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METRICS FOR ASSESSING DESIGN FREEDOM AND INFORMATION CERTAINTY IN THE EARLY STAGES OF DESIGN

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ABSTRACT

Our primary focus in this paper is on *open engineering systems* which are readily adaptable to changing design requirements. Designing an open engineering system allows a family of products to be developed around a common baseline model. This entails increasing design freedom and design knowledge during the early stages of design. Toward this end, developing *ranged sets* (as opposed to points sets) of top-level design specifications provides a means to improve system flexibility by increasing design knowledge while maintaining design freedom. Consequently, our secondary focus in this paper is on metrics for assessing the *design freedom* and *information certainty* associated with a *ranged set* of top-level design specifications. As a demonstration, these metrics are applied to an example problem, namely, the conceptual design of a family of aircraft. Our emphasis in this paper is on introducing open engineering systems and metrics for design freedom and information certainty, not on our example, *per se*.

NOMENCLATURE

AF	Engine Activity Factor
AR	Aspect Ratio, nmu (no meaningful units)
CSPD	Cruise Speed, Mach
DOC	Direct Operating Cost, $/hr
DF	Design Freedom
DPROP	Propeller Diameter, ft
DV	Design Variable
DV $Range_i$	Range of the i^{th} design variable
GAA	General Aviation aircraft
FAA	Federal Aviation Administration
IC	Information Certainty
LDMAX	Maximum Lift to Drag Ratio, nmu
PR_i, $PR_{i,initial}$	Performance range of the i^{th} performance measure and initial performance range
PURCH	Aircraft Purchase Price, $ (in 1970 dollars)
RANGE	Maximum Cruise Range, nautical miles (nm)

Satisficing	Solutions which are "good enough" but not the best (Simon, 1981)
SW	Sweep Angle of Aircraft Wing, degrees (°)
TR_i	Target range of the i^{th} performance measure
VCRMX	Maximum Cruise Speed, kts
WEMP	Aircraft Empty Weight, lbs
WFUEL	Aircraft Fuel Weight, lbs
WL	Wing Loading Estimate, lb/ft^2
WS	Seat Width, in

OUR FRAME OF REFERENCE: DESIGNING OPEN ENGINEERING SYSTEMS

As the Greek philosopher Heraclitus once said, "Nothing endures but change." In response to changes in the marketplace, "productive countries abandon old products and move on to new, higher value products." (Thurow, 1985) World-class manufacturers have responded by adopting product design and manufacturing systems that are more flexible, responsive and cost effective than ever before (see for example, Clark and Fujimoto, 1991; Drucker, 1990; Womack, et al., 1990). In terms of product design, we believe that one element of future U.S. competitiveness lies in the development of *open engineering systems* and the infrastructure to sustain them. We define open engineering systems as follows.

Open engineering systems are systems[1] *of industrial products, services, and/or processes that are readily adaptable to changes in their environment and enable producers to remain competitive in a global marketplace through continuous improvement and indefinite growth of an existing technological base.*

Potential benefits of designing open engineering systems include *increased quality, decreased time-to-market, improved customization* and *increased return on investment* which are enhanced through the system's flexibility, i.e., its capability to be adapted to change. Generally speaking, the more a company can quickly adapt its products to changing demands and requirements, the more it can saturate its market and the more benefits it will enjoy.

Some examples of open engineering systems include the IBM PC, Boeing 747, and the TAT[2]-building system in Finland (Sarja, 1989) . Several generations of IBM PCs have been developed, built around the Intel 80286, 80386, and 80486 chips, and the modularity of the components allows many variations to occur within each generation. Similarly, the Boeing 747-200, 747-300, 747-400, and 747-SP share a strong technological family resemblance, and few would argue with Boeing's view either of the family or the models within the family (Rothwell and Gardiner, 1988) . Meanwhile, the aim of the TAT-building project in Finland is to, "use as small a number of different structural component types...to form the required number of different combinations from them." (Sarja, 1989) The TAT-building system is designed to enable versatile product modification at an economical cost while still fulfilling user requirements. By using standardized elements and modules, the designers are able to offer a wide variety of alternative products while maintaining low design and manufacturing costs. An added benefit of the use of standardized elements and modules in the TAT project is decreased assembly time along with reduced cost estimates. See, for example, (Simpson, 1995; Uzumeri and Sanderson, 1995; Wheelwright and Clark, 1992; Rothwell and Gardiner, 1988) for additional products which exemplify our open engineering systems philosophy.

The basic premise in designing an open engineering system is to get a quality product to market quickly and then remain competitive in the marketplace through continuous development of the product line. This can be done through the development of a common *baseline model* where continuous development and improvement of the product line allows several generations, i.e., *families*, of systems to be developed around the common baseline. The IBM PC is an excellent example of this; however, the success of the IBM PC as an open engineering system was more serendipitous than planned. In order to reproduce this type of success for future open engineering systems, *a foundation needs to be developed for designing, realizing, sustaining, and retiring a family of systems which satisfy the changing needs of customers in a global marketplace.*

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[1] Here, a system refers to a grouping of associated entities which is characterized by a mental construct; one of these being the boundary (Mistree, et al., 1990).

[2] TAT in English can be understood as "Totally Adaptable Technology".

We approach designing open engineering systems from two different aspects: (1) increasing design knowledge in the early stages of design[3], and (2) maintaining design freedom during the early stages of design, as illustrated in Figure 1. By maintaining design freedom and increasing design knowledge in the early stages of design, specifically conceptual design as shown in Figure 1, design changes which typically occur in the later design stages can be avoided, and a potential time savings can be achieved. In this hypothetical and idealized process, rework is eliminated because maintaining design freedom and increasing design knowledge in the early stages of design helps prepare for unforeseen changes in the later stages of design and facilitates adapting to these changes because designers know more about the design earlier. This enables better decisions to be made before the freedom to make these decisions is eliminated. By maintaining design freedom and increasing design knowledge, *the flexibility of a system can be improved* and with a combined increase in efficiency, time-to-market can be reduced as shown in Figure 1. This approach is philosophically in harmony with that of open engineering systems since it enables companies to remain competitive in a global marketplace both today and tomorrow.

In our work, we have identified the following ways to increase design knowledge and maintain design freedom in the early stages of design. By spending a larger portion of time in the early design stages, design knowledge can be increased by:

a. determining how the design variables affect the system performance by identifying key design drivers and the significance of the design variables,
b. examining how the design variables change as a result of different design scenarios or trade-off studies,
c. developing a better understanding of the design space through enhanced concept exploration, and
d. posing and answering several "what-if" questions during the design process.

Similarly, by spending a larger portion of time in the early design stages, design freedom can be maintained by:

a. searching for satisficing[4], ranged sets of solutions rather than optimal or point solutions, and

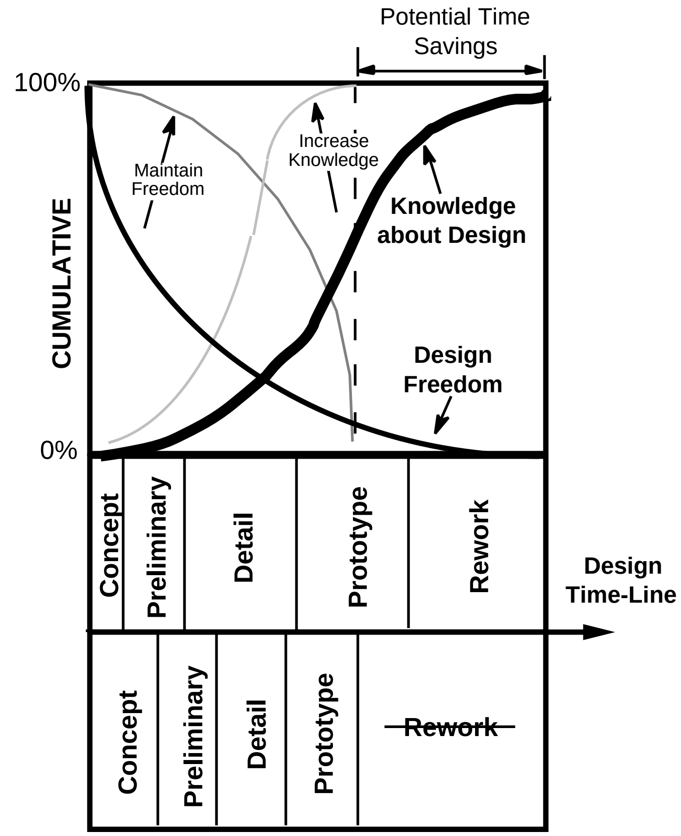

Figure 1. Reducing Time-to-Market by Increasing Design Knowledge and Maintaining Design Freedom

b. incorporating robustness into the design process to make the design insensitive to adjustments or changes which may occur in the later stages of design.

Implementation of these methods is presented in (Simpson, et al., 1996), and the details are not repeated here. We recognize that there are several ways to realize an increase in design knowledge and to maintain design freedom during the early stages of design. Our focus in this paper, however, is *not* on implementing these means for increasing design knowledge and design freedom, but on *measuring how well design freedom has been maintained and design knowledge has been increased during the design process.* Before we introduce our example, we must first answer the question, *how can we measure the extent to which design freedom has been maintained and design knowledge has been increased during the early stages of design?* We present our answer in the next section and our example problem in the section following.

[3] The early stages of design are characterized by *uncertain* or *ambiguous* information which is "soft" compared to information in the later design stages.

[4] Satisficing solutions are solutions which are "good enough" but not necessarily the "best" (Simon, 1981) .

METRICS FOR MEASURING DESIGN FREEDOM AND INFORMATION CERTAINTY

Overview of Relevant Literature

We have found little work which addresses the issue of quantifying design freedom. Krishnan and coauthors (1991) measure the loss of design freedom as a product's quality loss, i.e., the decrease in quality of task results due to constraints imposed by upstream decisions in a sequential process. Unfortunately, such quality loss cannot be measured in practice since the quality baseline cannot always be established. Habib and Ward (1991) offer Labeled Interval Calculus as a means to allow designers working with ranges of systems to compose a "generic" schematic and provide specifications; however, their approach is more concerned with processing design ranges associated with tolerances rather than design freedom, per se. Chen and her coathurs (1994) suggest designing *flexible products* which can be readily adapted in response to large changes in customer requirements by changing a small number of components or modules as a means to enhance design freedom. This work serves as a stepping stone for our open engineering systems paradigm, and it is along similar lines that some of Ishii's latest work falls. Ishii and his coauthors recently introduced the *variety importance-cost map* to help minimize the life-cycle cost associated with offering product variety (Ishii, et al., 1995) but neglected to discuss design freedom while hitting on several key ingredients of our open engineering systems paradigm.

Unlike design freedom, several metrics for information and design knowledge can be found in the literature. Suh, whose work is perhaps the most well known, has developed two global principles, or axioms, that serve as guidelines during design (Suh, 1990). According to the *Independence Axiom (Axiom 1),* a good design is one which maintains the independence of functional requirements. According to the *Information Axiom (Axiom 2),* among the designs which satisfy Axiom 1, the best design is the one with minimum information content[5] which is loosely translated as: 'keep it simple'. Suh offers metrics for both functional independence and information content; the latter of which is relevant to our work. To measure the information content of a design, Suh uses the following metric:

$$I = \mathrm{Log}\left(\frac{\text{system range}}{\text{common range}}\right) \tag{1}$$

which relates to the probability of success of achieving the specified functional requirements. In Eqn. 1, the common range is defined as the overlap between the *achievable performance range of the system and the target range for the system*. The system range is the *achievable performance range of the system*. If the system range and common range are the same, i.e., there is complete overlap between the two ranges, then the ratio in Eqn. 1 is 1, and I is equal to 0 which is the minimum. If there is no overlap, then the common range is zero, and I is infinite. By Axiom 2, a good design is one with minimum information content which corresponds to finding the design with the largest possible overlap between the achievable performance range and the target range.

Several other measures for information content and/or uncertainty are prevalent in the literature. Information theory (Shannon, 1949) was developed primarily by Shannon in the 1940's and was subsequently used to explain classical thermodynamics (Tribus, 1961) . The concept of minimizing the information content has also been related to the principle of maximum entropy (Erickson and Smith) and has been used to describe management of the design process as an "open system" of information (Starr, 1991). Antonsson and his students have developed the Method of Imprecision and suggested modeling uncertainty associated with imprecision by using fuzzy sets where a portion of the uncertainty is modeled stochastically (Antonsson and Otto, 1995; Wood and Antonsson, 1989) . Vadde, et al. (1994) have proposed the use of Bayesian statistics to model a portion of uncertainty along the design timeline. A recent review of additional methods for handling uncertainty and imprecision can be found in (Antonsson and Otto, 1995) .

Many of the aforementioned metrics, including Suh's, have been developed to *minimize the information content of a design rather than measure the increase in design knowledge as we intend.* Therefore, we propose alternate metrics for design knowledge and design freedom which are consistent with the design freedom and design knowledge curves illustrated in Figure 1. Our metrics are not meant to replace existing metrics, but rather provide a measure which is more appropriate for assessing how well design freedom is maintained and design knowledge is increased during the early stages of design. We begin with our definition and

[5] In his book (Suh, 1990), Suh has expressed this axiom differently. In later papers, Suh states the axiom the way it is given here. We believe that the two statements by Suh of the same axiom are not equivalent, but that is not of consequence to this paper.

metric for design freedom followed by our definition and metric for design knowledge.

Definition and Metric for Design Freedom

In the context of open engineering systems, we define design freedom as *the extent to which a system can be "adjusted" while still meeting its design requirements*[6]. For example, consider the design of a spring. If a spring is being designed to deliver *at least* 10 lbs of force when compressed for clamping purposes say, a spring which is capable of delivering 5 to 30 lbs of force would have more design freedom than a spring which is only capable of delivering 5 to 15 lbs of force, provided that the appropriate constraints are met in both cases. This is because the design parameters of the first spring can be manipulated, i.e., "adjusted" or "tweaked", more than the design parameters of second spring while still meeting the design requirement of delivering at least 10 lbs of force.

Based on this brief example and our definition for design freedom, measuring the overlap between the target ranges for the system performance measures and the achievable performance range of the system provides a way to measure design freedom. This overlap, when normalized against a reference value for consistency, allows us to track the evolution of a design and its associated design freedom. By comparing the performance range of a design at a particular point in the design process against its initial performance range provides insight into how far the design has evolved and how much the design freedom has been reduced. This allows us to remain consistent with the design freedom curve in Figure 1; design freedom is shown to be 1 at the outset of the design process, and decays to 0 as the design evolves toward realization. Consequently, our proposed metric for design freedom (DF) is:

$$\mathrm{DF} = \frac{1}{n}\sum_{i=1}^{n} \frac{\text{Overlap}_i}{\text{Initial Performance Range}_i}$$

$$= \frac{1}{n}\sum_{i=1}^{n} \frac{TR_i \cap PR_i}{PR_{i,initial}} \qquad (2)$$

[6] Our definition for design freedom is very similar to Suh's definition for information which is *the measure of knowledge required to satisfy a given functional requirement at a given level of the functional requirement hierarchy* (Suh, 1990). His definition for information is related to the probability of achieving the functional requirements of a system. We are concerned with the overlap that exists between given target ranges and the achievable performance ranges of the system at hand.

where **n** is the number of performance measures for the system, PR_i is the feasible performance range of the i^{th} performance measure, and TR_i is the target range for the i^{th} performance measure. To help clarify these quantities, the feasible performance range, target range, and corresponding overlap for fuel weight, one of the system performance measure from our example problem, are illustrated in Figure 2. $PR_{i,initial}$ is the initial feasible range of the i^{th} performance measure and has not been included in Figure 2; note however, that Eqn. 2 is extremely sensitive to the selection of $PR_{i,initial}$.

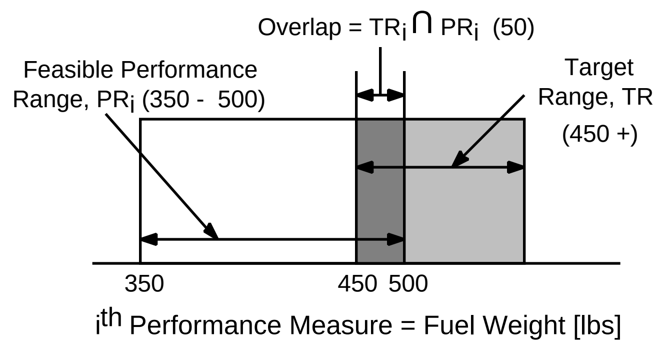

Figure 2. Measuring Design Freedom

If the performance range, PR_i, is completely contained in the target range, TR_i, then the design freedom associated with that performance measure is 1. If there is no overlap between PR_i and TR_i then the design freedom associated with that performance measure is zero. Since every performance measure will fall somewhere between these two extremes, the average of the design freedom of the **n** performance measures ranges between 0 and 1. Applying Eqn. 2 to our spring example, the first spring would have 4 times more design freedom than the second spring because the overlap between the feasible performance range of the first spring (PR_i = 5-30 lbs) and the target range (TR_i = 10+ lbs) is 4 times greater than that of the second spring (PR_i = 5-15 lbs) provided they both originate with the same $PR_{i,initial}$.

In a case where PR_i is a point, the design freedom associated with that point is defined as zero regardless of whether that point coincides with the target or not since there is no freedom associated with that performance measure. This is because there is no *overlap* between the performance range and the target range; hence, there is no room to "adjust" or "fine-tune" the design to meet changing requirements. This also explains why design freedom decays to 0 near the end of the design timeline; there is essentially no design freedom left in the system because only point solutions are realizable.

Definition of Design Knowledge and Metric for Information Certainty

By providing ranges for design variables rather than point solutions in the early stages of design, we can maintain design freedom for the later stages of design. However, because we are specifying ranges and not point solutions for the design variables, there is a level of uncertainty associated with the design. Consequently, knowledge about the design is not complete. In this regard, increasing design knowledge requires specifying *narrower ranges* or point settings for the design variables while maintaining design freedom in the later stages of design requires specifying *broader ranges* for the design variables. *Can we do both?* Before we answer this question we must first define what we mean by design knowledge and present a metric for measuring it. Only then can we determine the extent to which the trade-off between maintaining design freedom and increasing design knowledge occurs.

Our definition for design knowledge is *the extent to which a system's design parameters are known at a certain point in the design timeline.* By this definition, design knowledge is directly related to the *certainty of the information* regarding the design parameters of the system. Therefore, for the remainder of this paper, any reference to information refers to design knowledge as well. As a result, our metric for design knowledge measures the information certainty (IC) associated with a ranged set of design variables, namely,

$$\mathrm{IC} = \frac{1}{n}\sum_{i=1}^{n}\left(1 - \frac{\text{DV Range}_i}{\text{Initial DV Range}_i}\right) \qquad (3)$$

where **n** is the number of design variables (DVs), and DV Range_i corresponds to the permissible range of the i^{th} design variable. Obviously, a design variable with DV $\text{Range}_i = 0$ is a point and IC = 1 for that DV because there is no uncertainty associated with that design variable because it is a point.

Eqn. 3 is consistent with the design knowledge curve in Figure 1. Design knowledge at the beginning of the design process is zero and grows as the design evolves such that at the end of design process, knowledge about the design is 1. Eqn. 3 yields 0 at the initial starting point, indicating that there is no certainty, i.e., complete uncertainty, about the design, and increases to 1 as the design evolves and the *ranges* of the design variables approach zero. This indicates that the *certainty associated with the design increases to the point when all information regarding the design is known.* The design variable ranges are normalized against the initial design range in Eqn. 3 so that the information certainty associated with the design at any given point in the design timeline can always be compared with the initial starting point. At this stage of our work, defining the initial starting point is somewhat arbitrary.

Now that we have presented our metrics for design freedom and information certainty, it is time to demonstrate their usage. This is done in the next section with the aid of an example, namely, the design of a *family* of General Aviation aircraft in which three different *ranged sets* of top-level design specifications exist for the family of aircraft. By applying our metrics to these three different ranged sets of top-level design specifications, we can measure the extent to which design freedom has been maintained and information certainty has been increased in this example.

EXAMPLE: CONCEPTUAL DESIGN OF A FAMILY OF GENERAL AVIATION AIRCRAFT

Our example for this paper is the conceptual design of a family of General Aviation aircraft (GAA). Since space in this paper is limited, we provide only a brief synopsis of the problem and summary of the results. Details can be found in (Simpson, et al., 1996; Simpson, 1995). It is to these results, then, that we apply our metrics for design freedom, Eqn. 2, and information certainty, Eqn. 3, and discuss our findings.

Our objective for the General Aviation aircraft project (NASA and FAA, 1994) is to satisfy the diverse demands of the General Aviation industry through the development of a family of General Aviation aircraft designed using the open engineering systems paradigm (Simpson, 1995) . Toward this end, *ranged* sets of top-level design specifications are developed which are "common and good" for the 2, 4, *and* 6 seater aircraft configurations which constitute the family of GAA as shown in Figure 3.

In accordance with Step 1 in Figure 3, the following top-level design specifications and corresponding ranges provide

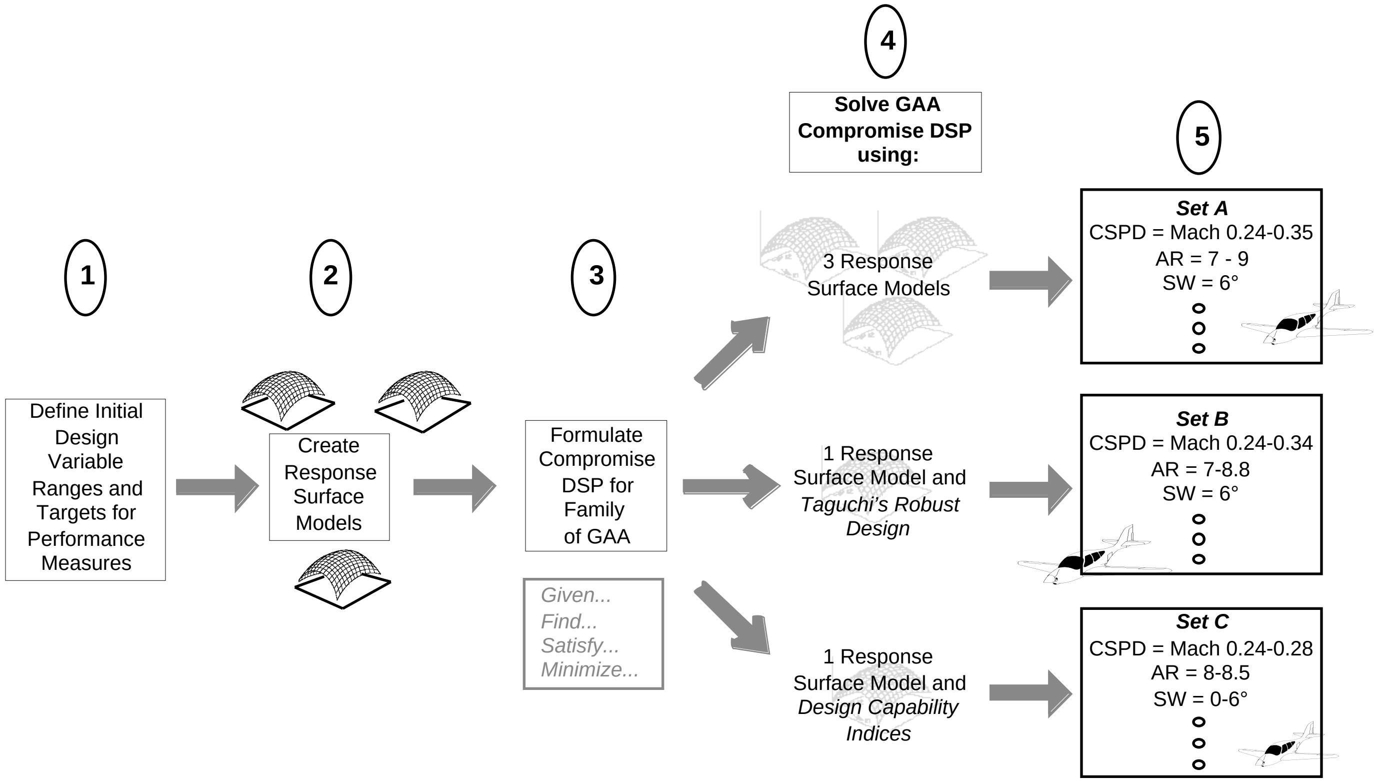

Figure 3. Steps for Conceptual Design of a Family of General Aviation Aircraft

the initial starting point for the conceptual design of the family of GAA:

1. Cruise speed, CSPD (Mach 0.24 ≤ CSPD ≤ 0.48)
2. Aspect ratio, AR (7 ≤ AR ≤ 11)
3. Propeller diameter, DPROP (5.5 ≤ DPROP ≤ 6.8 ft)
4. Wing loading, WL (19 ≤ WL ≤ 25 lb/ft^2)
5. Wing sweep angle, SW (0 ≤ SW ≤ 6.0°)
6. Engine activity factor, AF (85 ≤ AF ≤ 110)
7. Seat width, WS (10 ≤ WS ≤ 20.0 in)
8. Tail length/diameter, ELODT (3.0 ≤ ELODT ≤ 3.75)

along with the performance measure targets for each aircraft which are given in Table 1. For example, for the 2 seater GAA, a target of **450 lbs -** is listed for fuel weight. This indicates that a fuel weight of *450 lbs or less is desirable for the 2 seater GAA at this stage of the design process.* Similarly, we desire that all three aircraft achieve maximum lift to drag ratios of 17 or better as indicated by the **17 +** target listed in Table 1. The math model for the GAA example problem is included in Appendix A and is further described in (Simpson, et al., 1996; Simpson, 1995).

As shown in Step 2 of Figure 3, we rely heavily on second order response surface models (Box and Draper, 1987, Chen, et al., 1995, Khuri and Cornell, 1987) for the conceptual design of the family of General Aviation aircraft. These response surface models are based on computer simulations of the General Aviation Synthesis Program (NASA, 1978) . This enables us to perform parametric studies of General Aviation aircraft in a rapid manner. Three different solution methods are employed to determine appropriate ranged sets of top-level design specifications suitable for the conceptual design of the family of GAA, see Steps 3 and 4 in Figure 3. The solution methods for finding each ranged set of top-level design specifications are elaborated as follows, and the corresponding ranged sets of top-level design specifications, shown in Step 5 in the figure, are listed in their entirety in Table 2.

Table 1. Performance Measures and Targets for the 2, 4, and 6 Seater GAA

Performance Measure	Acronym	2 Seater GAA Targets	4 Seater GAA Targets	6 Seater GAA Targets
Fuel weight	WFUEL	450 lbs -	400 lbs -	350 lbs -
Empty weight	WEMP	1900 lbs -	1950 lbs -	2000 lbs -
Direct operating cost	DOC	$60/hr -	$60/hr -	$60/hr -
Purchase price	PURCH	$41,000 -	$42,000 -	$43,000 -
Max. lift to drag ratio	LDMAX	17 +	17 +	17 +
Max. cruise speed	VCRMX	200 kts +	200 kts +	200 kts +
Max. range	RANGE	2500 nm +	2500 nm +	2500 nm +

Table 2. Summary of Ranged Top-Level Design Specifications for the Family of General Aviation Aircraft

Design Variable	Top-Level Design Specifications - Set A		Top-Level Design Specifications - Set B		Top-Level Design Specifications - Set C	
	Designation	Value(s)	Designation	Value(s)	Designation	Value(s)
CSPD	open	Mach 0.24 - 0.35	open	Mach 0.24 - 0.34	open	Mach 0.24 - 0.28
AR	open	7.0 - 9	open	7.0 - 8.8	open	8.0 - 8.5
SW	fixed	6.0°	fixed	6.0°	open	0°- 6°
DPROP	open	5.5 - 5.9 ft	open	5.5 - 5.96 ft	open	5.5 - 5.96 ft
WL	open	20 - 25 lb/ft^2	open	20 - 24 lb/ft^2	fixed	23.75 lb/ft^2
AF	fixed	85	open	85 - 92	fixed	85
WS	open	14 - 20 in	open	15 - 18 in	open	17 - 17.5 in
ELODT	fixed	3.75	fixed	3.75	fixed	3.75

- Set A is found using three separate sets of response surface models for the 2, 4, and 6 seater GAA as shown in Step 4 of Figure 3 using a process similar to that described in (Chen, et al., 1995). A compromise DSP, (Mistree, et al., 1993) , is formulated for each aircraft, Step 3, and solved accordingly, Step 4, to determine the values of the design variables which satisfied as best as possible the targets, see Table 1, without violating any constraints[7]. The GAA compromise DSP formulation is included in Appendix A. The corresponding ranged set of top-level design specifications is the set of top-level design specifications which is the most "common and good" for all three aircraft.
- Set B is found using a single set of response surface models which include the number of passengers as a design variable, see Step 4 in Figure 3. The number of passengers is then treated as a noise variable[8] around which a ranged set of top-level design specifications for the family of GAA is developed. This process is described in (Simpson, et al., 1996) and is therefore not repeated here. Suffice it to say that through an adaptation of Taguchi's robust design and the utilization of the Robust Concept Exploration Method (Chen, et al., 1995) , a ranged set of top-level design specifications for the family of GAA is

[7] The constraints for the GAA can be found in Appendix A and are further described in (Simpson, 1995) . The constraints are of little importance in this work, however, since the only results that we have reported in this paper are those which are feasible.

[8] A noise variable is a variable in the system over which designers have no control. Robust design then serves to minimize the effects of noise in the system since this noise cannot be elminiated (Phadke, 1989) .

developed which is robust with respect to the number of passengers and therefore suitable for all three aircraft.

- Set C is found using the same set of response surface models as is used to find Set B; however, instead of using Taguchi's robust design to determine the top-level design specifications, design capability indices are used instead. Design capability indices are employed to assess the capability of a family of designs to satisfy a ranged set of design requirements such as we have here, e.g., a maximum lift to drag ratio of 17 or greater is acceptable. The application and use of design capability indices are thoroughly described in (Chen, et al., 1996) . As with Sets A and B, suffice it to say that design capability indices and a single set of response surface models are used to simultaneously design the aircraft by determining a ranged set of top-level design specifications which is robust with respect to the number of passengers and therefore suitable for the family of aircraft.

We present the corresponding ranged sets (A, B, and C) of top-level design specifications for our family of GAA in Table 2. The design variables in the ranged sets of top-level design specifications listed in Table 2 are classified as being either open or fixed; open corresponds to a permissible range while fixed corresponds to a point. This designation is determined based on answering a series of "what-if" questions regarding the various performance measures and how they influence the design, see (Simpson, et al. 1996) for further discussion.

Corresponding to each ranged set of top-level design specifications is a range for each performance measure, see Table 3. The ranges of the performance measures are found using an exhaustive search algorithm which employs the second order response surface models used during conceptual design (Simpson, 1995). The ranges presented in Table 3 represent only the *feasible performance ranges* associated with each ranged set of top-level design specifications since we are only concerned with feasible and achievable solutions. For each ranged set, the low value for each performance measure is listed first followed by its high value. Furthermore, the target range for each performance measure is repeated in Table 3. Using this information, we can apply our metrics for design freedom, Eqn. 2, and information certainty, Eqn. 3, to determine the extent to which design freedom is maintained and design knowledge has been increased during this stage of the GAA design process. We begin by assessing the design freedom associated with the *initial* ranged set of the top-level design specifications.

Table 3. Ranges of the Performance Measures for Each Ranged Set of Top-Level Design Specifications for the Family of GAA

GAA	Performance Measure	Target Range	Range Based on Set A		Range Based on Set B		Range Based on Set C	
2 Seater	fuel wt	450 lbs-	401.75	500.00	440.89	500.00	462.92	482.45
	empty wt	1900 lbs-	1833.77	1931.94	1833.62	1892.10	1854.46	1874.64
	DOC $	$60/hr -	51.99	80.00	52.49	80.00	53.27	69.05
	purchase $	$41000 -	41374.50	43407.90	41374.50	42771.80	41886.70	42419.50
	max. l/d	17 +	14.53	17.32	15.10	16.98	16.06	16.58
	max. speed	200 kts +	191.60	207.38	195.65	206.16	201.55	203.96
	max. range	2500 nm +	1879.86	2723.98	2086.97	2723.98	2177.74	2333.77
4 Seater	fuel wt	400 lbs-	362.65	470.65	405.59	471.13	428.19	448.34
	empty wt	1950 lbs-	1861.64	1971.12	1861.54	1925.72	1887.12	1907.65
	DOC $	$60/hr -	53.05	80.00	53.52	80.00	54.31	70.07
	purchase $	$42000 -	41786.60	44018.40	41786.60	43302.80	42357.50	42927.60
	max. l/d	17 +	14.11	16.91	14.71	16.57	15.68	16.20
	max. speed	200 kts +	188.49	204.27	192.67	203.23	198.41	200.89
	max. range	2500 nm +	1821.79	2644.28	2033.04	2644.28	2123.01	2272.72

6 Seater	fuel wt	350 lbs-	327.91	446.13	375.09	447.07	397.84	419.68
	empty wt	2000 lbs-	1886.06	2007.16	1885.74	1956.42	1915.76	1937.85
	DOC $	$60/hr -	53.62	80.00	54.06	80.00	54.87	70.60
	purchase $	$43000 -	42241.80	44690.60	42241.80	43888.10	42876.80	43490.00
	max. l/d	17 +	13.96	16.77	14.60	16.44	15.56	16.08
	max. speed	200 kts +	187.42	203.21	191.74	202.34	197.32	199.87
	max. range	2500 nm +	1781.87	2586.61	1997.24	2586.61	2086.43	2229.82

The high and low values for each performance measure corresponding to the *initial* design variable ranges are given in Table 4 along with the appropriate target ranges. The ranges of the performance measures were also found using an exhaustive search which utilized the second order response surface models used during conceptual design. As stated previously, the ranges presented in Table 4 represent only the *feasible performance ranges* associated with the initial ranged set of top-level design specifications.

The average design freedom listed for each aircraft in the far right column of Table 4 is computed using Eqn. 2 and is the *average of the design freedom corresponding to each performance measure for each aircraft.* The design freedom associated with the entire family of GAA presented at the bottom of the table is the average of the design freedom associated with the 2, 4, and 6 seater aircraft which constitute the family of GAA. *This value for design freedom represents the amount of design freedom in the system after having defined the design space but before any analysis has been performed in conceptual design.* Some observations regarding the data in Table 4 are as follows.

- The initial design freedom of the family of GAA measured using Eqn 2 is 0.2897 which is considerably less than 1. This indicates that we have significantly decreased our design freedom once we set the initial ranges for the design variables.
- For the 2 and 4 seater GAA, there is no design freedom associated with max. l/d. This is because there is no overlap between the *feasible* performance space and the target range of 17 + which means that this target can never be met with this range of top-level design specifications for these aircraft. Similarly, there is no design freedom associated with the purchase price for the 2 seater GAA.
- The magnitude of the individual design freedom measures indicates where the design is most flexible. For instance, the design freedom associated with empty weight is high for all three aircraft indicating that there is considerable flexibility associated with this performance measure. Conversely, the design freedom associated with max. range is substantially less indicating that there is less flexibility associated with this performance measure.

Table 4. Design Freedom Associated with the Initial Set of Top-Level Design Specifications

Aircraft	Goal	Low	High	Design Freedom
2 seater	fuel wt	396.25	500.00	0.518
	empty wt	1832.17	1941.92	0.618
	DOC $	55.35	80.00	0.286
	purchase $	41210.20	43719.20	0.0
	max. l/d	14.23	17.38	0.122
	max. speed	188.31	206.97	0.374
	max. range	1842.75	2724.99	0.255
	Aircraft's	**Design**	**Freedom =**	0.3104
4 seater	fuel wt	356.38	478.34	0.358
	empty wt	1853.26	1981.57	0.754
	DOC $	53.05	80.00	0.258
	purchase $	41524.40	44337.70	0.169
	max. l/d	13.94	16.90	0.0
	max. speed	186.11	203.89	0.219
	max. range	1798.98	2645.51	0.172
	Aircraft's	**Design**	**Freedom =**	0.2756
6 seater	fuel wt	319.66	461.55	0.214
	empty wt	1870.66	2017.94	0.878
	DOC $	53.62	80.00	0.242
	purchase $	41892.70	45013.00	0.355
	max. l/d	13.92	16.72	0.0
	max. speed	185.96	203.21	0.186
	max. range	1764.61	2588.50	0.107
	Aircraft's	**Design**	**Freedom =**	0.2832
Average	**Family**	**Design**	**Freedom =**	0.2897

The design freedom for the ranged sets of top-level design specifications, Table 2, and their corresponding performance ranges, Table 3, are computed in a similar manner using Eqn. 2 and only the final results are tallied in Table 5. Some observations regarding the data in Table 5 are as follows.

- In general, as the ranged set of top-level design specification narrows, the design freedom decreases. This is the general trend for each aircraft as well as for the design freedom associated with the family of aircraft (with the exception of the design freedom for the 2 seater GAA).
- For a given ranged set of top-level design specifications, the design freedom for the 2 seater GAA is larger than that of either the 4 or 6 seater GAA. This indicates that for a given ranged set of top-level design specifications, it is more difficult for the 4 and 6 seater GAA to meet their target ranges than it is for the 2 seater GAA.
- The design freedom associated with Set C is the smallest. It is 23% smaller than the initial design freedom, 15% smaller than the design freedom associated with Set A, and 12% smaller than the design freedom associated with Set B.
- Similarly, the design freedom associated with Set B, is 13% less than the original design freedom set, and is 4% smaller than the design freedom associated with Set A. The design freedom associated with Set A is only 8.8% less than the design freedom of the initial ranged set of top-level design specifications.

Based on these results, it appears that we are able to maintain design freedom to some extent during conceptual design by finding ranged, rather than point, sets of top-level design specifications. There is less than a 25% reduction in design freedom for any of the ranged sets of top-level design specifications, and all of the ranged sets of top-level design specifications maintain some degree of design freedom. *But how has design knowledge increased during this process?*

We can now apply Eqn. 3 to the ranged sets of top-level design specifications from Table 2 to determine the extent to which design knowledge has been increased during this stage of the design process. The computations are summarized in Table 6, and the values listed under the columns marked IC are measures of information certainty (IC) found using Eqn. 3.

- The information certainty associated with each point specification, e.g., ELODT in Sets A, B, and C, is 1.0, indicating complete certainty about these design variables. The larger the range, the more uncertain we are about that design variable and the lower the information certainty.
- As desired, as the range for a design variable narrows, the information certainty increases, e.g., the information certainty for WL is 0.167 in Set A, 0.333 in Set B, and 1.0 in Set C. The corresponding ranges of WL are 20 - 25 lb/ft^2, 20 - 24 lb/ft^2, and 23.75 lb/ft^2, respectively.
- As the ranged set of top-level design specifications narrows as a whole, the certainty in the information increases. Set C is the narrowest ranged set of top-level design specifications while Set A is the largest. The information certainty for Set C (= 0.784) is 17% larger than in Set B (= 0.667) which is 8.8% larger than in Set A (= 0.613). The information certainty of Set C is also 27.9% larger than that of Set A.

Table 5. Design Freedom Associated with Ranged Sets A, B, and C of Top-Level Design Specifications for the GAA Example Problem

Top-Level Design Specifications	**Design Freedom**			
	2 Seater GAA	**4 Seater GAA**	**6 Seater GAA**	**Family Average**
Initial Set	0.3104	0.2756	0.2832	0.2897
Set A	0.3006	0.2485	0.2436	0.2642
Set B	0.2772	0.2384	0.2441	0.2532
Set C	0.3200	0.1740	0.1761	0.2234

Table 6. Information Certainty for the Ranged Sets of Top-Level Design Specifications for the GAA Example Problem

	Initial Set			Set A			Set B			Set C		
DV	**Low**	**High**	**IC**	**Low**	**High**	**IC**	**Low**	**High**	**IC**	**Low**	**High**	**IC**
CSPD	0.24	0.48	0.00	0.24	0.35	0.542	0.24	0.34	0.583	0.24	0.28	0.833
AR	7	11	0.00	7	9	0.500	7	8.8	0.550	8	8.5	0.875
SW	0	6	0.00	6		1.000	6		1.000	0	6	0.000
DPROP	5.5	6.8	0.00	5.5	5.9	0.692	5.5	5.96	0.646	5.5	5.96	0.646
WL	19	25	0.00	20	25	0.167	20	24	0.333	23.75		1.000
AF	85	110	0.00	85		1.000	85	92	0.720	85		1.000
WS	14	20	0.00	14	20	0.000	15	18	0.500	17	17.5	0.917
ELODT	3	3.75	0.00	3.75		1.000	3.75		1.000	3.75		1.000
		Avg.:	0.00		Avg.:	0.613		Avg.:	0.667		Avg.:	0.784

It appears that design knowledge and design freedom are related based on these observations. An inverse relationship appears to exist between the certainty of the design information for a ranged set of specifications and the design freedom associated with that ranged set. As the information certainty increases, the design freedom decreases, as illustrated previously in Figure 1. For the GAA example problem, Set B has more design freedom than Set C but less information certainty than Set C. Moreover, Set B has higher information certainty but less design freedom than that associated with Set A. Set C has the most information certainty but the least design freedom. *So now what? What happens in the next stage of the design process? Do these numbers make sense?* These and other questions are discussed in the next, and final, section.

CLOSING REMARKS AND AVENUES OF FUTURE WORK

By finding ranged sets of top-level design specifications as opposed to point solutions in conceptual design, we are able to maintain design freedom while simultaneously increasing design knowledge through an increase in the information certainty associated with a design. This enables us to increase system flexibility and improve the adaptability of a design in the later stages of design. The work in this paper represents only the first in a series of steps which are required for the successful development of a foundation to design, realize, and sustain open engineering systems.

We have presented two metrics for measuring design freedom and design knowledge in the early stages of design and demonstrated their use in an example, namely, the design of a family of General Aviation aircraft. Use of these metrics allow us to assess the extent to which design freedom has been maintained and design knowledge, information certainty in particular, has been increased during the various phases of the design process. This enables us to track the evolution of a design and determine the flexibility of the design at any stage of the design process.

But several questions remain unanswered. *How long should design freedom be maintained and when it is it necessary to move to point solutions rather than range solutions? Are these metrics suitable for use during the later stages of design and if not, how should they be further modified?* Moreover, now that we have a means for tracking design evolution through these metrics for design freedom and design knowledge, *at what rate do we want to increase design knowledge during the design process and at what rate is it acceptable to let design freedom decrease?* Furthermore, based on our definitions for design freedom and design knowledge, the two appear to be related; *what is the exact nature of the relationship between design freedom and information certainty and is one of the metrics therefore redundant?*

It appears that the work in this paper raises some new and interesting questions. However, our work here represents only an initial step toward developing a foundation for designing families of products and measuring design freedom and design knowledge during their design. We recognize that a substantial amount of work is needed to further validate and verify the appropriateness of our metrics for design freedom and information certainty. By carrying the GAA example problem into the later stages of design and examining different products throughout the entire design and development process, we can determine if our metrics are appropriate for the later stages of design and provide further verification and validation of our work.

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APPENDIX A

We include the GAA compromise DSP for our example problem in this appendix. For a full description of the compromise DSP and its solution algorithm, refer to (Mistree, et al., 1993). For each of the key words of the compromise DSP (Given, Find, Satisfy, and Minimize), we present the actual formulation for our GAA example problem. Not included, however, are the actual second order response surface models which are employed to solve for the design variables. These can be found in (Simpson, 1995) and are not included here because of their length.

Given:

- General Aviation Synthesis Program, GASP
- # passengers (1, 3, or 5)
- Mission profile (altitude, range, etc.)
- Wing type (low)
- Landing gear type (retractable)
- Number of blades (3)

Find:

- The system variables, **X**( ):
  - the cruise speed, CSPD
  - the wing aspect ratio, AR
  - the sweep angle, SW
  - the propeller diameter, DPROP
  - the wing loading, WL
  - the engine activity factor, AF
  - the seat width, WS
  - the tail length to diameter ratio, ELODT

Satisfy:

- The system constraints, C(**X**):
  - takeoff noise ≤ upper limit: NOISE_MAX(**X**) ≤ 75 dbA
  - propeller tip speed ≤ upper limit: TPSPD_MAX(**X**) ≤ 850 ft/sec
  - direct operating cost ≤ upper limit: DOC_MAX(**X**) ≤ 80 $/hr
  - ride roughness factor ≤ upper limit: ROUGH_MAX(**X**) ≤ 2.0 n.m.u.
  - empty weight ≤ upper limit: WEMP_MAX(**X**) ≤ 2200 lbs
  - fuel weight ≤ upper limit: WFUEL_MAX(**X**) ≤ 500 lbs
- The system goals, G(**X**), for *brining mean on target*
  - minimize mean of fuel weight: WFUEL_AVG(**X**)/400 + $d_1^- - d_1^+$ = 1.0
  - minimize mean of empty weight: WEMP_AVG(**X**)/1950 + $d_2^- - d_2^+$ = 1.0
  - minimize mean of direct operating cost: DOC_AVG(**X**)/60 + $d_3^- - d_3^+$ = 1.0
  - minimize mean of purchase price: PURCH_AVG(**X**)/42000 + $d_4^- - d_4^+$ = 1.0
  - maximize mean of max. lift/drag: LDMAX_AVG(**X**)/17 + $d_5^- - d_5^+$ = 1.0
  - maximize mean of max. cruise speed: VCRMX_AVG(**X**)/200 + $d_6^- - d_6^+$ = 1.0
  - maximize mean of max. range: RANGE_AVG(**X**)/2500 + $d_7^- - d_7^+$ = 1.0

- The system goals, G(**X**), for *minimizing deviation*
  - minimize deviation of fuel weight: $3*WFUEL\_DEV(\mathbf{X})/50 + d_8^- - d_8^+ = 1.0$
  - minimize deviation of empty weight: $3*WEMP\_DEV(\mathbf{X})/50 + d_9^- - d_9^+ = 1.0$
  - minimize deviation of direct operating cost: $3*DOC\_DEV(\mathbf{X})/5 + d_{10}^- - d_{10}^+ = 1.0$
  - minimize deviation of purchase price: $3*PURCH\_DEV(\mathbf{X})/1000 + d_{11}^- - d_{11}^+ = 1.0$
  - maximize deviation of max. lift/drag: $3*LDMAX\_DEV(\mathbf{X})/1 + d_{12}^- - d_{12}^+ = 1.0$
  - maximize deviation of max. cruise speed: $3*VCRMX\_DEV(\mathbf{X})/10 + d_{13}^- - d_{13}^+ = 1.0$
  - maximize deviation of max. range: $3*RANGE\_DEV(\mathbf{X})/225 + d_{14}^- - d_{14}^+ = 1.0$

    subject to: $d_i^- \bullet d_i^+ = 0$ and $d_i^-, d_i^+ \geq 0$, for i = 1, 2, ..., 14.

Minimize:

- The sum of the deviation variables associated with:
  - the mean and standard deviation of fuel weight, d_1^+ and d_8^+
  - the mean and standard deviation of empty weight, d_2^+ and d_9^+
  - the mean and standard deviation of direct operating cost, d_3^+ and d_{10}^+
  - the mean and standard deviation of purchase price, d_4^+ and d_{11}^+
  - the mean and standard deviation of maximum lift to drag ratio, d_5^- and d_{12}^+
  - the mean and standard deviation of maximum cruise speed, d_6^- and d_{13}^+
  - the mean and standard deviation of maximum range, d_7^- and d_{14}^+

$$Z = \{f_1(d_1^+), f_2(d_2^+), f_3(d_3^+), f_4(d_4^+), f_5(d_5^-), f_6(d_6^-), f_7(d_7^-),$$
$$f_8(d_8^+), f_9(d_9^+), f_{10}(d_{10}^+), f_{11}(d_{11}^+), f_{12}(d_{12}^-), f_{13}(d_{13}^-), f_{14}(d_{14}^-)\}$$