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Excess Identification and Mapping in Engineered Systems

A system must continue to meet stakeholder needs throughout its service life to maintain value. Excess that is embedded into components during the design phase can enable in-service system evolution when new or changed requirements are introduced. However, while the concept of excess has been established in the literature, it is not clear how to identify and quantify the set of excesses in a particular design. This paper uses component properties and functional flow information to map and quantify the excess that exists within a system. Understanding the functional flow relationships between components allows for the bottlenecks at component interfaces to be identified. Those flows that do not limit the potential evolvability of a system can be removed from consideration, allowing for critical interface parameters to be highlighted and their capabilities quantified. The method is demonstrated on a consumer heat gun, where quantifying the excess within components allows for a reduced map to be created with irrelevant flows removed. Finally, changes to the system are explored to demonstrate how knowledge of component excess can be used to initially validate a proposed evolution. [DOI: 10.1115/1.4033884]

1 Introduction

After a system is put into service, it is likely that the requirements placed upon that system will change over time. Evolving a product to meet these new requirements can be approached from a generational context [1–4] where research in product platforming [5,6], inheritance [7,8], and the concepts of architecture scaling and modularity [9–12] shorten the design cycle and reduce redesign costs.

Evolution can also be achieved while keeping the system in-service. Prior research by Tackett [13] analyzed 210 engineered systems and found that excess—the surplus in a component or system once necessities have been met—is a critical factor for achieving service-phase evolvability. An initial exploration by the authors used decades of empirical knowledge to identify a subset of excesses for a nuclear carrier and explored how these excesses mapped to the expected lifespan of the system [14]. However, the question remains of how to identify the relevant excesses for any design problem when decades of guiding information are not available. This paper addresses this question by developing a method to map and quantify excess relationships within an engineered system.

Section 2 of this paper reviews design research literature pertaining to the modeling of component interactions and functional flows that provide a framework for identifying and mapping excess. This review is used to develop a method that identifies, quantifies, and represents excess. This approach is described in Sec. 3. Section 4 demonstrates the implementation of this approach on a consumer heat gun. Finally, conclusions and future work are discussed in Sec. 5.

2 Modeling Component Interactions and Flows

Techniques for managing the change of a system's architecture have received significant attention in the literature. For example, the foundation for research in changeable systems [15] is that flexibility is a system property that enables effective configuration modifications in response to uncertainties [16,17]. From this definition, many different measures of flexibility and changeability have been proposed. Rajan et al. [18] introduced a change mode and effects analysis procedure that considers the number of parts/modules, potential causes of change, potential changes, and the possible effects of the changes. Flexibility is then rated on a 1–10 scale and, when combined with a measure of occurrence, is used to calculate a change potential number. Koh et al. [19] use a similar procedure in that the designer identifies the dependencies between system components and estimates the effort associated with making a system change. To complete this process, designers must consider where changes initiate, how the changes propagate (both directly and indirectly), the likelihood of a change occurring, and the redesign effort associated with achieving the desired change. Techniques like those by Koh et al. and Rajan et al. excel in providing a measure by which different changes to a system can be compared but require subjective estimates about system flexibility and the impact of realizing the proposed changes.

Other works have explored system flexibility from a real options perspective, where decisions must be made about when (if at all) to exercise a predetermined change to a deployed system. Suh et al. [20] integrated change propagation concepts with component interaction matrices and real options analysis to assess which components in a product platform should be made flexible. This work demonstrated how achieving flexibility generally requires an initial increase in investment but can potentially suppress change propagation and lower switching costs. Expanding on this idea, Cardin [21] explored how thirty different design procedures supported design for flexibility across the tasks of baseline design, uncertainty recognition, concept generation, design space exploration, and process management.

Though none of the works specifically identify and/or quantify excess within a system, they closely relate to the questions of how much excess should be included, where it should be located, and how it can facilitate system changes. Perhaps, the closest work related to discussing excess are the guidelines to support product evolution developed by Beesemyer et al. [7] and Tilstra et al.

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[22], after studying existing products. A subset of these guidelines includes maintaining clearances and usable area, designing tunable components, and providing energy storage/importation capabilities. The implication of these guidelines is that excess within a system is needed when responding to changing requirements. For example, the B-52 has taken on many roles during its lifetime [23]. Originally designed and deployed in 1955 as a long-range nuclear strike bomber, the role of the aircraft has shifted to include low-altitude conventional bombing and serving as a platform for standoff weapons [23]. These role changes were enabled by the payload capacity associated with the airframe, the ability to expand the payload volume via the "big belly" modification, and a reinforced interface structure between wings and fuselage [23–25].

The hypothesis driving this work is that limitations to evolvability occur where components are incapable of accommodating changes to flows within the system. Therefore, modeling excess requires identifying the proper scope of system architecture and then characterizing and quantifying the flows between components.

2.1 Modeling Component Interactions. Design structure matrices (DSM) [26,27] were originally created to aid task planning but have been expanded to include additional detail about component relationships. Pimmler and Eppinger defined four classes of component interactions: spatial, energy, information, and material [28], while Sosa et al. [29] later added a fifth class of interaction, structural. Other researchers have used DSMs to create tools that quantify the risk of a proposed design change [30–32]. In these works, risk is the likelihood of a change occurring multiplied by its impact on redesign (how much work must be redone) [33]. Advancing this concept, Pasqual and de Weck [34] developed a change propagation network using information from the coupled product, change, and social domains.

Tilstra et al. [35] proposed a high-definition design structure matrix (HD-DSM) methodology with the intent of analyzing system flexibility for future system evolvability. Changes are mapped to the correct domain by making the DSM three-dimensional, such that each face applies to a particular domain. The domains are not only largely sourced from the functional basis defined by Hirtz et al. [36] but also used information from the DSM developments in Refs. [28] and [29] to add proximity and alignment (from the spatial domain), and strain energy, to account for direct component interactions. Figure 1 shows sample HD-DSM faces for a heat gun in the electrical energy, gaseous material, and thermal energy domains. Marked cells in a DSM (gray in Fig. 1) indicate a relationship or change dependency between components. Since each component affects itself, the diagonal of a DSM bears no useful information and is marked out.

Representing the system architecture at a component level is useful for defining an appropriate scope of analysis for evolvable system design. An apparent limitation of DSM-related approaches is that quantifiable information associated with component interactions is not available. Sosa et al. [37] introduced an equation to quantify the interface strength between two components, which measured the absolute criticality of interface interactions. However, criticality of interface interactions does not describe if the interface is incapable of accommodating flow changes—either in type or in magnitude. Therefore, modeling excess also requires the identification and quantification of flows between components.

2.2 Functional Decomposition. Functional decomposition characterizes the functionality of the system without requiring a specification of components to describe how that functionality will be realized [38]. Block diagrams are created where the blocks represent the functions of the system (rather than individual components or subsystems), and the arrows that pass between the blocks are labeled with the flow they represent [39], as in Fig. 2. Flows are characterized as being an energy flow, material flow, or information (signal) flow. To standardize the nomenclature associated with a functional decomposition, Hirtz et al. [36] developed a reconciled functional basis for functional flows and the functional vocabulary pertaining to system operation.

Applying functional decomposition approaches toward an exploration of system evolvability was discussed as necessary ongoing research in Ref. [40]. In making the case for functional decomposition, they state that functional changes to a system are likely after being put into service, and a good system overview will help designers manage and understand system complexity. The challenge of interface management when evolving a system is specifically discussed, as components can be replaced or modified to alter system functionality. This discussion ties directly into the concept of excess, as alterations of system functionality could involve modifying the flows or the addition or removal of flows. However, it is difficult to quantify flows in a functional model because a functional representation of a system does not describe how well the system achieves a function. Yet, it is possible to quantify the flows entering or exiting a component. For this reason, it is proposed that excess occurs at component interfaces when incoming flows can be accommodated at a greater magnitude than what is currently required. This requires the functional flows of a system to be described, but rather than representing the system as a functional diagram, a component flow diagram is used so that excess can be quantified.

2.3 Design Margins and Factors of Safety. The notion of excess can also be seen in the discussion of design margin. In Ref. [41], a design margin is described as "the extent to which a parameter exceeds what it needs to meet its functional requirements regardless of the motivation for which the margin was included." Often design margins are included to ensure proper operation of the system in the presence of uncertainty. Thunnissen builds on this idea by describing design margin as the quantity of surplus placed to mitigate uncertainty in the design process [42]. In this context, design margins were explored by considering how they should be probabilistically allocated to both design and

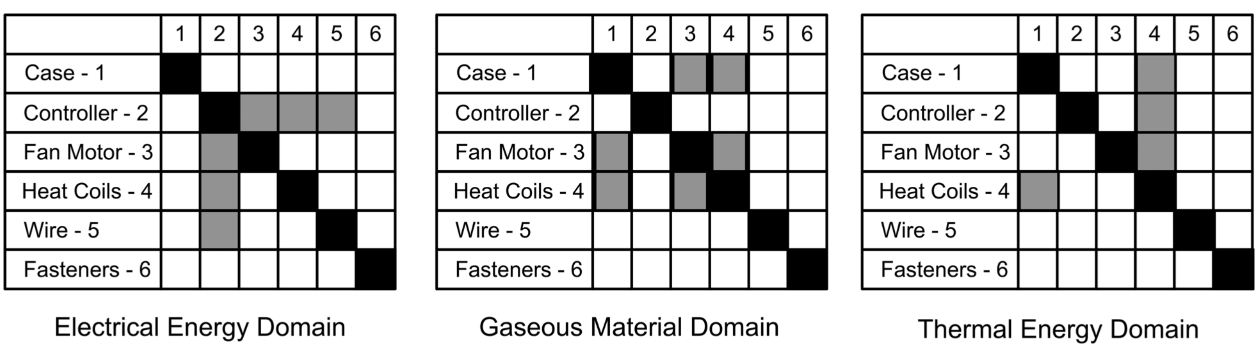

Fig. 1 Sample HD-DSM faces for a consumer heat gun

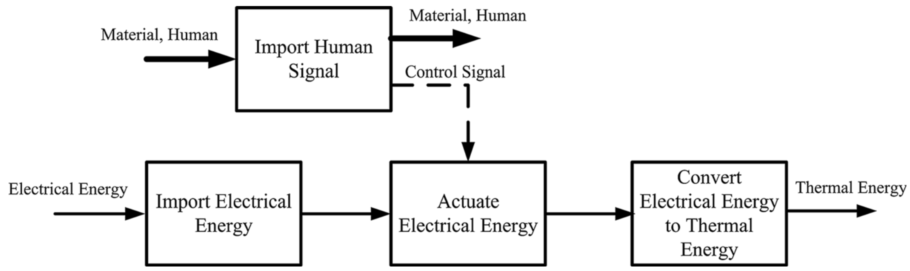

Fig. 2 Portion of a functional diagram for a heat gun

organizational parameters to allow for the successful completion of the original design.

From this review of the literature, it was concluded that a component–flow diagram could enable the mapping and quantification of excess within a system. A systematic treatment of excess must also address the functional flows of a component. Therefore, pertinent to this work is the set of functional flows described by Hirtz et al. [36]. Mapping flows through a component diagram of the system will identify component interactions that must be considered. Section 3 of this paper builds upon this structure and explains how excess is identified, quantified, and represented.

3 Approach for Modeling and Quantifying Excess

Excess is deliberately included in a system for reasons characterized by four categories. The first three categories—deterministic, epistemic, and aleatory—are differentiated by their associated uncertainties. The fourth category, consequent, originates as a byproduct of other design decisions.

- Deterministic excess is expected to be consumed over the course of the system's lifetime based on original system requirements. An example is the thickness of sacrificial plating that is expected to corrode while the system is in service.
- Epistemic excess is strategically incorporated to address future needs that are not yet realized but could reasonably occur during the system's lifetime. When making design decisions, designers might draw from sources such as institutional experience, expected technological trends, expected market trends, etc.
- Aleatory excess is concerned with future needs that are emergent and cannot be predicted by extrapolation or inference from available sources of information. This excess is used when an unpredictable future need emerges during a system's service life. Currently, no method exists to guide the placement of aleatory excess.
- Consequent excess results from using standardized components that exceed required capabilities. Examples include standardized fasteners and commercial-off-the-shelf components. These excesses may not be of significant quantity but can still be used to meet future needs.

The excesses within a system allow it to evolve while in-service and allow the system to maintain value for stakeholders over time. However, for excess to be a useful measure in design, decisions must be made about the resolution at which to consider excess in a system. This section describes an approach for identifying, quantifying, and mapping excess within a system. As this approach is designed for use during or after the embodiment phase for the original system, designers have access to stakeholder specifications, system architecture, and component parameters. A flowchart of the proposed approach is shown in Fig. 3.

3.1 Step 1: Identify System Components. Excess within a system occurs either at component interfaces or as a property of the component itself. Therefore, excess directly relates to the system architecture and the specifications under which those components operate. For excess to be meaningful and useful in the design process, it must be relatable to system or component requirements. The extent to which these requirements are described may pertain more to some components/subsystems than others, requiring a decision about the level of system resolution. At the lowest level of resolution, the components may represent the key modules of the system architecture. At the highest level of resolution, the designer would consider even the smallest possible system part (screws, transistors, etc.).

Detailed and rich representations of the system architecture will provide greater insight into where excess is present in a system. However, this comes at a cost of greater modeling complexity. This complexity may not be necessary for those components that are externally sourced, where the greater concern is the excess that exists at the interfaces with other components [43]. It is likely that different subsystems will be described at different levels of detail.

3.2 Step 2: Create Component–Flow Model for the Existing System Architecture. Every component carries out at least one function. Therefore, every component also has at least one input and output flow. Leveraging the advancements in functional decomposition, these flows can be characterized as energy, material, and signals. To maintain consistency with the established literature, the reconciled functional basis flow set developed in Ref. [36] is used as shown in Table 1.

To complete this step, a designer should describe the flows that exist between components, particularly where they interface. Once these flows have been identified, they can be characterized as entering and/or exiting each component, as shown in Fig. 4. This mapping is completed across all components so that an initial excess map can be created. Initial excess maps highlight the component–flow relationship that exists within the current system architecture.

There may be system-level specifications that do not directly map to an individual component or flow. For example, system mass is the sum of all system components. If system mass is defined as a hard constraint, a designer may consider the excess mass remaining when modifying system architecture. However, treating system-level requirements as hard constraints may not be part of an effective design process [44], and designers should explore the trades behind these requirements to understand which configurations lead to the greatest value.

While the flow between certain components can be easily described using an input/output relationship, the mapping for some components—like screws and bolts—can be more challenging. The function of a screw or bolt is to secure two objects, and the limiting factor is the load that it can withstand before failure. That load is created by mechanical energy transmitted to the screw or bolt from another component, or external to the system.

3.3 Step 3: Quantify Flows and Determine Interface and Component Capabilities. The next step is to quantify the capabilities of the components and the component interfaces. If the original system architecture is a valid configuration, then every component can handle the type and amount of flow that comes

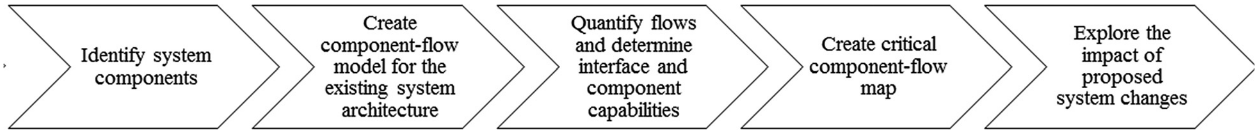

Fig. 3 Formalized excess mapping approach

into it. Further, the output flows from each component are of a proper type and magnitude so that compatibility is ensured with the other interacting components. These flow values are a lower bound, and some components are capable of handling more flow than currently demanded of them. The difference between the current flow and what the component is capable of receiving is considered excess. From a component perspective, every flow can be linked to a component parameter at an interface as shown in Table 2. These excess component parameters are similar in nature to the power conjugate complements defined by Hirtz et al. [36] for energy flows. While the power conjugate complements were defined as a means of providing greater detail of the flow description, the excess component parameters listed in Table 2 extend beyond energy and are specified to be measurable parameters. Further, this table intends to be an exhaustive resource linking functional flows to excess component parameters. Future work will need to explore a large number of systems to ensure this table captures all links between function flows and excess component parameters.

To provide an example, thermal energy will flow from a hotter component to a colder component due to their proximity in the system. While the units of heat energy are calories or joules, the ability for the component to properly receive the flow is not directly dictated by this number. Rather the maximum temperature of the component is a limiting parameter. If the heat flow is too great, the component will exceed its viable operating temperature and could melt. Therefore, the excess in the component due to an incoming flow of thermal energy is the temperature increase that could be accommodated. Similarly, the excess component parameter for a flow of material is the volumetric flow, unless it corresponds to a human body part.

It should be noted in Table 2 that there is no excess component parameter for a flow of signal in the form of a status. The rationale for this decision is that status signals primarily interact with the external environment and that no excess is linked with this interaction. Additionally, future work is needed to better understand and characterize the link between a flow of biological energy and component excess.

For each component, a component–flow diagram can be created with the excess component parameters identified. An example of this diagram is shown in Fig. 5. To construct this figure, the component name is placed at the center of the block. Then, the incoming and outgoing flows are defined. For this example, there are incoming flows of thermal energy, pneumatic energy, and electrical energy. Where the flow intersects the component boundary, two different values are listed. The upper value for each flow is the current operating state for the original architecture. Underneath this value, and in parenthesis, the maximum possible component parameter value is listed. By definition, excess at that interface is then calculated as the difference between the maximum possible value and the current operating state.

A similar structure is used for outgoing flows. Here, the excess in an outgoing flow represents the difference between what is leaving the component and what the component is capable of exporting. For some flows, it may be very difficult to calculate the upper limit as this number could be orders of magnitude higher than the current operating state, and it would not be reasonable to expect that number to be obtained. In these cases, the limit is represented by a double asterisk to highlight where excess exists in a component but is very unlikely to serve as a bottleneck.

In addition to the excess associated with flows, there is a geometrical excess for each component. This geometrical excess arises from scenarios where a component nests other components, and an interior volume remains. The interior volume that is not occupied could be used to increase the size of an internal component or to add a component that increases product functionality. However, since geometric volume does not flow between components like a material, energy, or signal, excess geometric volume is listed below the name of the component. If multiple regions of excess geometric volume exist, they are listed separately since a simple summation of this number presents a false indication of the available volume.

Table 1 Reconciled function flows (from Ref. [36])

Category	Type
Signal	Status
	Control
Material	Human
	Gas
	Liquid
	Plasma
	Mixture
	Solid
Energy	Human
	Acoustic
	Biological
	Chemical
	Electrical
	Electromagnetic
	Hydraulic
	Magnetic
	Mechanical
	Pneumatic
	Radioactive
	Thermal

3.4 Step 4: Create Critical Component–Flow Map.

The objective of mapping component excess is to identify limitations when the requirements of the system are extended beyond their original values. As this work is motivated by an interest in system evolution, components that cannot handle an expanded boundary of operating requirements must either be changed or the entire system should be replaced. However, if a large number of components and flows are identified for a system, it is possible that the component–flow diagram will be too cumbersome and burdensome to use.

Placing a focus on the component excess parameters that could constrain the evolution of a system will provide a designer with the most relevant set of information. In this step, a designer can

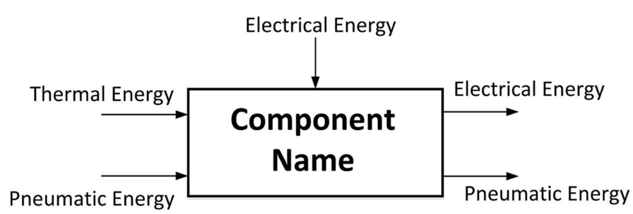

Fig. 4 Component–flow representation

Table 2 Linking functional flows to excess component parameters

Category	Type	Excess component parameter
Signal	Status	—
	Control	Transfer rate, analog or discrete
Material	Human	Body part
	Gas	Volumetric flow rate
	Liquid	
	Plasma	
	Mixture	
	Solid	
Energy	Human	Torque, force, frequency
	Acoustic	Frequency, amplitude
	Biological	—
	Chemical	*p*H, reactivity
	Electrical	Voltage, current
	Electromagnetic	Intensity, flux
	Hydraulic	Pressure
	Magnetic	Force
	Mechanical	Torque, force, frequency, RPM
	Pneumatic	Pressure
	Radioactive	REM
	Thermal	Temperature

eliminate flows from the diagram that would not impact system evolution. For example, while a power cord will output thermal energy, at the maximum possible operating current, the thermal energy created would not be enough to raise the temperature above the maximum operating temperature. Analysis of each flow and component excess parameter will allow for a reduced component–flow map to be created, if desired.

3.5 Step 5: Explore the Impact of System Changes. A fully realized component–flow map allows for modifications to be explored. These modifications could involve changing the magnitude of a flow, the change of a component, or the addition of a new component to the system architecture. By using excess, it is possible to determine the extent by which the requirements can be modified or whether a proposed change is possible. It is also possible to determine existing bottlenecks in the system architecture that may limit performance changes.

Two conditions can arise that require the excess map to be updated. Either the architecture changes in a way that alters the presence and/or arrangement of components depicted in the map or system specifications have been added or removed. The addition or removal of requirements could alter the map by affecting the components and/or relationships that must be represented. However, an already present requirement that is modified could change the amount of excess indicated by the map but not require the map to be altered. Rather, a modified requirement results in requerying the map to determine how excesses are affected.

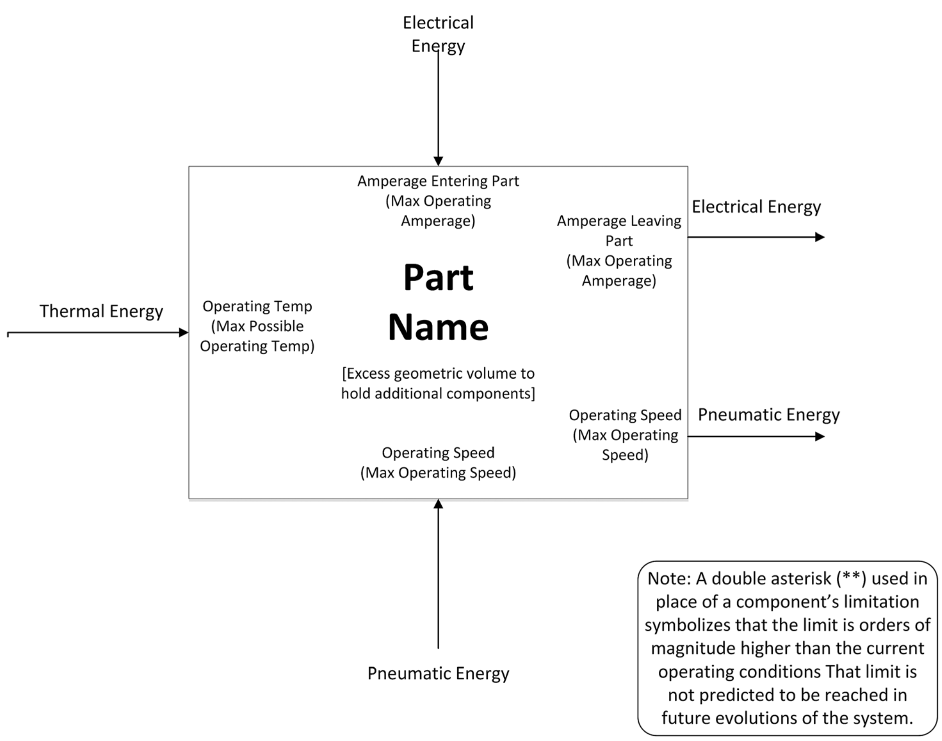

Fig. 5 Component–flow model structure

4 Implementation of Proposed Approach

This section demonstrates the approach for constructing an excess map by using a consumer heat gun. While containing a relatively small number of components, the interactions between the thermal, electrical, and mechanical domains make analysis of the system quite complicated. The objective of this demonstration is to highlight how changes to a system can be explored in the context of excess without the need for complicated simulations and analysis. Rather, the understanding of excess can highlight the important interactions between system components, and this information can then be used to guide the designer when running advanced simulations.

The heat gun used in this work was the Wagner HT1000 [45]. It operates in the 1.2 kW power range with two heat settings: 400 °C and 540 °C. Weight of the item was 5.78 N, and the air flow was reported to be between 350–425 L/min at low and 700–800 L/min at high speed [46]. The current of the device in operation was measured, and a value of 10 A was confirmed at 120 VAC. The mapping process follows Fig. 3 and the steps in Secs. 3.1–3.5.

4.1 Identify System Components. The individual components for the heat gun were identified as the switch, power cord, wires, motor, fan, nozzle (Fig. 6), heating element, and the case and cover (Fig. 7). While the components could be further decomposed, this level of granularity was selected because these components would be purchased from suppliers and/or involved in future evolutions of the system.

4.2 Create Component–Flow Model for the Existing System Architecture. Incoming flows to the system are the

- electrical energy from the wall to the power cord
- air (material) that comes in through the case vents
- human energy to the case so that the system can be held by the user
- human energy needed to move the switch to different control locations

Outgoing flows to the environment are the

- air (material) that is heated and expelled through the nozzle
- air's associated pneumatic energy exiting from the nozzle
- thermal energy exiting from the cover, the nozzle, and the case
- visual, olfactory, and auditory signals that indicate the current status of the heat gun

Having identified the input and output flows of the system, the focus shifts to mapping the flows between components. For brevity, the component–flow model for two components is shown in this section. Figures 8 and 9 show the basic component–flow representation model for the heating element and motor. The remainder of the basic component–flow representations can be found in the Appendix. Air material, electrical energy, and pneumatic energy are incoming flows to the heating element. The process of heating leads to thermal energy and electrical energy being output. For the motor, an input of electrical energy is converted into rotational energy, thermal energy, and a visual and auditory signal. Combining the flows from each component, a full component–flow model can be constructed, as shown in Fig. 10.

4.3 Quantify Flows and Determine Interface and Component Capabilities. The heat gun was dissected so that the manufacturer specifications for each component could be identified. When a component, such as the case, did not have manufacturer specifications available, the operating conditions were determined from a best estimate (such as material composition).

Switch:	Rated for 13 A current, and 125 °C operating temperature. Minimal human energy needed to operate.
Power cord:	Rated for maximum 15 A current and 60 °C maximum operating temperature.
Wires:	Rated for maximum 16 A current and 200 °C maximum operating temperature.
Motor:	Rated for 8.6 A current, 60 °C operating temperature, max output of 12,500 RPM at no load, and a stall torque of 41.2 mN·m [47].
Fan:	Material is assumed to be ABS plastic with a melting temperature of 105 °C [48]. Fan can withstand any reasonable input speed from the motor and can move as much air as the speed of the motor allows.
Nozzle:	Material is assumed to be stainless steel, so melting temperature is around 1397 °C. The amount and speed of air that can pass through the nozzle is limited by the capabilities of the motor.
Heatingelement:	Rated for 16 A current. The melting temperature of nichrome is 1400 °C [49], the ceramic is at least 1000 °C [50], and the mica board can withstand 700 °C [51], giving a 700 °C operating temperature. Element can also withstand any amount or speed of air that would reasonably be passed over it.
Case:	Material is assumed to be ABS plastic with a melting temperature of 105 °C [48].
Cover:	Material is assumed to be ABS plastic with a melting temperature of 105 °C [48].

Two key challenges of, and a main driver of the value associated with, engineering design are understanding where relationships exist between components and then determining how these relationships influence component behavior. By identifying the

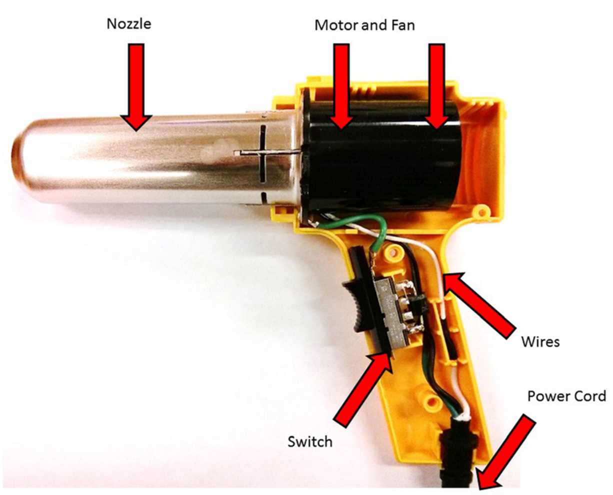

Fig. 6 Internal components of the heat gun

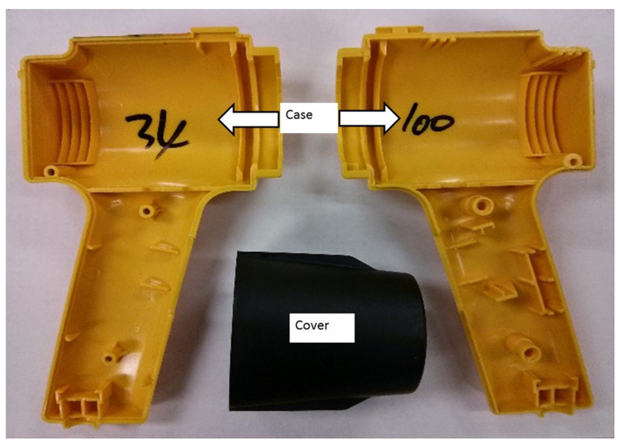

Fig. 7 Case and cover (numbers written by manufacturer)

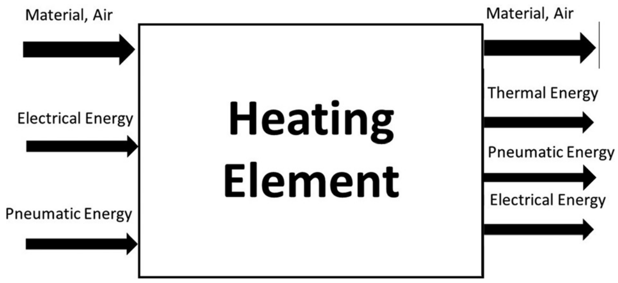

Fig. 8 Component–flow representation for the heating element

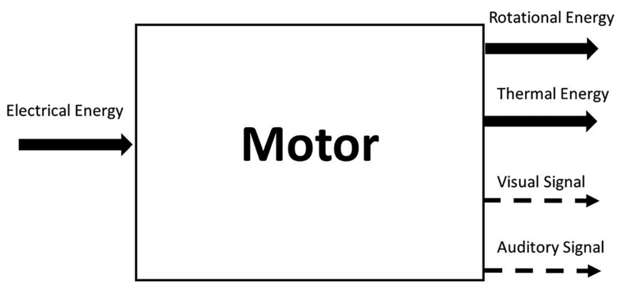

Fig. 9 Component–flow representation for the motor

critical flows that exist between components and using this information to quantify the excess existing at relevant corresponding component interfaces, this approach provides a way to explore the significance of component interactions. For the heat gun, this process begins with the construction of the component–flow models using the format described in Fig. 5. For brevity, only the model for the case and motor are presented in Figs. 11 and 12.

4.3.1 Motor. For the motor, there is an electrical energy input of 1.76 A, which is well below the 8.6 A maximum rating of the motor. Output flows from the motor include rotational and thermal energy; output signals from the motor have been removed in this figure. Using a Fluke VT04A Visual IR Thermometer [52], the temperature of the motor casing was found to be 28 °C. From the motor specification sheet [47], the rotational speed of the motor was established to be 10,380 RPM at maximum efficiency, producing 7.9 mN·m of torque.

4.3.2 Case. Input flows to the case are the thermal energies from the switch, wires, and motor. The temperature of the case was measured at multiple locations. The hottest temperature recorded was 31 °C at the barrel of the case where the nozzle, barrel, and case intersected. This number was slightly higher than the surface temperature of the motor. Part of this difference could be explained by the fact that the system had to be opened (as in Fig. 6) to get a temperature reading of the motor. Exposing this surface to air could have reduced the temperature reading. However, even with a few degree Celsius variation, there is a large amount of excess between the allowable operating temperature and the current operating temperature.

Air flows into the case at a rate of 800 L/min which was reported from the Wagner website [46] at the maximum output on the high setting. Human energy is inputted into the system to support (hold) the system. The upper limit on these flows is represented by asterisks. It is likely that any evolution of the system would not exceed the upper limit for the amount of human energy needed to support the system. Rather, the amount of human energy needed would be a tradeoff handled by the designer after customer preferences for system weight are determined. For air flow, the case does not limit the air flow into the heat gun. The limit is established by the motor and fan. The temperature on the outside surface of the case was measured to be a maximum of 30 °C.

There is volumetric excess because the case nests components. This volumetric excess is distributed between the barrel section around the motor and in the grip section beneath the switch. The barrel has an empty back space for air intake by the fan, a middle section that houses the fan and motor, and shelf rings at the front to mount the fan/motor combo as well as the end of the nozzle.

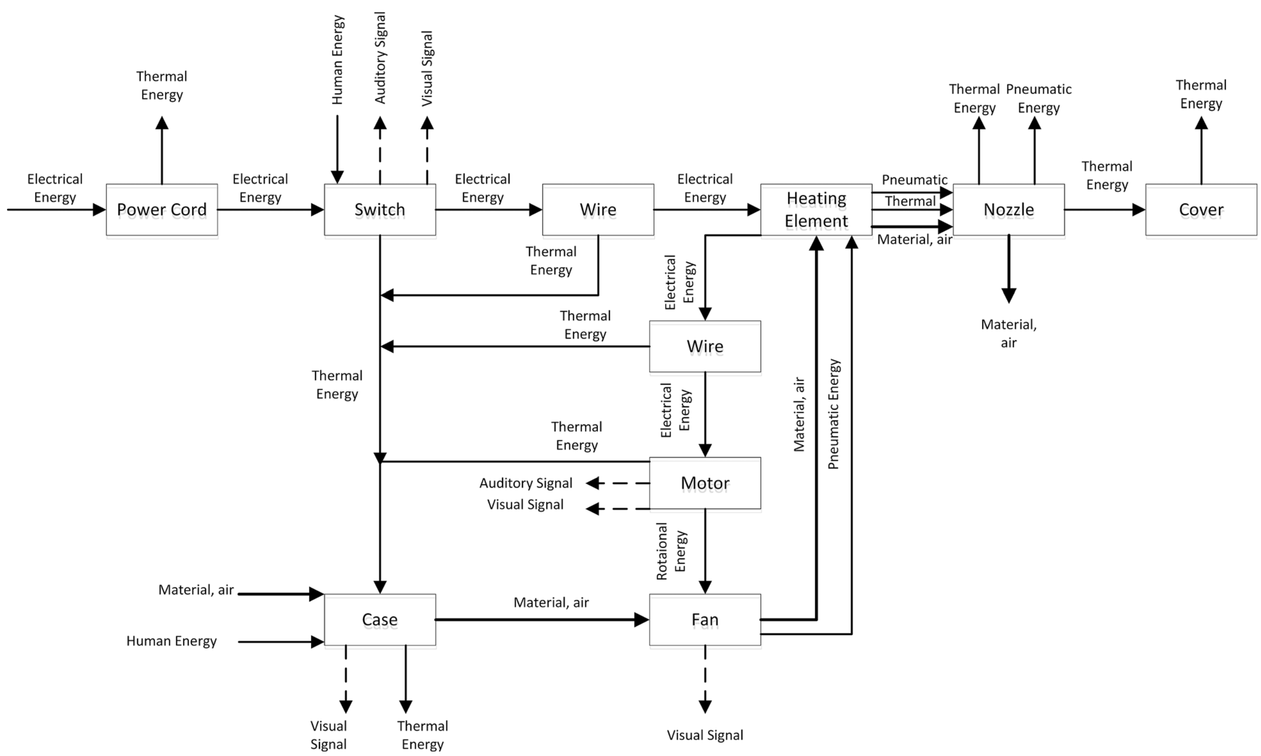

Fig. 10 Component–flow representation of the heat gun

While the back space is unoccupied, it is not considered excess because it is necessary for air intake. While the full length of the barrel section is occupied by the fan and motor housing, there is a ring of unused area surrounding the housing. The outside diameter of the fan and motor housing is 4.76 cm, while the inside diameter of the barrel section of the case is 6.03 cm, so there is a ring with 68.37 cm^3 of excess in the barrel section. Moving down the case, the grip section houses the switch and the wires. On both sides of the casing, there are also pins and connectors that attach the sides together, so those areas are not considered excess. However, below the switch in Fig. 6, there is 16.13 cm^3 of volume that could be used.

4.4 Create Critical Component–Flow Map. The analysis conducted in Sec. 4.3 was completed for each component. However, to make the component–flow map more accessible for the user, the irrelevant flows have to be removed. Using the quantified flow information, the following flows were removed from the map for each component:

Switch:	The switch releases a small amount of thermal energy. However, the amount of thermal energy released is very difficult to calculate. Readings from the visual IR thermometer were that the temperature near the switch was around 28 °C. This temperature differential would be seen by the case, but it was also not the temperature hot-point. Further, this temperature is well below the threshold of receiving a burn in an infinite amount of time (45 °C) [53].The auditory and visual signals were removed because they were outputs to the environment that had no upper bound. Also, the switch required minimum human energy, so this flow was removed as human energy would not be a limiting factor in future evolutions.
Power cord:	A small amount of residual heat is created during operation. The resistance of the wire is 6.385 Ω per 1000 ft. [54] and the cord is6 ft. in length. The power created is 3.831 W, and if the device runs for 20 min, the energy is 4.597 kJ. Assuming that the specific heat of dry air is 0.716 kJ/kg K, the density of air is 1.3 kg/m^3, and the insulation is 90% efficient, the temperature increase would be 1 K/m^3 of dry air. At maximum current flow through the cord, this thermal energy would never heat the cord beyond its operating temperature or cause a significant rise in the surface temperature where it could harm the user.
Wires:	Wires pass electrical energy between components and, consequentially, create a minimal amount of thermal energy. The resistance of the wire is 4.016 Ω per 1000 ft. [54] and the wire is 6 in. in length. The power created is 0.2 W, and if the device runs for 20 min, the energy is 0.24 kJ. Assuming that the specific heat of dry air is 0.716 kJ/kg K, the density of air is 1.3 kg/m^3, and the insulation is 90% efficient, the temperature increase would be0.025 K/m^3 of dry air. The thermal energy released in comparison to the maximum operating temperatures of the other components is very small and does not need to be considered further.
Motor:	Status signals for the motor are auditory and visual. These flows are eliminated from the excess map because the visual cue does not have an upper bound and the noise level of the motor alone is not close to the discomfort level of human hearing (more than 100 dB sustained over 15 min [55]).The thermal energy output from the motor is small in comparison with the maximum operating temperature of nearby components and can be removed from the map.
Fan:	Status signals for the motor are auditory and visual. These flows are eliminated from the excess map because the visual cue does not have an upper bound and the noise level of the fan was measured to be 80 dB on the high setting. The plastic fan can spin as fast as needed and move as much air and create as much pneumatic energy as the motor allows. All flows in and out of the fan can be excluded in the excess mapping process.
Nozzle:	The nozzle can handle an amount of air more than any future evolution would require. Both pneumatic energy and air (material) can be excluded from the excess map. The noise level of out the front of the system was measured to be 95 dB at the high setting.
Heating element:	The speed of the air and amount of air traveling over the heating element is controlled by the fan/motor combination and the size of the case.
Case:	The output thermal energy, air material, and signals may be eliminated because they are going out to the environment and are not close to the upper bound. The case also requires human energy, but this is eliminated because future evolutions would not cause the heat gun to be too heavy to lift.
Cover:	No flows were eliminated.

Having eliminated irrelevant flows from consideration, the reduced component–flow map with critical excesses is presented in Fig. 13.

4.5 Explore the Impact of System Changes

4.5.1 Modification 1: Replace Tri-Mode Switch With Variable Voltage Switch. One possible modification is that a consumer may desire a continuously variable heat output. There are at least two different solutions to this problem that could be pursued. In the current system architecture, the switch controls the amount of current going to the heating element and the motor simultaneously. A designer could replace the original switch with a dial that can modify the current flowing through the system. From the excess map presented in Fig. 13, the replacement dial must be able to pass at least 10 A, which is the current design amperage. Additionally, there is the 16.13 cm^3 of volume remaining below the current switch that could be used for the additional components needed for the dial switch.

A second solution would be to add a dial somewhere on the case exterior. A wire to this dial would have to be added and a variable resistor would be needed to control the current to the heating element. The heating element would have to be decoupled from the motor speed, and the designer would have to use the excess current within the system to ensure proper operation. A challenge of this solution is the limited space available for the dial switch and its components in the rest of the system. The designer would have to leverage the 1.27 cm wide ring (68.37 cm^3 of volume) around the fan and motor components to place the necessary equipment.

4.5.2 Modification 2: Increase Output Temperature. A second modification could involve increasing the output temperature. Achieving this requires increasing the current to the heating element. Consulting Fig. 13, the entire system is capable of handling a 3 A increase in current (from the original 10 A), with the switch being the first limiting factor. The components that have to be replaced at new desired current ranges are shown in Table 3.

Increasing the current to the heating element—and the other components in the system—does not come without additional

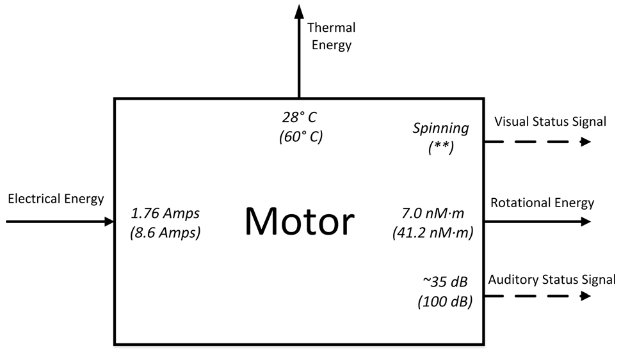

Fig. 11 Quantified component–flow diagram for motor

design ramifications. There will be additional thermal effects that must be assessed to ensure that the design modifications do not exceed the operating temperature excess associated with each component. While the details of this analysis go beyond the scope of this paper, the excesses shown in Fig. 13 indicate that the ability to increase the current of the system would be the limiting factor well before the operating temperature of the components were exceeded.

5 Conclusions and Future Work

The objective of this paper was to introduce an approach by which the excesses that exist within a system could be identified, quantified, and used to explore the feasibility of proposed system modifications. A review of the literature demonstrated that DSM-based approaches consider system architecture at the component level, identify interactions between components, but provide little quantitative information. Quantitative approaches that do exist focus on characterizing the strength of the component interaction, often as having a positive or negative correlation. Functional decomposition approaches explore the interactions within a system architecture by focusing on functional flows, and the quantification of flows as a tool for exploring system evolvability was identified as an area of needed research.

The approach presented in Sec. 3 establishes a five-step procedure that leads to the creation of a quantified component–flow diagram. Component definition begins with the designer establishing the appropriate level of detail that should be considered. The level of component detail considered in this step can be driven by the extent to which the system is modular or by the types of components that can be purchased from suppliers. A basic component–flow diagram is created to identify component interactions and the types of flows that must be quantified. Quantification of flows focuses on characterizing the current flow value and the maximum value that can be tolerated by the component while maintaining feasible operation. To reduce map complexity, non-critical flows can be identified and removed. The resulting component–flow diagram reveals where excess is present in components so that possible modifications to the system can be explored.

As shown in the consumer heat gun example, the strength of this method is that it offers a designer insight into the governing flow relationships between system components and identifies the excess that remains at critical component interfaces. This approach is not intended to provide a detailed analysis similar to that of advanced computer simulations. Rather, the identification and quantification of excess are intended to provide a designer with insights that can guide the conceptual design process associated with modifying a system in response to changing customer requirements. This challenge is clearly shown in the heat gun example.

Motor performance curves and analyses linking the electrical, fluid, and thermal domains would be needed to validate the final design. Yet, this approach demonstrates that the heating element is capable of taking additional current to produce additional heat, the motor is capable of providing additional torque to the fan, and none of the components are near a critical operating temperature. Increasing the current to these components could produce a larger output temperature, and modification options to the switch could be pursued that provide greater flexibility to the end user. Further, a strength of this approach is that it can be used to identify where excess does not exist within a system. This information can be used to support designers when specifying the technical requirements of a new component that is being designed or purchased off-the-shelf.

Future research in this area should explore the dissection of additional products so that designers can better understand the types and quantity of excess that commonly exist within a system. Trends should be explored to identify correlations associated with

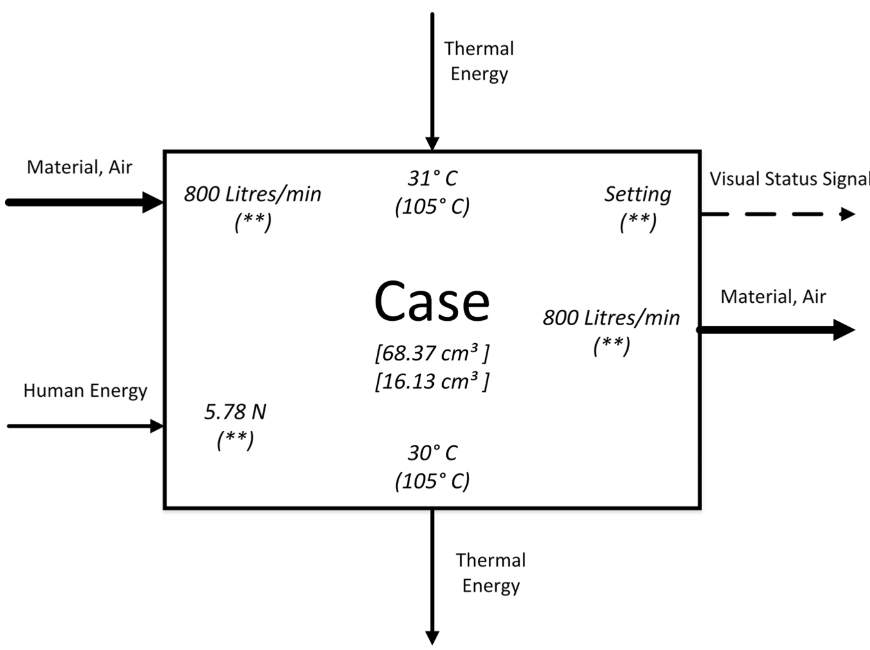

Fig. 12 Quantified component–flow diagram for case

Table 3 **Components to be replaced with increased current range**

Current Range	Components replaced
10–13 A	None
13–15 A	Switch
15–16 A	Switch and power cord
16 A and above	Switch, power cord, wires, and heating element

product type, number of system components, targeted market segment, and domain of application. Exploring additional products will allow a rigorous analysis of how to best handle scenarios where system-level specifications do not directly map to individual components. Additionally, research is needed to investigate if relevant flows for this approach can be more efficiently identified by linking them to the functional requirements of the system.

Then, there is a need to explore methods capable of informing designers about where excess should be placed so that it has the greatest benefit. This will require the quantification of expected performance benefits, likely obtained through conceptual design studies. Advancing research in this area will provide the capacity to measure system evolvability and give designers a greater ability to create systems that effectively respond to changing customer needs after the system has been put into service.

Research should also explore how this approach can be extended to complex systems. An early hypothesis is that, much like in functional decomposition, the component–flow diagrams could be created at different levels of abstraction. While this procedure offers advantages in terms of managing diagram complexity, establishing the appropriate component abstractions so that necessary information is not lost must be explored.

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Appendix: Basic Component-Flow Representations for Each System Component

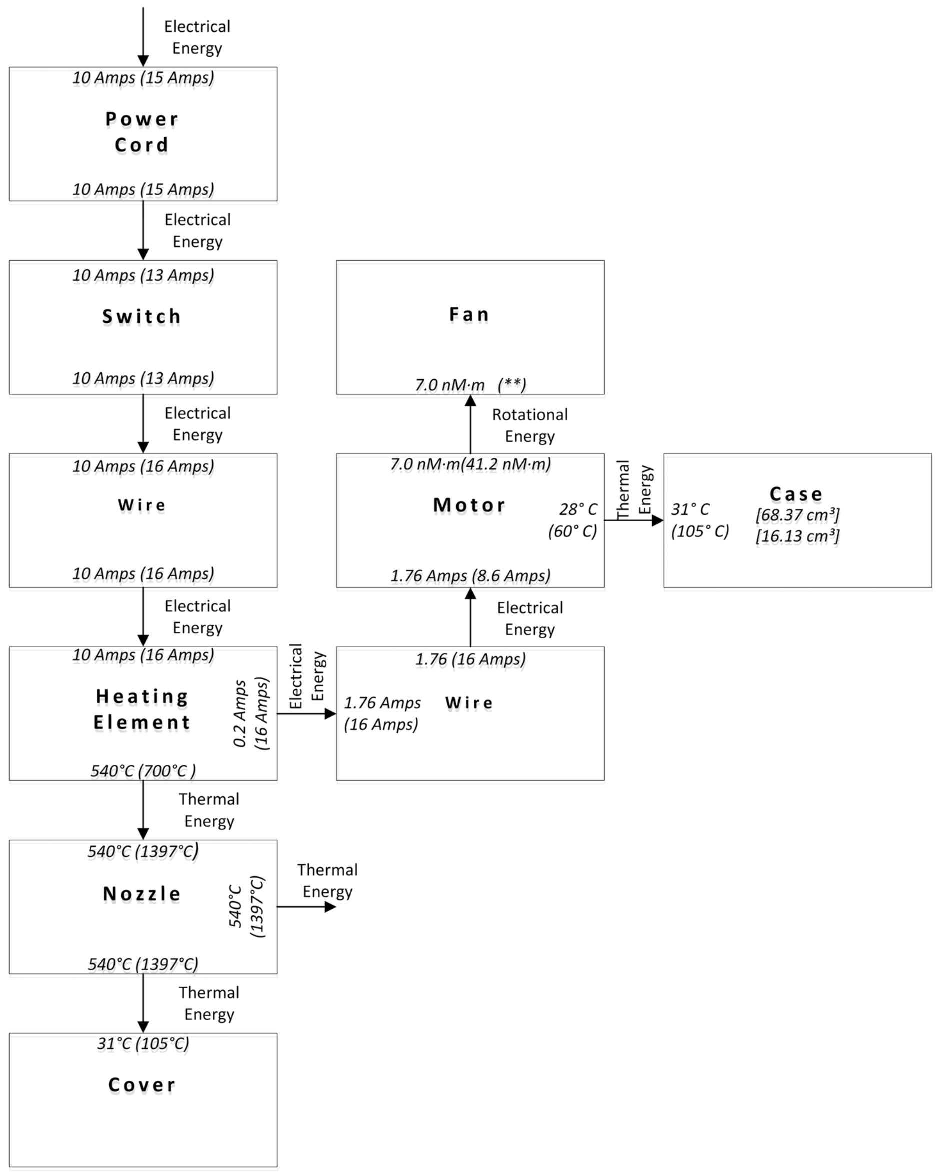

Fig. 13 Critical component–flow map for the heat gun

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