ABSTRACT

CANSLER, ETHAN ZACHARIAH. Identifying, Mapping, and Exploring Excess Relationships in Engineered Systems Relevant to Service Phase Evolution. (Under the direction of Dr. Scott Ferguson).

Engineers understand that attaining a full service life can add value to an engineered system. Ensuring that this is possible requires that excess be embedded within the design phase to enable system evolution when new or changed requirements are placed on it during the service phase. However, since future needs are by definition unknown, knowing with certainty which excesses to embed is impossible. This thesis addresses two research questions. The first concerns how excess in component relationships can be mapped throughout a system in a manner relatable to system stakeholder needs, thereby producing the set of excesses that affect system evolvability. This is accomplished by considering and selectively combining elements from existing techniques in the design literature for modeling systems and system change to develop a quantified flow diagram method for mapping excess within a system. The method is demonstrated using four case studies: a heat gun, a coffee maker, a toy dart gun, and a string trimmer. The second research question addresses how knowledge made available by the creation of a system excess map coupled with a set of potential future needs reveals if a design possesses sufficient excess to respond to future needs, and if not, where the shortcomings are. This approach is demonstrated using the toy dart gun. Results from the case studies show that the excess mapping method can successfully identify excesses throughout a system relevant to stakeholder needs, and that the stress test approach can successfully demonstrate the location of potential shortcomings in a design.

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Identifying, Mapping, and Exploring Excess Relationships in Engineered Systems
Relevant to Service Phase Evolution

by
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BIOGRAPHY

Ethan Cansler graduated as valedictorian of Franklin High School in Franklin, NC in 2009. He then studied at the University of Tennessee as a founding member of the Haslam Scholars Program, and worked as a student engineer at Oak Ridge National Laboratory's Spallation Neutron Source, until graduating Magna cum Laude in 2013 with a Bachelor of Science in Aerospace Engineering. In the fall of 2013 he began graduate studies at North Carolina State University in the System Design Optimization Lab under Dr. Scott Ferguson.

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Chapter 1: Introduction

Designs are created in response to market opportunities that are driven by the identification of customer needs. As the design process advances, needs are mapped to numerical specifications, which are in turn translated to a system architecture [1]. However, the environment in which a system operates, and the needs that it is responsible for satisfying, may change over the service life of the system. Changes to initial needs, or the identification of new needs, after the design has been fielded are hereafter referred to as 'future needs'.

1.1 Evolvability

The B-52 is one system that has successfully been able to respond to future needs. Originally designed and deployed as a long-range nuclear strike bomber in 1955, it is expected to serve until at least the 2040s [2]. Between its original introduction and now, the role of the B-52 has shifted from a high altitude nuclear strike bomber, to a low altitude conventional bomber, to a platform for standoff weapons [3]. The ability to take on 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 reinforcing the interface structure between wings and fuselage [4].

In contrast, the F/A-18 is a system that has failed to meet future needs. The F/A-18 was originally introduced in 1983 as a joint attack and air superiority fighter. Over time the needs that the system faced changed due to developing technologies. These needs included the ability to return unused smart weapons to the carrier rather than dropping them at sea unused (thereby placing additional load on the landing structures) and the requirement to accommodate a greater volume of electronic warfare equipment. An updated version of the plane deployed in 1995 was redesigned so thoroughly that there is only 10% commonality between the original and new airframes [5]. Such a drastic redesign indicates that the original system was not capable of evolving to meet future needs due to factors including insufficient structural capacity of the landing gear and insufficient volume available within the fuselage.

Ideally, all engineered systems would maintain value for system stakeholders by satisfying future needs and ensuring continued system operation. In this research the ability to maintain value when faced with future needs is made possible by service phase evolution – formally defined as the ability of a system to physically transform from one configuration to a more desirable configuration while in service. The motivation for evolvability research is based on the belief that systems capable of service phase evolution possess greater value over their lifespan than those that are not [6].

Other approaches in the literature to ensure that a system is capable of meeting future needs include reconfigurability [7] and robustness [8]. However, these approaches have shortcomings, particularly for systems that are expected to be in service for a significant amount of time. Implementing reconfigurability is a choice made in the design phase that explicitly allows aspects of the system to assume a range of configurations. These configurations can be a set of fixed points or a bounded range on a continuum. Airfoils that incorporate flaps and/or slats to change the wing's flight characteristics is an example of reconfigurable design.

Robust system design seeks to make a system insensitive to variations in its operating environment, without any alteration to the system while in service – a valid approach, but one that expends more resources than would be necessary if the system could be strategically changed. However, achieving robustness is often accomplished by sacrificing system performance. This is done by finding a location in the design space where the objective function contours are relatively flat. Such a location in the design space is often not co-located with the design that maximizes or minimizes system performance. Further, as the projected system lifespan is increased, the envelope of uncertainty is also expanded, meaning that applying robust design theory to a system with a long projected service life and completely unknown future needs would result in a drastically over-built (or under-performing) system.

In contrast, evolvable design seeks to allow changes to a system that are not explicitly prescribed in the design phase. Prior work [9] has demonstrated that one of the significant contributing factors to evolvability is excess, defined as the surplus in a component or system beyond what is currently required of it. This concept of excess in introduced in the next section.

1.2 Nature and Origins of Excess

Excess is defined as surplus in a system or component beyond what is currently required of it [9]. These potential surpluses occur in inter-component relationships, or relationships between components and the external environment. Much like enthalpy and entropy in thermodynamics, there is no such thing as ‘absolute excess’. Rather, excess is a relative measurement of the difference between the capabilities of the designed system and design specifications. These relationships fall into one of three categories: flow (transmitted energy, signal, or material), structural (stress or strain) or geometric (occupied length, area, or volume).

In practical engineering terms, excess occurs in situations such as:

- wiring carrying only 7 A of current when rated with an ampacity of 10 A,
- a pressure vessel operating at 200 MPa when it is certified for 400 MPa,
- an equipment room holding 20 m^3 of hardware when it can contain 35 m^3.

The surplus embodied by the Factor of Safety (FoS) is generally considered to be independent from the excesses used for system evolvability. As an example, consider a structure made of material with a yield strength of 300 MPa. With a FoS of 3, the usable material strength is 100 MPa. If subjected to a design load that produces stress of 70 MPa, the excess within the structure is 30 MPa. The only situation where part of the FoS for a system may be converted to usable excess occurs when the FoS has been revised downward due to either overly conservative initial estimates or a less severe operating environment than originally planned.

Intentional inclusion of excess in a system might enable future changes, or their presence may be a side effect of other factors. A common example of the latter results from the standardized sizing of commercial components such as fasteners, wiring, or externally sourced components. Practically, it is inefficient to size each fastener exactly to the required load. Rather, the smallest sufficient fastener from a list of standard sizes is chosen, creating some quantity of excess. Another example comes from enforcing component commonality. The 2x4 lumber studs used extensively in residential construction are employed for both load-bearing and non-load-bearing walls for the sake of easier construction, even though for the latter application their full strength is unnecessary.

Since designers are incapable of knowing the future, the excess that is originally designed into the system may not be constant over time. Rather, the excess present in a systems may vary due to system evolutions or changes in system specifications while in service. When, lower than anticipated service requirements are realized, excesses are created in the components that are consequently underutilized.

1.3 Motivation

The formulation shown in Equation 1.1 was developed in [9] and refined in [10]. Here, evolvability E is expressed as a function of excess X, evolvability gain per unit excess g_x, and the upper and lower bounds of usable excess x_l and x_u. Excess and its upper and lower usable bounds have the unit of percent (%) of the normalized design quantity that is being measured, while the gain per unit excess has units of reciprocal percent (1/%). Two classes of US Navy aircraft carrier – the *Nimitz* class and the *Ford* class – were compared based on four parameters: displacement, volume, stability, and electrical power. These parameters were sourced from the decades of empirical design experience reflected in [11] [12]. It was found that the *Nimitz* class aircraft carrier had an evolvability of 19.2 yr-%, while the *Ford* class carrier had an evolvability of 257 yr-%. These units resulted from the fact that the US Navy measures aircraft carrier evolvability in hypothetical years of extended service life. When using Equation 1.1, the numbers that are produced have meaning when they are compared, as they represent the relative evolvability of different design options for a single system. Hence, the *Ford* class was demonstrated to be significantly more evolvable than the *Nimitz* class.

$$E = \int_{x_l}^{x_u} X \cdot g_x \, dX \qquad (1.1)$$

Examining Equation 1.1 suggests that two main factors determine a system's evolvability: excesses and their associated gain factors. However, depending on the resolution of the system analysis, a very large number of system excesses are possible, ranging from high-level parameters such as power generation to low-level parameters such as tensile strength of the screws affixing speakers to bulkheads. The demonstrative case study in [9], comparing two classes of US Navy aircraft carrier, benefited from decades of empirical knowledge that told designers which excesses were important to enable service phase evolvability. Practically speaking, such knowledge allows designers to embed suitable quantities of these excesses in the system. Clearly, a subset of the possible excesses that can be described for a system are sufficient to describe a system's evolvability; however, the question remains of how to identify such excesses for general systems that do not necessarily benefit from prior experience.

Another consideration driving selection of excesses is that they must be of the correct type, quantity, form, and location to be usable in bringing about system change [13]. This means that for an evolution to occur, there must be the right kind of excess in every affected component, there must be enough of it, it must be of the right form, and it must be accessible to the component that requires it to undergo the evolution. As a simplified practical example, an evolution to a building might require placing a new piece of equipment in a specific location. However, the evolution may only proceed if there is sufficient volume, energy, and load-carrying capacity at said location within the building, if these excesses are collocated with the intended equipment placement, and if these excesses are of the correct form – i.e. the excess volume is in a shape that can accept the new equipment, the energy is electrical and of the correct voltage and/or frequency, and the load-carrying capacity of the structural members can be interfaced with the new equipment.

Therefore, the question remains of how to identify excesses within general systems that are relevant to system evolvability. This leads to the first research question explored in this thesis:

Research Question 1:
How can the presence and quantity of excess pertinent to service phase evolution be identified?

Bearing in mind that excess can be described at different system resolutions, a strategy to identify the excesses in a system most likely to influence its evolvability is needed. Continuing with the aircraft carrier example, it is easy to accept that the total allowable displacement of the ship is a useful parameter. On the other hand, the thickness of the steel rods used in the deck railings is highly unlikely to have an impact on the ability of the ship to evolve. It is not hard to categorize those two excesses as relevant and irrelevant, respectively, because they are extreme examples. However, exactly where to draw the line between relevant and irrelevant excesses is not clear.

Designers are incapable of knowing with certainty the future needs a system will face. When considering system evolvability, a simplifying assumption used in [10] was that the top level functions of a system remain fixed. In simple terms, this means that an aircraft carrier will always transport and launch aircraft and a coffee maker will always brew coffee. This assumption could be used to reduce the scope of excesses considered for their contribution to evolvability to those that contribute to the current functions of the system, as future functions would be related.

As excess is consumed to meet future needs, deliberate placement of excess in a system must be a function of unknowable future needs. Blindly adding excess to components or subsystems (even if they are the excesses identified as pertinent to system evolvability) adds cost without guaranteed benefit, leading to decreased system value. These considerations lead to the second research question:

Research Question 2:
How can designers relate the quantities of the identified excesses to the system's ability to meet future needs?

There is limited discussion in the literature regarding the inclusion of excess to meet future needs. The available literature generally describes situations where designers draw on past experience designing similar systems, as in [11] [12]. However, there is a lack of guidance for systems without the benefit of empirical design knowledge.

Designers need a method to examine the evolvability of general systems. The outcome of Research Question 1 includes the set of excesses that designers will be concerned with when designing for evolvability and their present amounts. Yet, there is no insight provided into how useful (or valuable) these amounts are. Portions of a design with excess quantities that artificially limit the ability of a system to change, relative to the other available excess quantities, diminish the evolvability of the design and reduce the utility of other excesses. Therefore, the idea that a system design can be stress tested to find ‘bottlenecks’ for system evolution is investigated. Beyond identifying locations in which excess should be added, the similar idea of revealing excesses that are superfluous, i.e. those that support system changes surpassing those enabled by the other excesses, is explored.

Chapter 2 of this thesis reviews works of the literature that pertain to system excess, evolvability, system change, and methods of representing systems. Chapter 3 discusses the underlying theory of this work’s contributions, while Chapters 4 and 5 address Research Questions 1 and 2, respectively. Chapter 6 discusses conclusions from the products of the preceding chapters and opportunities for continuing work.

Chapter 2: Background

No analytical method exists in the literature with the ability to map or quantify excess for an engineered system. Yet, it is recognized that system evolvability is intrinsically tied to engineering change. Exploring how to manage change within an engineered system is a topic that has received significant attention in the literature. This chapter discusses research introducing the concept of excess, explores methods of modeling a system, and characterizes how changes propagate.

2.1 System Evolvability and Excess

The last few years of evolvability-focused design research have seen a progression from design guidelines to mathematical formulations. Work in [14] [15], for example, introduced empirically-derived design guidelines to enable future evolvability. These guidelines are centered around:

- system modularity,
- scalability,
- reduction of unnecessary parts,
- decoupling interfaces,
- maintaining clearances and usable area,
- designing tunable components,
- and providing energy storage/importation capabilities in excess of the original requirements.

Other work in the literature, such as [16], describes design margin 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". Thunnissen [17], on the other hand, describes 'design margin' as quantities of surplus placed to mitigate uncertainty in the design process. These margins were probabilistically allocated to design parameters and organizational parameters (schedule, cost and risk). This work, however, focused on how design margins should be assigned to impact the successful completion of the original design rather than how they might lead to system evolvability.

Moving toward a more mathematical framework, Tackett et al. [9] introduced excess as a variable controlled by designers, meaning that they had control over the amount of surplus present in each component of a system. Further work developed a mathematical formulation of system evolvability as a function of excess [10] as was shown in Equation 1.1. This work investigated excess in two classes of naval aircraft carriers, the older *Nimitz* class and the upcoming *Ford* class. The *Ford* class was estimated to be more evolvable that the *Nimitz* class when considering an upgrade from traditional steam catapults to electromagnetic catapults for launching aircraft. A limitation of this work, however, was that it benefited from empirical knowledge of naval design experts that defined the types of excess within a system and how evolvability was tied into service life [11] [12].

2.2 Change Relationships between Components

Quantifying the excess within a system is necessary if it is to eventually be used as a parameter when designing for evolvability. A specific target of the literature review was strategies that integrate numerical information about components associated with change. 'Engineering change' has been defined as occurring while the system is still being designed, and is defined as "an alteration to parts, drawings, or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time." [18]. Service phase evolution is by definition different from engineering change, as it occurs after the system has been constructed and deployed. However, system evolution requires redesign, and works exploring engineering change may be applicable when predicting the ability of a system to evolve.

2.2.1 Design Structure Matrices

In its most basic form a Design Structure Matrix (DSM) is a square matrix diagrams where each column and matching row correspond to a component or design task [19] [20]. They are used to represent dependency relationships; the columns represent the originating component or task while the rows represent the affected component or task. The information content of DSMs has been expanded to include additional detail about component relationships. Pimmler and Eppinger [21], for example, defined four classes of interaction: Spatial, Energy, Information and Material. Sosa et al. [22] added a fifth class of interaction, Structural. With these five classes, all relationships between components could be described. However, the presence of five different interaction types on a two-dimensional plot led to challenges of effectively conveying information.

In support of analyzing flexibility for future system evolvability, Tilstra et al. [23] developed the High-Definition Design Structure Matrix (HD-DSM) methodology to account for direct change propagation potential throughout a multi-domain engineered system. The HD-DSM methodology maps changes to the domain to which they correspond, significantly increasing resolution over the traditional DSM. It accomplishes this by making the DSM three-dimensional, such that each face applies to a particular domain. The domains are collected in an 'Interaction Basis' and are largely sourced from the functional basis defined by Hirtz et al. [24] but also correspond to those used in [21] [22]. The HD-DSM process reveals an interesting point: provided that two dimensions of the DSM structure correspond to originating and receiving components, the DSM structure can be extended to any number of dimensions.

Importantly, this approach solves the information presentation issue experienced in prior work while actually increasing resolution. Figure 2.1 shows sample HD-DSM faces for a heat gun in the electrical energy, gas material, and thermal energy domains. Marked cells in a DSM (grey in Figure 2.1) indicate a relationship or change dependency between components. Since each component clearly affects itself, the diagonal of a DSM bears no useful information and is marked out.

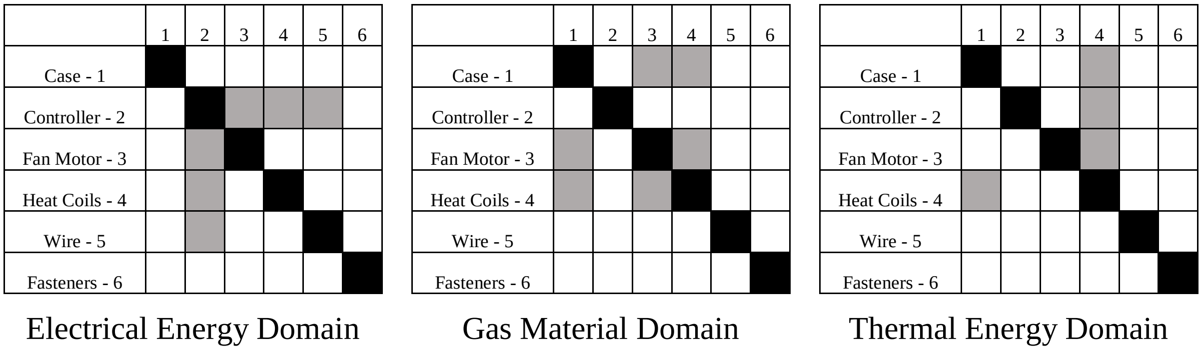

Figure 2.1: Sample HD-DSM Faces for Heat Gun

2.2.2 Change Propagation

A key segment of change research regards change propagation, which has been defined in the literature as “the process by which a change to one part or element of an existing system configuration or design results in one or more additional changes to the system, when those changes would not otherwise have been required” [25]. Clearly, change propagation is not desirable; ideally, a change to one component in a system design would never require change in another. Change propagation analysis has received increased attention in engineering design research because of the value associated with efficient change management in the system design process.

Eckert et al. [26], recognizing that some components will have a greater effect on system change than others, developed four classifications for components: constants, absorbers, carriers, and multipliers. Constants are unaffected by change and have no relationship with change whatsoever. Absorbers can absorb more changes than they cause and diminish change complexity. Carriers cause and absorb changes in roughly equal measure, and do not affect change complexity. Multipliers cause more changes than they absorb, and increase change complexity.

Researchers exploring change propagation must employ some form of network to account for the transmission of change from one node (whether component, designer, etc.) to another. The most basic form of change propagation analysis simply includes the information that one node changes another, without elaborating as to the nature or quantity of the change. Researchers have developed ways to encode more information into change propagation analysis, however. For example, Suh et al. [27] explored the use of quantified change propagation analysis to strategically embed product flexibility. Some forms of change propagation analysis target the overall risk to a design of change. Risk has been defined as the likelihood of a change times its impact on redesign (i.e. how much work must be redone) [28]. Tools have been developed to quantitatively describe risk, including the Change Propagation Method [29], RedesignIT [30], and a Matrix-Calculation-Based Algorithm [31].

Other researchers have sought to track changes over multiple domains; Pasqual and de Weck [32] developed a change propagation network that included information from the coupled product, change, and social domains. Over time, change propagation research has incorporated both more domains and numerical information to increase the resolution of the system change pathways being analyzed.

Change propagation analysis seeks to highlight sources of potential change to aid designers in minimizing its propagation. However, design for service-phase evolution mandates specific change(s) to specific component(s) and requires knowledge of physical component-specific parameters that change propagation analysis is generally not equipped to offer. Further, the presentation styles of change propagation analysis are typically not conducive to visualizing the impacts of a specific change or evolution throughout a system. To that end, other techniques from the literature were sought that are capable of representing an entire set of relationships between subunits of a system within a single view. The most promising candidate was functional modeling, as discussed next.

2.3 Functional Modeling

Functional models are a well-established method used to represent a system in terms of its functions and flows, rather than by the properties of its components. 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 functional flow they represent [33]. Of interest to this work is the concept of a functional chain, as described in [34], which identifies the main sub-functions of a system. For a dart gun, some of these function chains include converting human energy to kinetic energy of the dart, transmitting air from the atmosphere to the base of the dart (as propellant), and converting the aiming signal from the operator to a flight direction for the dart [33]. This approach allows a designer to consider what the system is intended to do. In an effort to standardize the nomenclature in a functional model, Hirtz et al. [24] developed a reconciled functional basis that addressed both the functional flows between components and the functional vocabulary pertaining to the individual components' operations. The ability to abstract a system has allowed functional modeling to be used for a variety of tasks that extend beyond pure conceptual design. For example, Kalyanasundaram and Lewis [35] used the functional models of two systems as the first phase in determining which functional flows would be shared in a unified product. Kurtoglu and Tumer [36] have also employed a functional model as a tool for evaluating functional-failure risk in systems in the conceptual design phase.

As a reference, a selected portion of a traditional functional diagram for a heat gun is shown in Figure 2.2.

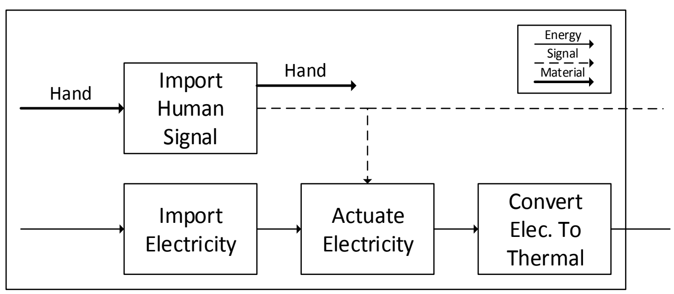

Figure 2.2: Portion of Heat Gun Functional Diagram

Similar to functional models are bond graphs, which are also simplified block representations of systems. However, bond graphs are concerned solely with flows of energy between components. Helms et al. [37] explored the use of computerized design catalogs in design synthesis applications via a modified bond graph architecture. This represents a fusion of block diagrams with equation-based physical effects. To be suitable for mapping excess, however, this method would also have to accommodate geometric and structural attributes.

While functional modeling is excellent for visualizing how flows of energy, signal, and mass travel through a system in terms of its functional blocks, there is no way to tell how these flows interact with the physical components of the system, nor are the flows quantified. Therefore, there are no provisions for the information that is needed when mapping excess – a physical architecture based set of quantified excess relationships (that include more factors than only flows of energy, signal, and mass).

2.4 Real Options Theory

Real options theory, originally used in the field of economics, has been adapted for use in engineering as described in [38]. A real option is the right, but not the obligation, to undertake a specific action. In the context of engineering, a real option is the ability to exercise a predetermined change to a deployed system, or in other words, a designed-in future evolution. Some works in the engineering literature [39] [40] have applied real options theory to the problem of maximizing system value when a finite set of future evolutions is known. However, the traditional formulation of real options analysis, reliant on a finite set of future needs, is incapable of analyzing systems with unknowable future needs.

2.5 Conclusions from Literature Review

Considering that excess will often occur in terms of base flows (energy, mass, or signal), a systematic treatment of excess must address the functional flows of a component. Therefore, pertinent to this work is the set of functional flows described by Hirtz [24]. This is divided between the three base types of flow—signal, energy, and mass—and sub-divided into specific types such as control signal, electrical energy, thermal energy, liquid flow, etc. Absent are geometric and structural parameters relevant to excess, but the involved flows are the same and already standardized in design nomenclature. While excesses observed in a system do not always belong to the energy, mass, or signal flow classes denoted in a functional diagram, aspects of the functional diagram method’s approach to flows do hold value for this work. Specifically, using arrows to map flows through a block-diagram based representation of a system, coupled with numerical quantification, is considered applicable to modeling excess in a system. It carries the additional benefit of being a visually accessible and intuitive means of tracking component relationships throughout a system, unlike with HD-DSMs.

Regarding DSM-based methods, though their visual arrangement is not suitable to mapping excesses in a system, aspects of their approaches are useful for mapping excess flows within a system. HD-DSMs assimilate information from any necessary domain, while change propagation approaches incorporate numerical information regarding component relationships. Since excess can occur in any component relationship, an approach capable of interacting with any domain is necessary. To standardize the domains of excess considered, a formal set of excesses, similar to the HD-DSM interaction basis, is also needed.

From this review of the literature, it was concluded that a form of quantified block-based flow diagram is a fusion of applicable characteristics from the published methods that satisfies the requirements of excess mapping.

Chapter 3: Foundational Theory

The preceding chapter detailed approaches in the literature pertaining to change and system modeling and analysis. This section details the underlying theory particular to the nature and treatment of excesses for enabling system change, and serves as the foundation of the work developed in Chapters 4 and 5.

The approach presented in this thesis is based on the assumption that future needs placed on a system are unknown, but bounded. Specifically, bounded means that the functional purpose of a function chain does not change over time. Such an assumption is supported by examples studied in the prior work of [10], wherein the demands placed on aircraft carriers over time did not shift the core purpose (launching aircraft) but did change the means by which that purpose was achieved (electromagnetic versus steam-driven catapults).

3.1 Categorizing Excess

Designers often deliberately include some quantity of excess for reasons discussed in the four categories below. The first three categories - deterministic, epistemic, and aleatory - are differentiated by their associated uncertainties, while the fourth category, consequent, originates as a byproduct of other design decisions.

- Deterministic excess is concerned with the excess that is expected to be consumed over the course of the system's lifetime based on original system requirements. A common example is the thickness of sacrificial plating that is expected to corrode in the service environment. Deterministic excess is assigned according to the environment that the system is expected to face and its designed service life.
- Epistemic excess is strategically placed within a design to address future needs that are not yet realized, but could reasonably occur during the system's lifetime. When placing epistemic excess, designers might draw from sources such as institutional experience, expected technological trends, expected market trends, etc.
- Aleatory excess is the most difficult to allocate, as it is concerned with future needs that are emergent and cannot be predicted by extrapolation or inference from available sources of information. This is the excess that is utilized when a wholly unpredictable

future need emerges in the course of the system's service life. No method exists to guide the inclusion of aleatory excess.

- Consequent excess occurs as a result of the presence of standardized components within a design that exceed required capabilities. Examples include fasteners and commercial off the shelf components that are chosen to accommodate standardized sizing, commonality, or to minimize redesign. These excesses may not be of significant quantity but can still be utilized to meet future needs.

If component relationships are considered, flows between components can be divided into two categories (as shown in Figure 3.1):

- Compatibility flows occur in the relationships required for a component to function, and always are shown as input flows. For an electric motor, compatibility flows could include the electrical current that the motor draws, the volume that the motor occupies, the ability to withstand/convey the waste heat of the motor away, the reaction torque from the motor, and the support reaction required for the weight of the motor.
- Functional flows occur in the functional outputs of components. These either become compatibility flows for other components or are system outputs across the control volume. For an electric motor, functional flows could include the torque and/or power that the motor develops, depending on which is important for the motor's particular application.

An implication of this classification scheme is that the indicated directionality of flow does not necessarily match that of the associated physical parameters. Rather, flow is always shown with the arrow pointing from the supplying component to the dependent component. An example of this behavior occurs when a component must dissipate a waste flow to operate. While the waste flow (of material, heat, etc.) is literally flowing away from the originating component, the arrow points from the component that dissipates the flow to the originating component. This is because the functionality of the originating component depends on the component that dissipates the waste flow.

Compatibility and functional flows are often linked, especially for components that transform input flow(s) of one type into output flow(s) of other type(s). As an example, consider an electric motor. If additional torque is required from the motor (one of its functional flows) it will require additional current (one of its compatibility flows). In contrast, as long as the same motor is used, the volume required to accommodate it (another of its compatibility flows) will not vary with the required torque. Critical to a system's functionality is the ability of each component to satisfy the requirements of any connected components. The presence of sufficient excess in each contributing component permits change to the desired performance characteristics of the system.

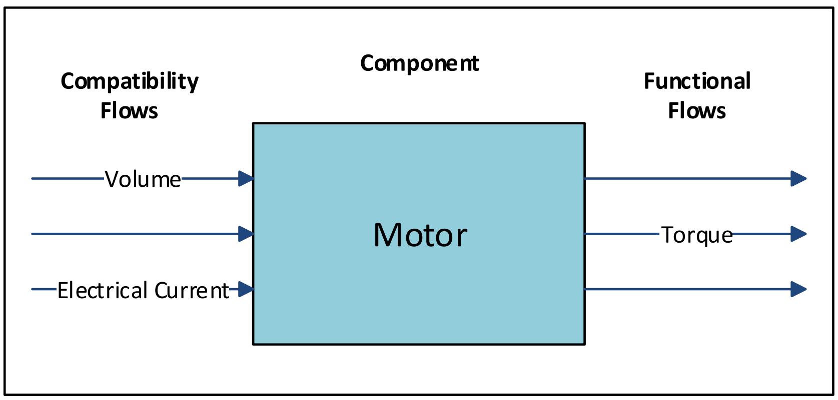

Figure 3.1: Compatibility and Functional Flows

3.2 Excess Basis

To effectively communicate in terms of excess, a unified vocabulary is necessary. This work defines a standard 'Excess Basis' to account for all possible types of excess present in an engineered system. To maintain consistency with the established literature, the reconciled functional basis flow set developed in [24] is used as the core of the excess basis, shown on the left side of Table 3.1. This basis is extended in this work to describe excesses that occur only in the context of stored properties. Two 'categorical' extensions and six 'type' extensions are needed, as shown on the right side of Table 3.1. The abbreviation scheme used in this thesis is shown in Figure 3.2.

Table 3.1: Excess Basis

Class	Category	Type	Abbr.
Flow or Storage	Signal	Status	S-S
		Control	S-C
	Material	Human	M-H
		Gas	M-G
		Liquid	M-L
		Plasma	M-P
		Mixture	M-M
	Energy	Human	E-H
		Acoustic	E-A
		Biological	E-B
		Chemical	E-C
		Electrical	E-E
		Electromagnetic	E-EM
		Hydraulic	E-Hy
		Magnetic	E-Mag
		Mechanical	E-M
		Pneumatic	E-P
		Radioactive	E-R
		Thermal	E-T
Storage only	Geometric	Length	G-1
		Area	G-2
		Volume	G-3
	Structural	Stress	S-σ
		Strain	S-ε

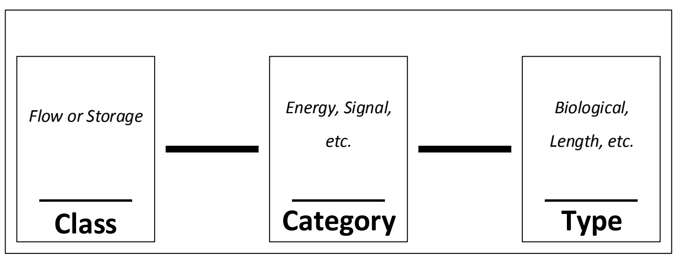

Figure 3.2: Naming Scheme for Excess Types

The first categorical extension is Geometric, with associated type entries of Length, Area, and Volume. These extensions were necessary because there was no provision for geometric characteristics in the existing flow set and they may not literally flow between components, as is the case with the parameters described in the original basis. For example, mechanical energy can flow through a shaft, material in gas form can flow through conduits, and control signals can flow through wires. However, the ability to describe geometric properties is crucial for characterizing certain excesses, and had been previously considered in work such as [21].

The second categorical extension is Structural, with associated type entries of stress (σ) and strain (ε). Structural excess occurs when an artifact could withstand a greater stress or strain than currently required. Component-level structural excesses may be consumed by other components within a system or by conditions imposed by the operating environment.

When describing structural parameters of components, the true excesses that are being consumed are stress and strain. However, designers may find it more convenient for certain applications to define state parameters such as Load, Pressure, and Torque to describe the structural excess relationships between components, with the understanding that such state parameters ultimately map back to the stress and strain characteristics of the materials. In view of these factors, the supplementary structural excess classification scheme shown in Table 3.2 is offered, and is used in the remainder of this thesis. As an example of why this ability is important, consider an artifact made via injection molding that has multiple ribs comprising a mounting interface for another component. While for a simple geometry such as a beam or shaft relating the loading capacity back to the tolerable stresses verges on trivial, the load tolerance of a more complex geometry cannot be so easily determined. Allowing designers to calculate the maximum loading conditions for a particular artifact once will therefore ease the use of the method by reducing the amount of required recalculations each time a differing load is considered.

Table 3.2: Structural Excess Optional State Parameters

Category	**Type**	**Abbr.**
Structural	Load	S-L
	Torque	S-T
	Pressure	S-P

The Geometric and Structural categories comprise the set of excesses that may exist solely within the Storage class, as none of the excesses described therein may flow between components. Inversely, any excess that can be classified as a Flow may also exist as a Storage, as anything that flows can also be stored. Since applied loading conditions cause strain energy to develop within artifacts, the Structural category can be viewed as a storage of strain energy [23].

Examples of all the signal, material, and energy flows described on the left side of Table 3.1 may be found in [34]. Each of these flows can also be stored and measured in some fashion. Signals can be recorded, the means of which depend on whether the signal is auditory, visual, electronic, etc. Material can be stored in an appropriate vessel; the units to use will depend on the material in question. Uncompressed gas would likely be measured in volume, while compressed gas would likely be measured in mass. Liquids and solids could be measured in mass or volume depending on which is more useful for the situation at hand. Storage of the varied energy types can always be measured in Joules or lbf. However, designers may find it more useful to adopt a similar treatment as for the stress-strain structural relationships described previously. In this way, stored thermal energy could be measured in Kelvin or degrees Fahrenheit, stored hydraulic energy could be measured by its pressure head, and stored pneumatic energy could be measured by its pressure, all with the understanding that the total energy being stored in each case is ultimately measured in the base units of energy.

The associated units for the stored properties on the right side of Table 3.1 are self-evident and depend only on whether the designer is working in the metric or imperial system and the scale of the artifact being designed (i.e. cm^3 would be appropriate for the volume of a small pressure vessel while m^3 would be appropriate for the volume of a room). However, which geometric excess to use for a given situation may depend on the designer's interpretation of the particular case. Consider that all objects exist in three dimensional space, with accompanying excess of volume. However, sometimes the pertinent excess in a design is the length that a component can extend to, or the area that can be used for the mating of two friction surfaces. Situations such as these mean that a three dimensional relationship can be distilled by designers to a concise description of the pertinent geometry for the particular instance of excess.

3.3 Resolution of Excess Flows

As stated in the motivation discussion of Chapter 1, excess can be described at ever increasing levels of resolution. Yet to be useful in the design process, decisions about the resolution at which to describe excess must be made. While some information and fidelity is lost in a simplified model, this process is similar to using a Taylor Series Expansion (TSE) to locally approximate system behavior with a reduced order function [41]. Stated another way, a TSE neglects higher-order terms that add complexity to the model but offer little significant information.

This work adopts this philosophy. As an example, consider an aircraft carrier. Top level excesses such as displacement or power generation are unquestionably relevant to the overall excess present in the system. However, the screws affixing speakers to bulkheads are irrelevant in terms of system excess, as they do not directly contribute to the primary functions of the system, are insignificant to replace if needed, and most importantly for this method, add information that does not aid designers in their exploration of system evolvability.

The set of excesses found for a particular system are important because their presence and their values will be a major factor in the ability of the system to evolve while in service, and therefore to maintain value for stakeholders over time. In practice, the component excesses considered will be a function of system architecture, customer needs and resulting system specifications. Additionally, the desired representation of the architecture chosen (i.e. the resolution for the overall system as well as for individual subsystems and components) will play a role; a system might be represented using its five major subsystems, or three of the subsystems might be further expanded while the other two remain black boxes because they are externally sourced. These factors are further discussed in the next chapter.

Chapter 4: Developing a Mapping Approach for System Excess

This chapter presents a method for constructing system maps of excess between subsystems, while using a consumer heat gun, depicted in Figure 4.2, as a demonstrative example. This method is intended to be used in parallel with the embodiment design of the original system, so that designers may explore the effect of excesses on the ability of the system to change as the original design progresses. As such, designers will have access to all of the information associated with the system design, including stakeholder needs, specifications, system architecture, and component parameters.

In this method, subsystems are abstracted as blocks with pertinent excess flows identified. Therefore, the inner workings of the subsystem can be treated as a black box. This ability is important for two main reasons. First, designers will often not need to analyze a system at the lowest level of assembly (i.e. fasteners). Second, designers may be using externally sourced components whose inner workings are not controllable by the designer. Here, each subsystem will be referred to as a component in an excess map, even if the subsystem could be further decomposed. The approach is detailed in the following sections. A flowchart giving an overview of the steps to map excess relationships throughout a system is shown in Figure 4.1.

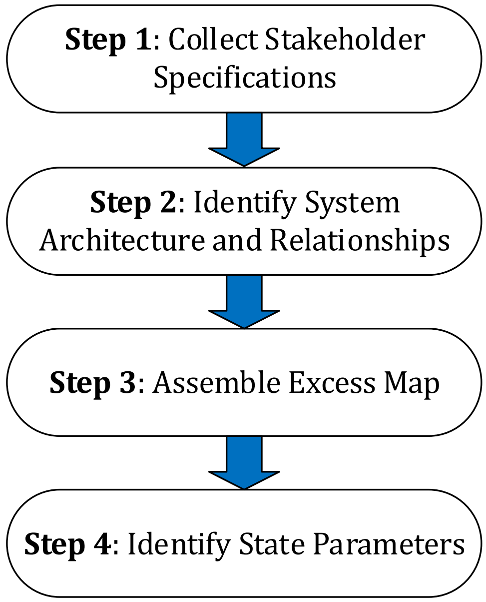

Figure 4.1: Excess Mapping Procedure

Figure 4.2: Heat Gun [42]

The heat gun analyzed was a basic consumer model in the 1200 W power range with two heat settings corresponding to 400 °C and 540 °C (T_{out}), based on the assumption of a 20 °C operating environment ($T_{ambient}$). The current draw of the device in operation was measured, and a value of 10 A as advertised on the packaging was confirmed. A temperature-independent specific heat of air at constant pressure (c_p) of 1.0 J/(g-K) was assumed for all calculations in this section.

4.1.1 Step 1: Collect Stakeholder Specifications

For component-level excesses to be meaningful and useful in the design process, they must be relatable to specifications as defined by system stakeholders. This is because the specifications are the quantified embodiment of stakeholder needs, and are what is expected to change in response to future needs. Numbers chosen to complete the specifications should be target values (the minimum that any design is expected to yield). These are available to designers in the embodiment design phase. The product of this step is a requirements list of quantified specifications in engineering language. These comprise the datums against which system level excesses are measured.

Case study example

In the absence of direct customer needs information, it was assumed that the customer needs were captured by the company producing the heat gun. Therefore, a subset of the customer needs are:

- Produce air sufficiently hot to melt plastic, desolder circuits, loosen floor tile adhesive, etc.
- Produce enough heated air flow to quickly accomplish tasks
- Be lightweight enough to use with one hand
- Be compatible with North American household electrical circuits

Based on the above customer needs, the following specifications were determined:

- Maximum output temperature ≥ 540 °C
- Total mass ≤ 500 g
- Power ≥ 1.0 kW
- Power ≤ 1.4 kW

The lower bound on the power draw was established to ensure a sufficient flow of energy to the work piece. Consulting the available heat gun models on the market indicated that a minimum bound for power is 1000 W. Assuming a mass flow rate of 2 g/s of air (the same as the example heat gun consumes) a 1000 W input results in an output temperature of 743 K or 520 °C as given in Equations 4.1 and 4.2.

$$T_{out} = T_{ambient} + \frac{I \cdot V}{c_p \cdot \dot{m}} \tag{4.1}$$

$$= 293\ \mathrm{K} + \frac{1000\,\frac{\mathrm{J}}{\mathrm{s}}}{1.0\,\frac{J}{gK} \cdot 2\,\frac{g}{s}} = 793\ K = 520\ °C \tag{4.2}$$

In this equation, T_{out} is the output temperature of the heat gun, $T_{ambient}$ is the ambient air temperature, I is the current feeding the heating coils, V is the main voltage, c_p is the specific heat of air at constant pressure, and $\dot{m}$ is the mass flow rate of air.

The upper bound was established based on the assumption that the user will be powering it from a household circuit with a 15A breaker, that the breaker's maximum continuous load is 80% of its rating per code [43], and that nothing else is operating on the circuit while the heat gun is being used. Since the vast majority of the current drawn by the heat gun is a resistive load, the assumption was made that

$$P_{max} = 15\ A \cdot 120\ V \cdot 80\% = 1440W \tag{4.3}$$

4.1.2 Step 2: Identify System Architecture and Relationships

The first decision made by the designer is the overall level of abstraction desired in the system excess map, or in other words, the intended level of assembly to be mapped. This decision is informed partly by the requirements list, which may pertain more to some components/subsystems than others. A starting point is the highest level of abstraction that separates the major components displaying modular behavior.

If subsystems exhibit enough complexity, further expansion may be required. However, designers may externally source some components, placing a lower bound on the level of abstraction of their representation [44]. Different subsystems may be described at different levels of abstraction for these reasons. Figure 4.3 demonstrates how a component representation can be expanded (or condensed) when needed in the course of mapping excess.

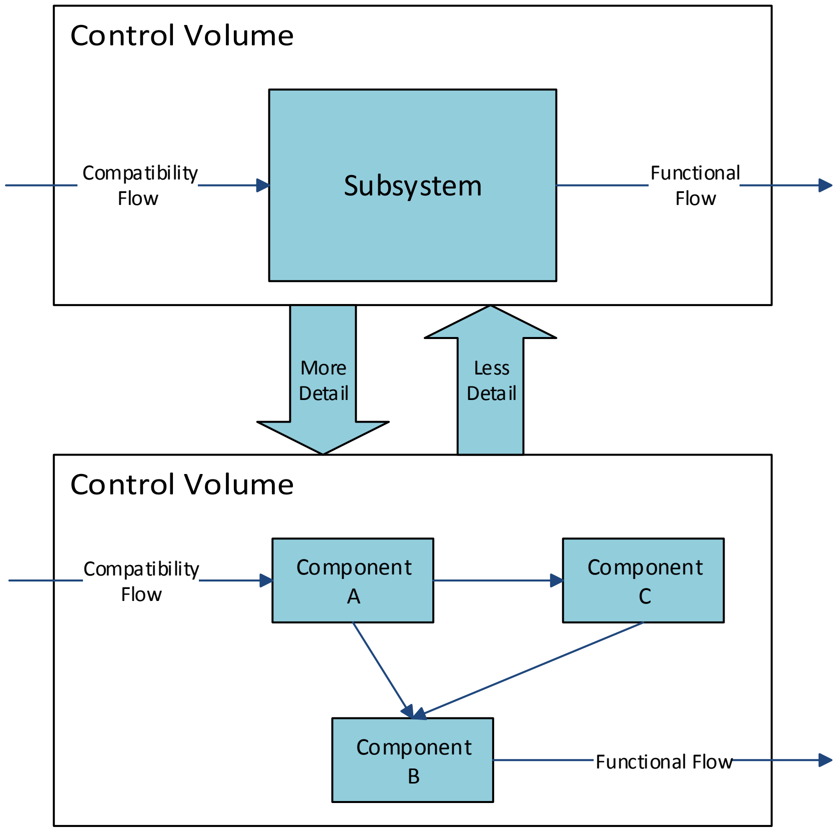

Figure 4.3: Variable Level of Abstraction

This step determines the component blocks and flows that populate the excess map, as well as the control volume that delineates the system from the external environment. Components, indicated by primary blocks, are square-edged rectangles. The excesses produced by components, shown in secondary blocks, are indicated by attached snipped-edge rectangles. The excesses are categorized and labeled as shown in using the abbreviations denoted in the left-most and right-most columns of Table 3.1. A visual example of a component block with attached excess blocks is shown in Figure 4.4.

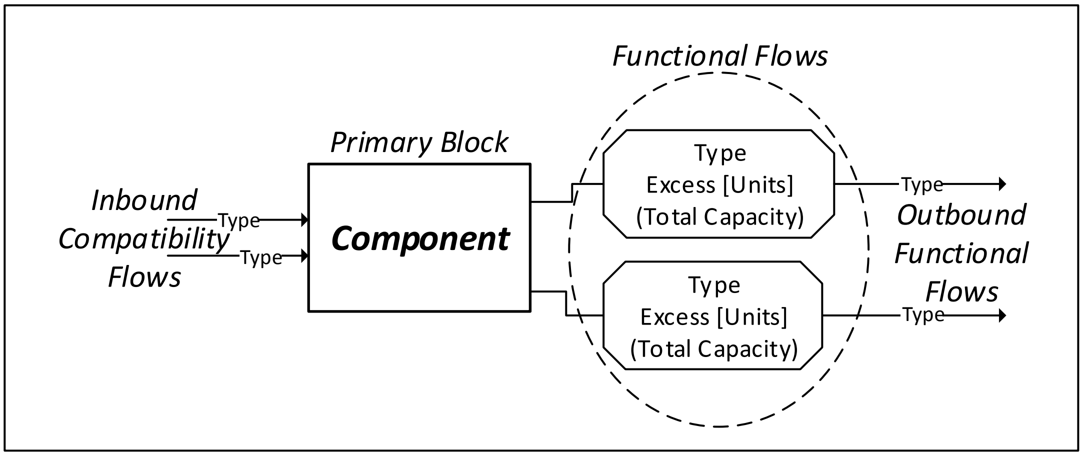

Figure 4.4: Excess Map Segment for General Architecture

First, each component is considered individually and the types of compatibility (input) and functional (output) flows are determined. This is done by consulting the original design information for the purposes and requirements of each component. Then, the values associated with these flows are quantified.

Some compatibility flows, such as an input of electrical energy that is converted by a component to an output of heat energy, are a function of the required functional flow values and will change if the functional requirements of the component are later altered. Other compatibility flows that are static properties of components (typically Storage class excesses such as loads or geometric requirements) are updated only if a different component is selected as replacement. Some components will produce excesses that are linked; i.e. utilizing one of the associated excesses will diminish another. This is indicated by drawing a double-ended arrow between the two excess blocks.

Once the compatibility flow requirements of all components are satisfied by functional flows from other components or the environment, the map's set of excesses is provisionally complete; all explicitly necessary excesses have been documented. However, it is possible that some excesses have been implicitly assumed. The final activity in this step is to take each component in turn and consider every possible excess from the Excess Basis. This forces the designer to consider the task of identifying relationships from a different perspective, and allows those that were not immediately clear to be captured. This activity reveals relationships driven by inter-component requirements that may have remained implicit, such as the requirement of a container to withstand the heat generated by internal components.

Case study example

The physical boundaries of the heat gun were used to define the control volume. Specifically, any energy or signal passing into or out of the device, whether electrical energy from the power grid, human energy from the operator, or heat from the nozzle, was viewed as crossing the control volume. The components selected were the self-contained subsystems: namely the case, controller, cord, fan, heating coils, and nozzle.

An important activity of this step is the selection of appropriate units for excess. The excess basis intentionally does not assign units to excess types, since the most appropriate/useful way to express a particular excess type is dependent on the situation at hand. In the case of a heat gun, it would be valid to describe the thermal excess of the nozzle in terms of Watts of dissipated energy. Most meaningful, however, is expressing the energy of the heated air in terms of its temperature in degrees Kelvin. This avoids the intermediate calculations that would be required to relate the thermal energy to a temperature threshold for the constituent materials of the heat gun.

Next, the excess blocks and flows are quantified, demonstrating the method's incorporation of numerical information. Normally, these values are available directly from the information of the embodiment design phase. For example, the internal volume of the case would be available from CAD files and the amperage draw of the heating coils would be known from the chosen component. Information regarding amperage input, ambient air temperature, and output temperature is used with the relationship given in Equation 4.1 to calculate thermodynamic properties of intermediate excess flows such as the mass of air which is heated.

Each component is discussed separately as follows. The overall assembly of the heat gun is shown in Figure 4.5 below.

Figure 4.5: Disassembled Heat Gun

<u>Case</u>

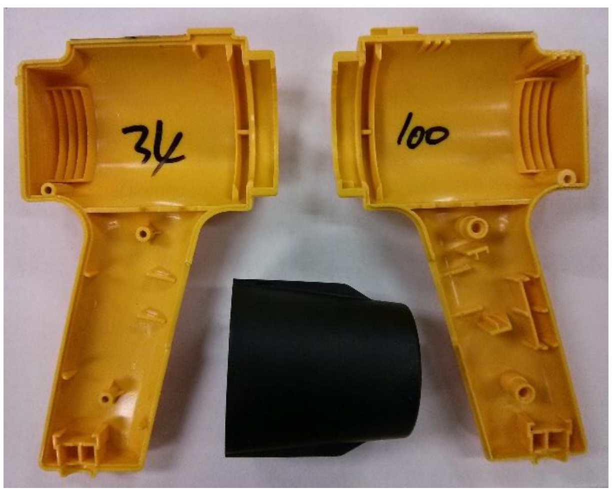

Figure 4.6: Heat Gun Case

The case, shown in Figure 4.6, is made of plastic and disassembles to three pieces: two mirrored grip/receiver pieces and a collar that locks onto the assembled grip. Assuming it is made of ABS plastic, the maximum use temperature is 105 °C [45]. The grip section provides volume for the switch to occupy and surface area for the switch to protrude through so that the user can interact with it. The barrel section provides volume to the fan and nozzle and withstands heat from the nozzle. Therefore, two distinct excess blocks for volume (Storage, Geometric, Volume or S-G-3 per the abbreviations listed in Table 3.1) and two distinct excess blocks for area (S-G-2) are shown since the spaces being occupied by the components are in separate locations in the case.

Finally, a thermal energy excess block (Flow, Energy, Thermal or F-E-T) is shown due to the dependence of the nozzle on the ability of the case to hold it at operating temperature. This highlights an important aspect of the excess relationships: their directionality is based on functional dependence, but this does not necessarily correspond to the direction of the involved physical flows. The actual heat is flowing from the nozzle to the case, but the nozzle is dependent on the ability of the case to withstand its steady-state operating temperature. Therefore, the relationship is shown as a functional flow of the case (its ability to withstand heat) satisfying a compatibility flow of the nozzle. The component and excess blocks for the case are shown in Figure 4.7.

The first volume excess (S-G-3) supplies volume to the fan, which occupies 100 cm^3 of the available 240 cm^3. The first area excess (S-G-2) supplies area to the nozzle, which occupies 11 cm^2 of the available 16 cm^2. The second volume and area excesses satisfy the needs of the switch, which occupies 8 of the available 13 cm^3 and the entirety (4 cm^2) of the available area.

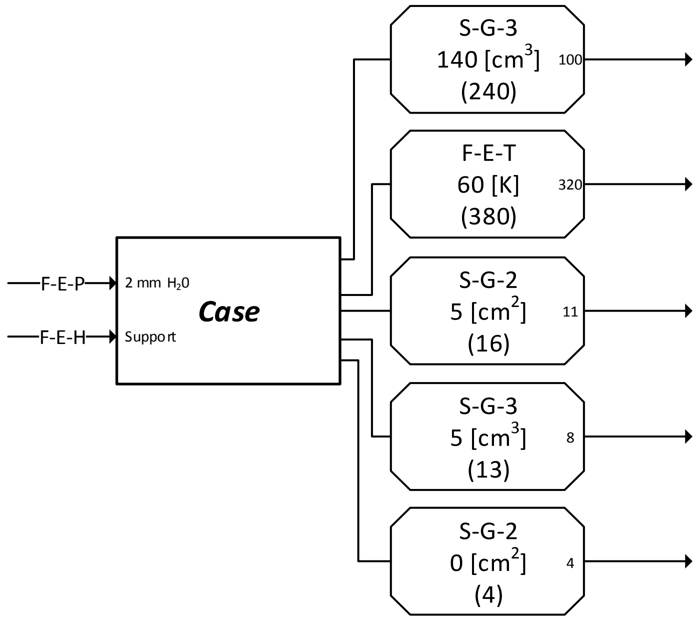

Figure 4.7: Case Excess Map Contribution

<u>Cord</u>

The cord and internal wiring is three-wire (hot, neutral, and ground) 18 AWG and therefore capable of carrying up to 14 A of current [43]. It requires electrical energy (F-E-E) from the environment and supplies electrical energy to the switch. The component and excess blocks for the cord are shown in Figure 4.8. The current passed on to the switch is 10 A, meaning that 4 A of excess current remains.

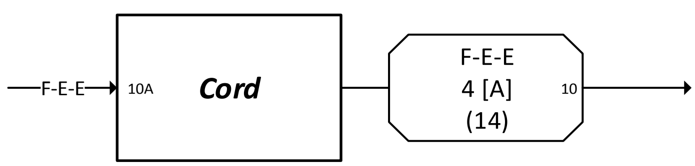

Figure 4.8: Cord Excess Map Contribution

Switch

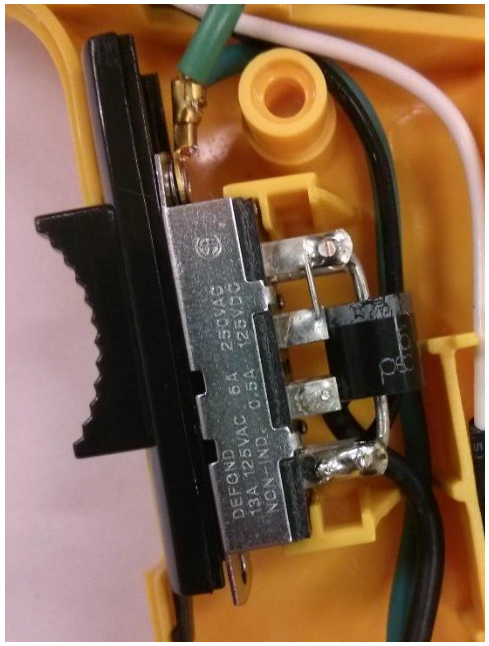

Figure 4.9: Heat Gun Switch

The switch, shown in Figure 4.9, is a three position sliding switch with positions corresponding to sequential markings of Off, Low, and High. In the Off position, the circuit is open. In the Low position, the circuit is fed by the current of the hot wire passed through a diode, making the current half-wave rectified. Therefore, the root-mean-squared (RMS) voltage fed to the heating coils and fan drops significantly; additionally, the diode itself drops the voltage by 0.6-0.7V [46] but this is insignificant compared to the adjusted half-wave rectified V_{RMS} of

$$V_{RMS} = \frac{V_{peak}}{2} = \frac{170\ V}{2} = 85\ V \quad (4.4)$$

In the High position, the switch feeds the full voltage directly to the circuit of the heat gun. The switch requires 8 cm^3 of volume (S-G-3) from the case, 4 cm^2 of area (S-G-2) from the case, a control signal from the user (F-S-C), and 10 A of electrical energy from the cord (F-E-

E). The component and excess blocks for the switch are shown in Figure 4.10; their values are based on the switch's function in the High position.

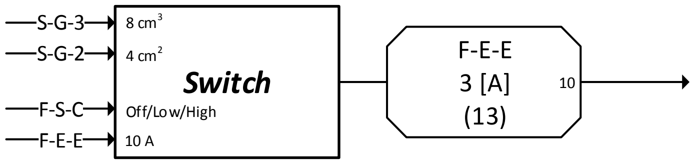

Figure 4.10: Switch Excess Map Contribution

Heating Coils

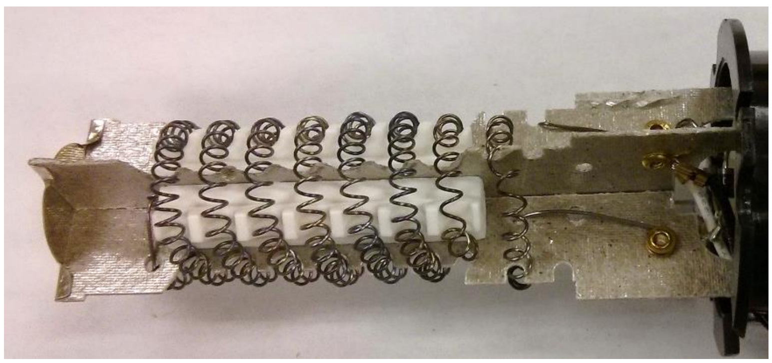

Figure 4.11: Heat Gun Heating Coils

The resistive heating coils, shown in Figure 4.11, are made of nichrome alloy and wrapped around a form made of mica sheets and ceramic supports. Not shown is the additional mica sheet that wraps around the coil assembly and rests between the coils and the nozzle as a heat shield. The melting temperature of nichrome is 1400 °C [47], that of the ceramic is at least 1000 °C [48], and the mica board can withstand 700 °C [49]. Therefore, the heating coils are limited to a maximum operating temperature of 700 °C or 970 K. The heating coils also function as a voltage divider for the fan, reducing the voltage to 11% of its input value (~12V on the High setting) before it is fed to the fan. Altering the location of the fan's tap into the heating coils would change the division of current between the fan and heading coils; hence, the excess of electrical flow that could be fed to the fan is correlated with the maximum air temperature that the coils can yield.

The airflow values are calculated as shown in Equation 4.5. Based on these numbers, the mass air flow through the heat gun at maximum temperature is approximately 2 g/s.

$$\dot{m} = \frac{P}{c_p \cdot (T_{out} - T_{ambient})} \tag{4.5}$$

The heating coils require 75 cm^3 of volume (S-G-3) from the nozzle, 2 g/s of airflow (F-M-G) from the fan, and 10 A of electrical energy (F-E-E) from the switch. The component and excess blocks for the heating coils are shown in Figure 4.12. They supply 810 K of thermal energy (F-E-T) out of a maximum 970 K to the nozzle and 0.2 A of electrical energy (F-E-E) out of a maximum 10 A to the fan.

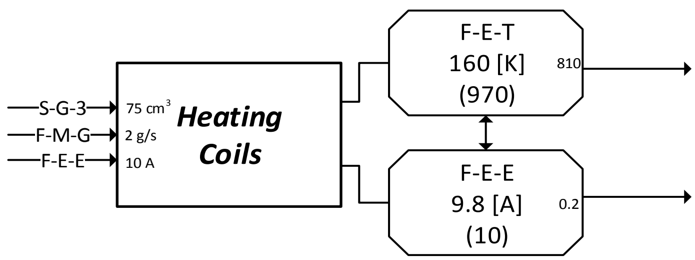

Figure 4.12: Heating Coils Excess Map Contribution

Fan

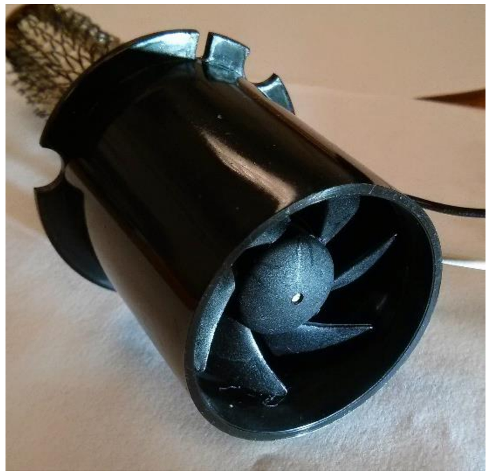

Figure 4.13: Heat Gun Fan

The fan, shown in Figure 4.13, is a 12V axial flow fan that delivers air from the case inlets to the heating coils. The fan has an integrated rectifier, which allows the AC current received from the coils to be converted to DC current. The fan, at its operating RPM, supplies approximately 2 g/s of airflow (F-M-G) to the heating coils and overcomes an estimated 3 mm H_20 of static pressure (a relationship of F-E-P) imposed by the case and nozzle. The values of estimated static pressure imposed by the case and nozzle were obtained by referencing the static pressure that commercially available 12V fans are capable of overcoming and examining the relative flow restrictions imposed by the case and nozzle. It is assumed that the rotational speed of the fan motor can be as much as doubled by adjusting the voltage fed to the fan, thereby creating excess in the two relationships. The fan affinity laws [50] for a constant diameter fan, shown in Equations 4.6–4.7, demonstrate how these excesses are linked, i.e. increasing airflow reduces the amount of additional static pressure that the motor can overcome. Volume flow rate is denoted by q and pressure by p. This linkage is indicated by a double-sided arrow between the excess blocks shown in Figure 4.14.

$$\frac{q_1}{q_2} = \frac{RPM_1}{RPM_2} \tag{4.6}$$

$$\frac{p_1}{p_2} = \left(\frac{RPM_1}{RPM_2}\right)^2 \quad (4.7)$$

The fan requires 0.2 A of electrical energy (F-E-E) from the heating coils and 100 cm^3 of volume (S-G-3) from the case. It supplies 1 mm H_2O of pressure (F-E-P) to the nozzle and 2 mm H_2O to the case out of a maximum of 12 mm H_2O pressure. It supplies 2 g/s of airflow (F-M-G) to the heating coils out of a maximum of 4 g/s. These two excesses are linked, meaning that if one is utilized the available excess in the other will decrease. Therefore, a double sided arrow is shown between the two excess blocks.

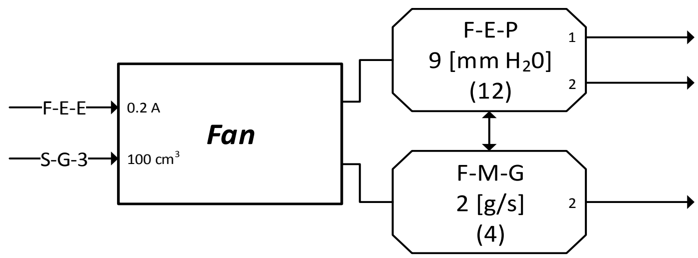

Figure 4.14: Fan Excess Map Contribution

<u>Nozzle</u>

Figure 4.15: Heat Gun Nozzle

The nozzle, shown in Figure 4.15, is formed of a mildly magnetic stainless steel, likely 304. Therefore its melting point is approximately 1400 °C [51]. The nozzle does impose some restriction on the airflow (F-E-P); however, its exit geometry is very similar to that of the heating coils, so the impact is minimal. The static pressure imposed by the nozzle is assumed to be 1 mm H_2O. The nozzle also requires cross sectional area (S-G-3) from the case, the ability for the case to withstand a temperature of 30 °C above the ambient due to heat flow from the nozzle (F-E-T), and heated airflow (F-E-T) from the heating coils. The component and excess blocks for the nozzle are shown in Figure 4.16.

The nozzle requires 1 mm H_20 of pressure (F-E-P) from the fan, 320 K of thermal energy (F-E-T) from the case, 11 cm^2 of area (S-G-2) from the case, and 810 K of thermal energy (F-E-T) from the heating coils. It supplies 810 K of thermal energy to the environment out of a maximum of 1670 K, and 75 cm^3 of volume (S-G-3) to the heating coils (the maximum available).

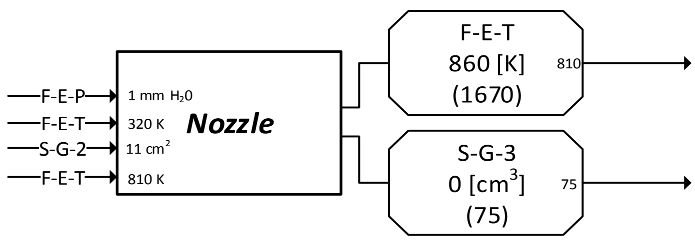

Figure 4.16: Nozzle Excess Map Contribution

4.1.3 Step 3: Assemble Excess Map

This step assembles the blocks and flows generated for each component in the previous step into a full excess map, according to their input and output flows. Compatibility flows that are not satisfied by other system components and consequently originate from outside the system boundary are placed in an Environment block, and flows that discharge outside the system boundary are labeled accordingly and cross the control volume. The Environment block exists to summarize and denote the compatibility flows that originate from the system's operating environment, and may be split into multiple blocks if desired to minimize visual complexity of the map. The equations relating output and input flows within and between components are not shown on the map; they may be encoded in a computational environment such as Simulink [52] or manually calculated.

Case study example

The process of assembling the excess map requires ensuring that the functional flows are matched with the correct compatibility flows. Components are presented with their summarized functional and compatibility flows in Table 4.1.

Table 4.1: Heat Gun Component Excesses

Component	*Compatibility Flows*	*Functional Flows*
Case	Flow-Material-Gas Flow-Energy-Human	Flow-Energy-Thermal Storage-Geometric-Volume (2) Storage-Geometric-Area (2)
Switch	Flow-Signal-Control Flow-Energy-Electrical Storage-Geometric-Volume Storage-Geometric-Area	Flow-Energy-Electrical
Cord	Flow-Energy-Electrical	Flow-Energy-Electrical
Fan	Storage-Geometric-Volume Flow-Energy-Electrical	Flow-Material-Gas Flow-Energy-Pneumatic
Heating Coils	Flow-Material-Gas Storage-Geometric-Volume Flow-Energy-Electrical	Flow-Energy-Thermal Flow-Energy-Electrical
Nozzle	Flow-Energy-Thermal (2) Storage-Geometric-Area Flow-Energy-Pneumatic	Flow-Energy-Thermal Storage-Geometric-Volume

During this step the Environment block is also defined. For this system, the required environmental flows are human energy (F-E-H) to support the heat gun, the control signal provided by a human hand (F-S-C) to actuate the control switch, electrical energy (F-E-E) from the power grid, and airflow (F-M-G). Finally, any outbound flows crossing the Control Volume are identified. The only such flow in this case is a flow of thermal energy passing from the nozzle to the environment.

4.1.4 Step 4: Identify State Parameters

Some of the datums created from system specifications will be relatable to single component outputs, such as ‘10 MW of electrical power’ would be for a single-generator system. However, the satisfaction of other specifications will be functions of multiple components, as in the case of ‘total mass must be less than 5 kg’. To verify satisfaction, state parameters (equations that are functions of multiple components’ characteristics) are defined. These parameters are indicated in a block labeled ‘State Parameters’. Information is drawn from component blocks and flows, but arrows are not required so that visual complexity of the map is not increased. Component properties that do not interact with excess flows but are relevant to state parameters are denoted within their respective block.

Case study example

Based on the system specifications, only two state parameters are required. The total system mass is summed from all components excepting the cord, since much of its mass may not be supported by the user. The amperage draw through the switch is summed and multiplied by the line RMS voltage. The finished excess map is shown in Figure 4.17. A full size version of the finished excess map is in the Appendix.

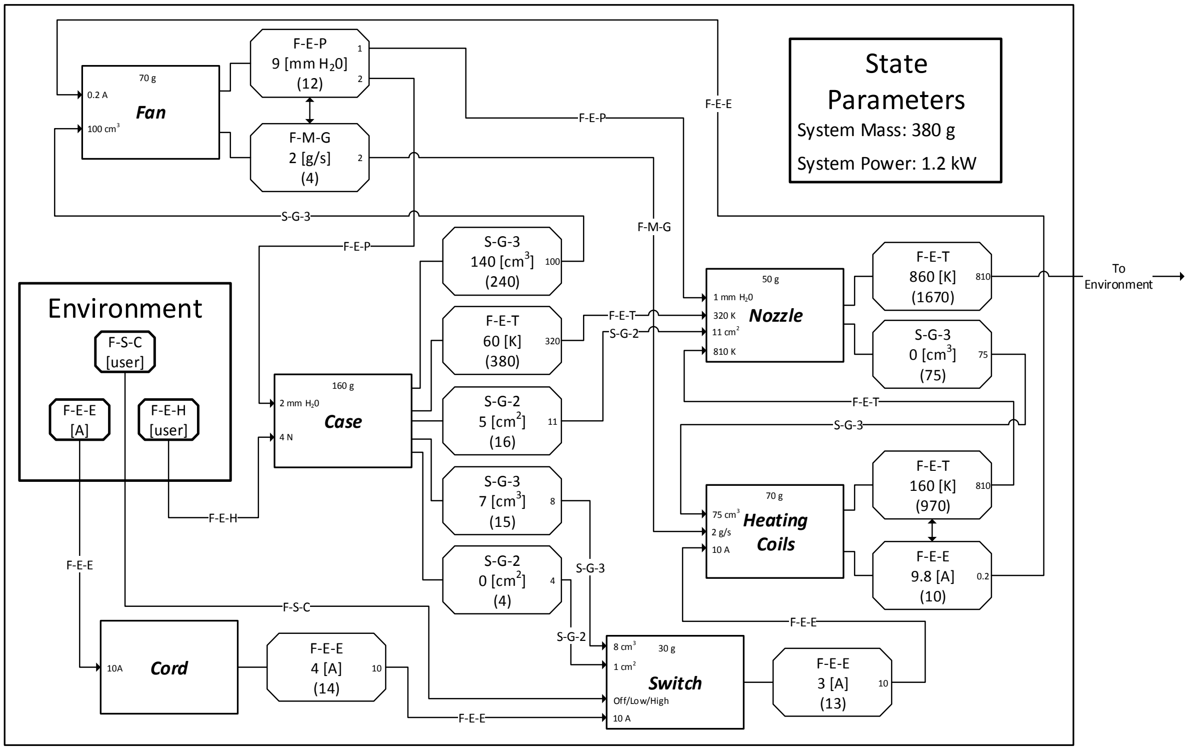

Figure 4.17: Heat Gun Excess Map

4.1.5 Evaluating System Level Excess

For a system excess map that incorporates equations relating component outputs and inputs, it is possible to query the map and determine the extent that system specifications may be exceeded; these values will be the system excesses. Additionally, for each top-level excess, it is possible to determine which component is at an excess threshold and may limit performance changes.

Case study example

Excess (X) in a specification is evaluated using the relationship in Equation 4.8.

$$X = Available - \Sigma\, Requirements \tag{4.8}$$

For the system in question, it was found that there exists 120 g excess in terms of allowable mass, using Equation 4.8 along with Equation 4.9. For excesses driven by state parameters, the ‘available’ amount is considered to be the bound on the state parameter, in this case 500 g.

$$m_{total} = m_{case} + m_{fan} + m_{coils} + m_{nozzle} \tag{4.9}$$

The maximum possible output temperature is 700 °C (an increase of 160K over the current high output temperature), which is limited by the heating coil assembly. The switch, rated at 13 A, is the lowest-amperage component that feeds electrical energy into the system; therefore, the electrical components also limit the heat gun to a maximum temperature of approximately 700 °C as detailed in Equations 4.10 and 4.11 below. Note that 12.8 A is used as the maximum current value because roughly 0.2 A is consumed by the fan, thereby reducing the total current that can be expended in the heating coils slightly.

$$X = \frac{12.8\frac{A}{s} \cdot 120V}{1.0\frac{J}{gK} \cdot \ 2.3\frac{g}{s}} - \frac{9.8\frac{A}{s} \cdot 120V}{1.0\frac{J}{gK} \cdot \ 2.3\frac{g}{s}} \tag{4.10}$$

$$= \frac{1540\frac{J}{s}}{2.3\frac{J}{Ks}} - \frac{1180\frac{J}{s}}{2.3\frac{J}{Ks}} = 160 \text{ K} \tag{4.11}$$

Though a higher temperature could also be achieved at the same amperage by lowering the mass flow rate, an end user might not perceive any performance improvement if the total power remained constant. Regarding the power specifications, the system might consume 200 W more or less and still meet both. The power value for the system was determined from Equation 4.12, where I is the current passing through the switch.

$$P = IV \tag{4.12}$$

Therefore, the limiting excesses for increasing the output temperature of the heat gun are the amperage rating of the switch and the temperature rating of the heating coil assembly.

4.1.6 Map Quality and Criteria for Update

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 specifications could alter the map by affecting the components and/or relationships that must be represented. However, an already present specification that is modified could change the amount of excess indicated by the map, but will not require the map to be altered. Rather, a modified need results in re-querying the map to determine how excesses are affected. The following sections implement and demonstrate the steps of the excess mapping process.

4.2 Case Study 1 Conclusion: Heat Gun Evolution Examples

Two examples of potential evolutions for the heat gun are given here to demonstrate the information made available to the designers by the excess map.

4.2.1 Heat Gun Evolution 1: Replace Tri-Mode Switch with Variable Voltage Switch

A possible future need for the heat gun is for the heat output to be made continuously variable. This could be accomplished by replacing the original switch, capable only of operating the heat gun in ‘low’ and ‘high’ temperature modes, with a dial switch that can vary the voltage across the entire possible range (with the minimum voltage set so that the 12 V nominal fan motor does not stall and thereby allow the heating coils to overheat and damage the device).

The feasibility of such a modification can be investigated by consulting the Switch block of Figure 4.17 and ensuring that a candidate replacement switch satisfies all existing functional flow requirements and can operate within the compatibility flow limits imposed by the supplying components to prevent change propagation. This means that a replacement switch must be able to pass at least 10 A (the present design amperage), must fit within 13 cm^3 inside the case, and must occupy less than 4 cm^2 of area on the case surface for the user to interface.

The ease of this process is one of the benefits of the excess mapping method; designers considering a change to a system can quickly determine the pertinent excesses and constraints for everything from a simple component exchange such as this to a more complicated alteration that can affect multiple components, as discussed in the next evolution.

4.2.2 Heat Gun Evolution 2: Increase Output Temperature to 750 °C

Another potential future need for the system is for the output temperature to be increased from 540 °C to 750 °C (1020 K) meaning a ΔT of 730 K. Consulting the system excess map of Figure 4.17, it is apparent that the nozzle can tolerate the evolution. Additionally, assuming that the ΔT between the case temperature and ambient air is linearly correlated with the ΔT imparted to the airflow, the new case temperature will be 62°C, as shown in Equation 4.13. This is still well within the maximum temperature of 105°C.

$$\frac{\Delta \mathrm{T}_{\mathrm{case}}}{\Delta \mathrm{T}_{\mathrm{airflow}}} = \mathrm{const} = \frac{30\ \mathrm{K}}{520\ \mathrm{K}} = \frac{\mathbf{42\ K}}{730\ \mathrm{K}} \tag{4.13}$$

However, the heating coils must be modified as their current maximum operating temperature is 700 °C. Also, assuming that the airflow rate is to remain constant, the flows of electrical energy must be considered. A ΔT of 730 K requires an energy input of 14 A. Therefore, the switch (rated at 13 A) must be upgraded, but there is sufficient excess in the cord.

$$\mathrm{I} = \frac{\dot{m} \cdot c_p \cdot \Delta T}{V} = \frac{2.3\frac{g}{s} \cdot 1.0\frac{J}{gK} \cdot 730K}{120V} = 12\ A \tag{4.14}$$

Upgrades to the switch and heating coils are governed by the available compatibility flows (volume and area for the switch, and volume for the heating coils) if changes are not to propagate to additional components in the design.

4.3 Case Study 2: Coffee Maker

The coffee maker used for the second demonstration was a 12-cup model as shown in Figure 4.18.

Figure 4.18: Coffee Maker [53]

This particular model was an automatic drip brewer producing up to twelve 5 fl. oz. cups of coffee using a basket filter. It was operated using an on-off switch without automatic shutoff functionality. The carafe was heated from below, maintaining the coffee at brewing temperature indefinitely.

4.3.1 Coffee Maker Excess Map Creation

Step 1: Collect Stakeholder Specifications

The coffee maker satisfied the following customer needs:

- Brew coffee
- Keep coffee hot after brewing
- Brew enough coffee for a family
- Brew coffee quickly
- Be safe to use and operate
- Operate from a standard household outlet

The corresponding specifications are:

- Deliver water at ≥ 93°C to coffee
- Maintain coffee at brewing temperature (93°C)
- Brew at rate of ≥ 150 mL/min
- Brew up to 1.8 L of coffee
- Limit heating element temperature to ≤ 240 °C in emergency
- Power ≤ 1.4 kW

The brewing rate specification translates to brewing an entire pot (1.8L, or twelve 5 fl. oz. coffee cups) of coffee within 12 minutes. The power specification was set as in Equation 4.3.

<u>Step 2: Identify Architecture, Appropriate Subassemblies, and Relationships</u>

The system boundaries were determined based on the operation of the system between when it is turned on and off. Therefore, it was assumed that water is already in the reservoir when the system is turned on and that the system remains on until the last cup of coffee is poured from the carafe. The components that display modular behavior are the body, cord, brew basket, heating element, hot plate, and carafe. Pertinent to the following discussion is the specific heat of water at constant pressure, c_p = 4.19 J/(g-K), and the assumption that the tap water placed in the reservoir is at 10°C while the brewing temperature of the coffee is 93°C. The numerical values of the inter-component relationships were determined as follows for each component.

Body

Figure 4.19: Coffee Maker Body

The body, shown in Figure 4.19, interacts directly with many of the other components, as shown by the large number of excess blocks in Figure 4.20. The body cannot be readily disassembled further; this consideration suggests that the system architecture is integral, designed for a specific use case. The body supplies volume (S-G-3) in separate regions to the carafe and brew basket. It also supplies area (S-G-2) and thermal tolerance (F-E-T) to the hot plate in the base, storage of liquid water (S-M-L) for the carafe's eventual receipt, a flow rate of water (F-M-L) to the heater, and an area (S-G-2) to the operating switch. Stamped on the components was an indication that the plastic material was polypropylene; hence its melting temperature is 135°C [54]. The component and excess blocks for the body are shown in Figure 4.20.

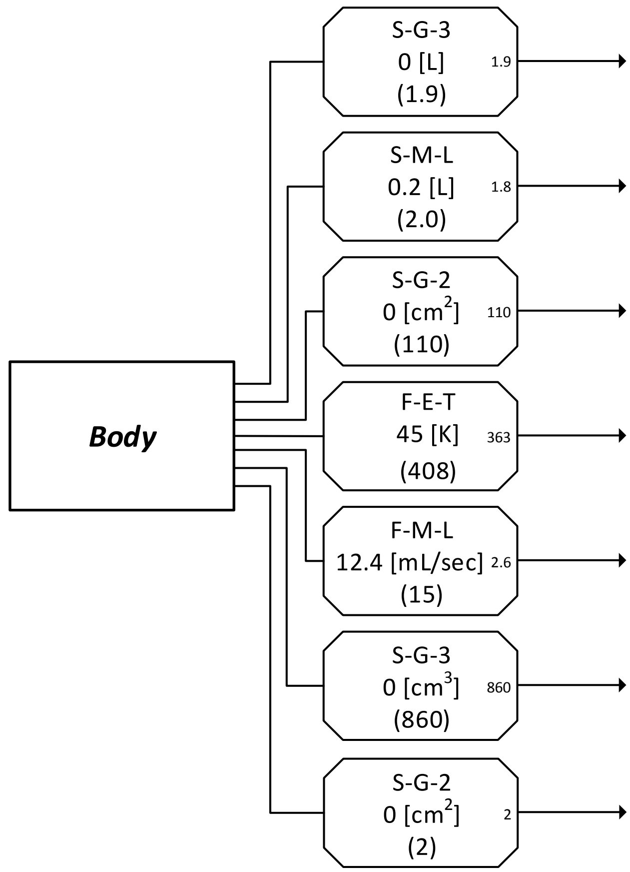

Figure 4.20: Body Excess Map Contribution

Cord

The cord is two-wire (hot and neutral) 18 AWG, and therefore capable of carrying 14 A of electrical energy (F-E-E) per [43]. In use, it carries 7.5 A to satisfy the needs of the heater, the only powered component. The component and excess blocks for the cord are shown in Figure 4.21.

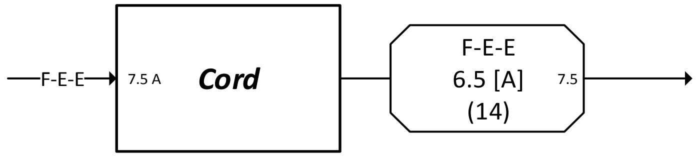

Figure 4.21: Cord Excess Map Contribution

Switch

Figure 4.22: Coffee Maker Switch

The switch, shown from the inside of the coffee maker in Figure 4.22, is a simple on/off rocker type, rated to 10 A, that governs the current flow from the cord to the heater. Its associated component and excess blocks are shown in Figure 4.23.

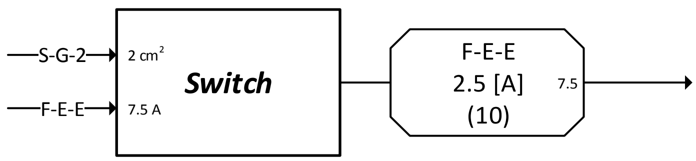

Figure 4.23: Switch Excess Map Contribution

Heater

Figure 4.24: Coffee Maker Heating Element

The heater consists of a resistive heating element sandwiched between a hollow tube for heating brew water and a flat face that interfaces with the hot plate using thermal grease. The heater has two functions: heat the water for brewing the coffee, and maintain the temperature of the hot plate after the coffee has brewed. To accomplish the first, it draws water from the cold reservoir in the body, heats it within the hollow horseshoe tube, and sends it up through the body to be dispersed through the brew head over the brew basket. The movement of the water is effected without a pump or any powered moving parts. Rather, there is a check valve in the inlet tube from the reservoir that prevents water from flowing in reverse. The water within the tube is locally heated to boiling, which converts some of it to steam, thereby producing enough pressure to propel the heated water up to the brew head. More cold water is then able to flow downward into the tube and the cycle repeats.

To accomplish the second purpose of maintaining the coffee at temperature after brewing (supplying F-E-T) the interface side of the heater is coated with thermal grease and placed against the underside of the hot plate. The maximum temperature value for the heating assembly is dictated by the melting point of aluminum, 933 K [55]. The heater is stamped 900W on the side, which was confirmed by its measured resistance of 16 Ω. Therefore, it draws

7.5A of current. This power is sufficient to raise 2.6 mL/sec of water from tap to brewing temperature, per Equation 5.5 (noting that 1 g of water is equal to 1 mL of water). This relationship governs the F-M-L excess that the heater provides.

$$\dot{m} = \frac{P}{c_p \cdot (T_{out} - T_{in})} = \frac{900\frac{J}{s}}{4.19\frac{J}{gK} \cdot (93K - 10K)} = 2.6\frac{g}{s} \tag{4.15}$$

Flow of electrical current to the heater is governed by a thermostat (shown on the right of Figure 4.24) and two sequential thermal safety devices, stamped at 240°C. Replacing the thermostat (or changing its set point) modifies the steady state temperature of the hot plate. The thermal fuses satisfy the specification that temperature be limited to ≤ 240°C in an emergency. However, their presence is not indicated anywhere on the excess map. This is because no excess is reasonable to describe such a relationship; since coffee is made with water, the maximum temperature that the brewing process could require anywhere on Earth (at or above sea level) is at most 100°C. That is also the limiting value for maintaining the coffee at temperature within the carafe. Therefore, no change to the thermal fuse cutout value should ever be necessary for any modification to the coffee maker that is consistent with its top level functional purpose of ‘brew coffee’.

The component and excess blocks for the heater are shown in Figure 4.25. That zero excess is present in the liquid flow rate (F-M-L) is a consequence of how the gravity-fed heating element operates; it will always heat the maximum possible mass flow rate of water that its power output allows, unless the power is cycled on and off.

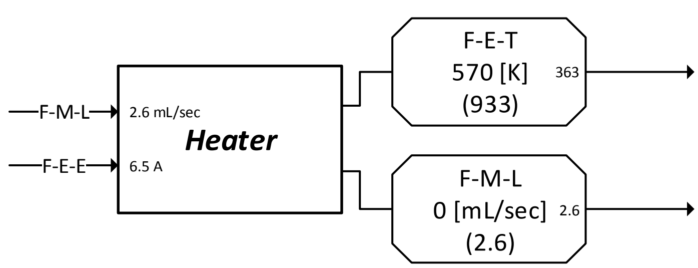

Figure 4.25: Heating Element Excess Map Contribution

Brew Basket

Figure 4.26: Coffee Maker Brew Basket

The brew basket, shown in Figure 4.26, sits in the top of the body under the brew head (consuming S-G-3) and holds the coffee filter and grounds. Its purpose is to accept hot water (F-M-L) and allow it to pass through the coffee grounds and filter before being drained to the carafe below (F-M-L). Its maximum flow value was determined experimentally by measuring the amount of water that passed through the basket orifice in thirty seconds. The component and excess blocks for the brew basket are shown in Figure 4.27.

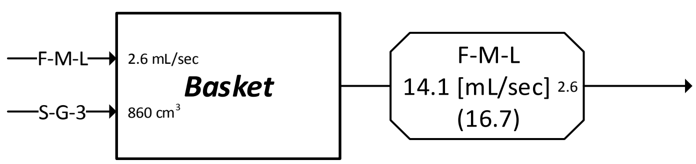

Figure 4.27: Brew Basket Excess Map Contribution

<u>Hot plate</u>

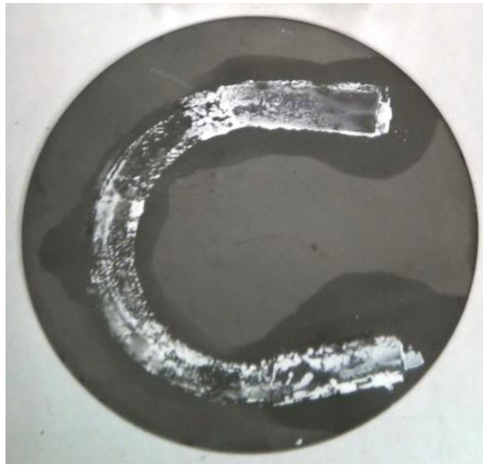

Figure 4.28: Coffee Maker Hot Plate

Shown in Figure 4.28 is the underside of the hot plate with residual thermal grease. It requires area (S-G-2) from the body, heat energy to maintain its operating temperature (F-E-T) from the heater, and tolerance of its operating temperature (F-E-T) from the body. It supplies heat energy (F-E-T) and area (S-G-2) to the carafe. Assuming that it is made of low-grade steel, its melting point is 1813 K as given by [56]. Its component and excess blocks are shown in Figure 4.29.

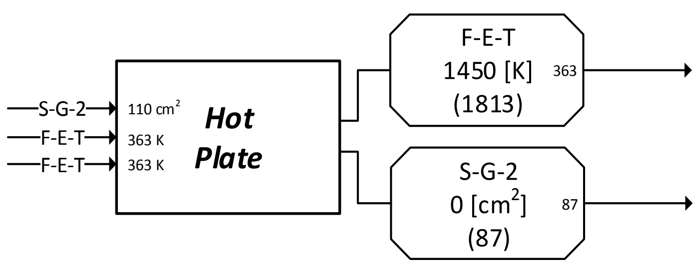

Figure 4.29: Hot Plate Excess Map Contribution

Carafe

Figure 4.30: Coffee Maker Carafe

The carafe, shown in Figure 4.30, is the recipient of the brewed coffee from the brew basket. It receives volume (S-G-3) and total liquid volume (S-M-L) from the body, and area (S-G-2) and heat energy (F-E-T) from the hot plate. Its excess is a storage of liquid (S-M-L), the final brewed coffee.

Note that flow rate is not considered as a compatibility flow for the carafe, as the rate at which it can receive liquid is essentially unlimited compared to the rate that a 900 W (or even 2 kW) heater can produce. Also, the liquid storage excess is shown as coming from the body since it is the total amount of water in the reservoir that dictates the final amount of brewed coffee present in the carafe.

The component and excess blocks for the carafe are shown in Figure 4.31.

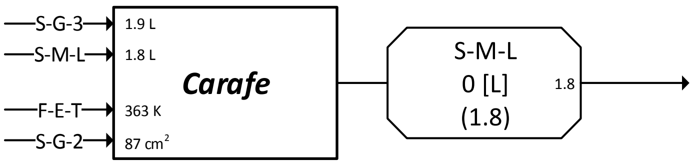

Figure 4.31: Carafe Excess Map Contribution

Step 3: Assemble Excess Map

The summarized compatibility and functional flows for the components of the coffee maker are given in Table 4.2.

Table 4.2: Coffee Maker Component Excesses

Component	*Compatibility Flows*	*Functional Flows*
Body	N/A	Storage-Geometric-Volume (2) Storage-Material-Liquid Storage-Geometric-Area Flow-Energy-Thermal Flow-Material-Liquid
Cord	Flow-Energy-Electrical	Flow-Energy-Electrical
Switch	Flow-Energy-Electrical	Flow-Energy-Electrical
Heater	Flow-Energy-Electrical Flow-Material-Liquid	Flow-Energy-Thermal Flow-Material-Liquid
Brew Basket	Flow-Material-Liquid Storage-Geometric-Volume	Flow-Material-Liquid
Hot Plate	Storage-Geometric-Area Flow-Energy-Thermal (2)	Storage-Geometric-Area Flow-Energy-Thermal
Carafe	Storage-Geometric-Volume Storage-Material-Liquid Storage-Geometric-Area Flow-Energy-Thermal	Storage-Material-Liquid

For this system, the only required environmental flow in operation is electrical energy (F-E-E). The outbound flows crossing the control volume (for purposes of satisfying the system specifications) are the liquid storage (S-M-L) of the carafe and flow rate (F-M-L) from the brew basket.

Step 4: Identify State Parameters

The only required state parameter for the coffee maker was the system power, derived as in Equation 4.12, using the amperage passing through the cord for I. The finished excess map is shown in Figure 4.32. A full size version of the finished excess map is in the Appendix.

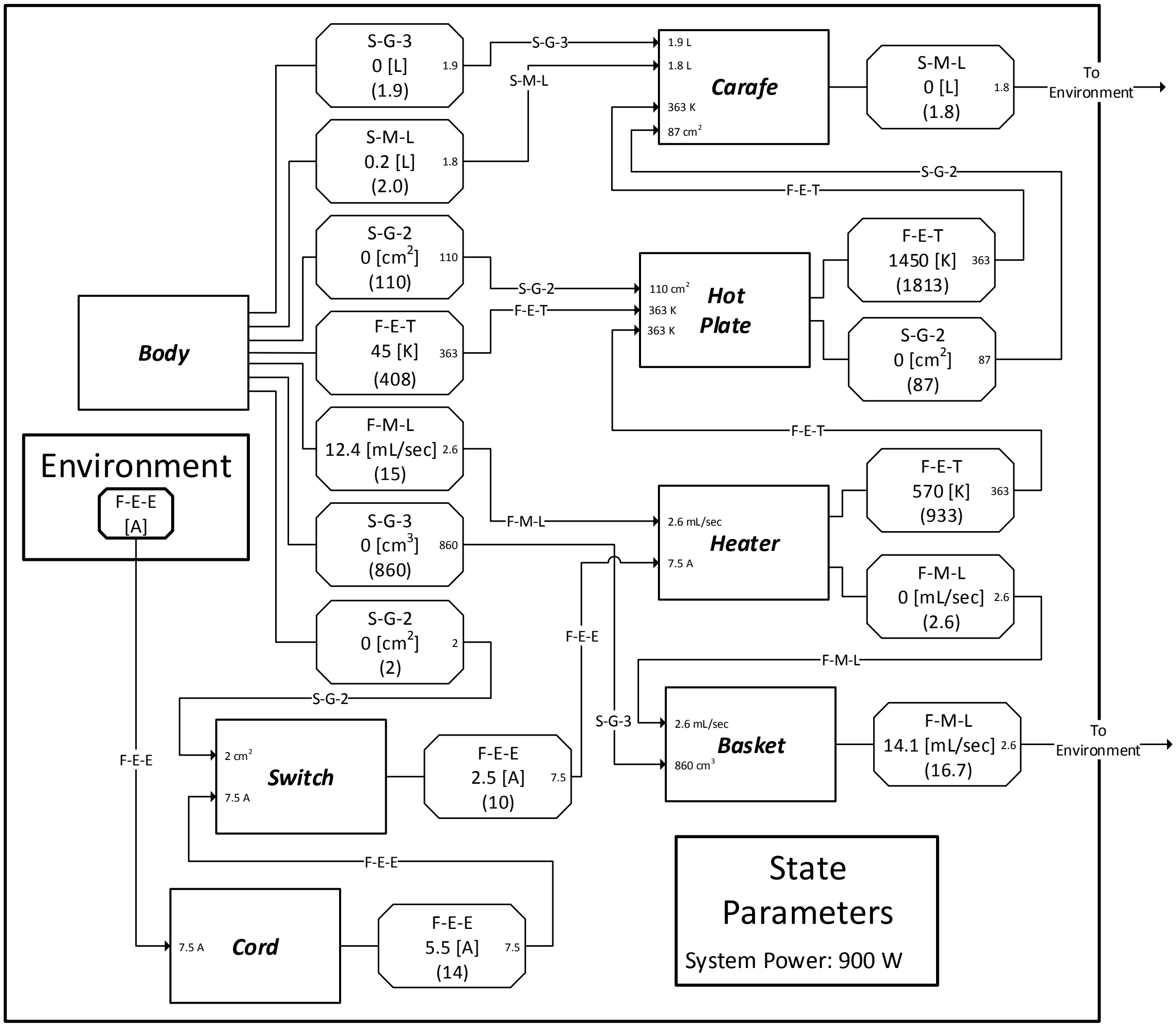

Figure 4.32: Coffee Maker Excess Map

Evaluating System Excesses

The coffee maker satisfies all of the specifications placed on it, but with minimal or no excess in some cases. The power specification has the most excess (in terms of relative increase) with 500 W additional power being permissible from the wall outlet. The brewing rate of 2.6 mL/sec satisfies the required ≥ 2.0 mL/sec, but cannot be increased without replacing the heater with a higher-wattage unit. Likewise, the carafe holds at maximum the required 1.8L, but no more. If it was desired to replace the carafe, there is no excess volume in the body to accommodate a larger carafe.

This general lack of excess points to a design that has been optimized for a narrow purpose to minimize cost. For an inexpensive, mass-produced (and essentially disposable) product such as the coffee maker in question, the term ‘excess’ as used in this paper becomes synonymous with ‘excess’ in layman’s usage: superfluous and wasteful. Therefore, for this coffee maker, the general lack of excess can be viewed as an example of good design for a product performing a very deterministic task.

4.3.2 Coffee Maker Evolution Examples

Two possible evolutions are presented to demonstrate the use of information from the excess map in system evolution.

<u>Coffee Maker Evolution 1: Brew Full Pot in Two Thirds the Time</u>

A possible future need for the system is to brew a full pot of coffee in less time than was originally intended. Reducing the brew time to two thirds of the original would mean increasing the flow rate by a factor of 1.5, thus the new flow rate would be 3.9 mL/sec. This would affect the flow rate output of the brew basket, since that is what addresses the brewing rate specification. Consulting Figure 4.32 shows that the brew basket can tolerate up to 16.7 mL/sec, while the body can tolerate up to 15 mL/sec. However, between the body and brew basket is the heater, which is already producing its maximum flow rate of 2.6 mL/sec. Since, in this case, flow rate is directly proportional to the input power to the heating element, the new power required is 1350W as given by Equation 5.5.

$$P_{new} = 1.5\, P_{old} = 1350W \tag{4.16}$$

This new value does not conflict with the power limit specification of 1.4 kW, and so all that remains is to check each of the affected components. 1350W corresponds to 11.3A at $120V_{RMS}$, which can be tolerated by the cord but not the switch. Therefore, to reduce the brew time to two thirds the original time, the heater and switch would have to be replaced.

Coffee Maker Evolution 2: Utilize Single-Serve Coffee Pods

A popular method of preparing coffee today involves single-portion coffee pods. A possible future need for the coffee pot is to use these pods instead of the conventional filter with loose grounds.

Evolving to meet such a need would result in a significant alteration to the system architecture. Single serve coffee pods require a system that can deliver pressurized heated water, as well as a receptacle for the pod itself that differs greatly from the conventional filter basket. On the other hand, no carafe or hot plate is required since the coffee is brewed directly into the serving vessel. For such an extreme evolution, use of the excess map in Figure 4.32 reduces to consulting the compatibility flow for the components that would be replaced to effect the evolution. Such an evolution would be possible if:

- The coffee pod holder could fit within the volume in the body currently occupied by the brew basket (860 cm^3).
- The new control interface could fit within the area currently occupied by the switch, 2 cm^2, assuming that the ability to select a coffee mug size is desired. Given that this is unlikely to be possible, the body would have to be modified as well to allow the larger control interface. However, if a single size coffee mug is assumed, it would be possible to use the existing switch as a toggle to run the rest of the evolved system.
- The requisite pump and whole-volume heater could fit somewhere within the body. The volume occupied by the original heater was not indicated on the original map because a more powerful conventional heater could have been added without requiring more volume (i.e. a heater of the same geometry but greater resistance and therefore greater power could have replaced the original). There is not sufficient volume in the location of the original heater, and more volume would be required for the new components. This is because single-serve coffee machines heat all of the brewing water at once and then inject it at pressure into the coffee grounds, rather than boiling it intermittently and relying on gravity to drip water through the grounds; heating all the water at once naturally requires greater volume. However, the excess map does indicate an excess of (S-M-L) for the cold water reservoir. Some of this could be occupied by

new hardware, since a single-serve brewing system does not require the same amount of water in its reservoir as a conventional drip coffee maker. Logically, the volume required for the full-size heater should not be significantly greater than the volume of a single mug of coffee, meaning that there is definitely sufficient volume available in the existing water reservoir. Likewise, a small pump that only needs to develop a head on the order 30 cm should not be more than several cubic centimeters in volume, which again could fit without issue in the existing cold water reservoir. The addition of both these pieces of hardware to the portion of the body currently functioning as the cold water reservoir would still leave enough water storage volume for multiple cups.

- The electrical draw for the modified system is less than 14 A to remain compatible with the existing cord.
- The body is not exposed to temperatures exceeding 135°C by any of the modifications.

4.4 Scalability Case Study

Since excess maps are intended to be constructed during the embodiment phase of design, they will logically be made by individual designers or design teams who are familiar with the system in question. For more complex systems comprised of subsystems created by different design teams, excess maps will be submitted/exchanged as part of the design documentation. To demonstrate this process, a string trimmer as shown in Figure 4.33 was disassembled into three subsystems: the Engine, Transmission, and Attachment. Three individuals created excess maps for their respective assigned subsystems, and the results are detailed in the following subsections. For this demonstration, no numerical values were collected since the object of the exercise was to show how excess maps for subsystems can be joined.

Figure 4.33: String Trimmer [57]

A subset of the customer needs and corresponding specifications satisfied by the string trimmer are summarized in Table 4.3.

Table 4.3: String Trimmer Needs and Specifications

Needs	**Specifications**
Cut weeds quickly	(1) Cutting swath in cm
Run for an adequate amount of time	(2) Fuel volume in mL
Be easy to carry	(3) Total mass in kg (state parameter)
Be sufficiently powerful	(4) Engine power in W
Cut moderately thick weeds	(5) String diameter in mm
Comfortable length	(6) Handle-to-end length in m (state parameter)
Carry extra line	(7) String storage volume in cm^3

It was assumed that the interfaces between the components were mandated in advance for all three designers/design teams for the components. Therefore, the geometry of the interfaces was fixed for the overall design. The maximum power that it can transmit was treated as a state parameter.

In keeping with the assumption that the design of subsystems is divided between multiple design teams, the overall specifications for the system were split where necessary and assigned to their corresponding subsystems. Therefore, the engine was responsible for

- Specification 2
- Specification 4
- A portion of Specification 3 was allocated to the motor

The transmission was responsible for

- Delivering the power from Specification 4
- Supporting weight from Attachment
- Providing length for mounting user interfaces
- A portion of Specification 3 was allocated to the transmission
- A portion of Specification 6 was allocated to the transmission

The cutting attachment was responsible for

- Specification 1
- Delivering the power from Specification 4
- Specification 5
- Specification 7
- A portion of Specification 3 was allocated to the attachment
- A portion of Specification 6 was allocated to the attachment

These specifications drove the excess maps created in the following subsections.

4.4.1 Subsystem 1: Engine

The engine was the most complicated subsystem, and its excess map was naturally the most detailed based on the guidance of decomposing a system to the elements that display modular behavior.

The engine requires length (S-G-1) from the transmission for the grip, human energy (F-E-H) for the starter cord and grip, air flow (F-M-G) for the carburetor, and control signal (F-S-C) for the trigger, carburetor, and stop switch. It produces mechanical energy (F-E-M) for the transmission, and holds a quantity of fuel (S-M-L) to satisfy the corresponding system specification. Its excess map, with internal component relationships, is shown in Figure 4.34. Note that in this map there are two environmental blocks; the information is presented in this way to minimize visual complexity.

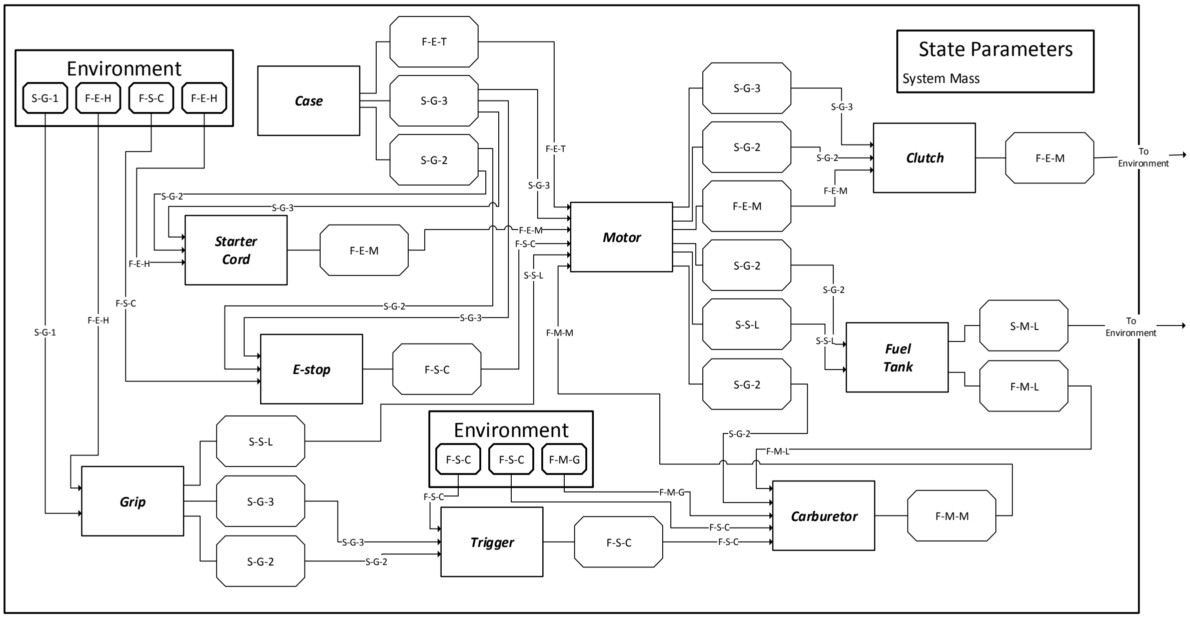

Figure 4.34: Engine Excess Map

4.4.2 Subsystem 2: Transmission

In contrast to the engine, the transmission was the simplest of the three subsystems considered, and its excess map reflects that fact. It requires human energy from the user for the handle and mechanical energy from the engine for the shaft. It provides support (S-S-L) to the cutting attachment, mechanical energy (F-E-M) to the attachment, and length (S-G-1) to the engine's grip. Its excess map is given in Figure 4.35.

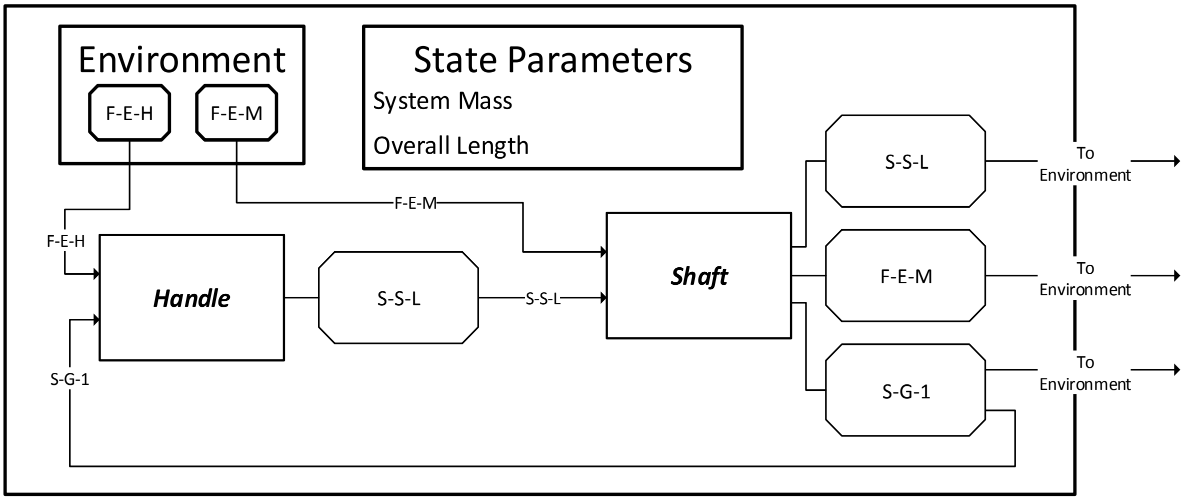

Figure 4.35: Transmission Excess Map

4.4.3 Subsystem 3: Cutting Attachment

The cutting attachment requires mechanical energy (F-E-M) and support (S-S-L) from the transmission. It provides a diameter of cutting swath (S-G-1), delivered mechanical power (F-E-M), volume of the stored cutting string (S-G-3), and diameter of the cutting string (S-G-1) to satisfy its specifications. The excess map for the cutting attachment is shown in Figure 4.36.

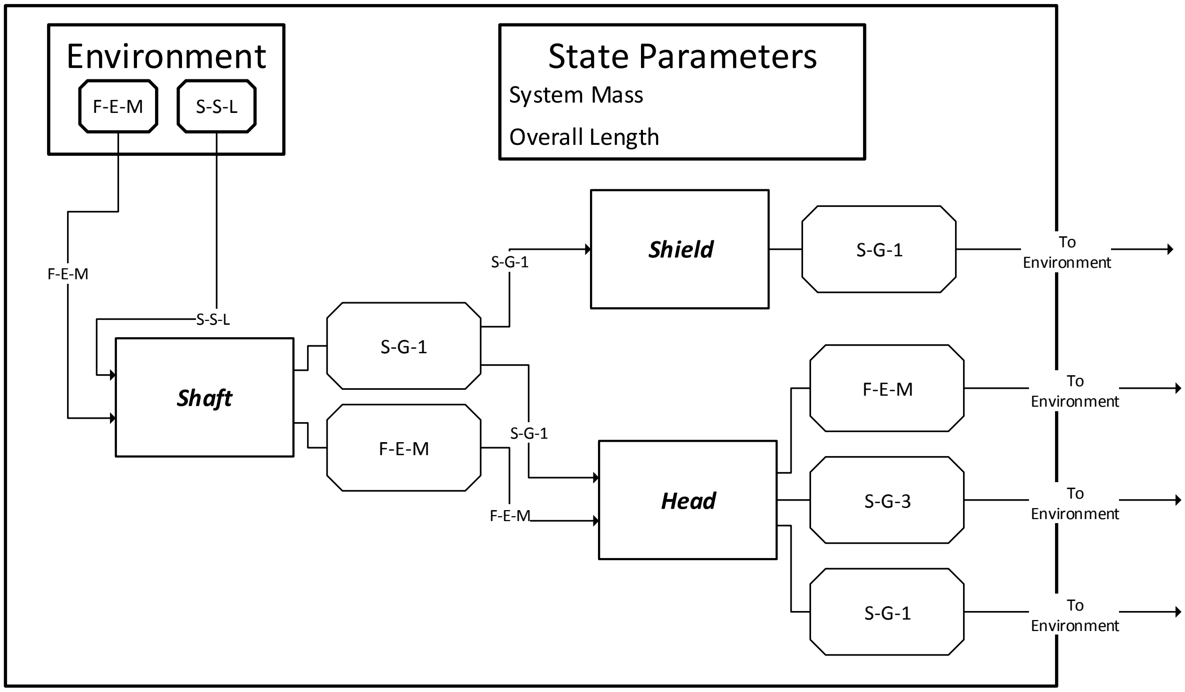

Figure 4.36: Cutting Attachment Excess Map

4.4.4 String Trimmer Excess Map

Based on the results for the three individual subsystems, a composite excess map for the string trimmer was created as shown in Figure 4.37. A full size version of the finished excess map is in the Appendix. The environmental flows for each of the subsystems that are not satisfied by another subsystem are displayed in the Environment block, while the excesses that address system level specifications are shown as outputs to the environment. These excesses combined with the state parameters address all of the system-level specifications placed on the design.

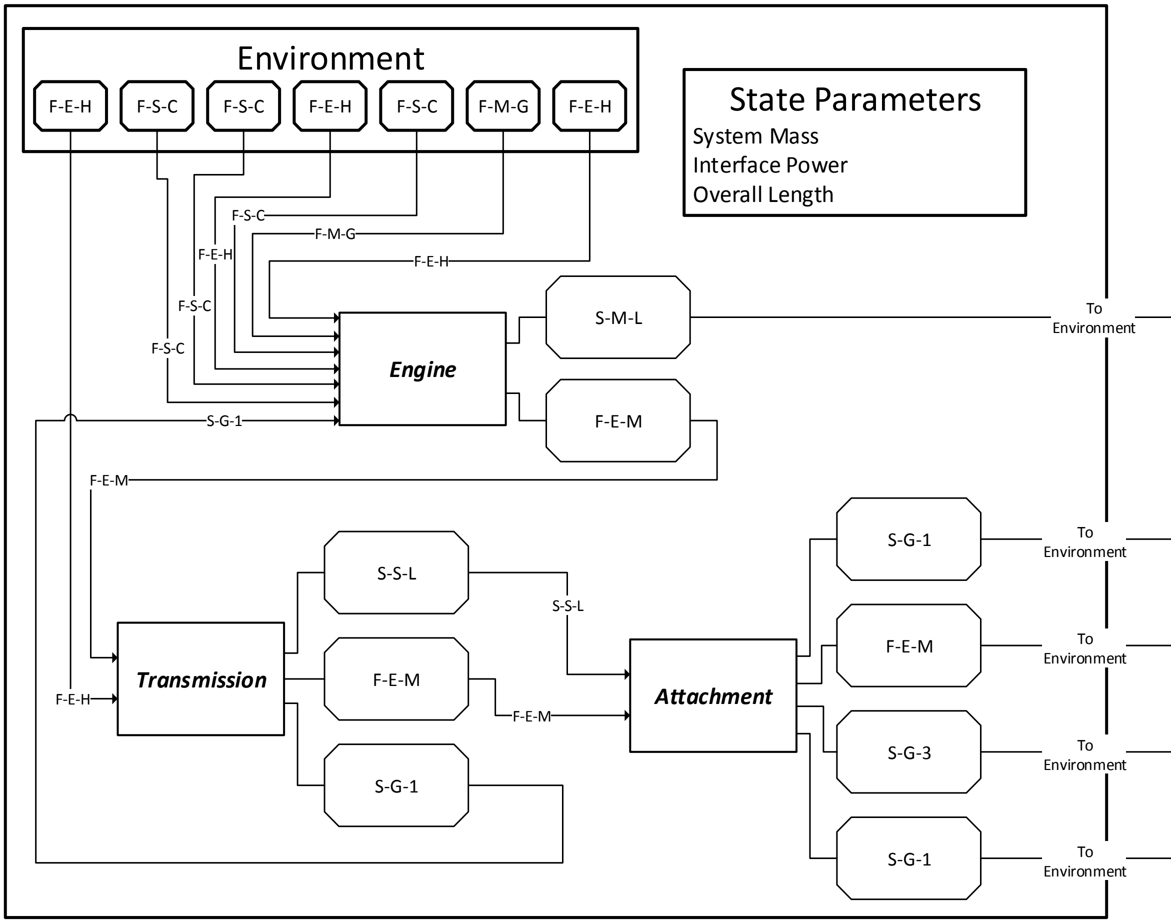

Figure 4.37: String Trimmer Composite Excess Map

This example demonstrates how the excess mapping method scales to more complex systems that are designed by multiple individuals/teams. The separate excess maps created by designers or teams for subsystems are condensed into individual component blocks, and the excess flows that cross the control volume are mapped to other component blocks or to/from the system environment.

This procedure can be applied to any system, provided that the excess maps for each subsystem are created per the guidelines given in Section 4.1 and the system-level specifications are divided clearly between the respective design teams. By building up maps for complex systems in this way, it is possible to create multi-level maps, each one at a finer level of detail. This is advantageous because it allows the designer to restrict their attention to only the portion of interest within a system, at a desired level of granularity, without being overwhelmed by all of the relationships between all of the components at the finest level of detail.

The excess mapping method developed in this chapter delivers to designers the set of excesses that affect a system's ability to evolve to meet future needs. Excess maps incorporate the quantities of available excess as well as the types, and therefore can be used to explore the effect of a change to a system on the amount of excess that remains. However, knowing which excesses are important for evolvability and their present designed amounts does not mean that the ideal amount of excess to embed is clear. The next chapter develops an approach to aid designers seeking to embed useful quantities of excess for evolvability.

Chapter 5: Stress Test Approach

This chapter builds on the excess mapping method of Chapter 4 by coupling the excess maps with future changes to explore the relationship between excess and evolutions to meet future needs. Specifically, this approach helps to address the problem of allocating epistemic excess when empirical design experience and 'rules of thumb' are unavailable.

5.1 Stress Testing in Engineering

Varying types of stress testing are encountered across different fields of engineering. The most obvious is literal stress testing, performed on artifacts as a means of ensuring their quality and safety, and/or of verifying analytical models, as described in [58]. The type that underpins the approach taken by this paper, however, comes from software engineering. In general terms, software stress testing exposes computer programs to conditions that could overwhelm their ability to function [59], demanding "resources in abnormal quantity, frequency, or volume" [60]. These tests go beyond the nominal operating conditions that the software was designed for, in terms of either increased demands or reduced resources [61], to determine how the system reacts to potential future needs. This process reveals bottlenecks within the software that limit its ability to function under off-design conditions.

The steps are described in the following subsections, following the process shown in Figure 5.1, and assume that a system excess map has been created per the guidelines given in the previous chapter.

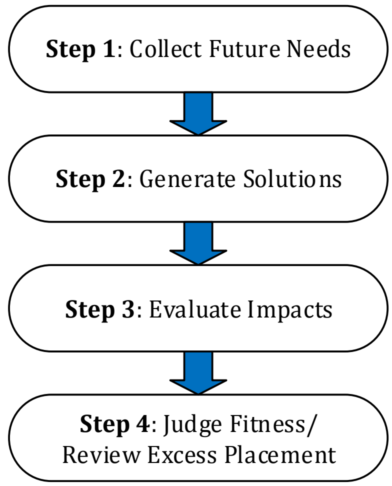

Figure 5.1: Stress Test Approach Flowchart

5.2 Stress Test Approach Steps

The following subsections detail the steps involved in stress testing a system.

5.2.1 Step 1: Collect Future Needs and Specifications

This step guides the application of the remainder of the stress test approach, and entails acquiring the set of needs that the system will be tested against. Ideally, information about possible future needs will be available from external sources such as marketing information or historical changes similar systems have been required to undergo. However, such information is not required. Designers may still apply this approach using only the original design specifications as a base if necessary, since the primary functions of the system are believed to remain the same over time and the original specifications embody the satisfaction of these functions. At a minimum, designers should consider varied usage environments and the possibility that stakeholders will desire increased performance as embodied in the system-level specifications.

Information about future needs (if sourced externally) must be represented by new or updated design specifications for the excesses in the system to be measured against. Where possible and appropriate, each specification should be posited to have differing levels of severity, three at minimum. This is meant to give a designer insight into how the system responds to various degrees of required change. The values of the points to choose are subject to designer discretion for each particular case – for a specification that is unlikely to change significantly, alterations of +5%, +10%, and +20% could be appropriate. On the other hand, for a specification with no clear reasonable upper bound, alterations of +20%, +50%, and +150% could be justifiable. It is recommended that the spacing of these points is nonlinear so that the design space can be more efficiently explored (relative to a linear set of points). Such a nonlinear spacing allows designers to explore the results of a 'minor', 'in between', and 'drastic' change. However, designers may explore more than three points if they feel the expenditure of effort is worthwhile.

Each future need will first be examined individually (i.e. as though only one occurs at a time) in the following steps, so that the impacts of two different needs applied at the same time are not confounded. In general, quantities of excesses consumed by one change cannot be assumed to be usable to effect other changes as well – consider a wire that feeds current to a system. If a change is made that requires an additional ampere of current, that excess cannot be applied to a second change that also requires additional electrical energy to be conveyed by the wire.

In general, the bounds of this step can be expanded depending on the circumstances of the particular design. This decision is a function of many considerations such as available designer effort, budget to embed excess, expected system lifetime, and anticipated volatility of service environment. Therefore, the number and plausibility of future needs considered is left to the designers of a particular system.

5.2.2 Step 2: Generate Solutions

For each posited future need, solution paths are determined using the excess map and knowledge of the system's design. Designers in the embodiment phase of system design will be capable of altering the system design, using the existing design as a starting point, to satisfy future needs. Multiple options should be found where possible; in general, the number of solution paths will be proportional to system complexity. The solutions should be as straightforward as possible so as to yield the most realistic options set. Ideally, all solutions for a future need can be realized by modifying individual components or subsystems without changing the system architecture. Realistically, many solutions will impact multiple components by propagating changes from functional flows to compatibility flows, possibly requiring some components to be replaced. There will naturally arise some scenarios where only drastic solutions will suffice and major modification to the system architecture is required. These cases indicate future needs that the system is ill-suited to respond to as presently designed.

5.2.3 Step 3: Evaluate Impacts

In general, there are three possible outcomes when exploring solutions to meet future needs:

- All affected components possess enough excess to evolve the system; excess in the components are reduced to either a positive or zero value by the solution.
- One or more affected components have insufficient excess, indicating that for the system to evolve, components would have to be upgraded or replaced.
- Some portion of the system architecture does not support the solution; i.e. the signal/mass/energy flows between multiple components cannot be adjusted in magnitude or redirected in application to enable the evolution. A result of this type raises important questions for the designer. If the posited future need is an outlier, highly unlikely to actually occur, then the system design is likely acceptable. However, if the posited future need is known to be a reasonable possibility, this result indicates that the design might not be fit for purpose and should be carefully reevaluated.

Once all the impacts of the individual needs have been considered, a matrix, similar to a DSM, is constructed to examine which potential needs could require the same excesses as other potential needs. Each potential need receives a row and corresponding column so that its interactions with other needs can be marked. These areas of overlap trigger a review so that designers can examine the ability of the system to respond to simultaneous future needs that require the same types of excess. The matrix is upper triangular since the interactions are non-directional, and so filling out the entire matrix would only duplicate information.

5.2.4 Step 4: Judge Fitness/Review Excess Placement

After considering the results of all future needs scenarios, designers will be capable of judging whether a design is likely capable of changing to meet future needs that are realized once the system is deployed. Beyond this judgment, designers will have gained insight into the relations between individual excesses and the system's evolvability. Some components may emerge as bottlenecks to system evolution because they possess no or limited excess. Others may appear to so far outstrip other components that their excess is superfluous. Such cases may result from oversights in the design process and present an opportunity to lower system cost by eliminating some excess, or may be due to the factors discussed in Section 3.1 concerning excesses as side effects of other factors. These insights into component-level excesses can be used to inform decisions of adding or subtracting excess from the system design.

5.3 Stress Test Case Study Preliminaries

For the case study of this approach, a toy dart gun shown in Figure 5.2 was used, as it offered a greater potential variety of future needs than the heat gun or coffee maker but could still have all of its excess flows identified and quantified via reverse engineering. The details of its excess map creation are given in this section.

Figure 5.2: Toy Dart Gun [62]

5.3.1 Toy Dart Gun Excess Map Creation

The plastic pieces that comprise the dart gun were assumed to be ABS plastic with a yield strength of 40 MPa, and a Factor of Safety of 2 was assumed. This meant that yield strength of the plastic was treated as 20 MPa with a corresponding shear strength of 10 MPa. The pertinent measurements for calculations concerning components that contain and/or compress air were measured and are given in Table 5.1.

Table 5.1: Dart Gun Component Measurements

Component	Volume (mL)	Radius (mm)	Wall Thickness (mm)
Flex tube	2.26		
Slide pump	24.1	10	1.7
Charge PV	18.2	11	1.7
Barrel tube	7.22	6.5	1.9

The compression of gas by the hand slide pump was assumed to be isothermal since it occurs over a relatively long period of time. The expansion of gas when the dart is fired was assumed to be adiabatic since it occurs very quickly.

For isothermal compression and expansion:

$$PV = const \tag{5.1}$$

For adiabatic compression and expansion:

$$PV^{\gamma} = K = const \tag{5.2}$$

$$W_{adiabatic} = K \frac{V_f^{1-\gamma} - V_i^{1-\gamma}}{1-\gamma} \tag{5.3}$$

Where W is work, P is pressure, V is volume, V_f is final volume, V_i is initial volume, and γ is the ratio of gas specific heats (1.4 for air).

Any figures involving dart flight distance assume level fire from a height of 1m. Therefore, the time of flight (neglecting drag) for any dart is given as

$$TOF = \sqrt{\frac{h}{\frac{1}{2}a}} = \sqrt{\frac{1m}{\frac{1}{2}\left(9.8\frac{m}{s^2}\right)}} = 0.45\ sec \tag{5.4}$$

Using the results of Equation 5.4, the elementary relation KE = ½ mv^2 and the known 1.5g mass of a dart, the plot shown in Figure 5.3 is created to show the required kinetic energy for a dart as a function of flight distance.

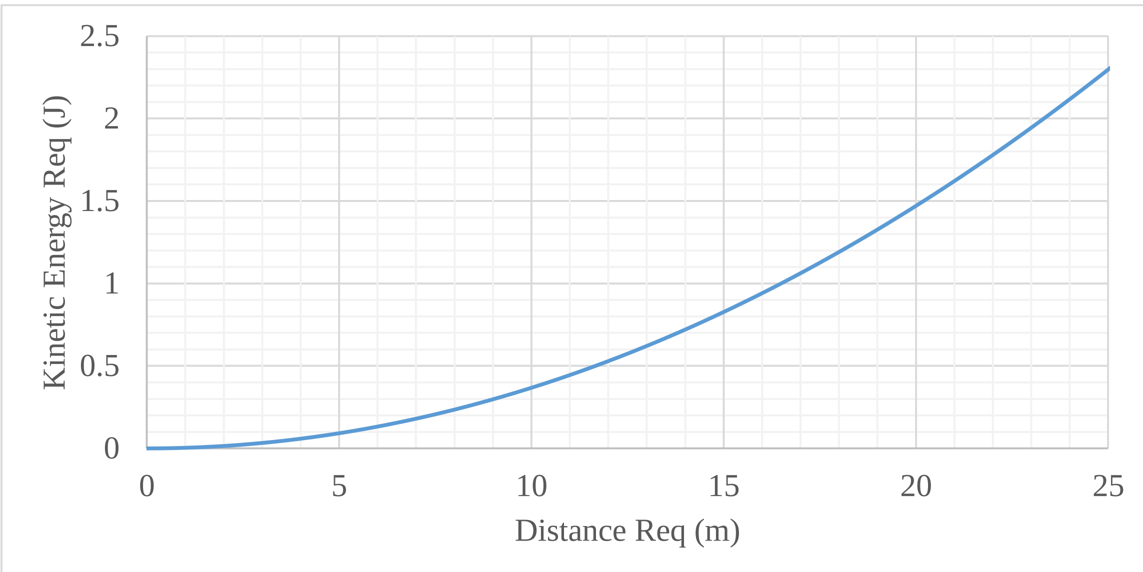

Figure 5.3: Dart Kinetic Energy Required vs. Distance for Level Fire at 1m

When analyzing cylindrical components that function as pressure vessels, the hoop stress was considered to be the limiting loading scenario and was calculated by Equation 5.5, where P is the pressure, r is the mean radius, and t is the thickness.

$$\sigma_h = \frac{Pr}{t} \tag{5.5}$$

This can be rearranged into Equation 5.6 to give the maximum working pressure as a function of the material yield strength (assumed 20 MPa for ABS plastic as earlier noted), the wall thickness, and radius.

$$P_{max} = \sigma_{yield} \cdot \frac{t}{r} \quad (5.6)$$

Step 1: Collect Stakeholder Specifications

A subset of specifications embodied in the design are:

- Fire 1.5g foam suction-tipped darts
- Operate in air at 1 atm pressure
- Fire darts of dimensions 13mm OD x 6.4mm ID x 57mm long
- Fire darts 6m (assuming level fire at height of 1m)
- Hold 6 darts
- Weigh less than 900 g
- Trigger pull force less than 15N

Step 2: Identify Architecture, Appropriate Subassemblies, and Relationships

The components that display modular behavior are the body, slide grip, slide pump, flex tube, check valve/release, charge pressure vessel, floating pressure seal, rotary barrel, trigger/advance assembly, and ratchet shaft. Their contributions to the excess map are detailed in the following subsections.

Body

Figure 5.4: Dart Gun Body

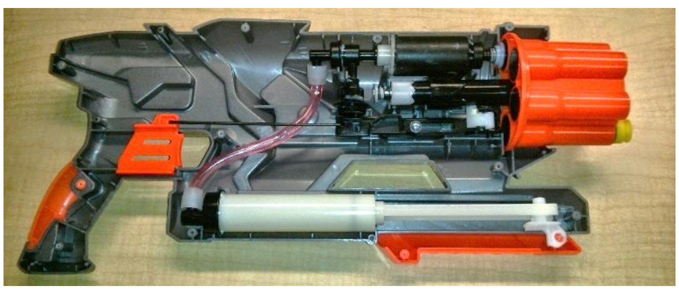

Figure 5.5: Dart Gun Component Layout

The body of the dart gun, shown in Figure 5.4, supplies volume (Storage, Geometric, Volume or S-G-3) to the slide pump and charge pressure vessel, and mandates a radial distance (Storage, Geometric, Length or S-G-1) from the axis of rotation for the dart pattern in the rotary barrel.

The component and excess blocks for the body are given in Figure 5.6. The first volume excess block supplies 26 mL of space out of a maximum 78 mL to the charge pressure vessel. The length excess block supplies a 45 mm radial distance (from the axis of rotation to the dart chamber) to the rotary barrel and has no excess remaining. The second volume excess supplies all of the available 24 mL of space to the slide pump.

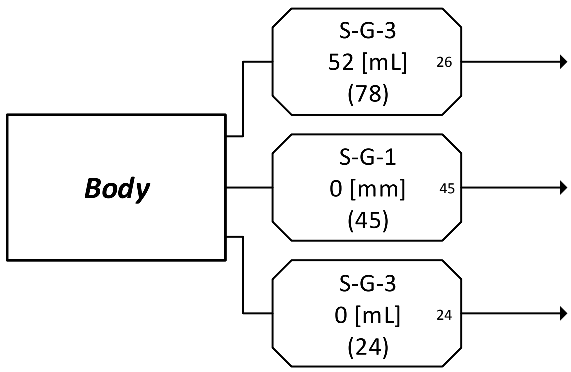

Figure 5.6: Body Excess Map Contribution

Slide Grip

Figure 5.7: Dart Gun Slide Grip

The slide grip, shown in Figure 5.7, is where the user's hand grips the dart gun and operates the slide pump. The screw posts on the right side nest together and interface with the slide pump, transferring energy to compress the air, and can tolerate a maximum load as given in the excess block in Figure 5.8 based on its dimensions and the properties of ABS plastic.

Assuming an isothermal compression, the relation in Equation 5.1 applies. Using an initial pressure of 101 kPa (one atmosphere), an initial volume of 42 mL (the slide pump, flex tube, and charge pressure vessel) and a final volume of 18 mL (the flex tube and charge pressure vessel), the final gauge pressure in the charge pressure vessel is 135 kPa. Given that the inner diameter of the slide pump is 19mm, with a corresponding area of 284E-6 m^2, the resulting force transmitted from the slide grip to the slide pump at the bottom of its stroke is 38N using the elementary relation P=F/A. Given the cross-sectional area of the screw post that functions as a structural member under shear load, 18mm^2, along with the maximum shear load of 10 MPa, a maximum shear force of 180N can be applied. This is represented by a load excess (Storage, Structural, Load or S-S-L).

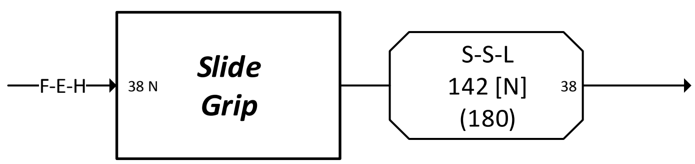

Figure 5.8: Slide Grip Excess Map Contribution

Slide Pump

Figure 5.9: Dart Gun Slide Pump

The slide pump, shown in Figure 5.9, takes in atmospheric air and compresses it for use elsewhere in the dart gun. It requires volume (Storage, Geometric, Volume or S-G-3) from the body. Its radius and wall thickness, given in Table 5.1, yield a maximum working pressure of 3.4 MPa as shown in the excess block of Figure 5.10 using Equation 5.6.

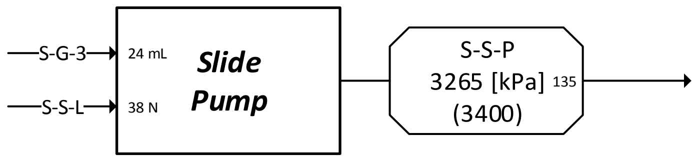

Figure 5.10: Slide Pump Excess Map Contribution

Flex Tube

Figure 5.11: Dart Gun Flex Tube

The flex tube, shown in Figure 5.11, conveys compressed air from the slide pump to the check valve. It is made of vinyl tubing that is rated to 1 MPa based on its wall thickness (1 mm). This is represented by a pressure excess (Storage, Structural, Pressure or S-S-P).

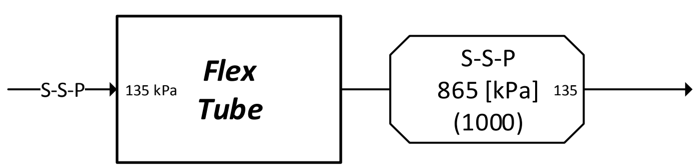

Figure 5.12: Flex Tube Excess Map Contribution

Check Valve/Release

Figure 5.13: Dart Gun Check Valve/Release

The check valve and release assembly, shown in Figure 5.13, allows unidirectional flow of compressed air into the charge pressure vessel, and controls its release to the barrel by actuation of the seal at the assembly's base. Based on its measurable wall dimensions at its widest cylindrical portion (the worst case stress scenario for hoop stress), its maximum working pressure is estimated to be 1.4 MPa using Equation 5.6 with a wall thickness of 0.7 mm and a radius of 10 mm. The component and excess blocks are shown in Figure 5.14.

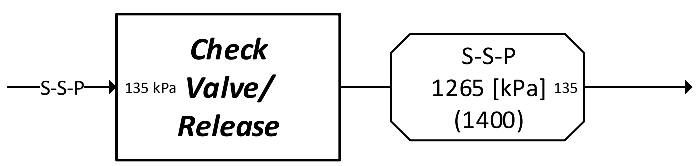

Figure 5.14: Check Valve/Release Excess Map Contribution

Charge Pressure Vessel

Figure 5.15: Dart Gun Charge Pressure Vessel

The charge pressure vessel, shown in Figure 5.15, contains the compressed air that powers the flight of the darts. It requires volume (Storage, Geometric, Volume or S-G-3) from the body. It is actuated by the check valve/release assembly, which attempts to release the pressure in the charge pressure vessel through the check valve. This causes a piston to retract within the charge pressure vessel, sealing the orifice to the check valve while opening the orifice to the rotary barrel. The maximum working pressure is 5.8 MPa based on the dimensions of the charge pressure vessel given in Table 5.1 and the results of Equation 5.6, as shown in Figure 5.16.

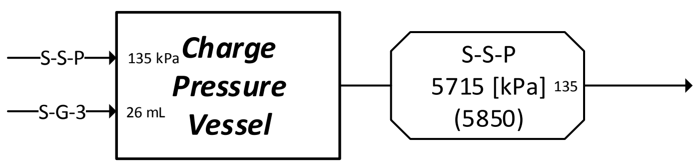

Figure 5.16: Charge Pressure Vessel Excess Map Contribution

Floating Pressure Seal

Figure 5.17: Dart Gun Floating Pressure Seal

The floating pressure seal, shown in Figure 5.17, attempts to ensure that the full pressure from the charge pressure vessel reaches the rotary barrel. It uses a spring to press a flat rubber seal (hollow in the center to permit air flow) against the barrel. However, the spring is relatively weak, and based on its measured spring constant (130 N/m), deflection at operating conditions (9mm) and the dimensions of the rubber seal (13.5mm OD x 6mm ID), only 10 kPa of pressure can be contained as shown in Equation 5.7.

$$P_{max} = \frac{F_{spring}}{A_{seal}} = \frac{k \cdot x}{\frac{\pi}{4}(OD^2 - ID^2)} = \frac{130\frac{N}{m} \cdot 0.009m}{\frac{\pi}{4}(.0135m^2 - .006m^2)} = 10\ kPa \quad (5.7)$$

Empirical flight testing results found that darts fired level from 1m above the ground reached 6m. Consulting Figure 5.3 shows that the corresponding kinetic energy (and hence the work done on the dart) must be approximately 0.12 J. Using Equation 5.3 with P = 10 kPa, V_i = 15.6mL (the volume of the charge pressure vessel) and V_f = 22.8 mL (the volume of the charge pressure vessel plus a dart chamber) results in an adiabatic work done on the dart of 0.05 J – clearly less than that actually imparted to the dart. This means that while the floating pressure seal functions as a blowoff valve for any pressure above 10 kPa, back pressure causes the delivered pressure to the dart to be higher than the cracking pressure of the floating pressure seal.

Using the known work required for a flight of 6m (0.12 J) and back solving Equation 5.3 to find the original pressure results in 25 kPa, the pressure that is actually delivered to the dart by the floating pressure seal. These considerations are represented by a pressure (Storage, Structural, Pressure or S-S-P) excess block in Figure 5.18.

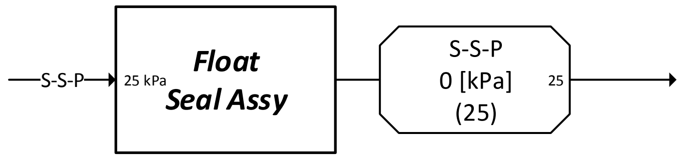

Figure 5.18: Floating Pressure Seal Excess Map Contribution

<u>Rotary Barrel</u>

Figure 5.19: Dart Gun Rotary Barrel

The rotary barrel, shown in Figure 5.19, requires a linear positioning (Storage, Geometric, Length or S-G-1) of 45 mm between its dart pattern and its axis of rotation with respect to the body, receives a positioning signal (Flow, Signal, Control or F-S-C) from the ratchet shaft, and receives compressed air (Storage, Structural, Pressure or S-S-P) from the charge pressure vessel/floating pressure seal. It can tolerate up to 5.8 MPa of pressure (S-S-P) based on the dimensions of the individual chambers and contains six darts (Storage, Material, Solid or S-M-S). Its component and excess blocks are shown in Figure 5.20.

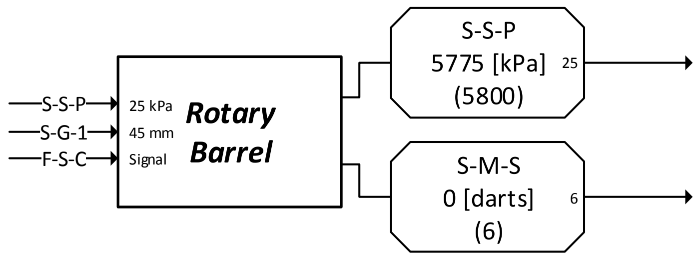

Figure 5.20: Rotary Barrel Excess Map Contribution

Trigger/Advance Assembly

Figure 5.21: Dart Gun Trigger/Advance Assembly

The trigger/advance assembly, shown in Figure 5.21, receives human energy (Flow, Energy, Human or F-E-H) as input to the trigger and translates it to a positioning signal (F-S-C) to the ratchet shaft. The geometry of the assembly means that, depending on the geometry of the ratchet shaft, any rotation from 40° to 180° can be commanded. The assembly also actuates the release in the check valve/release to fire the gun; however, this is not modeled as it is not reasonable to describe any excess in the binary relationship. The component and excess blocks for the trigger/advance assembly are shown in Figure 5.22.

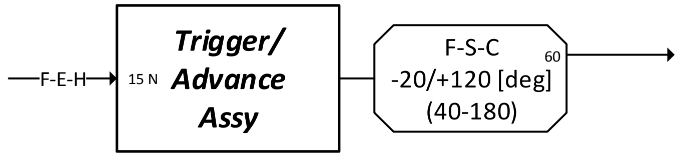

Figure 5.22: Trigger/Advance Assembly Excess Map Contribution

Ratchet Shaft

Figure 5.23: Dart Gun Ratchet Shaft

The ratchet shaft, shown in Figure 5.23, translates the control signal (F-S-C) from the trigger/advance assembly to a commanded rotational advance (F-S-C) of the rotary barrel. While the trigger/advance assembly is not set to a fixed rotational amount, the ratchet shaft may only rotate in set increments of 60° due to its construction. The black and white pieces are keyed to one another and may only move in 60° increments with respect to one another; changing this would require replacing both the black and white shaft pieces and therefore the vast majority of the ratchet shaft assembly. The component and excess blocks for the ratchet shaft are shown in Figure 5.24.

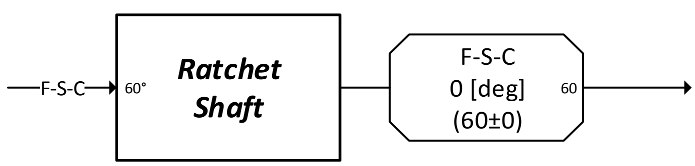

Figure 5.24: Ratchet Shaft Excess Map Contribution

Step 3: Assemble Excess Map

The summarized compatibility and functional flows for the components of the dart gun are given in Table 5.2. The environment block for this system consists of two human energy relationships (Flow, Energy, Human or F-E-H); one to operate the pump and the other to pull the trigger.

Table 5.2: Dart Gun Component Excesses

Component	*Compatibility Flow*	*Functional Flow*
Body	N/A	Storage-Geometric-Volume (2) Storage-Geometric-Length
Slide Grip	Flow-Energy-Human	Storage-Structural-Load
Slide Pump	Storage-Geometric-Volume Storage-Structural-Load	Storage-Structural-Pressure
Flex Tube	Storage-Structural-Pressure	Storage-Structural-Pressure
Check Valve/Release	Storage-Structural-Pressure	Storage-Structural-Pressure
Charge Pressure Vessel	Storage-Geometric-Volume Storage-Structural-Pressure	Storage-Structural-Pressure
Floating Pressure Seal	Storage-Structural-Pressure	Storage-Structural-Pressure
Rotary Barrel	Storage-Structural-Pressure Storage-Geometric-Length Flow-Signal-Control	Storage-Structural-Pressure Storage-Material-Solid
Trigger/Advance Assembly	Flow-Energy-Human	Flow-Signal-Control
Ratchet Shaft	Flow-Signal-Control	Flow-Signal-Control

Step 4: Identify State Parameters

There is only one necessary state parameter for the dart gun, total mass. The individual component masses are indicated within the component blocks. The completed dart gun excess map is shown in Figure 5.25. A full size version of the finished excess map is in the Appendix.

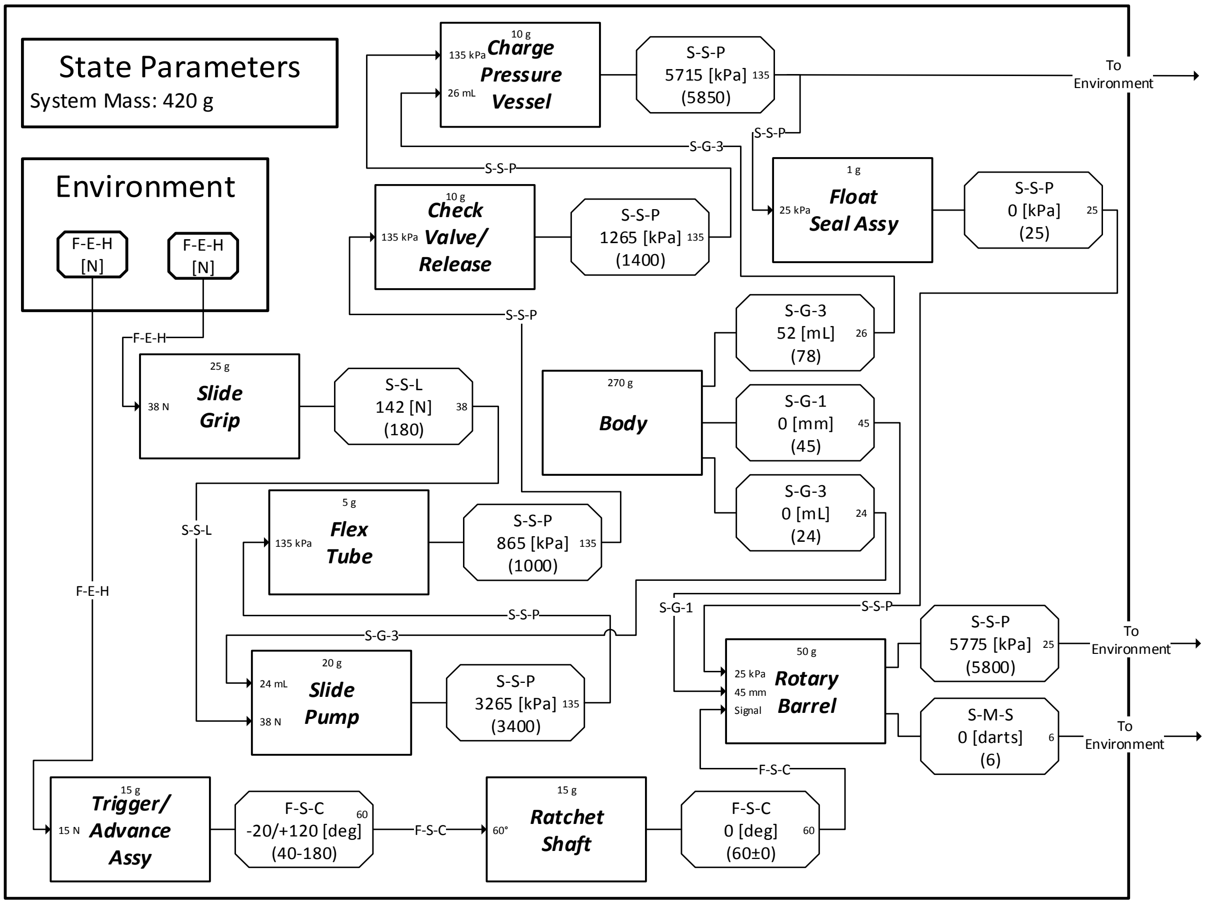

Figure 5.25: Toy Dart Gun Excess Map

5.4 Stress Test Case Study

This sections details the use of the stress test approach on the toy dart gun.

5.4.1 Step 1: Collect Future Needs and Specifications

A list of potential future needs was generated, considering the initial performance requirements placed on the gun and possible modifications, bearing in mind the constraint that top-level functional behavior is fixed. For the dart gun the top-level function can be described in the verb-noun nomenclature of functional modeling as ‘transmit darts’. The needs are listed here:

- Fire darts farther (+50%, +100%, +200%)
- Fire heavier darts (+50%, +100%, +200%)
- Increase dart accuracy
- Hold more darts (+50%, +100%, +200%)
- Fire underwater
- Fire in vacuum
- Self-powered (no pumping)

5.4.2 Steps 2 and 3: Generate Solutions and Evaluate Impacts

Steps 2 and 3 are discussed together for each of the examined future needs. This is done so that the reader may see the solutions for and impacts of each posited future need together, rather than having to remember the set of solutions for every need before discussion of the solution impacts.

5.4.2.1 *Fire Darts Farther*

As originally designed, the gun fires darts to a distance of 6m. For the stress-test analysis, three different evolutions were considered: fire darts 9m, 12m, and 18m (50%, 100% and 200% increases, respectively).

Three approaches to boost the range of the darts were considered:

- Replacing the spring in the floating pressure seal assembly (shown in Figure 5.17) to increase pressure delivery to the barrel
- Replacing the hand pump mechanism with a tank of compressed gas and a regulator
- Adding a small propellant charge to the base of each dart

<u>Approach 1</u>

An analysis of the pressure energy flows through the dart gun combined with the information in Figure 5.3 reveals that there is sufficient energy contained within the charge pressure vessel to propel a dart 14m. This conclusion results from the following analysis:

- The pressure delivered by a single pump is calculated as follows:

$$P_1V_1 = (1\ \text{atm})(24.1 + 18.2 + 2.3\ \text{mL}) = P_2V_2 \quad (5.8)$$

$$V_2 = (18.2{+}2.3\ \text{mL}) \rightarrow P_2 = 2.3\ \text{atm} = 236\ \text{kPa} = 135\ \text{kPa gauge} \quad (5.9)$$

- If the full 135 kPa is delivered to the dart according to Equation 5.9, it results in a work of 0.7 J. This is sufficient, according to Figure 5.3 to propel the dart 14m.

However, this energy is delivered to the barrel via the floating pressure seal assembly. This assembly uses a spring to press a flat rubber seal against the base of the rotary barrel. The maximum air pressure that it can transmit is limited by the force with which the spring compresses the seal against the barrel. As designed, the spring is relatively weak with a rate of 130 N/m. Given the dimensions of the rubber seal (13.5 mm OD x 6.0 mm ID), the floating pressure seal assembly can only contain a pressure of 10 kPa from the relation P=F/A (given a spring compression of 9mm). In essence, this assembly functions as a blowoff valve for any pressure exceeding the cracking pressure of 10 kPa. However, as a blowoff valve, the assembly has inadequate ventilation, resulting in significant back pressure that produces a pressure in the barrel somewhere between the charge pressure and the cracking pressure.

Comparing empirical flight results and the thermodynamic and kinematic equations suggest that, for a charge pressure of 135 kPa, the floating pressure seal assembly delivers roughly 25 kPa to the barrel - about two and a half times its cracking pressure. This confirms that there is back pressure that prevents the floating pressure seal from functioning as an ideal blowoff valve. These considerations are condensed in the excess map of Figure 5.15 as a S-S-P (storage, structural, pressure) excess of 25 kPa for the floating pressure seal.

For a dart to reach 9m, a pressure of at least 55 kPa is required. Information from the excess map shows that if the floating pressure seal assembly's ability to contain compressed air is increased to 55 kPa, no other modifications to the system are required. This results from consulting Figure 5.3 to find the required dart kinetic energy to reach 9m (0.3 J), solving Equation 5.3 to find the corresponding initial pressure (55 kPa) and comparing that to the pressure provided by a single pump (135 kPa). Since the required pressure is less than that provided by a single pump, a single pump is sufficient. Consulting the S-S-P excesses within

Figure 5.25, attached to the slide pump, flex tube, check valve, charge pressure vessel, and rotary barrel indicates that those components are capable of withstanding the 135 kPa generated by a single pump, and therefore also the 55 kPa required for propelling a dart to 9m. However, the floating pressure seal is only capable of transmitting 25 kPa of pressure, and therefore must be upgraded. Similarly, increasing the range to 12m only requires that the delivered pressure be increased to 95 kPa, still less than the pressure made available in the charge pressure vessel by a single pump.

To reach the 18m goal the pressure supplied by a single pump is insufficient. However, the presence of a check valve in the compressed air path means that the hand slide pump could be cycled more than once to add air to the charge pressure vessel. With two pumps the dart gun can produce a charge pressure of 270 kPa, and consequently can fire up to 20m. This was concluded by using Equation 5.1 while doubling the volume of the slide pump and leaving the flex tube and charge pressure volumes the same, since the flex tube volume functions as dead space and the charge pressure vessel is behind the check valve. Using 270 kPa as the initial pressure in Equation 5.3 yields a work of 1.5 J and a corresponding range of 20m. Consulting the S-S-P blocks of Figure 5.25 determines that all components save the floating pressure seal are capable of withstanding 270 kPa. Therefore, to increase the dart gun's range to as much as 20m, only replacing the spring in the floating pressure seal is required.

An alternate approach to generating sufficient pressure to launch a dart 18m would be to lengthen the region of the body that contains the hand slide pump so that a longer slide pump could be added later. An increase of 55mm in the length allocated to the slide pump, resulting in an additional volume of 13 mL, would allow a maximum pressure of 270 kPa from a single pump. This would presumably increase customer satisfaction since range of up to 20m could be produced from a single pump.

Approach 2:

Consumer paintball guns powered by carbon dioxide tanks demonstrate how a small container of pressurized gas connected to a regulator can provide propellant energy. As a primary energy source, the tank and regulator could replace the slide pump assembly within the gun's handle. As a secondary energy source (used to increase the charge pressure from that provided by a single pump) portions of the propellant gas could be conserved. If a more extreme range is desired, replacing the slide pump mechanism with a gas tank and regulator would allow ranges of up to 38m (limited by the flex tube), provided that the compressed gas tank could occupy a volume of 24 mL or less (the volume denoted by the S-G-3 excess in Figure 5.25 consumed by the hand slide pump). Given that the orange hand slide would no longer be required, its removal would expose openings in the body that could be used to refill the gas canister with no further modification.

Approach 3:

The third approach considered was to add a consumable explosive charge to the barrel along with each dart (much as bags of gunpowder were placed behind shells in artillery pieces). However, a major obstacle to this strategy quickly became apparent. First, it is questionable whether the use of consumable propellant agrees with the customer need of reusable ammunition. Second, the darts themselves could become damaged by the heat of explosions. This solution reveals a limitation of the excess mapping method. The excess map in Figure 5.25 is generated as a function of customer needs and the system architecture present in embodiment design. Therefore, it is a product of the original solution determined by the engineers, in which isothermally compressed atmospheric air is used as the propellant. As a result, the temperature capabilities of the materials are not considered. When the solution approach to a potential future need changes from that originally taken in embodiment design, designers must be conscious of factors that were not originally included – in this case, the temperature sensitivity of darts and system materials. Since the dart is assumed to be supplied as a standardized external input to the system's function, it was not included in Figure 5.25.

A cursory search reveals that the burning temperature of black powder is at least 550 °C [63] while the melting temperature of polyethylene foam (which the darts are assumed to be made of) is 265 °C [64]. Black powder is a relatively elementary explosive, and several more powerful explosives have been developed. Any explosive powerful enough to give a significant contribution to the darts' muzzle velocity would likely produce at least localized burning of the foam material, meaning that one of the key customer needs would be invalidated.

Therefore, only the first two approaches considered to address this need are valid based on the customer needs given.

Conclusions:

If greater range is desired, the spring in the floating pressure seal will need to be replaced with a stiffer version to increase the cracking pressure of the assembly. This alone is actually sufficient to increase the range to over 20m, in conjunction with an additional pump from the hand slide pump. If a greater increase in range is desired, the hand slide pump should be replaced with a compressed gas tank and regulator that can deliver pressures that are limited only by the weakest component in the gas flow path, the flex tube, which permits a 38m range.

Theoretically, the gun could be pumped up to a maximum pressure of 1 MPa (based on the pressure that one pump would generate if the dead space of the flex tube was the final volume). However, with such great pressure the simple model used for work done on the dart would break down due to flow restrictions between the charge pressure vessel and the barrel.

5.4.2.2 *Fire Heavier Darts*

As originally designed, the dart gun fires standard darts with a mass of approximately 1.5g a distance of 6m. For the analysis, three different evolutions were considered: fire 2.3g, 3.0g, and 4.5g darts (an increase of 50%, 100%, and 200% respectively) the same distance. These masses correlate to 0.20J, 0.27J, and 0.40J of required kinetic energy at the muzzle, respectively. The assumption is made that the increase in mass of the dart is solely a function of the density of the foam and/or tip mass (i.e. the darts are the same dimensions as the standard darts).

Firing heavier darts, as in the previous scenario, reduces to a problem of imparting additional kinetic energy to the dart. Therefore, two approaches were considered (bearing in mind that adding an explosive charge is impractical): increasing the floating pressure seal spring's stiffness and replacing the hand slide pump with a compressed gas tank and regulator.

Approach 1:

A single pump can produce up to 0.74J of work delivered to a dart, far in excess of that required for even a dart three times heavier than the standard, provided that the cracking pressure of the floating pressure seal, denoted in the attached S-S-P block in Figure 5.25, is increased to 135 kPa with a stiffer spring.

Approach 2:

Replacing the floating pressure seal spring is sufficient for up to an 8g dart to be propelled 6m. However, if for any reason an extremely heavy dart were desired, the pressure supplied by a compressed gas tank could propel up to a 29g dart 6m, limited again by the maximum pressure allowed by the check valve.

Conclusions:

Little challenge is presented by firing a heavier dart. A dart three times heavier than the standard can be fired using a single pump if the spring in the floating pressure seal is replaced as described in the previous scenario. Of note is that if a combination of increased range and increased mass were desired, a compressed gas tank might become the most viable solution to increase the energy delivered to the darts.

5.4.2.3 *Fire in Vacuum*

The dart gun as designed relies on the ready availability of air as propellant for the darts. However, in a vacuum, any propellant would have to be supplied as well.

Approach 1:

Given that the darts are assumed to remain unchanged and therefore inert, the propellant cannot be supplied by the hand slide pump as designed. The projectiles are foam and so cannot be moved by alternate propulsive means such as electromagnetic fields. Given these considerations, the only available solution enabling the dart gun to fire in a vacuum using gas as a propellant is to replace the hand slide pump with a cylinder of compressed gas and a regulator. Additionally, the spring in the floating pressure seal must be replaced with one that produces a higher cracking pressure. The availability of paintball guns of similar size indicates the feasibility of such a solution. This solution enables fire of up to 38m in Earth's gravitational field.

Approach 2:

Compressed gas is not the only possible means of propelling a dart. Another option is mechanical propulsion, as in the case of the flywheel propulsion mechanism used by some dart guns. Unfortunately, the geometry of a flywheel propulsion mechanism requires that there be two opposing flywheels, and that the darts be fed individually, typically from a box rather than drum magazine. Further, flywheel propulsion requires electrical energy to operate, meaning that every component in the existing architecture that handles gas flow would be discarded. Since the existing advance mechanisms (the trigger/advance assembly and the ratchet shaft) are designed for a rotary barrel rather than a box magazine, they would have to be replaced as well. Ultimately, for the dart gun architecture to be converted to a mechanical propulsion scheme, every internal component and the rotary barrel would have to be discarded, and the body would have to be significantly modified. Therefore, the only viable approach to converting the dart gun to fire in a vacuum is the approach discussed previously.

Conclusions:

An external supply of compressed gas is the only reasonable solution to the need of firing in a vacuum, and also to the potential future need of terrestrial self-powered fire. Additionally, such a modification would allow semi-automatic fire since the gun as configured already advances to a new chamber with each pull of the trigger.

5.4.2.4 *Fire Underwater*

This potential need presents the same limitations as the vacuum-firing case above. This is because, though the gun would in this case be surrounded by a fluid that could be drawn into the hand slide pump, the fluid is incompressible and therefore cannot be used as propellant in the dart gun as configured. As a result, the immediate solution is the same as for the vacuum case: replace the hand slide pump with a compressed gas cylinder and regulator. However, the need to fire underwater presents another complication. In contrast to the nominal usage case in which the working fluid is air, and drag on the dart is neglected in calculations, water as a flight environment produces drag three orders of magnitude greater, which cannot be neglected. Treating the dart as a flat-nosed cylinder and assuming a drag coefficient of 0.8, it is functionally impossible for the dart to travel 6m before dropping 1m within Earth's gravitational field. Simulations were run to numerically integrate a dart's position given initial displacement and velocity, and it was found that even giving the dart a muzzle velocity of 2 km/s was insufficient to propel it beyond a meter. This is due to the relatively large cross-sectional area to mass ratio, coupled with the immense drag that water exerts. Given that imparting such a massive amount of kinetic energy (3 kJ, which is still insufficient) is clearly impossible for the dart gun (as it would require a pressure of 700 MPa, far greater than any of the S-S-P excesses denoted in Figure 5.25. Therefore, the only feasible solution is to modify the darts so that they are in some way self-propelled. However, designing such a complicated mechanism as a self-propelled underwater dart is beyond the scope of this paper. Realistically, such a radical change in application would likely not benefit from the existing design, optimized for firing darts in an atmosphere with negligible drag.

5.4.2.5 *Increase Accuracy*

Before the dart gun was disassembled, it was noted that successive shots fired from the same position were not tightly grouped. While this is certainly a function of both the gun and the individual darts, it is conceivable that a future need for the gun is for it to be made more accurate. Historically, two approaches have been used to increase the accuracy of projectiles fired from barrels: spin-stabilization provided by rifling and increased barrel length.

Approach 1:

The rifling approach has the benefit of allowing the existing rotary barrel to be modified, thus requiring no new components. Consulting the S-S-P block attached to the rotary barrel in the excess map of Figure 5.25 shows that the rotary barrel as designed has sufficient thickness to contain 5.8 MPa of pressure, two orders of magnitude more than the pressure it is exposed to as designed. Half of its 1.9mm thickness could be removed locally for rifling while still leaving a maximum permissible pressure of 2.9 MPa, certainly adequate for any of the scenarios discussed here.

However, this approach might have limited effectiveness for foam darts. This is because in an actual firearm, the force of the explosion is sufficiently powerful to permanently deform the relatively soft lead of the bullet in such a way that it conforms to the rifling in the barrel, ensuring both a nearly gas-tight seal and a guaranteed interaction between the bullet and the rifling (and a resulting spin-stabilization). In the case of a dart gun, foam darts would not be sufficiently deformed by the relatively low pressures involved to mate well to the rifling. While the limited frictional interaction could still be enough to make the darts spin, the larger issue is that the propellant gas would very likely leak around the darts to some degree with a negative effect on the dart's range. Therefore, while possible, rifling the rotary barrel's chambers would likely not yield the desired results.

Approach 2:

Given the lack of promise of the first approach, lengthening the rotary barrel bears exploration. A benefit of the current system design is that any rotary barrel with the same base flange dimensions and chamber number/pattern may be swapped into the dart gun without modification to any other components. Therefore, while lengthening the rotary barrel's chambers obviously requires a new rotary barrel, no other components would be affected. In principle, the longer a barrel is, the more accurate the projectile becomes. Additionally, the energy transfer from the charge pressure vessel to the dart is more complete with a longer barrel as shown in Equation 4.16, due to the larger final volume. However, the work done by friction on the projectile is also increased, and the air in the charge pressure vessel can only be expanded so much before a negative pressure gradient is created relative to the atmosphere. Therefore, experimental testing would need to be done with varying length barrels to determine the optimal length. Regardless of the final length selected, this approach would work to both increase accuracy and, to a lesser extent, range.

Conclusions:

If increased accuracy is desired, the only practical solution is to replace the rotary barrel with one of increased length. The exact length would have to be determined by experimental testing.

5.4.2.6 *Hold More Darts*

The dart gun as designed holds six darts in its rotary barrel. For this analysis, three different evolutions were considered: holding 8, 12, and more than 12 darts. Two approaches were considered: enlarging the rotary barrel and switching to a box magazine.

Approach 1:

The most direct solution to this need is to redesign the rotary barrel to accommodate more darts. Examining the radius of the dart chamber pattern, denoted in the S-G-1 block attached to the Body in Figure 5.25 and flowing to the rotary barrel (which is fixed for the barrel as a function of the body geometry) reveals that a redesigned barrel could be created that holds 8 darts. The ratchet shaft would also have to be replaced, since it is keyed to a particular number of darts by its number of positive stops, as shown by the F-S-C block in Figure 5.25. For 12 darts to be accommodated, the barrel, body, and ratchet shaft would have to be redesigned. This would be non-trivial, since the body would have to be redesigned to diameter of the dart chamber pattern, which entails repositioning the charge pressure vessel and floating pressure seal with respect to the barrel's axis of rotation. In principle, this could be done for an indefinite number of darts. However, it is worth noting that the area and volume of the barrel are a function of the square of the dart chamber pattern diameter, while the number of darts is directly proportional to its diameter. This means that building a bigger barrel is a spatially inefficient strategy to increase the number of darts held by the gun beyond small increases.

Approach 2:

A box magazine can hold any number of darts, limited only by the practicality of its resulting size. Eight, twelve, or twenty darts could be held by such a magazine with the only difference between the capacities being its resulting length. However, the question at hand is whether the dart gun can be modified with a reasonable amount of effort to accept a box magazine rather than a rotary barrel. Consulting the layout of the dart gun as shown in Figure 5.5, it becomes apparent that such a redesign could be performed by removing the barrel, modifying the body to accept a box magazine horizontally, aligned with the floating pressure seal, and building an additional assembly to fit between the existing ratchet advance shaft and box magazine that translates the rotary motion of the ratchet advance shaft to a linear motion of the box magazine. While a non-trivial modification, it could be done and would easily allow a doubling, perhaps tripling of the number of darts held.

Conclusions:

Holding eight darts would require modification of only two components, the rotary barrel and ratchet advance shaft. Converting the dart gun to use a box magazine is possible, but the requisite effort suggests that it is only worthwhile if a substantial increase in dart capacity is desired.

5.4.3 Step 3 Continued: Review Overlapping Future Needs

Based on the results of the preceding solutions for future needs, Table 5.3 shows the possible interactions between various future needs. A bold X indicates a definite interaction, and a regular X indicates a possible interaction. These are the areas that require review by designers to further understand how multiple realized future needs could impact the system.

Table 5.3: Overlapping Future Needs

		Farther			Heavier			Increase Accuracy	Hold more darts			Vacuum/ Self Powered
		50%	100%	200%	50%	100%	200%		50%	100%	200%	
Farther	50%				**X**	**X**	**X**	X				
	100%				**X**	**X**	**X**	X				
	200%				**X**	**X**	**X**	X				
Heavier	50%							X				
	100%							X				
	200%							X				
Increase Accuracy												
Hold more	50%											
	100%											
	200%											
Vacuum / Self Power												

The only two needs that are directly related, i.e. satisfying one will directly affect the ability to satisfy the other, are firing darts farther and firing heavier darts. This is because both needs relate to the amount of kinetic energy delivered to the darts, and therefore relate to the pressure delivered to the dart. Examining the kinetic energy required for all of the possible combinations of distance and mass increases, using the relationship $KE = ½mv^2$, Figure 5.3, and Equation 5.3 reveals that if the spring in the floating pressure seal assembly is replaced to allow a cracking pressure of 270 kPa (that provided by two pumps) the dart gun can evolve to fire regular darts 200% farther (18m), 50% and 100% heavier darts 100% farther (12m), and 200% heavier darts 50% farther (9m). If the slide pump is replaced with a compressed gas tank and regulator and the spring is also replaced, 200% increases in both mass and range can be achieved. Therefore, designers must consider how likely they believe it to be that both needs will be realized, and if so, what levels of increase will be desired. A reasonable approach in the design phase might be to replace the spring with a stiffer version that can contain up to 270 kPa, so that the dart gun only needs to be modified in service if significant increases in both distance and dart mass are required.

A need for increased accuracy is noted to be possibly related to the ability to fire darts farther and/or with greater mass because the best identified solution, increasing the length of the barrel, could have side effects such as increased friction on the dart, thereby impacting the amount of energy needed by the dart. However, without empirical testing data of a longer barrel design it is impossible to know what impact this realized need could have on the system's ability to satisfy others, and so the possible interaction is left highlighted for designers to consider if appropriate in the future.

On the other hand, the if the need to hold more darts is realized, it should not affect the energy delivery systems within the dart gun because the modifications that it requires apply to the geometry of the body and do not affect the components that deliver energy to the dart. Likewise, altering the gun to fire in a vacuum (and consequently also to be self-powered) does not negatively impact the ability to satisfy other future needs; indeed, adding a compressed gas propellant system would allow 200% increases in both dart distance and mass by default, as long as the floating pressure seal's spring was also replaced.

5.4.4 Step 4: Judge Fitness/Review Excess Placement

Table 5.4: Summary of Dart Gun Stress Test Results

Need	Solution Strategy	Components Replaced/*Modified*
Fire Farther	Replace Spring	Floating pressure assy spring
	Comp Gas Tank and Regulator	Floating pressure assy spring, Hand slide pump
Fire Heavier Darts	Replace Spring	Floating pressure assy spring
	Comp Gas Tank and Regulator	Floating pressure assy spring, Hand slide pump
Fire in Vacuum/ Self Powered	Comp Gas Tank and Regulator	Floating pressure assy spring, Hand slide pump
Fire Underwater	N/A	N/A
Increase Accuracy	Rifling	*Rotary Barrel*
	Longer bore	Rotary barrel
Hold More Darts	Enlarge rotary barrel	Rotary barrel
	Box magazine	Rotary barrel, Body

Stress testing the dart gun revealed an unexpected conclusion: several potential future needs can be partially or entirely addressed by replacing a single piece, the floating pressure seal assembly's spring, with a stiffer version. For an inexpensive consumer product, the dart gun possesses substantial excess in all components that function as pressure vessels, and is capable of responding to several varied potential future needs. The only need that presented an insurmountable challenge was to fire underwater. However, this need is impossible to realize for any consumer dart gun based on the results of the numerical simulations performed.

Component excesses in Figure 5.26 highlighted in red indicate where designers might consider adding excess for the sake of future needs. Excesses highlighted in blue are possibly superfluous based on the results of the stress test. These two sets of excesses are discussed in the following subsections.

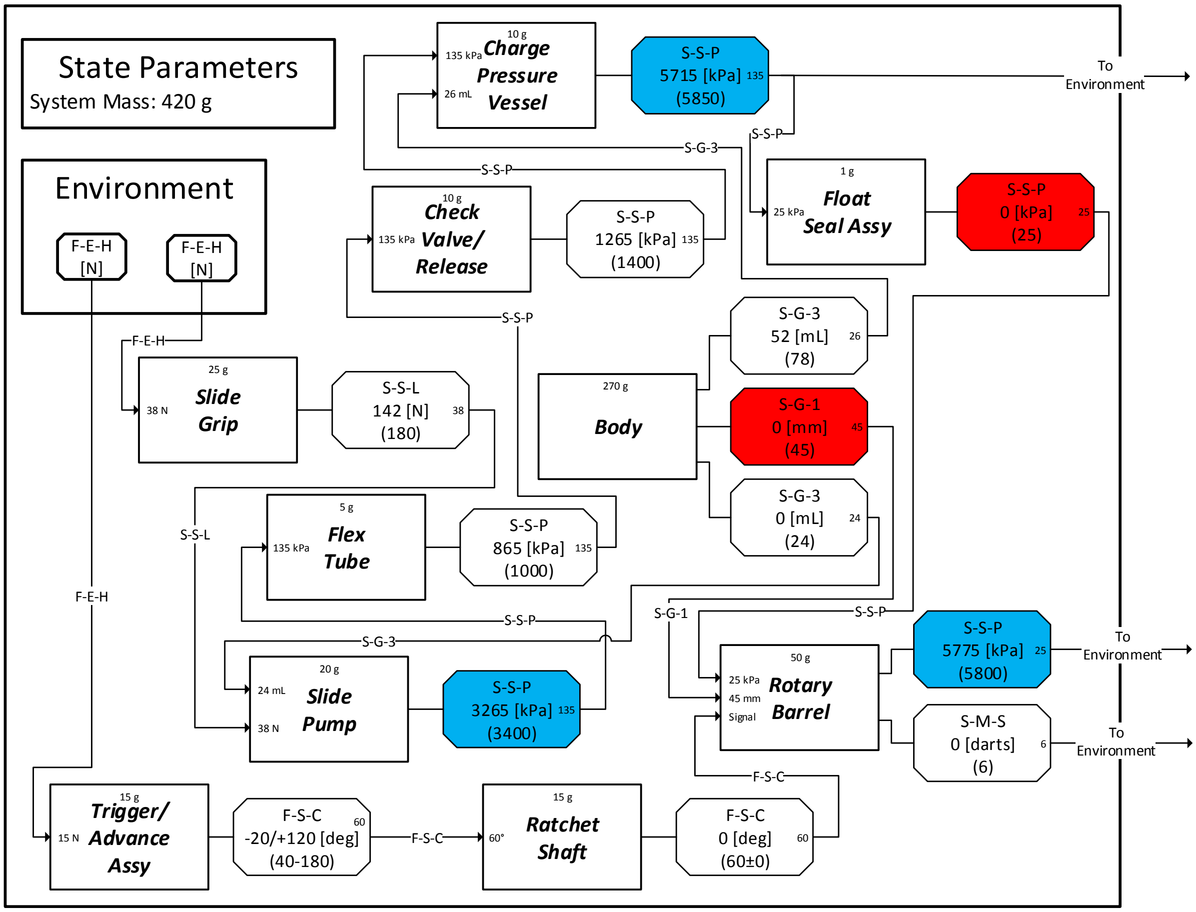

Figure 5.26: Dart Gun Stress Test Conclusions

5.4.4.1 *Potentially Inadequate Excesses*

A clear result of the study is that the spring in the floating pressure seal should be replaced with one with a stiffness of at least 1700 N/m (from the existing spring with stiffness 130 N/m). The increased force between the seal and rotary barrel could potentially cause binding issues due to increased static friction; however, the surfaces are already extremely smooth and a light, long life lubricant or non-stick coating could be added to the base of the rotary barrel to address any resulting problems from the added frictional force. This spring modification would allow the gun to use all of the pressure generated by a single pump, and therefore to fire up to 14m without any other modifications. Springs with higher compression rates could also be considered, but at a minimum, embedding this excess would allow the gun to function to its full potential in terms of range based on the current pump configuration.

Another change that could be made in the design phase is to increase the volume available to the tube of the slide pump by 15 mL from the current 37 mL (indicated in the S-G-3 excess block attached to the Body). This could be done by lengthening the area of the body allocated to the hand slide pump, or by expanding its cross-sectional area. Embedding this excess would allow for a higher charge pressure from a single pump if the hand slide pump were later replaced with a larger version. This would presumably increase value to the customer by not requiring multiple pumps of the slide to reach higher pressures when greater range or projectile mass is desired.

These are the areas that adding epistemic excess should be considered by the designers to reduce the possibility of bottlenecks. Whether or not these recommendations are actionable depends on how likely the designer finds the realization of the particular future need scenarios that drove them. This knowledge might come from various sources, such as past experience with similar products, knowledge of aftermarket modification by customers, or by feedback obtained directly from customers.

5.4.4.2 *Potentially Superfluous Excesses*

The pressure vessels present in the design – the slide pump, charge pressure vessel, and the chambers of the rotary barrel – all possess excess an order of magnitude greater than what is required of them. Initially, it might appear that these are inefficient design choices that might benefit from paring back the available excess in these components. In context, the check valve assembly limits the system pressure to about 0.5 MPa while the flex tubing can tolerate 1 MPa, but the slide pump can contain 3.4 MPa safely and is the weakest pressure vessel. However, it is likely that the presence of these excesses are side effects of other factors. Considering that the plastic is not particularly thick (the chamber walls in the rotary barrel are thickest and still less than 2mm) it is likely that manufacturability considerations were the primary driver behind the wall thicknesses. Further, the fact that ABS plastic is an inexpensive material to manufacture from means that any savings by removing some of the excess would be minimal at best. Therefore, it is likely best to leave the design of the pressure vessels as-is because doing so incurs little if any value penalty.

The stress test approach developed in this chapter assists designers in finding component level excesses within a system that unduly limit the ability of the system to change, compared to the limits imposed by the remainder of the component level excesses. Moreover, the results of the approach suggest values of excess to embed to rectify these bottlenecks within the system. The approach does not require any specific information regarding potential future needs, but if it is available to designers the approach can make use of it to guide the changes considered for the system, thereby improving the quality and applicability of the approach's results. The next chapter presents the conclusions of the works demonstrated in this thesis.

Chapter 6: Conclusions and Future Work

This chapter returns the discussion to the original research questions. The works that addressed them, the excess mapping method and stress test approach, are summarized and their contributions are reviewed. Finally, opportunities for future work are considered.

6.1 Research Question 1: How can excesses pertinent to service phase evolution be identified in a general system?

The work detailed in Chapter 4 defines a framework with which to map excess in an engineered system via a combination of features sourced from existing methodologies: HD-DSM's, functional diagrams with their associated flow set, and flow diagrams. The process of developing this map reveals the relationships between components in which excesses are present that can affect the ability of the system to change. The fusion of techniques from the methods in the literature allows the mapping of excess relationships between components in a system based on customer needs information coupled with architectural knowledge from embodiment design. These component level excesses are relatable to the top level system needs, meaning that designers can see how component level excesses affect the ability of the system as a whole to change. The produced method uses block diagrams coupled with quantified flows, and defines two component-level flows: functional and compatibility. Current system objectives and their consequent needs drive the selection of components for inclusion. Inter-component relationships are labeled according to the excess basis that identifies excesses based on their Class, Category, and Type. Overall, the excess basis represents an extension to the extant functional modeling flow set to encompass all possible types of excess relationships within a system. It accomplishes this by adding a Storage class, which addresses that all flows may be stored in a system and that geometric and structural excess considerations may also be treated as a form of storage. This basis may be further extended in future if designers desire finer description of excesses.

As noted in Chapter 4, the excess mapping method's application to complex systems would differ only in that the map would be constructed in pieces, for each of the subsystems present in each level of assembly, so that a multilevel excess map is the final product. Unlike dynamical modeling methods which can scale poorly to complex systems due to un-modeled relationships, the results of the excess mapping method are insensitive to scale. This is because while dynamical models must make simplifying assumptions, disregarding smaller effects that may amass to considerable error, excess relationships are well characterized and defined with a high degree of confidence. This is largely because excess relationships are simpler, concerning only the bounds on capabilities of a system at steady-state.

Using an excess map, system information available as part of the embodiment design phase can be selectively transferred to a conceptual-phase design in terms of future evolutions. In general, the maps generated by this method offer insight into both system excesses and the governing flow relationships between system components, thereby allowing designers to determine if a system is likely capable of responding to future needs. The excess mapping method of Chapter 4 presents an improvement over other methods available in the design literature because no other method presents, in a quantified manner, the properties of components or subsystems (excesses) within a design that will enable it to meet future needs.

6.2 Research Question 2: How can designers relate the identified excesses to the system's ability to meet future needs?

The stress test approach presented in Chapter 5 aids the process of judging the fitness of a design for potential future needs. An excess map is first generated for the system that distills the system to its inter-component relationships critical to satisfying the customer needs-driven requirements list. The excess map allows designers to rapidly determine the extent of system changes that a particular evolution will require. Once the preliminary work of creating an excess map is completed, the stress test approach generates a set of future need scenarios to evaluate the system against. Ideally, external information sources, such as marketing data or historical information concerning similar systems, are available to designers to guide the future needs considered. However, if no such external information is available the approach can also generate a set of future needs by considering increases to the high level specifications driving the system. Further, multiple degrees of severity of future needs or change to specifications are considered to increase understanding of the current bounds of system evolvability. Evolutions to satisfy each future need are found using the designer's knowledge of the system architecture, using multiple paths if possible for each future need to increase the insight into the system's ability to evolve. Generally, each evolution requires either modification or replacement of some component(s) in the system architecture. The extent of the changes depend on the excesses present within the components, which can be quickly referenced by use of the excess map. Once the set of evolutions in response to potential future needs is found, areas of overlap are identified and the system's response to simultaneous future needs is explored where appropriate. Shortcomings that are identified in the available excess can then be used to direct where epistemic excess is embedded within the system, thereby reducing bottlenecks within a system that limit the ability to change. Further, potentially superfluous excess can be identified which offers the opportunity to improve system value. Beyond showing where excesses can be added to or removed from a system, the stress test approach ultimately aids in validating the system against potential future stakeholder needs, which helps to ensure stakeholder value.

6.3 Opportunities for Future Work

A possible direction of future research is the development of metrics to analytically describe the excess present in a system, and to relate excesses in individual components to system objectives. It is expected that continued development of excess modeling will result in the ultimate ability to determine the gains per unit excess required by the prior work of [5], and hence the capacity to measure the evolvability of a system. Another application of the method to systems of significant complexity is the development of a software-based GUI which would allow for multiple-level representations of a system, i.e. where a primary block representing a subsystem may be opened to reveal the constituent components with specifically mapped excess relationships.

Other opportunities for future work include testing the effectiveness of the stress test approach on a clean sheet design problem, and exploring how the approach scales to more complex systems. Another possible avenue of research is to modify the excess mapping method so that it is less dependent on the initial solution strategy embodied in the architecture, and thereby capable of offering more useful information when considering solution strategies that are a significant departure from the original.

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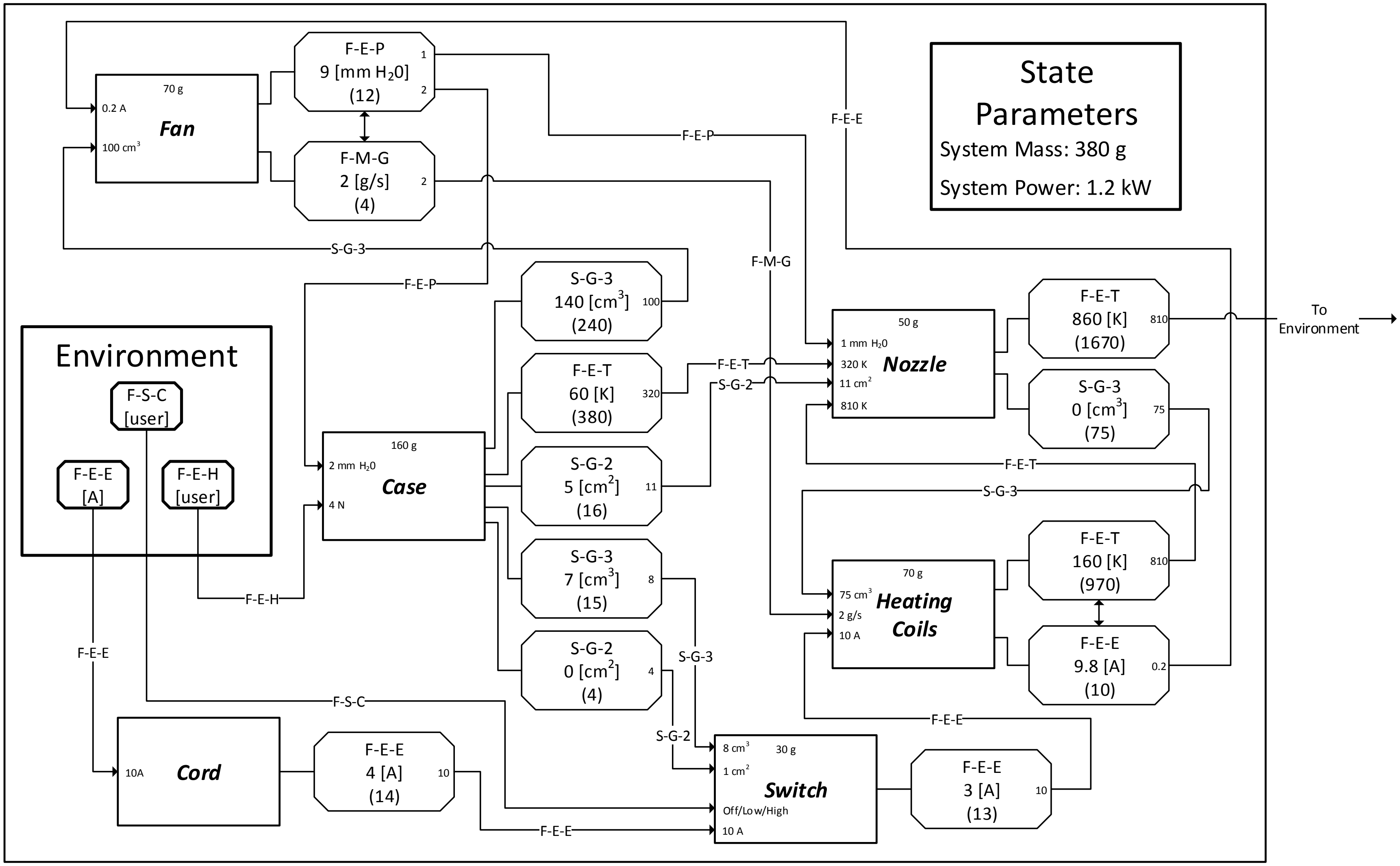
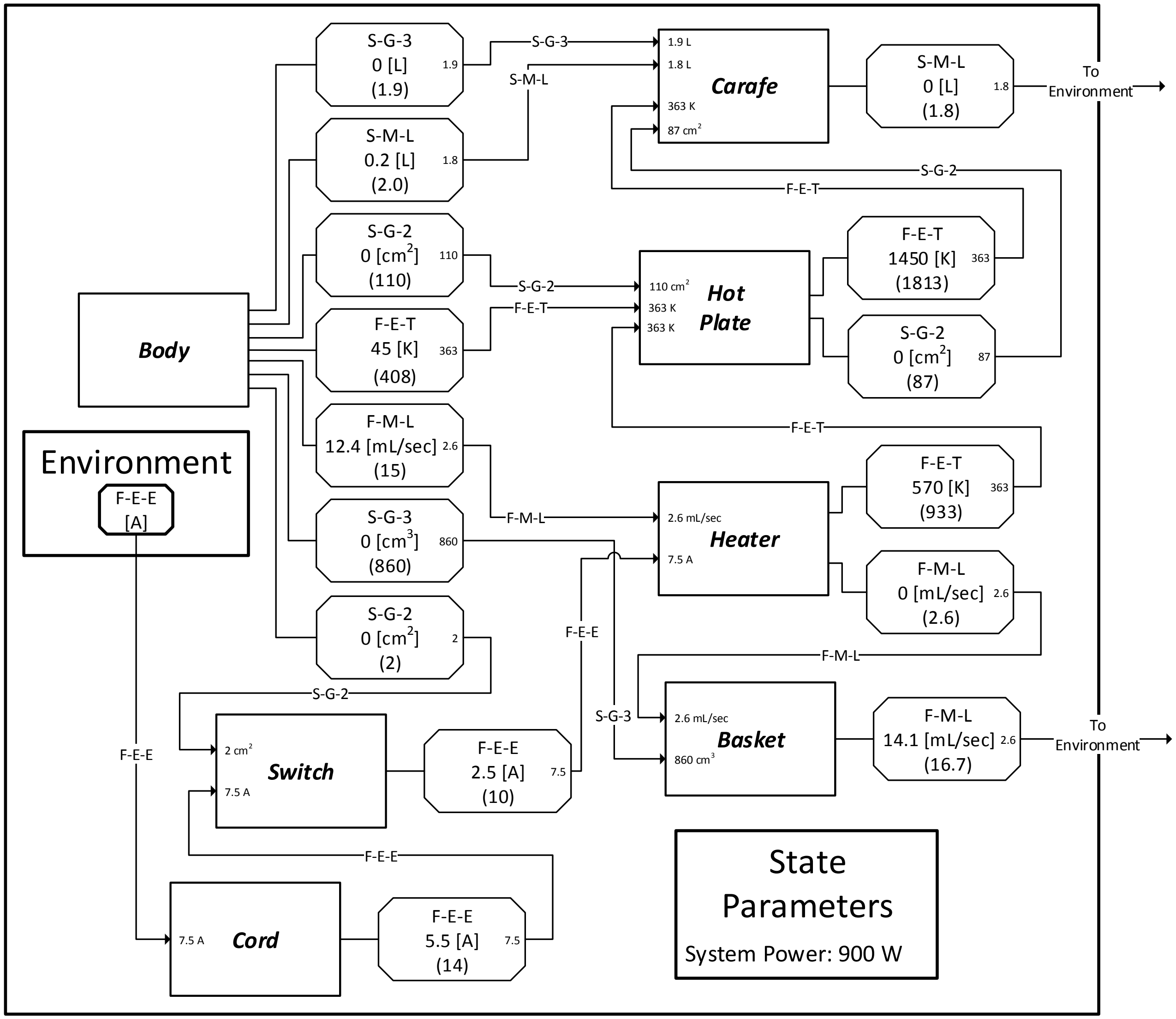
APPENDIX

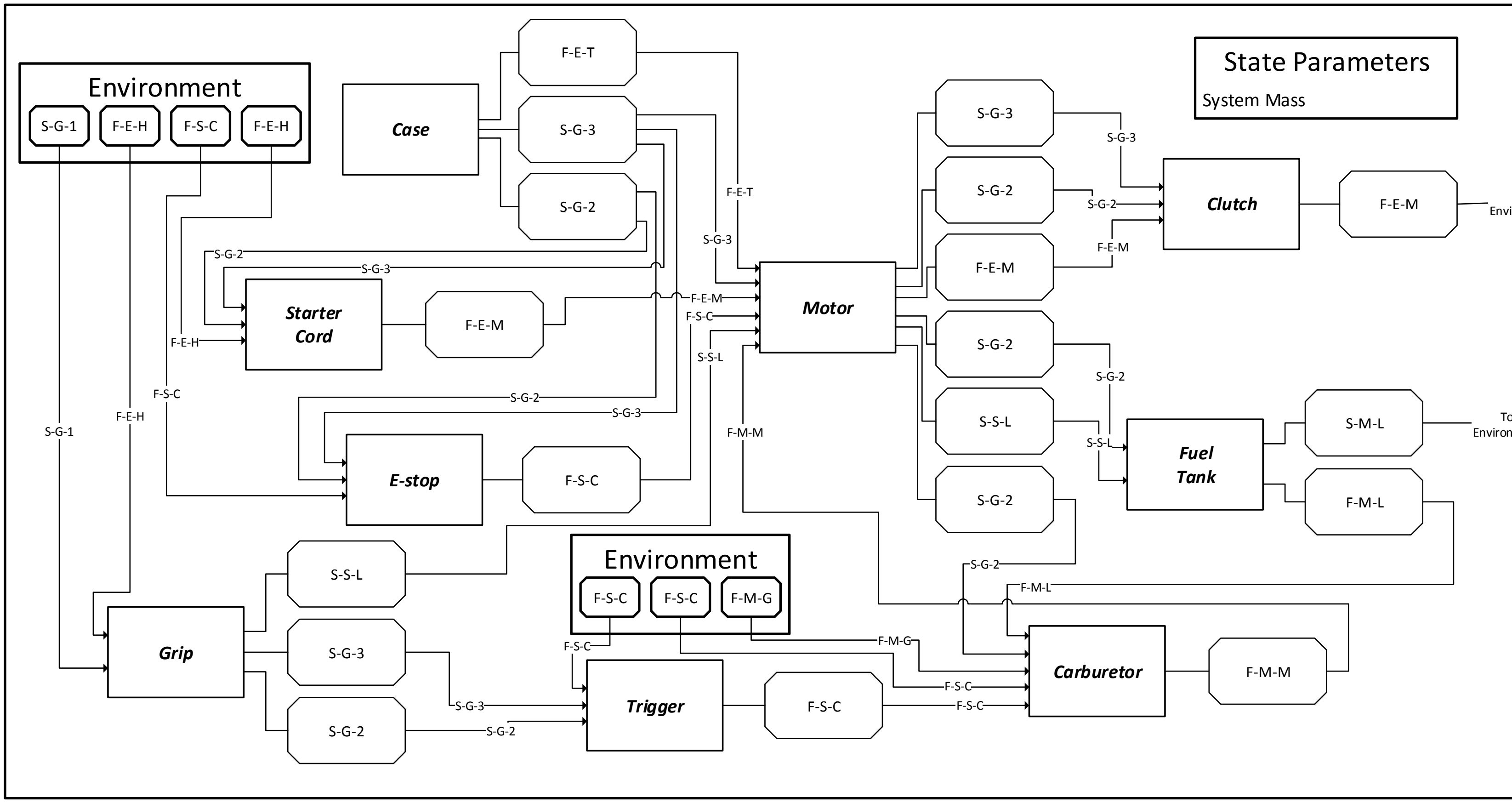
The following pages contain full-size excess maps for the heat gun, coffee maker, string trimmer, and toy dart gun.


State Parameters
System Mass: 380 g
System Power: 1.2 kW
Fan
70 g
0.2 A
100 cm3
F-E-P
9 [mm H2O]
(12)
F-M-G
2 [g/s]
(4)
Environment
F-S-C
[user]
F-E-E
[A]
F-E-H
[user]
Case
160 g
2 mm H2O
4 N
S-G-3
140 [cm3]
(240)
F-E-T
60 [K]
(380)
S-G-2
5 [cm2]
(16)
S-G-3
7 [cm3]
(15)
S-G-2
0 [cm2]
(4)
Nozzle
50 g
1 mm H2O
320 K
11 cm2
810 K
F-E-T
860 [K]
(1670)
S-G-3
0 [cm3]
(75)
Heating Coils
70 g
75 cm3
2 g/s
10 A
F-E-T
160 [K]
(970)
F-E-E
9.8 [A]
(10)
Cord
10A
F-E-E
4 [A]
(14)
Switch
30 g
8 cm3
1 cm2
Off/Low/High
10 A
F-E-E
3 [A]
(13)
To Environment

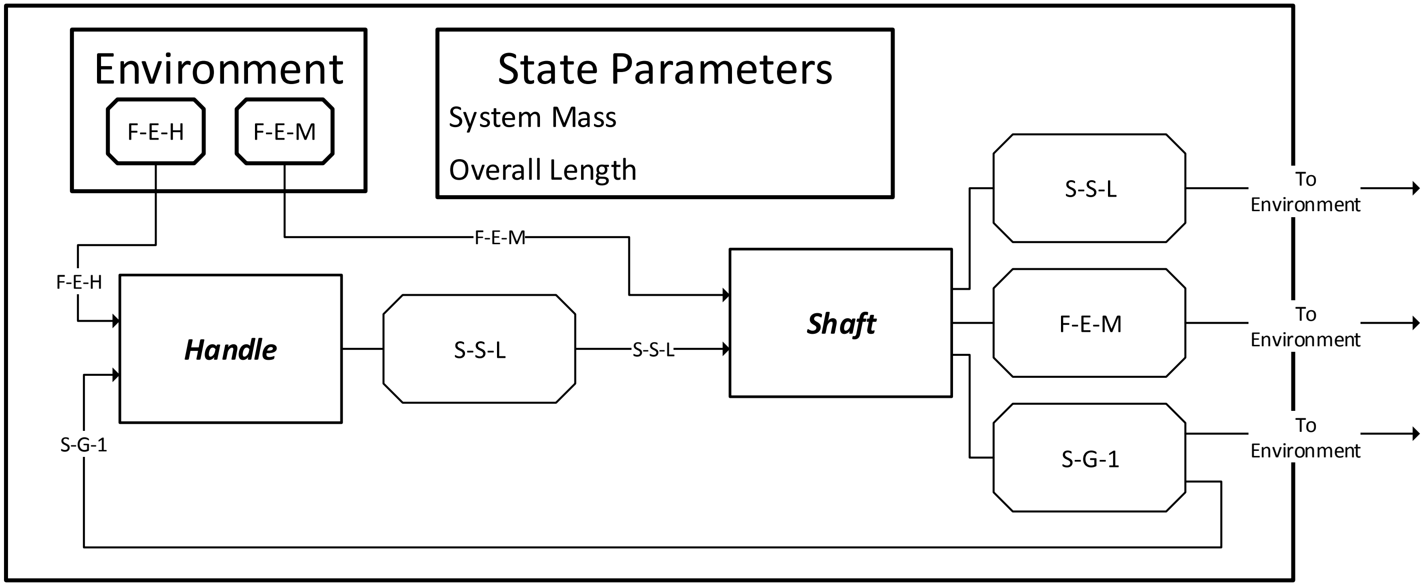
Heat Gun



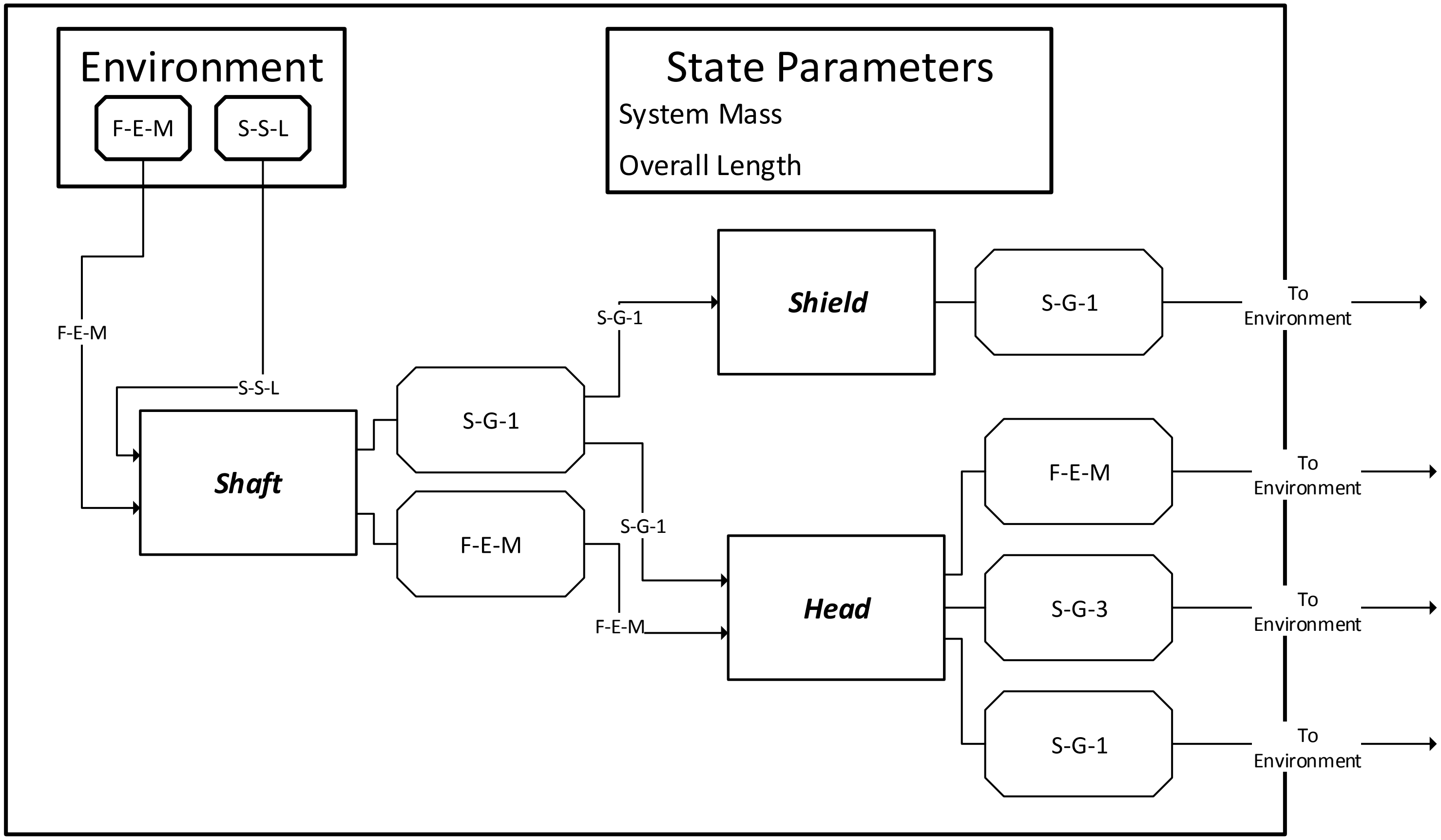
Coffee Maker



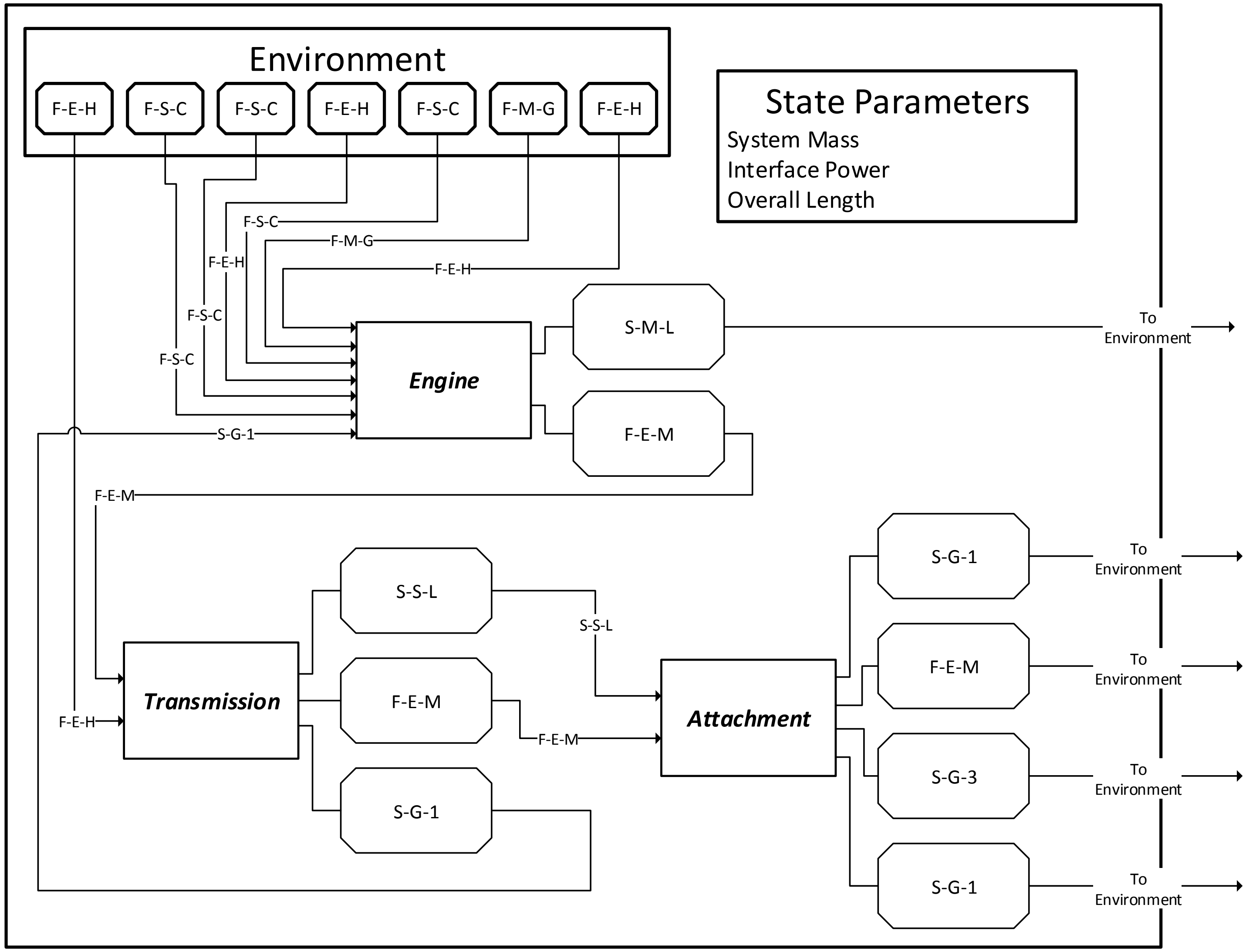
String Trimmer Engine



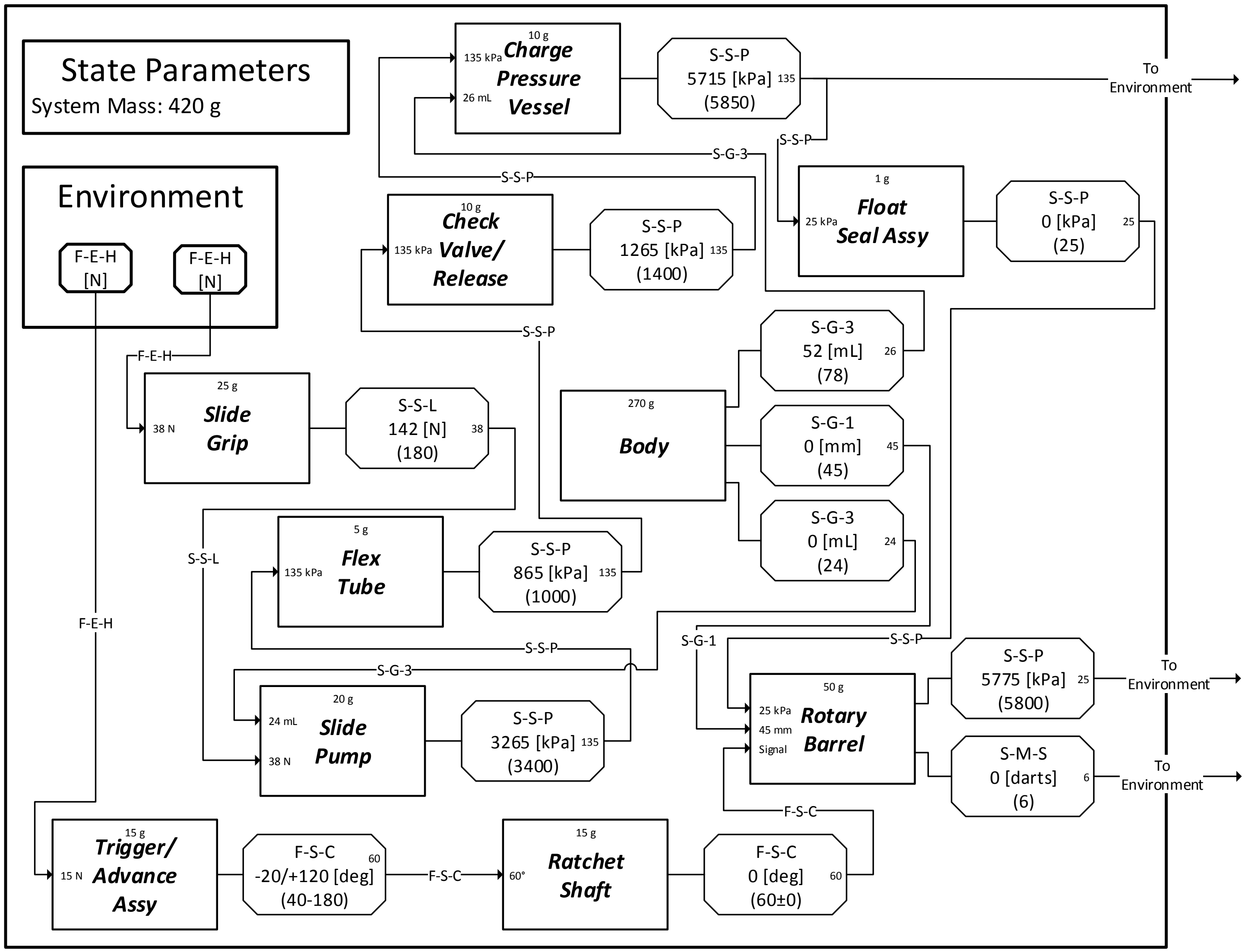
String Trimmer Transmission



String Trimmer Attachment



String Trimmer Composite



State Parameters
System Mass: 420 g
Environment
F-E-H [N]
F-E-H [N]
10 g Charge Pressure Vessel
135 kPa
26 mL
S-S-P 5715 [kPa] (5850) 135
To Environment
S-S-P
S-G-3
S-S-P
10 g Check Valve/ Release
135 kPa
S-S-P 1265 [kPa] (1400) 135
1 g Float Seal Assy
25 kPa
S-S-P 0 [kPa] (25) 25
S-S-P
F-E-H
25 g Slide Grip
38 N
S-S-L 142 [N] (180) 38
S-G-3 52 [mL] (78) 26
270 g Body
S-G-1 0 [mm] (45) 45
S-G-3 0 [mL] (24) 24
S-S-L
5 g Flex Tube
135 kPa
S-S-P 865 [kPa] (1000) 135
F-E-H
S-S-P
S-G-3
S-G-1
S-S-P
20 g Slide Pump
24 mL
38 N
S-S-P 3265 [kPa] (3400) 135
50 g Rotary Barrel
25 kPa
45 mm
Signal
S-S-P 5775 [kPa] (5800) 25
To Environment
S-M-S 0 [darts] (6) 6
To Environment
F-S-C
15 g Trigger/ Advance Assy
15 N
F-S-C -20/+120 [deg] (40-180) 60
F-S-C
15 g Ratchet Shaft
60°
F-S-C 0 [deg] (60±0) 60

Dart Gun