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# A METHODOLOGY FOR THE DEVELOPMENT OF AUTOMATED CONSUMER PRODUCTS

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## ABSTRACT

This paper presents research on a methodology to develop functional models to be utilized during conceptual design activities for products aimed at automating or assisting with currently manual tasks. Process models are utilized to investigate potential customers current actions, and functional models are utilized to capture functionality of the tools currently implemented by the customer. From these models, a designer can gather information on the customer needs and the customer's desired goals and outcomes. Models of the processes and tool functionality based on the customer's current process are combined to synthesize a new functional model for a product to more efficiently complete the customer's desired task. The methodology presented fits within the outcome-driven design paradigm where products are designed based on customer's tasks and their desired outcomes.

*Keywords: Process, function, configuration, outcome-driven design, automation.*

## 1 INTRODUCTION

It is commonly recognized that for the design of an automated product or service to succeed, the needs of the customer must be considered throughout the design process and embodied by the final design in a manner that makes the automated operations truly useful to the customer. This process, however, is often foiled by the very people it is designed to help—the customers [1]. It is not a trivial process to translate customer needs—often in customer voice—into an engineering metric or design specification, and there is no guarantee that the customer needs are all-inclusive or even specify the actual "root" need of the customer. Outcome-driven design, proposed by Ulwick [1] aims to circumvent this dilemma by prescribing that designers focus on the customer's desired outcome and develop technologies and services to assist users in achieving their desired outcome more effectively. Ulwick notes, "that customers ... have jobs with functional dimensions to them that arise regularly and need to get done," and "when companies focus on helping the customer get a job done faster, more conveniently, and less expensively than before, they are more likely to create products and services that the customer wants" [1]. Christensen, in *The Innovator's Solution*, agrees stating that those who "target … products at the circumstances in which customers find themselves, rather than at the customers themselves, are those that can launch predictably successful products" [2]. Christensen restates this saying that "the critical unit of analysis is the circumstance and not the customer" [2]. To that end, this research proposes a methodology to investigate the circumstances where a product will be used such that a more complete picture can be developed for the customer's current processes and a deeper understanding of the desired outcome can be achieved. Information from the customer's current process is utilized as a basis for the customer needs and as building blocks for automated products. Functional models [3] provide the structure to capture the operability of products currently employed by the customer, while process models [4] capture the circumstances and customer actions of how products are currently employed by the customer. These functional and process models, generated from the customer's current actions, are combined to synthesize a new functional model for the conceptual design of an automated solution with the goal of facilitating the customer in achieving their desired outcome.

The organization of this paper is as follows: First, related work is reviewed and is followed by an overview of the Functional Basis, functional modeling and process modeling. A manual can opener is used as an example through these sections. Following this background, the approach and methodology are presented as well as relevant considerations discovered during this research. The methodology is demonstrated by returning to the manual can opener; the functional and process models generated for the manual can opening process are synthesized into a new functional model for an automatic can opener. The synthesized can opener functional model is compared to an existing automatic can opener found in the Design Repository housed at the Design Engineering Lab in the discussion section, and conclusions follow.

## 2 BACKGROUND

While there is no rule prescribing that products designed to assist a customer with achieving a desired outcome be automated, the primary focus of this research is on the conceptual design of automated systems to replace and aid with predominately manual processes. Automated systems such as these often tend to be mechatronic in nature blending mechanical, electrical, computer and control systems into a single synergistic product; there is no rule, however, stating that they must be mechatronic, therefore, for generality, we will call them automated products. Whether the product is truly mechatronic or automated, functional modeling tends to lend itself well to this type of multi-disciplinary design due to the aggregated nature of each model. Chains detailing the transformations required of each flow are often generated independently, but in a final model, they are aggregated to illustrate how each flow must interact to affect the desired transformations and bring about the desired customer outcome. In this research, functional modeling and process modeling are employed together to integrate the actions of the final product with the operations of final product to capture these multi-disciplinary product characteristics during the conceptual design of automated systems.

### 2.1 Design of Automated Systems

Recognizing this need that mechatronic systems require an integrated approach to the design process, the research of Li Chen, et al. establishes a functional modeling methodology for the representation of mechatronic systems during the conceptual design stage [5]. Jayaram, et al. then builds upon their methodology providing a further refined approach to functionally represent mechatronic systems [6]. Other research on integrated conceptual design for mechatronic systems by Gausemeier et al. focuses on developing a functional modeling language specifically applicable to mechatronic systems [7]. The modeling language develops hierarchical breakdown for a conceptual design of a mechatronic system starting with the overall subsystem and decomposing each subsystem into known system and solution elements. These functional modeling schemes, while being able to capture the interactions between various domains present in a mechatronic system, try, however, to establish conventions that could be considered beyond the scope of the conceptual design phase and fail to present a straightforward approach to integrated system design.

In recognition of the need for synergy between elements in the design of automated systems, Middleton explains principles for the development of automation concepts. These principles are directly applied to a chemical lab environment, but are, however, directly applicable to any manual process [8]. The proposed five-step plan details the process from conceptual design through implementation and provides a framework emphasizing the importance of gathering a complete knowledge of the process to be automated. Middleton recommends that designers “reengineer the processes for automation” [8], and that “the best method for developing this detailed understanding is process mapping” [8].

In manufacturing, similar methodologies for the development of automation concepts for system automation have been put forth. Judd et al. propose a methodology for manufacturing system design based upon the object-oriented and rapid prototyping principles [9]. The system, eXecutable Specification (XSpec), focuses on increasing efficiency of a design by coordinating engineering disciplines and consists of a methodology specifying the importance of gathering customer needs and developing models of the processes [9]. In an effort to increase efficiency and further formalize manufacturing systems, Gu et al. propose a four phase methodology for a systematic design approach to manufacturing systems which starts with defining system requirements and functionality [10]. During the second phase, functionality is correlated to process variables and design parameters; this is followed by the configuration design in the third phase. The final phase specifies the detailed system design.

While these techniques for lab and manufacturing automation have detailed methodologies specifying how to develop the automation and extolling the virtues of gathering customer needs, they fail to provide detail on how the designer should understand the process and the needs. Rigorous methodologies are not provided detailing how to gather customer information and formalized nomenclatures are not utilized. The research presented in this paper addresses these shortcomings through an outcome-driven approach where formal functional and process modeling based on the Functional Basis is applied to investigate customer actions, identify expected goals, and derive customer needs.

## 2.2 Functional and Process Modeling with the Functional Basis

Functional and process modeling can trace their roots to value analysis where Miles [11] and Rodenaker [12] first used verb-noun pairs and input-output transformations to describe product functionality. Miles developed functional representation based upon the premise that a product's usefulness stems from its functionality [11], while Rodenacker defines functions and develops models of transformations of energy, material and information to describe a product's usefulness [12]. Roth extends Rodenacker's research by adding additional functions for mechanical design [13]. A set of twelve is then proposed by Koller [14], which Hundal subsequently refines with a proposed set of function and flow classes [15]. Pahl and Beitz present the idea of a functional basis for product decomposition with material, energy and signal flows [3]. Little et al. add information flows to Hundal's work to further refine a functional basis set [16]. Standardized sets of function and flow terms are then proposed separately by Szykman in [17] and Stone in [18] and are subsequently reconciled to form the Functional Basis [19].

### *2.2.1 Functional Basis*

The Functional Basis has emerged as a standard lexicon consisting of two sets of morphemes—one for functions and another for flows. Each set of morphemes is comprised of three levels of detail: primary, secondary, and tertiary, and are provided in two levels of detail in Tables 1 and 2.

*Table 1. Primary and secondary flow classes [19]*

| *(Class)* **Primary** | Material | Signal | Energy | | |
|---|---|---|---|---|---|
| **Secondary** | Human | Status | Human | Electrical | Mechanical |
| | Gas | Control | Acoustic | Electromagnetic | Pneumatic |
| | Liquid | | Biological | Hydraulic | Radioactive |
| | Solid | | Chemical | Magnetic | Thermal |
| | Plasma | | | | |
| | Mixture | | | | |

*Table 2. Primary and secondary function classes [19]*

| *(Class)* **Primary** | Branch | Channel | Connect | Control Magnitude | Convert | Provision | Signal | Support |
|---|---|---|---|---|---|---|---|---|
| **Secondary** | Separate | Import | Couple | Actuate | Convert | Store | Sense | Stabilize |
| | Distribute | Export | Mix | Regulate | | Supply | Indicate | Secure |
| | | Transfer | | Change | | | Process | Position |
| | | Guide | | Stop | | | | |

The use of a standard lexicon, such as the Functional Basis, for all functions and flows in the models allows for direct comparisons to be made between the process and functional models. Functional and process models may be used to research existing products and customer actions, and may be archived and accessed for future applications. Functional and process information based upon the Functional Basis can also be divided as chunks that can be directly aggregated to create new conceptual designs where process models provide interaction information concerning the application of vital tools through manual processes, and functional models provides flow transformation information on the inner workings of the tools. By using the same lexicon for process and function, similarity is maintained between all model structures allowing for models to be more readily integrated, archived and reused for conceptual design activities.

### *2.2.2 Functional Modeling*

Functional modeling provides a technique to model the flow changes and interactions within a product. Generally, functional models consist of at least two levels: (1) a black box model describing the overall functionality of the product and (2) a sub-functional model detailing functional changes on each flow through the product, and their generation is guided by the following steps: (1) generate a black box model based on customer needs, (2) generate function chains for each flow, (3) aggregate function chains into a functional model and (4) verify each customer need is addressed by at least one sub-function. As an example to the generation of a functional model consider the manual household can opener shown below in Fig. 1.

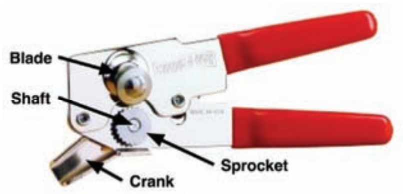


*Figure 1. Manual can opener*[1]

First, a black box model (Fig. 2) is generated based upon the customer's needs for the product. The customer needs are used to identify the overall functionally, which for the manual can opener is to *separate solid material*. Flows required to perform the overall functionality are also identified from the customer needs. For the can opener, the input flows include: the operator, the operator's energy (since it is manually powered, controlled, etc.) and an unopened can; the output flows include: the opened can, its lid, the operator and any reactionary energies.


*Figure 2. Black box model of a manual can opener*

The functional model of the can opener decomposes the black box and is generated by considering the transformations of each flow modeled in the black box. For each flow, a chain of functional transformations is developed. Chains are then aggregated to form the functional model. The functional model of the can opener (Fig. 3) follows the operator, the operator's energy and the unopened can through the product modeling the transformations of each flow required to deliver the desired outcome. For instance, the operator's energy is first imported into the can opener at the crank as human energy. The human energy is then converted to mechanical energy through the act of rotating the crank. A shaft transfers the mechanical energy to the sprockets, which guide the can (modeled as solid material) along a rotating blade removing the can's lid (also modeled as solid material). Once the can's lid has been removed, the desired operation is complete, and all flows are exported from the product.

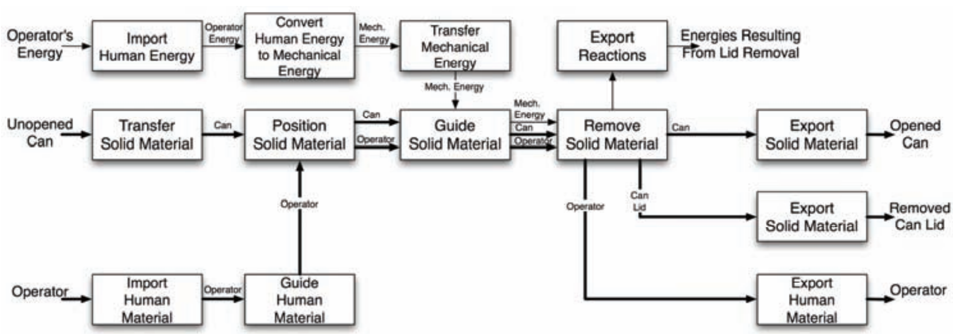


*Figure 3. Functional model of a manual can opener*

[1] Image from: http://www.focuspg.com/finditem.cfm?itemid=1930

### *2.2.3 Process Modeling*

The process modeling methodology applied through this research, and described below, is based on traditional functional modeling. Process modeling provides a framework for modeling customer's actions and operations with products through two types of models: event and configuration. The following terms related to process modeling are used throughout this paper:

- **Process Modeling:** The overall approach to modeling a series of customer-driven, product-based actions related through input and output flows, the product being designed, and time [20].
- **Configuration:** A specific discrete instance of the overall functionality of the product occurring as a part of an event. Collectively many configurations define an event of the product [20].
- **Event:** A set of configurations of a product, which may relate to the environments where the product is used, changes to the operability of the product, specific applications of the product, or sequencing of operations during the usage of the product [20].
- **Process:** The sum of defined events that occur with respect to the product as a whole and aim to meet a particular goal. Processes are tied together via the product, material, energy and signal flows [20].

Typically, process models are developed at three distinct levels of detail: black box (process) model, event model and configuration models. The black box (process) model is considered the highest-level event model, and it describes the overall goal or outcome of the customer through operation of a product. Event models are a decomposition of the black box and consist of a chain of events each describing an individual customer operation. A configuration model decomposes each event to describe the individual changes or actions that are required to complete a particular event. Each of these levels of detail are more specifically defined as:

- **Black Box (Process) Model:** The high-level process model defined by a single event representing the entire task to be accomplished.
- **Event Model:** A more detailed process model consisting of multiple events that collectively define the customer's operations with the product.
- **Configuration Model:** A detailed model of the individual actions and changes occurring to the product as a whole and involved in completing a particular event.

To generate a process model, the following six steps are followed: (1) Identify the overall process to be completed and the requirements necessary to complete the process. (2) Generate a black box model for the process being modeled defining the overall process and all required material, energy and signal flows. (3) Identify and formulate events necessary to complete the process as well as their required input/output flows. (4) Formulate the event model consisting of chains of event. (5) Decompose each individual event into a more detailed configuration model detailing the discrete changes to the product. (6) Verify that each process requirement is addressed within the process models.

As an example of how to generate process models, consider the operation of the manual can opener shown in Fig. 1 and modeled functionally in Fig. 2 and 3. (1) The first step to generating a process model is to identify the overall process and the requirements. For the can opener, let's consider two potential operation events during its ownership, can opener storage and can lid removal. For these events, the can opener must easily configure for storage as well as for can lid removal. Since the can opener is manual, it must have a mechanical advantage to afford operation to a wide range of operators, and finally, since the diameter of a can is non-standard, the operation of the can opener must be independent of the cans diameter. (2) Once the process is fully understood, a black box model (Fig. 4) of the process is generated specifying the high-level event and all necessary flows.

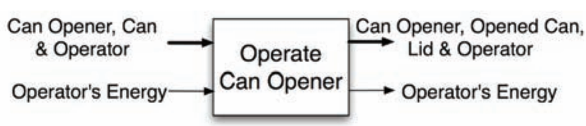


*Figure 4. Black box (process) model for the operation of a manual can opener*

(3) Individual events are now decomposed from the black box detailing the operations expected by the customer. For the can opener, these events will be its storage, *store can opener*, and can lid removal, *remove can lid*. Flows necessary are the can, the can opener, the operator and the operator's energy. (4) An event model is now generated linking each of the identified events through the flows. The

event model, shown in Fig. 5, models the store can opener event as well as the remove can lid event. These events are connected through the material flow of the can opener. The material and energy flows for the operator are present in both events. The operator flows are discontinuous between the storage and operation events to represent that the flows do not have to represent the same operator.

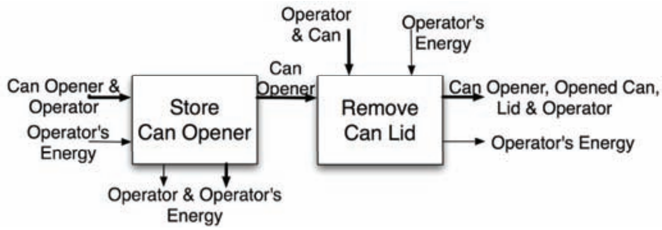


*Figure 5. Event model of the operation of a manual can opener*

(5) A configuration model is generated similarly to a functional model with the designer "being the flow" and considering what changes must occur to the product—the manual can opener in our example—to achieve the desired outcome. The configuration model of the event *remove can lid* shown in Fig. 6 models the operator collecting up the can opener, *couple human & can opener*, before coupling the can opener to the can. Once coupled, the can's lid—modeled as *solid material*—is removed. To monitor the removal, the operator detects the progress of the lid's removal. The operator processes status, and once the lid is fully removed, the can and the can opener are divided. Following the operation, the can opener, opened can, lid and the operator flows are exported from the system. (6) The process modeling process is concluded with the modeler verifying that each of the requirements identified in step one are represented at least once in the process model.

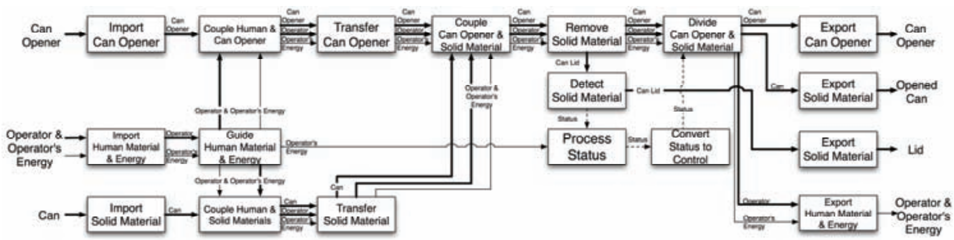


*Figure 6. Configuration model for the remove can lid event*

## 3 APPROACH & METHODOLOGY

The initial goal of this research is to investigate the relationship of functional and process models such that both may be employed to assist with the collection of customer needs from a customer-based, outcome-driven perspective. As a methodological statement, both functional and process models are prescribed to be generated in conjunction with the collection of customer needs to design products to assist customers with manual processes. Potential automated subsystems to assist with each manual process are then synthesized—in the form of a functional model—for each manual process based upon the functional and process models. During this process a number of considerations are discovered:

- When creating a conceptual functional model for an automated solution, functionality can be derived from the customer's current process and the products currently being employed. From the functional models developed for the products, function chains detailing core functionality can be extracted. From the process model, the customer's actions indicate sensing, operability and mobility requirements for an automated solution.
- Since the functional model of the automation solution is being developed at the conceptual level, human-based interactions with the product require little change when considered for the functional model of the automation solution. Human energy—a secondary Functional Basis term—may be rewritten as its primary level term, energy, to represent an unknown energy source in the conceptual design.

- Process and functional models from the manual process often reveal an array of human senses such as vision with eyes and tactility with skin that obviously cannot exist in their natural form in an automation solution and must be replaced with engineered solutions. Sensors, whether in humans or automated devices, also require processing. These sensors and their processors, however, when modeled functionally with the Functional Basis, have the same functionality whether they are solved via a natural solution or an engineered solution and only require a change with the energy source.
- Needs and objectives may change with the automation of a manual process. Alternatively, they may not be fully met with the customer's process. Formal methods for determining customer needs, which are well established in design literature and can be found in many design engineering texts [21-24], should be followed in conjunction with the process and functional decompositions of the customer's current process to ensure that all customer needs are identified.

From the approach taken in this research, the following six-step methodology, illustrated in Fig. 7, is derived:

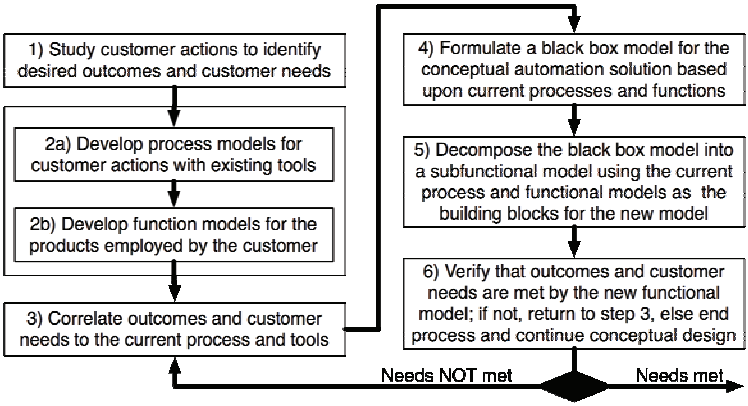


*Figure 7. Approach for the development of conceptual functional models for automating processes*

The first step is to fully explore and understand the customer's current actions, the goals desired, and the products currently employed by the customer as they work to reach a desired goal. Exploring the current process should reveal the majority of the needs of the targeted customers. The proposed methodology, first, prompts the designer to study the customer's actions in the current manual process. Process and functional modeling are employed to more fully explore the manual process and any products currently used by the customer. Once designers fully understand the current manual process, needs that have been identified are correlated to the current process to identify its shortcomings. From the collected functional and process information, a black box model is generated for a product to automate the manual process. The black box model considers the overall functionality and all input/output flows, and is decomposed into a functional model detailing the transformations required for all input and output flows. Once the functional model is generated, it is verified with the collected customer needs and automation objectives to ensure that all requirements are met.

The methodology is formalized as the following set of six steps:

1. Determine the automation objectives. Discuss the current process with the customers; discuss the products currently being used. What are the shortcomings? What are the benefits? Monitor the customer while carrying out the process.
2. Develop models of the current process and any products currently being used during the process following the procedure outlined in Sect. 2.2.2 and Sect. 2.2.3. Use the Functional Basis [19] for terminology to ensure consistency between both functional and process models.
3. Correlate customer needs and automation objectives to the process and functional models; if discussions with the customer reveal needs are not met in either model, use the unattended customer needs to determine additional functions and flows to address the unmet needs.
4. Develop a black box model for the automation solution considering the black box functionality and the inputs from the process model, its associated product, and all unattended customer needs.

5. Develop a conceptual functional model for the automation solution by:
    a. Extracting the core functionalities from the functional models of the products currently used in the manual process,
    b. Converting human interactions such as mobility, actuation, sensing, operational energy, etc from the process models into non-energy specific functional equivalents,
    c. Aggregating the core functionalities with the non-energy specific functional equivalents for the process-based product interactions,
    d. Developing and aggregating function chains for each of the flows not addressed in the manual process.
6. Verify that all of the customer needs are addressed by functionality within the final functional model; if they have not all been met, return to Step 3 to identify and borrow the functionality in original current processes. If the functionality is not in the original process and functional models, address the customer needs by correlating function and flow to each of the needs and aggregating the additional functionality into the newly synthesized functional model.

Following the application of the above methodology, the designer has a functional model representing the required operations for a product to automate or assist a customer with a previously manual process. At this point, the designer is in the conceptualization phase of engineering design [3] where the functional model is a key part of a design framework to ensure that customer needs are fully captured in potential solutions principles. To apply the functional model in the design framework, components may be paired to each of the functional operations [3, 21], the concept may be modularized based on functionality [25], behavioral analysis may be performed to validate model operability [26] and concept robustness can be improved through function-based failure [27] and risk [28] analysis.

## 4 EXAMPLE—AUTOMATION OF THE CAN OPENING PROCESS

### 4.1 Automation of the Can Opening Process

When developing an automation solution to replace or assist with a manual process, it is important to fully understand the manual process and the product being replaced with the new technology. To that end, let's consider, once again, the can opener example explored previously in Sect. 2.2.1 and 2.2.2. First, an automation objective must be determined; let's assume that the manual can opener does not provide adequate mechanical advantage to allow operators to easily remove the lid from a can. Thus, an automatic can opener is required such that the can opener itself provides the power for lid removal. The second step is to model the current manual process of removing the can lid and to model the manual can opener. These models have previously been generated in Sect. 2.2.1 and 2.2.2. Third, customer needs are correlated to the process and functional models; a potential correlation of customer needs to function-flow pairs taken from the functional and process models is provided in Table 3.

*Table 3. Customer need to function correlation*

| Customer Need | Function-Flow Pair |
|---|---|
| Powered removal of can lid | • Convert Human Energy to Mechanical Energy<br>• Transfer Mechanical Energy<br>• Remove Solid Material (lid) |
| Easy to place can | • Guide Solid Material (can)<br>• Position Solid Material (can) |
| Easy to remove opened can | • Divide Can Opener & Solid Material (can)<br>• Export Solid Material (lid)<br>• Export Solid Material (can) |
| Start when can is placed | • Detect Solid Material (can)<br>• Process Solid Material (can) |
| Stop when lid is removed | • Detect Solid Material (lid)<br>• Process Solid Material (lid) |

Since the manual can opener and the assistive/automatic can opener share the same objective—remove a lid from a can—the black box functionality remains the same. The only change that must occur is with the energy input flows (Fig. 8); the secondary flow, human energy, is converted to its primary type, energy, to represent the unknown specifics about the energy used in the conceptual design.


*Figure 8. Synthesized conceptual black box model for an automated can opening product*

The black box model is now decomposed into a functional model describing the specific transformations occurring to each input and output flow. During this decomposition process, specific functionality may be extracted from the functional and process models initially generated for the process based around the manual can opener. Both the functional and process models describe the importation of the can, positioning for lid removal, and exportation of the lid and open can. These mobility function-flow pairs are borrowed from the manual process to describe how the operator and can should interact in the new concept. From the process model, functionality describing the detection and processing of the status of the can is borrowed; the operator, however, no longer performs this detection. Instead, human energy is replaced with energy to specify an unknown energy source. Also, from the functional model, the transfer and conversion of energy are borrowed. Again, the flow of human energy is represented with the primary level term, energy. To complete the energy flow function chains, the function blocks, actuate energy and distribute energy, are added addressing the customer need for the can opening process to be automatically start and stop. To activate the automatic on/off capability of the can opener, the can is detected upon placement into the automatic can opener (modeled as detect solid material) and the status of the lid removal is detected during operation (also modeled as detect solid material). A complete, aggregated functional model for the conceptual can opener is provided in Figure 9.

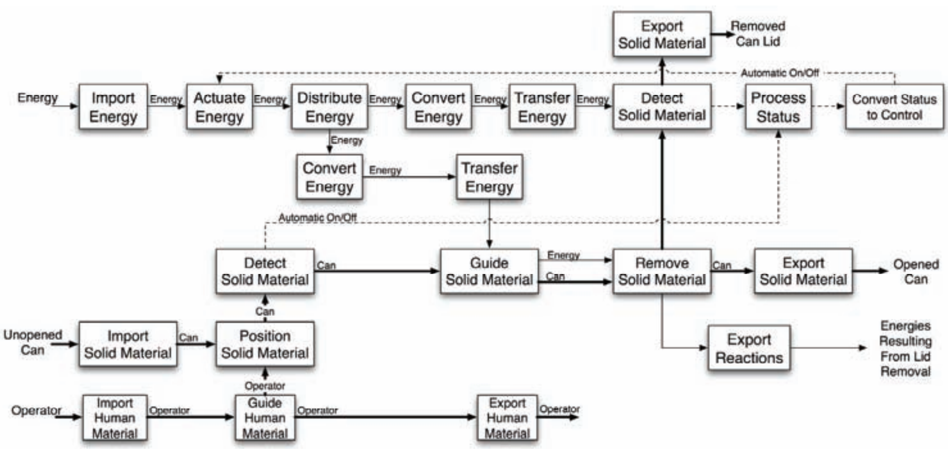


*Figure 9. Synthesized conceptual functional model for an automated can opening product*

## 4.2 Discussion

This functional model generated during the conceptual design of a product generates a framework for subsequent conceptual design activities. This framework can be visualized through the can opener example. During conceptual design, the energy source for the can opener is unknown, thus we broadly term the motive power source as energy. Broadly defining a flow at the primary level of the Functional Basis allows for a wider variety of alternatives to be considered during conceptual design; for instance, the can opener could be wind-up with a spring to store the energy or solar powered with a

battery to store energy, or use a laser to cut off and remove the can lid. Once a solution principle is chosen for each functional transformation, the functional model should be updated to reflect additional functionality required for the chosen solution principles. This additional functionality, termed auxiliary functions [3], may continue to be added even into the embodiment phases of design. It is an iterative process possibly requiring multiple iterations until solution principles have been identified for all additional functionality. At the completion of this iterative process, embodiment of the design continues with special layouts being developed, materials being selected, cost analysis being performed and finally, with detail design, the design is turned into a final product [3].
Through this research, each of the synthesized models was compared to actual products currently on the market to for correlations and inconsistencies. The manual can opener can similarly be compared to an existing automated can opener (shown in Fig. 10) found in the Design Repository housed at the Design Engineering Lab. Both the existing and concept have similar black box models sharing the same high-level functionality, separate solid, and many of the same flows. The operator has been more specifically called out as hand and the flow of energy in the concept has been replaced with the secondary flow, electrical energy, in the existing product. The functional models also share similar functionalities; both the concept and the existing product rely on the operator to position the can for operation, and once the lid has been removed, both devices trigger an automatic actuation of energy to stop operation.

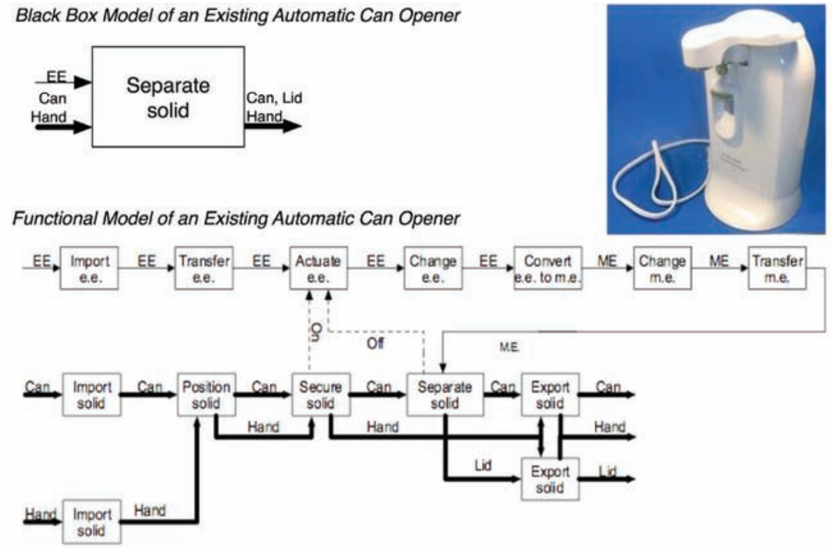


*Figure 10. Black box and functional models for an existing automatic can opener[2]*

There are differences as well. The existing product is less automated than intended with the concept; the actual product relies on the operator's hand to secure the can into place while the concept uses the energy of the device to guide the can into the appropriate removal position. Also, there are flows in the existing product such as, change electrical energy, convert electrical energy to mechanical energy, change mechanical energy, and transfer mechanical energy, to deal with the electrical energy flow. These flows dealing with specific implementation have yet to be considered in the conceptual functional model, and would not be directly considered until concept generation. If the design process were to continue for the conceptual functional model of the automated can opener, solution principles would be paired to function, auxiliary functions were identified, and new solution principles would be paired to the auxiliary functions. This would occur iteratively until a concept is fully developed. It is then possible that the updated functional model would more closely resemble the can opener found in the Design Repository; however, depending on the customer needs, chosen solution principles and

[2] Functional model from: http://repository.designengineeringlab.org

identified auxiliary functions, it is just as likely that the can opener may share very little in common with the existing product in the Design Repository.

## 5 CONCLUSIONS

During product design it is important to remember that "customers—people and companies—have jobs that arise regularly and need to get done. When customers become aware of a job that they need to get done in their lives, they look around for a product or service that they can hire to get the job done" [2]. These jobs are the outcomes for which customers seek products and services to assist. When developing products within an outcome-driven design paradigm, it is important to fully understand the current process taken by the customer. The methodology developed through this research provides the starting point for a designer to develop conceptual functional models based on a process currently taken by a customer.

In this paper, we demonstrated how functional and process modeling may be employed to investigate a customer's current process and the tools being employed through that process. The combination of these models is then demonstrated such that conceptual functional models may be generated for a potential solution to assist or automate the job of the customer.

Further research will investigate the models generated from the customer's manual process for potential weaknesses in the customers' current actions. Places where weaknesses exist in the customers' current actions represent ideal locations where automation could be utilized to allow the customer to more effectively reach their desired outcome. Integrated functional and process modeling would thus be generated very early in the design process and be iterated as the design evolves. So, instead of the design-based abstractions focusing on how the product will include each feature, it will focus on the outcomes expected by the customers as they complete their tasks.

## REFERENCES


[1] Ulwick, A.W. *What Customers Want: Using Outcome-Driven Innovation to Create Breakthrough Products and Services*. 2005 (McGraw-Hill, New York).

[2] Christensen, C.M. and Raynor, M.E. *The Innovator's Solution: Generating and Sustaining Successful Growth*. 2003 (Harvard Business School Press, Boston).

[3] Pahl, G., Beitz, W., Feldhusen, J. and Grote, K.H. *Engineering Design: A Systematic Approach*. 2007 (Springer Verlag).

[4] Nagel, R.L., Stone, R.B. and McAdams, D.A. A Process Modeling Methodology for Automation of Manual and Time Dependent Processes. *ASME International Design Engineering Technical Conferences*, DETC2006-99437, Philadelphia, PA, 2006).

[5] Chen, L., Jayaram, M. and Xi, J.F. A New Functional Representation Scheme for Conceptual Modeling of Mechatronic Systems. *Design Engineering Technical Conferences and Computer and Information in Engineering Conference*, Montreal, Canada, 2002, (ASME).

[6] Jayaram, M., Chen, L. and Xi, J.F. Functional Modeling of Complex Mechatronic Systems. *Design Engineering Technical Conferences and Computer and Information in Engineering Conference*, Chicago, Il, 2003, (ASME).

[7] Gausemeier, J., Flath, M. and Möhringer, S. Conceptual Design of Mechatronic Systems Supported by Semi-Formal Specification. *IEEE/ASME International Conference on Advanced Intelligent Mechatronics Proceedings*, Como, Italy, 2001, (IEEE/ASME).

[8] Middleton, S.R. Developing an Automation Concept That Is for Your Laboratory. *Clinical Chemistry Forum,* 2000, 46(No. 5), 757-763.

[9] Judd, R.P., Vanderbok, R.S., Brown, M.E. and Sauter, J.A. Manufacturing System Design Methodology: Execute the Specification. *IEEE/IFIP International Workshop on Rapid System Prototyping*, Research Triangle Park, NC, 1990, pp. 97-115 (IEEE/IFIP).

[10] Gu., P., Rao, H.A. and Tseng, M.M. Systematic Design of Manufacturing Systems Bases on Axiomatic Design Approach. *College International pour la Recherche en Productique*, 2001.

[11] Miles, L. *Techniques of Value Analysis and Engineering*. 1961 (McGraw-Hill, New York).

[12] Rodenacker, W. *Methodisches Konstruieren (Methodical Design)*. 1971 (Springer, Berlin, Heidelberg, New York).

[13] Roth, K. *Konstruieren Mit Konstrktionskatalogen (Design with Construction Catalogs)*. 1982 (Springer Verlag, Berlin).

[14] Koller, R. *Konstruktionslehre Für Den Maschinenbau (Mechanical Engineering Design)*. 1985,

Berlin: Springer-Verlag).
[15] Hundal, M. A Systematic Method for Developing Function Structures, Solutions and Concept Variants. *Mechanism and Machine Theory,* 1990, 25(3), 243-256.
[16] Little, A., Wood, K. and McAdams, D. Functional Analysis: A Fundamental Empirical Study for Reverse Engineering, Benchmarking and Redesign. *Proceedings of the 1997 Design Engineering Technical Conferences*, 97-DETC/DTM-3879, Sacramento, CA, 1997).
[17] Szykman, S., Racz, J. and Sriram, R. The Representation of Function in Computer-Based Design. *ASME Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, DETC99/DTM-8742, Las Vegas, NV., 1999).
[18] Stone, R. and Wood, K. Development of a Functional Basis for Design. *Journal of Mechanical Design,* 2000, 122(4), 359-370.
[19] Hirtz, J., Stone, R., McAdams, D., Szykman, S. and Wood, K. A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts. *Research in Engineering Design,* 2002, 13(2), 65-82.
[20] Nagel, R., Greer, J.L., Stone, R.B. and McAdams, D.A. Functioncad: A Functional Modeling Application Based on the Function Design Framework. *ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, DETC2009-87010, San Diego, CA, 2009, (ASME).
[21] Otto, K. and Wood, K. *Product Design: Techniques in Reverse Engineering, Systematic Design, and New Product Development*. 2001 (Prentice-Hall, New York).
[22] Ulrich, K.T. and Eppinger, S.D. *Product Design and Development*. 2004 (McGraw-Hill/Irwin, Boston, MA).
[23] Cross, N. *Engineering Design Methods: Strategies for Product Design*. 2000 (John Wiley & Sons, LTD, Chichester).
[24] Ullman, D.G. *The Mechanical Design Process*. 2002 (McGraw-Hill, Inc., New York).
[25] Stone, R., Wood, K. and Crawford, R. A Heuristic Method for Identifying Modules for Product Architectures. *Design Studies,* 2000, 21(1), 5-31.
[26] Hutcheson, R.S., McAdams, D.A., Stone, R.B. and Tumer, I.Y. Function-Based Behavioral Modeling. *ASME International Design Engineering Technical Conferences*, DETC2007-35337, Las Vegas, NV, 2007, (ASME).
[27] Stone, R.B., Tumer, I.Y. and Van Wie, M. The Function-Failure Design Method. *Journal of Mechanical Design,* 2005, 127(3), 397-407.
[28] Grantham Lough, K., Stone, R.B. and Tumer, I.Y. The Risk in Early Design Method (Red). *Journal of Engineering Design,* 2007, 18(1).

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