Proceedings of ICAD2004
The Third International Conference on Axiomatic Design
Seoul – June 21-24, 2004
ICAD-2004-35

CASE STUDY: AXIOMATIC DESIGN OF THE SPACE SHUTTLE WING – LEADING EDGE

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ABSTRACT

Axiomatic design is emerging as a superior method of design, particularly when innovation versus incremental design is needed. However, the quantity of case studies to support education is limited, particularly those involving large systems and subcomponents. This paper is a teaching case study based on the Columbia Space Shuttle. In particular, it focuses on setting up the redesign of the shuttle's wing – leading edge.

The discussion is broken down into three areas. First, a review of Columbia's forensic engineering data was completed to obtain design information. This helps establish the design problem. Second, a simple overview of axiomatic design is offered. Emphasis is placed on understanding the basics of how the approach forces the design back to first principles and set-up of the design domains. Finally, an "imperfect" design setup is discussed, which should form the foundation for teaching discussions.

Keywords: engineering education, axiomatic design, axioms, Columbia space shuttle, engineering case study, large system analysis.

1. INTRODUCTION

Often forensic engineering studies serve as high quality content for education case studies. This case is meant to set up and stimulate critical thinking about how axiomatic design might be applied to solve design issues raised by the Columbia Accident Investigation Board (CAIB) investigation of the Columbia space shuttle disaster (Shuttle Mission STS 107).[1] While the design issues raised are "large systems" issues, the scope being assigned is the redesign of the wing- leading edge, stemming from CAIB recommendation 3.3-2.

The recommendation was to improve the impact resistance of the reinforced carbon-carbon leading wing edge.[2] In addition, while not publicly stated in the report, the final design solution should significantly improve reliability. Shuttle design reliability was at 1 vehicle loss in 148 missions (post-Challenger improvement standard – which was originally 1 vehicle loss in 78 missions in the original design[3]).

> *"Shuttle reliability is uncertain, but has been estimated to range between 97 and 99 percent. If the Shuttle reliability is 98 percent, there would be a 50-50 chance of losing an Orbiter within 34 flights … The probability of maintaining at least three Orbiters in the Shuttle fleet declines to less than 50 percent after flight 113."*
>
> -The Office of Technology Assessment, 1989

However, in the face of the Columbia disaster, NASA was determined to move up meeting its pre-Columbia 2007 safety reliability goal of no more than 1 loss in 325 missions.[4]

2. Columbia Design Issues

On February 1st, 2003, the space shuttle Columbia disintegrated over Arizona at Mach 21 at an altitude of 73 km. From the 11% of the structure which was recovered (including the wheels and a tape recorder with data from key sensors) and forensic engineering evidence, the CAIB concluded that Columbia, and its crew, were lost due to a breach in the shuttle's thermal protection system (TPS) on the leading edge of the left wing. The proximate cause of the failure was a lift-off debris strike 81.7 seconds into the flight. The debris strike had been identified as a piece of shuttle tank insulating foam which separated from the external tank, subsequently striking the shuttle's left wing on the lower half of reinforced carbon-carbon (RCC) panel number 8. During re-entry the TPS breach allowed superheated air to penetrate and melt the aluminum sub-structure, leading to the catastrophic failure.[5]

The foam strike had no major impact on the overall mission, which met all its in-flight objectives.[6] However, it caused catastrophic failure at the point when both thermal and mechanical stresses on the shuttle wings were at their greatest – during reentry.

RCC resembles a hi-tech fiberglass. More specifically, it is made up of layers of special graphite cloth, which are molded to shape at very high temperatures.[7] Refurbishment of the TPS – including RCC repair and/or replacement - took an average of 67 days before the shuttle was ready for the next launch. The goal was to launch 50 flights per year. However, current performance, largely due to TPS refurbishment repair cycle time and costs, had

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deteriorated to only being able to turnaround 24 flights per year by 1989. The per-mission refurbishment cost was more than $140 million.[8]

Debris strikes and the need to strengthen the impact resistance of the leading edge were known issues well before Shuttle Flight STS 107 (see Figure 1). *Foam loss has occurred on more than 80 percent of the 79 missions for whom imagery is available, and foam was lost from the left bipod ramp on nearly 10 percent of missions where the left bipod ramp was visible following External Tank separation.*[9]

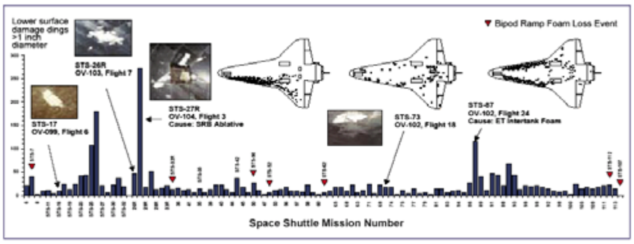


Figure 6.1-6. This chart shows the number of dings greater than one inch in diameter on the lower surface of the Orbiter after each mission from STS-6 through STS-113. Flights where the bipod ramp foam is known to have come off are marked with a red triangle.

Figure 1: History of Shuttle debris strikes.[10]

Ames Research Center had even proposed equipping the shuttle with tile repair kits because of the frequency of debris strikes. However, Howard Goldstein, who recently retired as the Ames Research director, had publicly commented that TPS improvements were not on the priority list. A specific concern was whether or not a debris strike could actually be detected.[11]

The secondary failure was the breech in Columbia's thermal protection system (TPS). This system is made up of several materials including RCC panels, insulating tiles, and thermal blankets. As indicated earlier, the specific breech was in the wing leading edge RCC panel.

The material RCC was at the heart of why the shuttle functioned and often considered the critical success factor in meeting wing leading edge design requirements. Lockheed Martin Missiles and Fire Control, developed RCC for the shuttle's nose cap, chin panel, wing leading edges and T-seals. RCC has reasonable strength across its operational temperature range (-250 F to 3,000 F). Its low thermal expansion coefficient minimizes thermal shock and thermo-elastic stress. Each wing leading edge consists of 22 individually unique RCC panels made up of a laminate of graphite impregnated rayon cloth. These are phenolic resin impregnated and layered, one ply at a time, autoclave cured, trimmed, and inspected. The panels are then fired and converted to carbon. Density is increased by vacuum impregnation with furfural and subsequent firing. The outer layers of the carbon substrate are converted to a nominal 0.03-inch layer of silicon carbide through argon firing at 3000 F. As the silicon carbide cools, small hairline cracks form because the difference in thermal expansion rates of the silicon carbide and the carbon substrate. Subsequently the RCC panels are vacuum-impregnated with tetraethyl ortho-silicate to fill the pores in the substrate, and the hairline cracks are sealed.[12]

The wing leading edge structural subsystem (see Figure 2) consists of the RCC panels, the upper and lower access panels, and the associated attachment hardware. On Columbia, two upper and lower A-286 stainless steel spar attachment fittings connected each RCC panel to the aluminum wing leading edge spar. The gap seals, more commonly called T-seals, are attached to their associated RCC panel by two Inconel 718 attachments. The upper and lower carrier panels, which allow access behind each RCC panel, are attached to the spar attachment fittings after the RCC panels and T-seals are installed. The lower carrier panel prevents superheated air from entering the RCC panel cavity. A small space between the upper carrier panel and the RCC panel allows air pressure to equalize behind the RCC panels during ascent and re-entry.

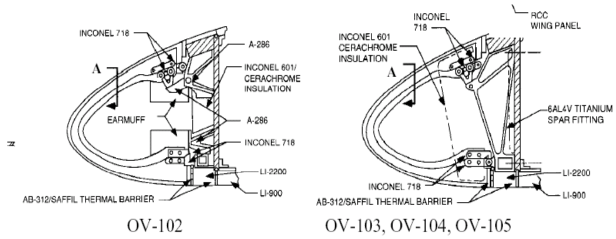


Figure 2: Details of the orbiter structure and RCC leading edge structure [13]

The major internal support structures in the mid-wing are constructed from aluminum alloy. Since aluminum melts at 1,200 degrees Fahrenheit, the mid-wing truss tubes were destroyed and wing structural integrity was lost when the TPS breech occurred.[14] Figure 3 (from the CAIB report) clearly shows that Panels 8-13 had the shortest life expectancy, and therefore had both significantly tougher design challenges and requirements.

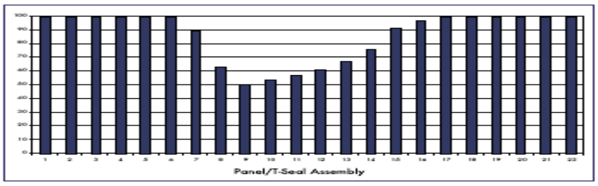


Figure 3.3-4. The expected mission life for each of the wing leading edge RCC panels on Columbia. Note that panel 9 has the shortest life expectancy.

Figure 3: Space Shuttle TCC Tile Life Expectancy by Location [15]

What may be significant is that initial debris impact occurred during relatively low temperature conditions while the leading edge was under compressive loads. Yet, at the time of failure thermal and structural performance were at peak conditions.

The original RCC design specifications essentially had no impact resistance. Supposedly, RCC was "highly resistant to fatigue loading during ascent and entry" within its operating temperature range.[16] Columbia's critical RCC panels 8 and 9 were at their design half -life (50 flights) and might have even be the oldest panels in the shuttle fleet.[17]

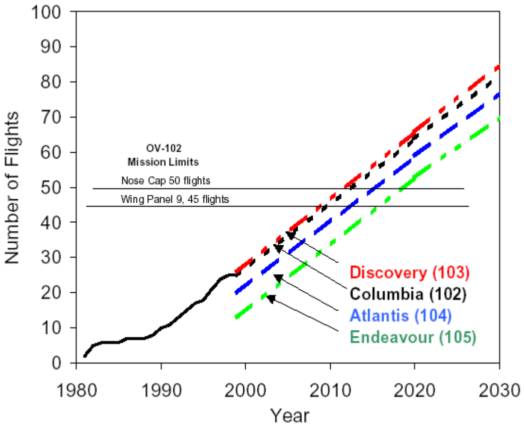


Figure 4: RCC Panel Life by Shuttle [18]

3. Debris Impact Studies

In seven launches of the space shuttle there had been instances when the shuttle tank had shed large chunks of foam. Five of them had occurred with the Columbia.[19] The STS 107 debris was a piece of external tank foam insulation with a cross section estimated at 24 +/- 3 inches and 15 +/- 3 inches and 5 ½ inches thick. Impact velocity was estimated between 400 to 600 mph.

In essence, the orbiter "ran into the foam", as the foam essentially was traveling at about 1600 mph before release and had slowed to close to 1000 mph by the time the orbiter – still traveling at 1600 mph – hit it. *The foam slowed down rapidly because such low-density objects have low ballistic coefficients, which means their speed rapidly decreases when they lose their means of propulsion.* [20] The finding about relative velocity suggests any debris coming off the shuttle system posed a more significant threat understood previously.

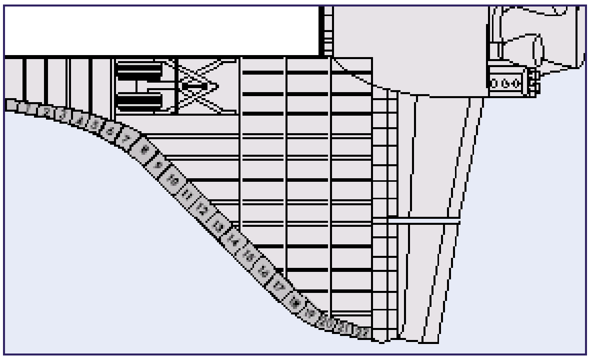


Figure 3.3-1. There are 22 panels of Reinforced Carbon-Carbon on each wing, numbered as shown above.

Figure 5: RCC Panel Locations

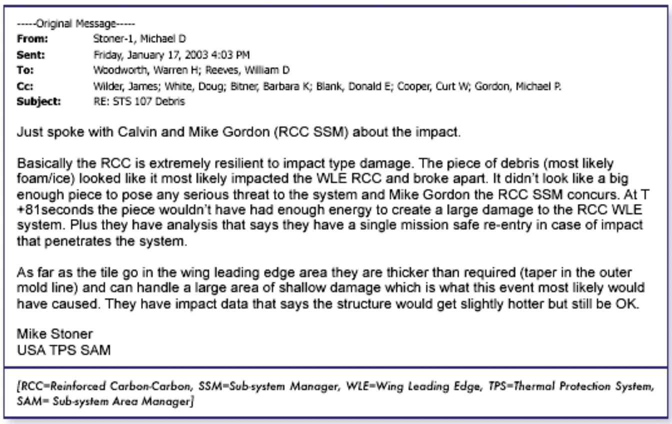
Given the number of RCC panels (see Figure 5) and the probability of a foam strike, what was the extent of probable damage? The CAIB concluded that *while the RCC composite material and associated support hardware are remarkably tough and have impact capabilities that far exceed the minimal impact resistance specified in their original design requirements, tests demonstrated that this toughness was exceeded by foam impact. The impact tests demonstrated that foam could cause a wide range of impact damage, from cracks to a 16- by 17-inch hole.*[21] The results of the impact test are shown in Figure 6.

Figure 6: RCC impact test damage

Prior demonstration tests had established the orbiters could survive re-entry with holes of up to ¼ inch diameter in the lower surfaces of panels 8-10, or 1-inch diameter in other RCC panels. There had been several other hypervelocity impacts on at least 43 other flights. The largest to date had been a 1.9 x 1.6 exterior gash and 0.5 x 0.1 interior gash on Shuttle Mission 45, March 1992. [22]

While not well understood, the RCC panels also exhibited an increasing surface roughness with age. The CAIB reported increasing concerns, since the late 1980s, about roughness. *Higher wing roughness can contribute to early transition from laminar to more thermally stressful turbulent aerodynamic flow during re-entry, thus exposing* *the vehicle to an exceptionally hot flight profile. In particular, early boundary layer transition (BLT) added to the suspected wing damage could have posed a fatal combination.*[23]

As often happens in investigations, there was a "smoking gun". The Stoner memo (Figure 7) suggests inadequate analysis of the impact force prior to the subsequent wing failure.[24]



-----Original Message-----
From: Stoner-1, Michael D
Sent: Friday, January 17, 2003 4:03 PM
To: Woodworth, Warren H; Reeves, William D
Cc: Wilder, James; White, Doug; Bitner, Barbara K; Blank, Donald E; Cooper, Curt W; Gordon, Michael P.
Subject: RE: STS 107 Debris

Just spoke with Calvin and Mike Gordon (RCC SSM) about the impact.

Basically the RCC is extremely resilient to impact type damage. The piece of debris (most likely foam/ice) looked like it most likely impacted the WLE RCC and broke apart. It didn't look like a big enough piece to pose any serious threat to the system and Mike Gordon the RCC SSM concurs. At T +81seconds the piece wouldn't have had enough energy to create a large damage to the RCC WLE system. Plus they have analysis that says they have a single mission safe re-entry in case of impact that penetrates the system.

As far as the tile go in the wing leading edge area they are thicker than required (taper in the outer mold line) and can handle a large area of shallow damage which is what this event most likely would have caused. They have impact data that says the structure would get slightly hotter but still be OK.

Mike Stoner
USA TPS SAM

[RCC=Reinforced Carbon-Carbon, SSM=Sub-system Manager, WLE=Wing Leading Edge, TPS=Thermal Protection System, SAM= Sub-system Area Manager]

Figure 7: Stoner's Memo - RCC Impact Performance

4. Design Approach

As one might expect the complexity of redesign was not in any single attribute area, or even one that appeared primary. At the heart of the redesign challenge is an unresolved conflict between the need for wide ranging thermal insulation matched with a requirement for impact strength due to debris strikes, all while retaining aerodynamic capability. Classic iterative design methods often fail when fundamental performance capability (impact resistance) is missing. How then might one apply axiomatic design to enable preliminary design decisions to be made without doing an exhaustive quantitative analysis?

5. Axiomatic Design - Overview

Dr. Nam Pyo Suh in his most recent book, Axiomatic Design, Advances and Applications[25], had extended his original design methodology beyond a product focus. The top down nature of axiomatic design is ideally suited to complex systems such as the Space Shuttle.[26]

Axiomatic design has its strength in deriving design requirements based on first principles and science. The design is customer driven either as customer attributes – of their needs, expectations, specifications, bounds, or laws; or through their imposed constraints. The constraints act as boundary conditions – like a design envelope, over functional requirements, design parameters, and process variables.

Axiomatic design also allows the designer to quickly determine what is higher priority and ensures a broader systems view. This is better understood by understanding the language of axiomatic design – particularly axiom, theorem, and corollary. [27]

- Axiom – simply a statement of an obvious truth. More scientifically, a principle that itself is not the subject of a proof, but which is the basis for enabling the proof of other things. There are no observed counterexamples or exceptions.
- Theorem – a proposition derived from axioms, which are usually not readily apparent. These may often be proved from accepted axioms.
- Corollary – a proposition that is derived from an axiom or other proposition that has been "proven".

At the heart of the axiomatic design approach are two axioms:

Independence: Maintain the independence of functional requirements (FR). In practice this means if you change a design parameter (DP) it only affects one FR. The goal of this axiom is to maximize independence to achieve the best adjustability and controllability of the design solution.

Information: Minimize the information content of the design. Most often this refers to the measure of knowledge required to complete a design. However, more information in design is really a function of the probability of success, or the chance that it will work. In engineering language it is a function of the range/tolerance (or fit of the design compared to the constrained range of input).[28]

Figure 8 shows the various ways a design can meet or not meet the information axiom.

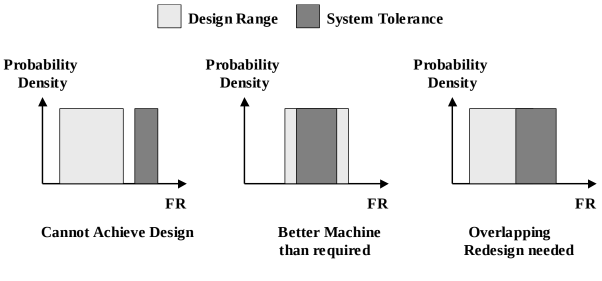


Figure 8: Generalized Range vs. Tolerance "Fit" Scenarios

In a later work the concept of domains were added.[29] The four distinct domains are:

- Customer domain which specifies customer attributes (CA)
- Functional domain characterized by functional requirements (FR)
- Physical Domain characterized by design parameters (DP)
- Process domain characterized by process variables (PV)
- In any domain a constraint can be imposed. Constraints are the specification of a characteristic that the design solution must possess to be acceptable to its customers and to the company designing it.

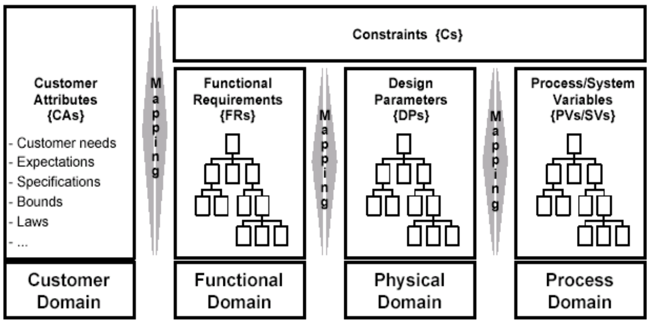


Figure 9: Axiomatic Domains [30]

The functional domain establishes the design objectives. The solution then emerges in the physical domain as design parameters specify the solution and the "how" it is built requirements emerge in the process domain. A simple analogy is that the customer might say "I want better gas mileage", the functional requirement would be "maximize gas mileage". The designer might specify a minimum essential design constraint, such as "no less than 43.5 mpg". The DP might then as emerge as a fuel cell engine (being at the "highest level"). A more process oriented example for a hotel might be when a customer wants "a friendly customer experience" which then translates into a functional requirement of "minimize customer wait time" and perhaps "provide entertainment for customers". Design parameters for the first might emerge as "customer reservation system", "number of staff working", or even "Check-in Kiosks". For the second maybe "television", "non-traditional bell-hops", etc.

The *process of design* in axiomatic design is the iterative work done to map between domains and resolve conflicts and improve the outcomes. The power of axiomatic design is embedded in these two concepts – decomposing, or subdividing elements – such as functional requirements – to smaller, more manageable chunks, then interconnecting those via zigzag mapping. This decomposition and zigzag mapping can be shown visually, or more often, translating domain elements into a correlation matrix, also known as design matrix. In its simplest form two domains are related by a design matrix [A] or [B]:

(FR) = [A] (DP) where:

FR = functional requirements

DP = design parameters

A = design matrix

(DP) = [B] (PV) where:

DP = design parameters

PV = process variables

B = design matrix

As with most design techniques the design engineer must apply some level of critical thinking in selecting requirements. The best designers establish FRs in a way that best satisfies a set of market or customer needs (what the customer says they need), and represent his or her characterization of perceived needs (the unspoken customer requirements). This often requires driving to the minimum essential number of FRs at each level of the hierarchical FR tree. This decomposition by hierarchy in each domain results in a tree of requirements, sub-requirements, sub sub-requirements, etc. This tree is known as a leaf diagram (in the computer technology world) or the domain hierarchy (in production and process design). To minimize the higher-level requirements requires investing up-front time to understand the customer needs and design issues.

Most often the FR= [A] DP is expanded into design matrix. Life would be easy for most designers if the design were only a single functional requirement, requiring a single design parameter, with only one process variable requirement. Reality for most engineers is a myriad of levels and interconnectivity. Generally, the complexity falls into three broad categories related to the complexity of the design matrices (related to [A]). These are:

1. Uncoupled designs where the vectors in the [A] matrix are diagonal (no crossover);
2. Decoupled designs are "transformed" by inclusion of a triangular matrix; and,
3. Coupled designs consist mainly of non-zero elements.

	Uncoupled			**Decoupled**			**Coupled**		
	DP11	DP 12	DP13	DP11	DP 12	DP13	DP11	DP 12	DP13
FR11	X	0	0	X	0	0	X	X	X
FR 12	0	X	0	X	X	0	0	X	0
FR 13	0	0	X	X	X	X	X	0	X

Figure 10: Typical Design Matrix Outcomes

As shown in Figure 10, the design may be uncoupled and relatively easy to deal with both for decomposition and domain mapping, or involve more complexity requiring decomposition and zigzag mapping to either decouple a design or clarify the design is coupled and to what extent.

6. Axiomatic Design Setup

The first step is to establish customer, functional, and physical domains. Needs may be derived from external needs of the market, broad economy, and politics (federal, state, and local regulation). Then include any internal parameters such as NASA's vision, goals, and strategies and governance factors – normally thought of as policies, strategies, and recommendations.[31] This might lead to a high-level design FR and DP statements to guide the remainder of the work:

FR: Meet all nominal operating conditions that the shuttle wing leading edge may expect to encounter.

DP: An Impact and Thermal Resistant Wing – Leading Edge Panels.

Defining customer requirements requires taking a broad view of whom the customers for the shuttle are. For our purposes we will look at end-use customers as Society and "Public Opinion"; The NASA Design Team as the internal customer; the CAIB review board is representative of society – since it included Congressional oversight; and NASA as the business customers; and the shuttle crews are the employees.

Preliminary customer attributes for the "large system" (orbiter level) might include:

CA 1: Society Safety – minimize the potential for catastrophic shuttle failure that results in ground level damage.

CA 2: Employee Safety – minimize the potential for catastrophic shuttle failure that results in loss of shuttle crew lives.

CA 3: Business Profitability – maximize the profitability of the design solution.

CA 4: Delivery – minimize the time required to design and implement the design solution.

CA 5: Maintainability – maximize the maintainability of the solution.

CA 6: Integration – maximize the integration of the leading edge design in the overall shuttle redesign.

Functional Requirements

The next step is to relate CAs into specific FRs. At the same time consider what constraints (Cs) might also be necessary to satisfy the customer needs.[32] The FRs must be determined in a *solution-neutral environment* - defining FRs without thinking about DPs (i.e., the "how" or the solution). FRs simply are the "something desirable" that is the project goal.[33] Relating the FR to the CAs a starter list might include:

FR 1: Maximize Ground Safety - Increase shuttle safety to ensure the potential of catastrophic event impact on the ground meets minimum criteria.

FR 2: Maximize Crew Safety - Maximize wing leading edge design life to exceed safety reliability of 1 loss in 325 flights.

FR 3: Minimize Costs - Minimize impact of wind leading edge design on shuttle turnaround costs - not to exceed $ 140 million.

FR 4: Reduce Shuttle Back-in-Service timing - All wing redesign should be ready to implement within 6 months.

FR 5: Minimize Repair Cycle Time - All wing redesign should not reduce the 24-shuttle units/year availability.

FR 6: Ensure Design Integration - All wing redesign should meet overall shuttle redesign goals.

The next step in axiomatic design is to map FRs of the functional domain into the physical domain by identifying the design parameters (DPs). DPs are "how" we are going to satisfy specific FRs. DPs must be so chosen that they are consistent with the constraints.

Then we evaluate a side-by-side build of the design parameters and test for independence and decouple design parameters. This often reveals coupling of original requirements that may be too close to decouple. Overcoming this may require treating an FR as a constraint and identifying omissions such as target design life. Finally, rework the functional requirements to get them to the appropriate level, as some of the initial functional requirements were at the system (total orbiter) level.

Doing the level 2 decomposition by focusing on level 1 orbiter functional requirements of aerodynamics and aero-thermal protection led to narrower-scope wing leading edge requirements of:

FR1	Maintain necessary aerodynamic shape for flight stability
FR2	Limit high temperature exposure of the aluminum frame
FR3	Withstand surface temperatures
FR4	Withstand debris strike
FR5	Attach (wing leading edge) to wing
FR6	Surpass failure rate objective
FR7	Maintain cost effective replacement
FR8	Deliver economical weight

Constraints:

C1	Total orbiter costs not to exceed $ 140 million
C2	Complete all redesign in 6 months.
C3	Aluminum temperature not to exceed 350 F
C4	Failure rate of no more than 1 in 325 missions

Start mapping the design parameters:

DP1	Wing Shape Operations
DP2	Air Flow Barriers (to prevent hot air penetration)
DP3	Surface Thermal Insulation (Properties)
DP4	Surface (Wing Leading Edge) Material Toughness Properties
DP5	Wing Leading Edge Connection System
DP6	Wing Leading Edge materials
DP7	Leading Edge Wing Unit Costs
DP8	Leading Edge Total Weight

During the mapping process, the design must satisfy the Independence Axiom. Building out their design matrix for the above functional requirements and design parameters resulted in an initial correlation matrix [A] of:

$$\begin{array}{l c cccccccc l}
FR1 & & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & DP1 \\
FR2 & & X & X & 0 & 0 & 0 & 0 & 0 & 0 & DP2 \\
FR3 & & X & X & X & X & 0 & 0 & 0 & 0 & DP3 \\
FR4 & & X & X & X & X & 0 & 0 & 0 & 0 & DP4 \\
FR5 & = & X & X & X & X & X & 0 & X & X & DP5 \\
FR6 & & X & X & X & X & X & X & X & X & DP6 \\
FR7 & & X & X & X & X & X & X & X & 0 & DP7 \\
FR8 & & X & X & X & X & X & X & X & X & DP8
\end{array}$$

Upon examination, one might conclude this is coupled design, largely because of the inclusion of weight and cost. Perhaps a resolution is to consider shifting the wing leading edge weight and cost from design requirements to constraints.

Next test the Information Axiom to determine if a design is superior to others in terms of the Information Axiom, which states that the one with the highest probability of success (i.e., the lowest information content) is the best design. Some of the issues that might be raised are:

DP1	What latitude is there in wing shape?
DP2	Does modifying the RCC panel material also mean that T-seal changes will also be required?
DP3	What was the min-max temperature profile?
DP4	What was the specific impact requirement?
DP5	What are the implications of the RCC roughness increase over time?

It needs to be understood that axiomatic design does not provide the information content of the design solution. As an example, we have to collectively agree on the design conditions we expect to meet for "impact strength" and " design lifetime" and understand how to manage the design vs. those constraints. A challenge during the decomposition is have enough "know-how" to gauge the separation of constraints and goals at each level in the hierarchy.

Author's Closing Note

In using this case study consider problems related to further decomposition, integration of axiomatic design in other areas related to the Columbia systems failure, and in developing students' critical thinking skills, particularly clarifying and solving the design problem. The start of the solution, as presented here, is by no means perfect and should be the start of discussions with students on how to set-up and make progress with the axiomatic design solution.

Acknowledgements

I'd like to thank Dr. Nam P. Suh and his MIT students that took the time to encourage and critique the development of this paper. In particular, one of Dr. Suh's friends, Dr. Taesik Lee also provided valuable insights.

Prof. Steve Yurgartis, also provided encouragement and coaching during development of the origin of this paper, as part of my Master's program at Clarkson University.

Milton Jones and my peers in Six Sigma at Bank of America were extremely giving in their continued support in both time and money. They have allowed me this opportunity to continue pushing the boundary of new techniques of integrating marketing and engineering in Six Sigma for Growth.

A special thanks to my wife and family, for their patience while I juggle work and writing papers, such as this, as part of developing my Six Sigma for Growth methodology.

The crew on shuttle Columbia's last flight consisted of Rick D. Husband (Commander), William C. McCool (Pilot), Michael P. Anderson (Payload Commander), David M. Brown (Mission Specialist), Kalpana Chawla (Mission Specialist), Laurel Blair Clark (Mission Specialist) and the first Israeli astronaut Ilan Ramon (Payload Specialist). In some small way I hope to honor them by prompting discussions to prevent future large system failures through improved engineering education.

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