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EXPLORING THE RELATIONSHIP BETWEEN EXCESS AND SYSTEM EVOLUTIONS USING A STRESS-TEST

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ABSTRACT
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 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. To address that challenge, this paper draws on an excess mapping method developed in previous work that demonstrated how to map component relationships based on excess interactions. This method is now used in a stress test approach to explore how a system design is affected when faced with various possible evolution scenarios. This study has two results: first, a judgment of whether the current system design possesses sufficient excess for it to respond to future needs. Second, quantitative estimates of excesses to add if the current design excess is judged to be insufficient. A demonstrative example is presented using a dart gun, which determines that the system as designed is likely adequate for a variety of possible future needs.

1 INTRODUCTION
Customer needs create a market opportunity that drives the creation of designs by engineers. As the design process advances, needs are mapped to numerical specifications, which are in turn translated to a system architecture. A fielded system is the ultimate result of the customer needs known to engineers in the design phase. However, the environment that systems face and the customer needs that they are responsible for satisfying may change over the system's service life. Changes to initial needs, or new needs that arise, after the design has been fielded are hereafter referred to as 'future needs'. Maintaining value for system stakeholders may require the physical system to evolve over time so that it can continue to operate in the face of these future needs. Two definitions are useful when talking about these change:

Service-phase evolution: the ability of a system to physically transform from one configuration to a more desirable configuration while in service.

Excess: the surplus in a component or system beyond what is currently required of it [1].

Designers are unfortunately incapable of knowing with certainty the future needs a system will face. To meet future needs excess is consumed and must be of the correct type, quantity, form, and location to be usable to effect system change [2]. Blindly adding excess to components or subsystems adds cost without guaranteed benefit, leading to decreased system value. These considerations drive a challenge facing the design community: how can excess be embedded within a system to increase its value?

There is limited discussion in the literature regarding the placement of excess to enable future evolution. The available material generally describes situations where designers draw on past experience designing similar systems, as in [3] [4]. However, there is a lack of guidance for systems without the benefit of empirical design knowledge.

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Figure 1: Dart Gun [5]

This paper explores how the consumption of excess might allow for system evolution. This exploration is enabled by a system excess map and a set of potential future needs. As a demonstrative example, the toy dart gun shown in Figure 1 is used because the system can be discussed in detail while still providing enough complexity to warrant investigation. The excess map is used to identify where a system possesses sufficient excess to satisfy a particular evolution. The outcome of this analysis is a judgment of the changeability of the design and indications of where excesses might be added or removed to increase system value. These results are detailed for the study of a toy dart gun but are realizable for any system by use of the procedure given in Sections 4 and 5.

2 BACKGROUND

This section discusses research concerning system excess, as well as a broader coverage of methods that offer information about how properties of components within a system, such as excesses, affect the ability of the overall system to change.

2.1 EXCESS

Tackett et al. [1] determined that excess is a crucial component for the ability of systems to evolve in service, and introduced excess as a variable controlled by designers. Further work developed a mathematical formulation of system evolvability as a function of excess [6]. This application of excess was shown using two classes of naval aircraft carriers but benefited from empirical knowledge about the excesses needed for aircraft carriers to attain their full service lives [3] [4].

The role of excess at the component level was explored in [7], where a method to identify and map excesses was presented. The method's theory built from the observation that excesses often occur in terms of the inter-component flows of energy, mass, or signal. This notion was extended from the flows described by functional modeling and functional decomposition. The functional basis developed in [8] was expanded into an Excess Basis that included geometric and structural parameters not described by flows. The method drew from the component-specificity of design methods such as Design Structure Matrices [9] but maintained some of the abstraction provided by functional modeling that connected components using flows. However, the significance of individual excesses within components and the impact on overall system performance was still not clear.

2.2 REAL OPTIONS THEORY

Real options theory, originally used in the field of economics, has been adapted for use in engineering as described in [10]. 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. Some works in the engineering literature [11] [12] have applied real options theory to the problem of maximizing system value when a finite set of future reconfigurations is known. In the context of this paper, the reconfigurations are equivalently described as evolutions based on a known set of potential future needs. However, the traditional formulation of real options analysis cannot analyze systems with unknowable future needs.

2.3 CHANGE RELATIONSHIPS BETWEEN COMPONENTS

Change propagation analysis [13] is the study of how change in the design of one component can spread throughout a system, affecting other components and causing further change to a design. Change propagation analysis is usually applied to systems in the design phase to promote a more efficient design process. Pasqual and de Weck [14] incorporated information from the coupled product, change, and social domains into their analysis. The highest-resolution form of multi-domain change propagation analysis is the High-Definition Design Structure Matrix (HD-DSM), which incorporates change dependency information for each domain in a separate layer of a three-dimensional DSM [15].

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) [16]. Tools have been developed to quantitatively describe risk, including the Change Propagation Method of Clarkson et al. [17], the RedesignIT tool of Ollinger and Stahovich [18], and the Matrix-Calculation-Based Algorithm of Hamraz et al. [19].

However, the available methods for change propagation seek to highlight sources of potential change. Design for service-phase evolution mandates specific change(s) to specific component(s) and requires knowledge of component-specific parameters that change propagation analysis is generally not equipped to offer.

2.4 STRESS TESTING

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 [20]. 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 [23], demanding “resources in abnormal quantity, frequency, or volume” [24]. These tests go beyond the nominal operating conditions that the software was designed for, in terms of either increased demands or reduced resources [25] 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.

3 THEORY

This section describes the theories that underlie the excess mapping method and stress test approach.

As noted in [7], a core assumption when designing for system evolvability is that top-level functions remain fixed. The clarification offered previously is that an aircraft carrier will always launch aircraft, a car will always carry some combination of passengers and cargo, etc. A more clear definition is provided here for the benefit of this and future work. The top-level functions described by the verb-noun pairs of functional modeling are what remain constant in a system. Simple systems may be reducible to one such function: for a dart gun, the function is ‘shoot darts’ [26]. More complex systems will require multiple top-level function descriptions: for an aircraft carrier, ‘contain aircraft’, ‘move aircraft’, and ‘defend self’ would all be appropriate. A corollary of this assumption is that future needs of a system are likely to be related to the present needs; consequently, the excesses that could be applied to the current needs are likely to be useful for future needs.

3.1 NATURE OF EXCESS

Excess has been previously defined as the surplus in an artifact beyond what is currently required of it. In practical engineering terms, this translates to situations such as: wiring carrying only 7A of current when it is rated for 10A, a pressure vessel operating at 200 MPa when it is certified for 400 MPa, or an equipment room holding 20 m^3 of hardware when it can contain 35 m^3. To be clear, the surplus embodied by the Factor of Safety (FoS) is generally considered to be wholly separate from the excesses that are to be used for system evolvability. 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. Treating the material properties reserved to maintain a FoS as usable excess is, generally speaking, unsafe and unacceptable engineering practice.

Excesses in a system may be intentionally included to 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, etc. It is generally infeasible to exactly size each fastener to the required load; very rarely will the fastener used in a system meet exactly the design load plus the FoS. In practice, the smallest sufficient fastener from a list of standard sizes is chosen, thereby embedding some quantity of excess. Another example of such a factor comes from mandated commonality of components. 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. Many excesses result from the economies of scale of producing standardized sizes.

3.2 CATEGORIZING EXCESS

Designers often include some quantity of excess for reasons discussed in the three categories below. These categories are differentiated by their associated uncertainties: design margin, epistemic, or aleatory.

- Design margin is concerned with the excess that is expected to be consumed over the course of the system’s lifetime based on the original system requirements; a common example is the thickness of plating that is expected to corrode in the service environment. Design margin is assigned deterministically 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.

Real options theory relies on the inclusion of system excess to permit future evolutions. However, the available literature requires a finite set of future needs and consequent evolutions. Since many cases exist in system design when potential future needs are not finite, it is useful to consider epistemic and aleatory excesses within a design as enablers for real options that are defined as future needs are realized.

Considering inter-component interactions in which excess can occur – flows of energy, signal, and mass or parameters of geometry and structural ability – excess can be divided into two categories:

- Compatibility excesses occur in the interactions that are required for a component to function, and always are shown as input flows.
- Functional excesses occur in the functional outputs of components. These either become compatibility excesses for other components or are system outputs over the control volume.

Compatibility and functional excesses are generally linked, especially for components that transform input flow(s) into output flow(s).

4 EXCESS MAPPING

This section reviews an approach for constructing maps of excess relationships in a system. Subsystems are abstracted as blocks with the excess flows attached. This allows the inner workings of the subsystem to be treated as a black box. Each subsystem will be referred to as a component in the constructed excess map, even if the subsystem could be further decomposed. A completed excess map for the dart gun in Figure 1 is shown in Figure 2 and represents the finished product of the method described in the following subsections. The coloring of specific blocks concerns the discussion in Section 6.3

4.1 DEFINE/COLLECT CUSTOMER NEEDS FOR SYSTEM

For component-level excesses to be meaningful and useful in the design process, they must ultimately be relatable to system needs as defined by system stakeholders. Therefore, this step entails the collection of system needs. While future needs are, by definition, unknowable, the rationale described in Section 3.3 means that current needs are the foundation of this step. Examples could include ‘the system must operate for a long time’, ‘the system must be lightweight’, or ‘the system must fit into a shipping container’.

4.2 SET SPECIFICATIONS FOR SYSTEM PERFORMANCE

The collected customer needs must be expressed as engineering specifications. Numbers chosen to complete the specifications should be target values (the minimum that any design is expected to yield, though not necessarily the minimum that would be acceptable in a deployed system). At the end of this step, the designer has a requirements list of quantified specifications in engineering language. These comprise the datums against which system level excesses are measured.

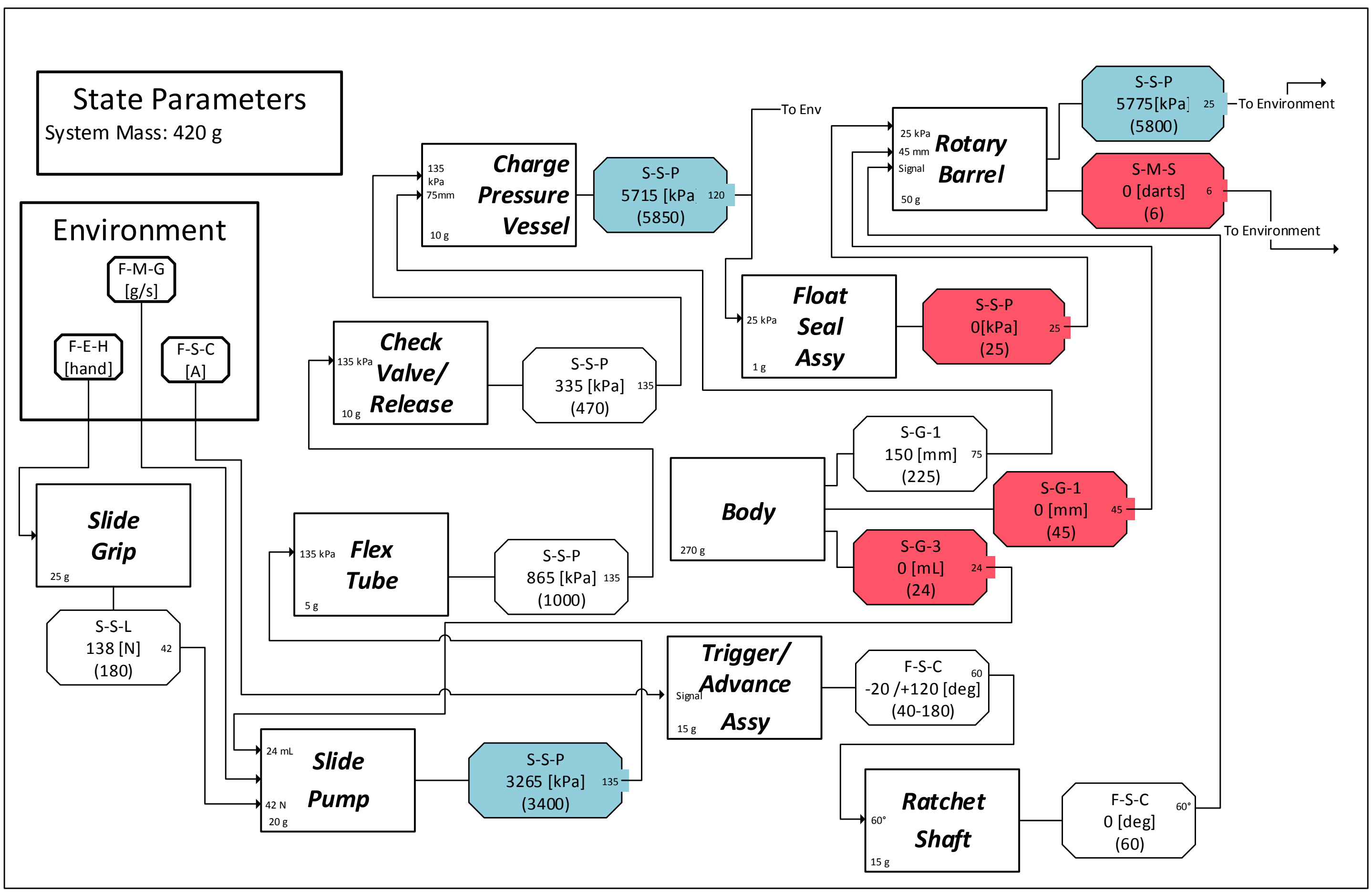

Figure 2: Dart Gun Excess Map

4.3 IDENTIFY ARCHITECTURE AND APPROPRIATE SUBASSEMBLIES

The next 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 suggestion is to begin at highest level of abstraction that separates the major components that display modular behavior. In systems with subsystems of significant complexity, further expansion may be required. Different subsystems may be described at different levels of abstraction for this reason.

This step determines the component blocks and flows that populate the excess map. Also required is the identification of the system's control volume describing the input and output flows originating from, or discharging, to the environment. Components, indicated by primary blocks, are square-edged rectangles. The excesses produced by components, shown in secondary blocks, are indicated by snipped-edge rectangles. The excesses are categorized and labeled using the abbreviations denoted in the left-most and right-most columns of Table 1.

For designers building an excess map in embodiment design, the component interactions to include as excess flows should be clear. Consideration would include the required inputs for each component to function (compatibility excesses). Once all components have their compatibility excess flow requirements satisfied by functional excess flows from other components or the environment, the map's set of excess interactions is complete.

4.4 POPULATE EXCESS MAP

This step requires the designer to consider each component and identify the values of inputs (compatibility excesses) and outputs (functional excesses). Flows that originate from outside the system boundary are placed in an Environment block. Flows that discharge outside the system boundary are labeled accordingly. 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 [27] or manually calculated. No new interaction values or intra-component equations are created when building an excess map; rather, they are selectively transferred from the information of the embodiment design phase.

4.5 IDENTIFY STATE PARAMETERS

Some of the datums created when defining product specification will be relatable to single component outputs, such as '10 MW of electrical power' would be for a single-generator system. Other specifications may be functions of multiple components, which requires the creation of state parameters (equations that are functions of multiple components' characteristics). In this analysis, the relevant state parameter is total mass as shown in Figure 2. These parameters, if present, 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 can be minimized. Component properties that do not interact with excess flows but are relevant to state parameters are denoted within their respective block.

After this step, the excess map is complete and can be used to explore the interaction between excesses and potential evolutions caused by future needs.

Table 1: Excess Basis

Class	*Category*	*Type*	*Abbr.*
Flow or Storage (F- or S-)	Signal	Status	S-S
		Control	S-C
	Material	Human	M-H
		Gas	M-G
		Liquid	M-L
		Solid	M-S
		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 (S-)	Geometric	Length	G-1
		Area	G-2
		Volume	G-3
	Structural	Load	SL
		Torque	ST
		Pressure	SP

5 STRESS TEST APPROACH

This paper builds on prior work by extending the excess mapping method with future changes to explore the relationship between excess and evolution. Specifically, this approach helps to address the problem of allocating epistemic excess when empirical design experience and 'rules of thumb' are unavailable. The steps are described in the following subsections, following the flow described in Figure 3, and assume that a system excess map has been created per the guidelines given in the previous subsection.

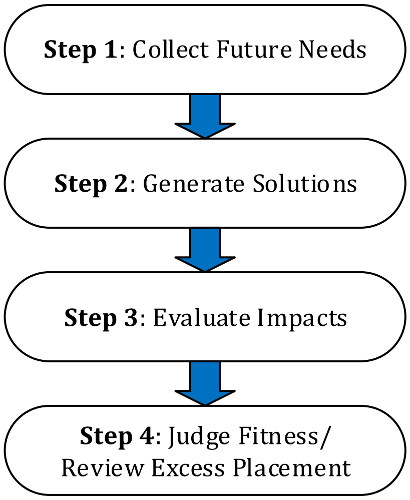

Figure 3: Stress Test Approach Flowchart

5.1 COLLECT FUTURE NEEDS AND SPECIFICATIONS

It is assumed that designers will be able to derive this information from a combination of sources including: knowledge of competing products, expected technological developments within the product's lifetime, designer intuition, etc. In addition, brainstorming techniques could be used to elicit future needs if these sources offer too few results. Any posited future need is acceptable if it remains consistent with the assumption that the top-level function(s) of a system remain constant. However, the bounds of this step can be scoped 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.

At a minimum, designers should consider varied usage environments and the possibility that stakeholders will desire increased performance from the system-level functional outputs.

5.2 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 excesses to compatibility excesses, possibly requiring some components to be replaced. However, 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.

5.3 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 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.

For needs that can be satisfied by numerical alterations of an original specification (i.e. hold twice as much pressure or require one third the time to cycle) it may be instructive to posit degrees of change and see how tolerant the design is to varying degrees of change in future needs.

5.4 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.

6 DEMONSTRATIVE EXAMPLE

The system considered in this analysis is a generic toy dart gun, chosen for its moderate complexity and the variety of future need scenarios that could be posited. Its ability to be reverse engineered means that it is representative of a system that is fully understood by its designers. It is powered for each shot by a hand slide pump, fires darts successively from a six-dart barrel, and is discharged by a double-action trigger.

6.1 EXCESS MAP CREATION

The customer needs embodied in the design are:

- Fire standard reusable darts
- Hold multiple darts
- Use only human power
- Advance automatically through darts until empty
- Be lightweight
- Fire darts across a room

A subset of specifications embodied in the design are:

- Fire 1.5g foam suction-tipped darts
- Accept darts 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
- Can fire dart every 2 seconds

The dart gun was disassembled as shown in Figure 4 and an excess map, shown in Figure 2, was created based on the guidelines presented in the previous section. The plastic pieces were assumed to be ABS plastic with a yield strength of 40 MPa, and a Factor of Safety of 2 was applied.

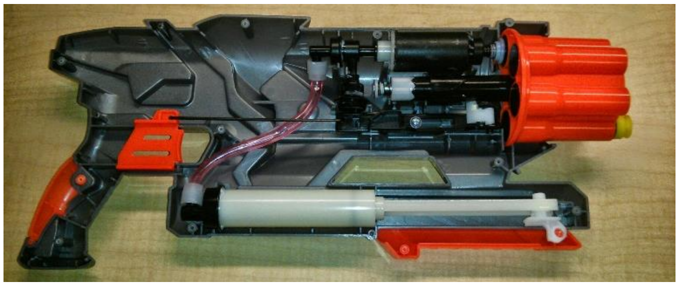

Figure 4: Disassembled Dart Gun

The pertinent measurements for pressure vessels are given in Table 2.

Table 2: Component Measurements

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

6.2 STRESS TEST APPROACH

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 as 'transmit darts'. The needs are listed here:

- Fire darts farther
- Fire heavier darts
- Increase dart accuracy
- Hold more darts
- Fire underwater
- Fire in vacuum
- Self-powered (no pumping)

Assumptions and calculations regarding dart gun:

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

For isothermal compression and expansion:

$$PV = const \tag{1}$$

For adiabatic compression and expansion:

$$PV^{\gamma} = K = const \tag{2}$$

$$W_{adiabatic} = \frac{K\left(V_f^{1-\gamma} - V_i^{1-\gamma}\right)}{1-\gamma} \tag{3}$$

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).

As noted in the specifications list, the dart flight distance was measured assuming level fire from a height of 1m. Therefore, the time of flight (neglecting drag) for any dart is given as

$$TOF = \sqrt{\frac{h}{\frac{1}{2}a}} = \sqrt{\frac{1m}{\frac{1}{2}\left(9.8\frac{m}{s^2}\right)}} = 0.45 \text{ sec} \tag{4}$$

Using this assumption, the required kinetic energy imparted to a dart can be determined as a function of flight distance.

When analyzing cylindrical components that function as pressure vessels, the hoop stress was considered to be the limiting loading scenario and was calculated by Eqn. 5, where P is the pressure, r is the mean radius, and t is the thickness.

$$\sigma_h = \frac{Pr}{t} \tag{5}$$

For brevity, not all future needs are discussed here. Those that yield the most meaningful results for the system's design are described as follows.

6.2.1 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:

- Replace the spring in the floating pressure seal assembly to increase pressure delivery to the barrel
- Replace the hand pump mechanism with a tank of compressed gas and a regulator
- Add a small propellant charge to the base of each dart

Approach **1:**

An analysis of the pressure energy flows through the dart gun combined with the information in Figure 2 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:
  $$P_1V_1 = (1 \text{ atm})(24.1 + 18.2 + 2.3 \text{ mL}) = P_2V_2 \qquad (6)$$
  $$V_2 = (18.2{+}2.3 \text{ mL}) \rightarrow P_2 = 2.3 \text{ atm} = 236 \text{ kPa} = 135 \text{ kPa gauge} \qquad (7)$$
- If the full 135 kPa is delivered to the dart according to Eqn 3, it results in a work of 0.3 J. This is sufficient to propel the dart 14m.

However, this energy is delivered to the barrel via the floating pressure seal assembly, which uses a spring to press a flat rubber seal against the base of the rotary 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 F=P/A (given a spring compression of 9mm). These considerations are condensed in the excess map of Fig 2 as a S-S-P (storage, structural, pressure) excess of 10 kPa, since at the instant of firing the floating pressure seal functions as a pressure vessel. In essence, this assembly functions as a blowoff valve for any pressure exceeding the cracking pressure of 10 kPa. 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 indicates that there is back pressure that prevents the floating pressure seal from functioning as an ideal blowoff valve.

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 finding the required dart kinetic energy to reach 9m (0.3 J), solving Eqn. 3 to find the corresponding initial pressure (55 kPa) and comparing that to the pressure provided by a single pump (135 kPa). Therefore, a single pump is sufficient. Consulting the S-S-P excesses within Figure 2, attached to the slide pump, flex tube, check valve, charge pressure vessel, and rotary barrel indicates that those components are capable of withstanding 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. Increasing the range to 12m only requires that the delivered pressure be increased to 95 kPa, still less than the pressure generated 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. Consulting the S-S-P blocks of Figure 2 determines that all components save the floating pressure seal are capable of withstanding 270 kPa. To increase the dart gun's range to as much as 20m, only replacing the spring in the floating pressure seal is required.

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 27m (limited by the check valve), provided that the compressed gas tank could occupy a volume of 24 mL or less (the volume denoted by the S-G-3 block in Figure 2 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. 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. This solution reveals a limitation of the excess mapping method. The excess map in Figure 2 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. 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 2.

A cursory search reveals that the burning temperature of black powder is at least 550 °C [28] while the melting temperature of polyethylene foam (which the darts are assumed to be made of) is 265 °C [29]. Black powder is a relatively elementary explosive; any explosive powerful enough to give a significant contribution to the darts' muzzle velocity would burn 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 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 pump should be replaced with a compressed gas tank and regulator that can deliver pressures limited only by the weakest component in the gas flow path, the check valve, which permits a 27m 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.

6.2.2 FIRE HEAVIER DARTS

As 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 the same distance. These masses correlate to 0.20J, 0.27J, and 0.40J of required kinetic energy at the muzzle, respectively. Heavier darts are assumed to have no increase in dimensions.

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: 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 2, 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. If both increased range and increased mass were desired, a compressed gas tank might become the most viable solution.

6.2.3 FIRE IN VACUUM

The dart gun relies on the availability of air as propellant for the darts. In a vacuum, propellant would also have to be supplied.

Approach 1:
Given that the darts are assumed to remain 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 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 27m 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 mechanism requires two opposing flywheels, and that the darts be fed individually, typically from a box rather than drum magazine. Further, flywheel propulsion uses electricity 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.

6.2.4 FIRE UNDERWATER

This potential need presents the same limitations as the vacuum-firing case above, as the surrounding fluid is incompressible. 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. Water as a flight environment produces drag three orders of magnitude greater than air, 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. 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 2). Therefore, the only feasible solution is to modify the darts so that they are in some way self-propelled. 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.

6.2.5 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 2 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 while leaving a maximum permissible pressure of 2.9 MPa.

However, this approach might have limited effectiveness for foam darts. This is because the foam darts would likely not be sufficiently deformed 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 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:

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 Eqn 3, 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 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.

6.2.6 HOLD MORE DARTS

The dart gun as designed holds six darts in its rotary barrel. For this analysis, three 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 2 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 2. 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 4, it becomes apparent that such a redesign could be performed by removing the barrel, modifying the case 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.

6.3 DISCUSSION OF RESULTS:

Stress testing the dart gun revealed an unexpected conclusion: several potential future needs can addressed by replacing the floating pressure seal assembly's spring with a stiffer version. 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 comparable product based on the numerical simulations performed. Component excesses in Figure 2 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.

6.3.1 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. This 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 embedding this excess would allow the gun to function to its full potential.

An inefficiency in the current design that was highlighted was the dart chamber pattern of the rotary barrel, reflected in the S-M-S (Storage, Material, Solid) excess block for the rotary barrel. For a barrel with the given diameter, eight darts could be held; the current configuration presents a waste of volume. On the other hand, the design could be modified to accept a box magazine, which would markedly increase the dart capacity. Another change that could be made in the design phase is to increase the volume available to the tube of the slide pump. This could be done by lengthening the section 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.

These are the areas that adding epistemic excess should be considered by the designers. 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.

Table 3: Summary of 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

6.3.2 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, 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.

7 CONCLUSIONS AND FUTURE WORK

The stress test approach presented in this paper is shown to aid 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 interactions critical to satisfying the customer needs-driven requirements list. These interactions are in terms of energy, mass, and signal flows or geometric and structural parameters. The excess map allows designers to rapidly determine the extent of system changes that a particular evolution will require. Future need scenarios to test the system design against are found from information sources available to the designer. Possible future needs may also be brainstormed by the designers if other sources prove insufficient. Evolutions to satisfy each future need are found, using multiple paths if possible for each future need to increase the insight into the system. 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. Shortcomings that are identified in the available excess can then be used to direct where epistemic excess is embedded within the system. 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 aids in validating the system for future customer needs, ensuring value for system stakeholders.

It is acknowledged the example presented in this paper is a relatively simple system that is unlikely to be evolved. However, the focus of this paper was to explore the possible value associated with using a stress test approach combined with an excess map. Future work will apply this approach to more complex systems of varying technological readiness and variability in customer needs as a function of time. The decision to use the dart gun was made for two primary, related reasons. First, the artifact could be fully described at the subsystem / component level, and therefore could be used to simulate the stress test approach process. Second, the authors wished to make sure that the approach would yield meaningful results for even simple systems. Given the quality of the results produced, including some that were unexpected, the path is clear to future exploration of more complex systems using this approach. 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 more useful when considering solution strategies that are a significant departure from the original.

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