series of valves. Fuel is *imported* into the system, *distributed* through a fuel rail and *regulated* with an injector. The fuel and air are then *mixed*. These functions are represented in the functional model shown in Figure 7.

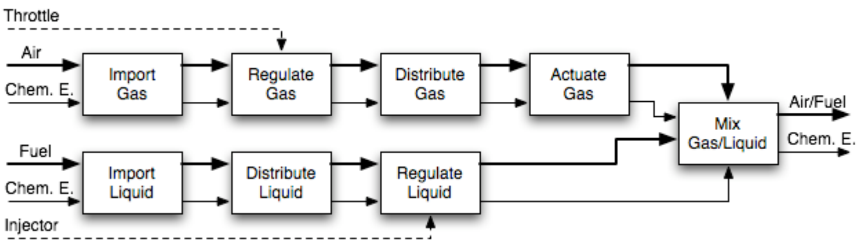

Figure 7. Induction System Functional Model

This FSFM is used to identify additional requirements that are specific to this particular solution. Examples of such requirements for the powertrain system appear in Table 8.

Table 8. Induction System Requirements

Type	Flow	Requirement
Input	Air	Temperature, pressure
Output	Air/Fuel	Mixture
Input	Fuel	Pressure
Input	Throttle	Signal type (electrical, mechanical)
Input	Injector	Signal type (analog, digital)

3.2.4 *Iterating to Find Feasible Solutions*
At this point in the design process, a single solution has been considered. If multiple feasible solutions are desired for a product, the previous three steps should be repeated starting with a selection of new solutions for product functionality. These steps should be repeated until a sufficient set of solutions has been identified. The performance of the solutions relative to the product-level requirements should then be compared to select solutions for evaluation in the next phase of the design process.

Only one solution was considered for the powertrain system. However, additional solutions could be identified by selecting different physical solutions for the functions in the CFM. For example, a rotary or gas turbine engine could be selected for the *convert chemical energy to rotational energy* function and an automatic or manual transmission could be selected for the *change rotational energy* function

3.3 FuSE During Embodiment Design
FuSE enables four activities during the embodiment design phase of systems engineering including: auxiliary functionality identification, CFM development for sub-systems and auxiliary functionality, detailed behavioral modeling including system to sub-system level requirements flowdown and identification of solutions for auxiliary functionality and sub-systems.

3.3.1 *Auxiliary Functionality Identification*
The first activity to be completed during the embodiment design phase of FuSE is to identify auxiliary functionality. Auxiliary functions do not contribute directly to the overall functionality of the product but are necessary to support the primary functions. Examples include functions required to mitigate potential failures, structural functions in systems whose primary functionality is not structural and functions to ensure safe operation of a product. Tools such as the Function-Failure Design Method [8] can be used as this point to assist the identification of failure modes based on the functional model. As these functions are identified, they should be added to the functional model of the product.

Examples of auxiliary functions for the powertrain system include thermal protection and structural functionality. Since the engine will produce waste heat (which should be added to the functional model at this point in the design process), the components in the system will get warm and need to dissipate heat in order to maintain a safe temperature. This functionality can be represented with an *inhibit thermal energy* function (insulation) and a *distribute thermal energy* function (cooling surfaces, fins, etc.). Additionally, the components of the system must transmit structural forces in the form *mechanical energy* from reaction forces, this can be modeled with a *distribute mechanical energy* function. These functions appear in Figure 8.

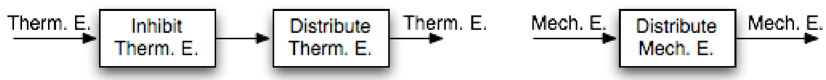

Figure 8. Powertrain Auxiliary Functions

3.3.2 *Sub-system Level Functional Modeling*
Once auxiliary functionality has been identified, sub-systems should be identified and modeled. Sub-systems may be subdivisions of existing systems or groups of related auxiliary functions. For example, the thermal protection functionality included in the powertrain system could be grouped as a sub-system of each of the existing three systems (induction, engine and drivetrain). Additionally the structural elements of these systems could be grouped into a structural sub-system.

3.3.3 *Detailed Behavioral Modeling and Requirement Flowdown*
Once sub-system and auxiliary functionality has been identified, conceptual behavioral models should be created to flow requirements down from the system level to the sub-systems and auxiliary functions.

The thermal protection sub-systems of the various powertrain systems could be modeled using simplified heat transfer equations and the structural sub-systems could be modeled using basic stress calculations (since form-specific solutions have not been identified for these sub-system, detailed models cannot be used). These models are used estimate internal states in the sub-systems. The internal temperatures and stresses in these sub-systems could then be used as locations for identifying sub-system level requirements.

3.3.4 Solution Identification for Auxiliary Functionality and Sub-systems

Just as in the conceptual phase of design, solutions should then be identified for the auxiliary functionality and sub-systems that have not already been investigated. The process should follow the same steps used in the conceptual design process: potential solution identification, behavioral model development, model assembly, model solution and finally evaluation of the solution relative to existing requirements. Just as in the conceptual design stage, tools such as design repositories and morphological matrices can be used in this step. After this step in the design process, feasible solutions should be identified for all of the functionality in the product. The remainder of the design process, the detailed design phase, is then performed using existing techniques.

For the powertrain system, various kinds of insulation could be used to solve the *inhibit thermal energy* functionality of the thermal protection sub-systems of the four systems. Potential solutions to the structural sub-systems include various mount geometries, fastening methods and bolt types.

3.4 Discussion

The FuSE method consists of three phases that correspond to the first three stages of a traditional design process. The objective of the FuSE method is to apply functional modeling throughout the design process to formalize and integrate the activities that occur during design. These activities include the mapping of customer needs to desired functionality, requirements identification and flowdown, behavioral modeling as well as the identification, modeling and selection of solutions at the system and sub-system levels. Specific improvements over traditional design practices include:

1. A standardized functional modeling method that is applicable throughout the design process
2. Conceptual functional models that limit form-specific assumptions and are used for identifying potential solutions to product functionality
3. Form-specific functional models that assist detailed behavioral model identification
4. Behavioral model development based on a functional model which:
    a. Promotes model storage and re-use
    b. Assists the assembly of behavioral models by using the flow connectivity information in the functional model
    c. Enables requirements flowdown though the use of CBMs
5. Well defined methods for identifying, modeling and evaluating solutions
6. Improved identification and representation of auxiliary functions through the use of function-based design tools such as FFDM

4. CONCLUSIONS

FuSE is a function-based design method that is applied throughout the early design stages of a product's systems. FuSE uses functional models to represent the evolution of a product's design as it goes through the design process. The models themselves are used to identify locations for requirements and serve a starting point for generating behavioral models at varying levels of fidelity. The objective of FuSE is to create a standardized, function-based method for performing the first three stages of design. Once these phases are over, traditional practices are used to finish the design.

This method was developed to comply with Pahl and Bietz's requirements for a design methodology. It is a problem-directed approach, functional modeling techniques can be applied throughout the design process to a wide variety of engineering problems. The method is compatible with existing concepts and methods including currently proposed design methodologies and system behavioral modeling methods. The method facilitates the reuse of knowledge by identifying previous solutions to specific design problems through common functionality. Since most of the tasks involved in applying FuSE involve drawing functional models and generating tables of requirements, the method is compatible with modern data processing systems. However, the application of FuSE to a system would be facilitated by the development of specific function-based software applications that assist the creation of functional models and integration of evaluation models. Such a tool would reduce the amount of “hand-work” that is involved in creating the models and could better handle the hierarchical nature of functional models than a series of static graphics (the status quo of functional modeling).

Currently, work is being done to develop a mathematical modeling framework for representing and integrating behavioral model elements. The modeling framework is intended to be used with a functional modeling development application and will enable a designer to create a behavioral model for a system by selecting or creating model elements for the functions in the functional model. The modeling methodology is being applied to model the dynamics of a complete automobile and includes model types from multiple modeling paradigms including algebraic equations, dynamic models, lookup tables and curve fits from experimental testing. The powertrain example presented in this paper represents a piece of this larger system model [1].

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