EXPLORATION OF THE MIRRORING HYPOTHESIS AS AN EARLY DESIGN PHASE PARAMETER

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Dedicated to my family, who gave unwavering support to following my childhood dreams, and to Dan Dumbacher, who helped turn them into a career.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

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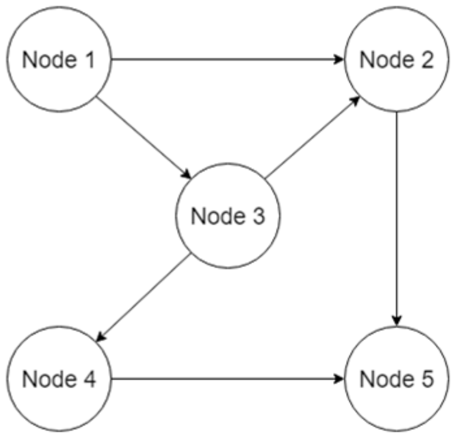
The mirroring hypothesis states the organization architecture and the product architecture tend to "mirror" or mimic each other. There are two types of investigations into this phenomenon: descriptive and normative. Descriptive studies ask whether mirroring is present in an organization/product pair. Normative studies ask whether mirroring affects the performance of an organization/product pair. Much of the mirroring hypothesis literature claims to observe mirroring or claims mirroring improves the performance of the product. While there is still work to be done in the descriptive and normative realms of mirroring hypothesis research, there is a distinct gap in research investigating mirroring in the design phase of products and whether it can be used as a strategy during that phase. This work aims to demonstrate that differently mirrored organization/product pairs working the same example problem produce different design solutions. This demonstration leads into an investigation on where in the life cycle mirroring would be most useful as a design parameter when designing a product. The results of this thesis show that for this specific example problem, mirroring has an effect on the design solutions, and given a Department of Defense acquisition life cycle, there are opportunities where mirroring could be advantageous to use as a design strategy. This work challenges others interested in the topic to not just ask why does mirroring occur in design, but how can it be used to make the design better.

1. INTRODUCTION

Architectures in product design are invisible labyrinths of rules which are constructed either to understand how something will behave, why something has its behavior, or to explicitly define the behavior of that something [1]. Depending on the field of the designer (e.g. business or engineering), architecture in design concerns the organization architecture or the product architecture. The organization architecture dictates the hierarchy and distribution of decision-making authority, the organizational performance measures, and the rewards and consequences of the outcome of the design [2]. The product architecture has been shown to be an important predicator of product performance, product variety, process flexibility and even the path of industry evolution [3]. Given the impact of both architectures, their composition is critical to the success of the design. The mirroring hypothesis posits that the architecture of a product and the architecture of the organization from which the product is developed will mirror, or align, in composition and structure [4]. Mirroring hypothesis research in industry applications has largely been an observation of natural phenomenon or a strategy for existing products which is executed in the production or operations phase of a product life cycle. This work seeks to demonstrate the mirroring hypothesis as a design parameter in the early design phase of a product design trade study and discuss its implication in product design diversity and application within a product life cycle.

1.1 Architecture Definitions

Architectures can be defined by a network which is composed of nodes and links. A node is a physical or virtual entity of the architecture, and links are the edges that connect those entities. Networks can be described by a diagram or a matrix as shown in Figure 1.1 [4] [5].



	Node 1	Node 2	Node 3	Node 4	Node 5
Node 1		x	x		
Node 2					x
Node 3		x		x	
Node 4					x
Node 5					

Figure 1.1: Example of a Directed Architecture

Figure 1.1 is an example of a directed architecture in which the arrows indicate the flow of communication between the linked nodes. The matrix indicates this flow by placing an x where the nodes in the row communicate to the nodes in the columns (e.g. Node 1 communicates to Node 2 and Node 3). Literature about the mirroring hypothesis use both undirected, or no arrows on the links, and directed architectures for the organization and product depending on the metrics of its links (i.e. how the links are defined). The nodes, links, and metrics used for the organization architectures are described in Section 1.2 and the nodes, links, and metrics used for the product architectures are described in Section 1.3.

1.2 Organization Architecture

The design of an organization architecture in mirroring hypothesis literature primarily arises out of the management and economic fields. Researchers and designers in these fields often design with the belief that the product architecture cannot be changed, but the organization architecture can [4]. Purposefully designing the organization‘s architecture can assist in coping with complexity [6] and simplifying bureaucracy [7] within the organization. Literature relevant to the mirroring hypothesis defines an organization as: individual, discipline specific, design teams [8] [9] [10], individual firms [11] [12] [13], or across an industry [3] [14] [6]. Individual, discipline specific, design teams are individuals, or groups of individuals, focused on the design of a specific discipline (e.g. propulsion, avionics, payload, etc.) who then interact to create a specific product [8]. Individual firms exist across a spectrum from traditional, commercial firms to open collaborative organizations, also known as open source organizations in the software field. Commercial firms refer to organizations who have a distinct hierarchy of sub-organizations, contractors, or groups which perform differentiated tasks toward a specific goal [11]. Open collaborative organizations predominantly exist in the software field and are composed of volunteer contributors, who could be from different organizations, and who possess different goals with no overarching authority dictating their contribution to the product [3] [15]. There may be organizations whose type would lie between traditional, commercial firms and open collaborative organizations depending on the amount of authority that is imposed over their organization architecture. Research studying an industry does not focus on one firm but rather draws conclusions from the analysis of multiple individual firms within the industry to address an industry-level issue or form an industry level conclusion such as why designing an eco-friendly building is difficult in the construction industry [16] [17]. Regardless of what type of organization is being analyzed, the organization architecture fundamentally describes "who does what" [4].

An organization architecture is the scheme by which the tasks in the technical architecture are assigned to people or teams (nodes) who will perform the tasks plus the organization ties, such as communication channels, geographic collocation, or employment relations, that link those people [4]. The technical architecture, in this case, being the architecture of the product the organization produces. In this work, the terms technical architecture and product architecture are synonymous. The nodes are traditionally defined by the organization hierarchy. Hierarchies are depending on the organization itself, but there does exist commonalities across types of firms producing the same product such as the majority of organizations producing an aircraft will have an entity to design a propulsion system. The links used in mirroring hypothesis analyses as disparate and depend on the type of organization being analyzed, the research objectives of the analysis, and the availability of data for that objective. For example. Austin-Breneman et. al. performed a distributed design team study in which individual subjects acted as the nodes and the links connecting them was communication over online platforms of each individuals point design [9]. Since this was a controlled study, the researchers had full visibility over communication between team members and how they interacted. Conversely, communication in a commercial firm is nuanced and harder to measure. Data collecting methods, including interviews, questionnaires, and reliance on company data, are often implemented in industry level mirroring hypothesis studies such as Howard and Brian analyzed supply chain relationships through the use of mailed surveys [18]. However, understanding and measuring the mirroring between organizations and their products in the software industry is relatively easier since the user modifying the code and their interactions during the modifications is documented by the codes source files such as in MacCormack et. al. [3]. The definition of the organization architecture used in mirroring hypothesis studies are defined by not only the organization being analyzed but the availability of the link data being collected and the method by which it is collected.

1.3 Product Architecture

Product architecture design in mirroring hypothesis literature primarily arises from the engineering or software field. Converse to the organization literature, designers in these fields tend to assume the organization architecture cannot be changed but the product architecture can [4]. Mirroring hypothesis literature often distinguishes between a physical product and a virtual product. While modern day physical products are often produced virtually in the design phase of their life cycle, literature explicitly describing the mirroring hypothesis dates back to the 1960s [4]. The design of physical products was not heavily virtual in the early years of mirroring hypothesis research. Additionally, the production and operations phases of a product life cycle have distinct differences in the goals of that phase between a physical and virtual product. For these reasons, physical products and virtual products are described separately in subsections 1.3.1 and 1.3.2 respectively.

1.3.1 Architectures of Physical Products

Products can be defined at the component, sub-system, or system level. An example of the different tiers of system extrapolation is depicted in Figure 1.2.

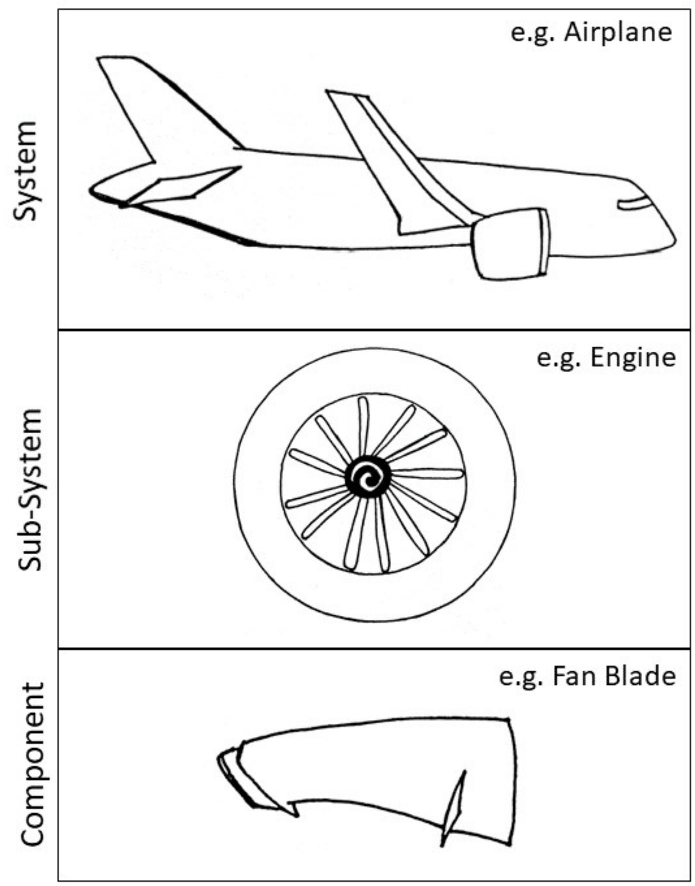


Figure 1.2: Example of Product Node System Extrapolations

Figure 1.2 demonstrates the component level as the sub-parts within a discipline such as the fan blade of an engine, the sub-system level are the discipline specific systems such as the engine, and the system level is the integration of the discipline sub-systems such as the airplane. The links between product nodes are typically shared design parameters or interfaces for a physical product such as the architecture used by Shibata et. al. to describe numerical controllers where the structural elements of the controller were the nodes and the links between them were the interfaces between the structures [19].

Mirroring is measured at the different system extrapolation levels as well as at different phases of the products life cycle design, production, and operations. In a traditional, physical product design life cycle, the design phase starts with a need that requires a physical product, those needs are developed into design trade-offs and testing, and ends with the blueprints of a final design [20]. The majority of work done in the design phase focuses on research imposed scenarios in a controlled testing environment rather than on industry applications [9]. The production phase takes the blueprints of the design and builds the required product [20]. For example, Tan et. al. analyzed the product architecture of the Boeing 787 supply chain [21]. Operations involves the delivery, use, and end-of-life procedures of the product [20]. The majority of product architecture studies in mirroring hypothesis literature focus on the production phase of the product.

The example problem chosen in this work focuses on the design of a physical product. Due to the large contribution virtual products have made to mirroring hypothesis literature, it is appropriate to describe virtual product architectures.

1.3.2 Architectures of Virtual Products

Analysis of the product architecture of virtual products, especially software products, has made a significant impact in research on the mirroring hypothesis due to the ease of access to product data. One of the more significant impacts is the conceptualization of Conways Law. Conways Law states, organizations which design systems are constrained to produce designs which are copies of the communication structures of these organizations [22]. Conways Law is essentially another name for the mirroring hypothesis and is heavily referenced in mirroring hypothesis studies coming out of the software or computer science realm.

The fundamental building blocks of a virtual product start with functions that are designated to perform certain tasks. A collection of related functions and processes form a source file, and a collection of source files form a directory [3]. For example, MacCormack et. al. uses function dependencies within the source files of a software code as a product architecture where the dependencies are the links and the source files are the nodes. They used this product architecture definition to compare the mirroring between different organization structures creating similar products [3].

A traditional virtual product life cycle differs from a physical product in that the design phase ends with the definition of the product structure, the production phase is the coding, testing, and integration of that product, and, finally, operations involves the installation and maintenance of the product [23]. Due to the ease of collecting software data, especially data which is not considered intellectual property, virtual products are a driving research focus in understanding mirroring both as a concept and across the life cycle [4]. Like the physical product studies, most mirroring hypothesis studies on virtual products focus on the production phase of the life cycle [24] [25] [26].

1.4 The Mirroring Hypothesis

The mirroring hypothesis and its related literature compare organization and product architectures and the relationships between the two architectures that lead to their commonalities or differences. This relationship is valuable to understand due to both architectures heavy influence on an organization or products success. Research in the mirroring hypothesis is believed to have started with research on task partitioning [1] and product development [4]. Arguments for the mirroring hypothesis were generally unidirectional as in mirroring existed either from organization to product or product to organization until von Hippel in 1990 posited that both relationships could exist simultaneously [27]. Additionally, mirroring exists on a spectrum. An organization can either be completely unmirrored, no links or nodes match between the organization and product architecture, completely mirrored, links and nodes completely match between the organization and product architecture, or somewhere in-between (i.e. partial mirroring). For example, Figure 1.3 demonstrates a completely mirrored organization/product pair where the nodes and links between the two pairs match one for one.

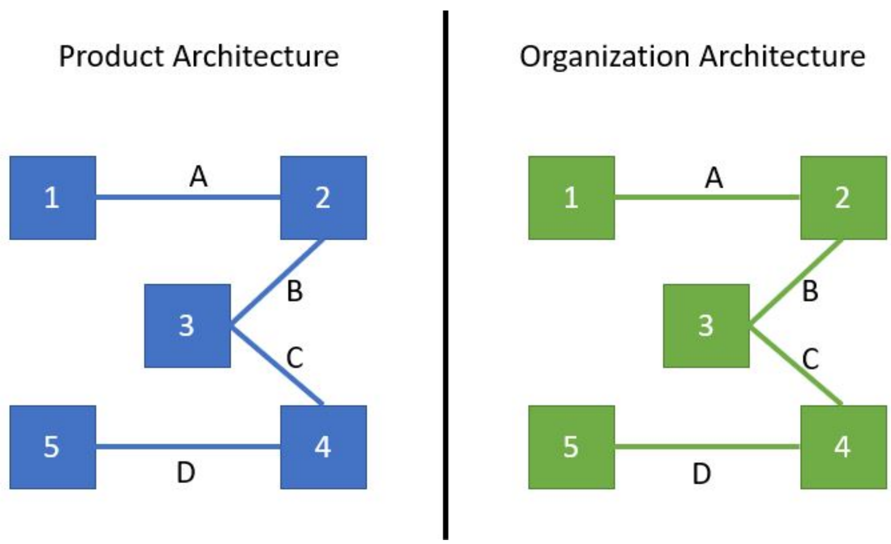


Figure 1.3: Example of a Completely Mirrored Organization/Product Pair

Whereas Figure 1.4 demonstrates a completely unmirrored or organization/product pair where none of the nodes or the links that connect them match between the two architectures.

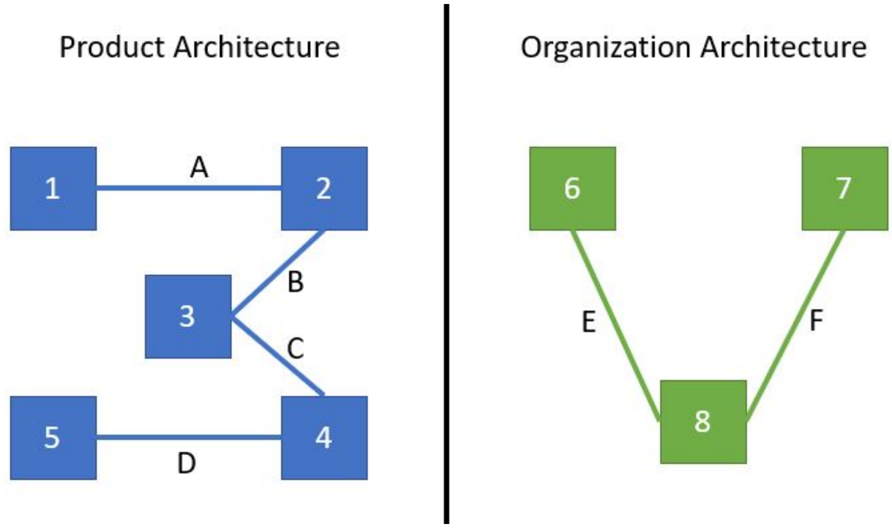


Figure 1.4: Example of an Unmirrored Organization/Product Pair

In between the completely mirrored pair and the unmirrored pair exists partial mirroring. Partially mirrored organization/product pairs share the same nodes and links, but are not one for one between all nodes and links. Partially mirrored organization arise out of organizational constraints such as prohibitive cost or infeasible logistics of a completely mirrored system [4]. Figure 1.5 demonstrates an example of a partially mirrored organization/product pair where similarities and discrepancies between the organization and product architectures exist within one system.

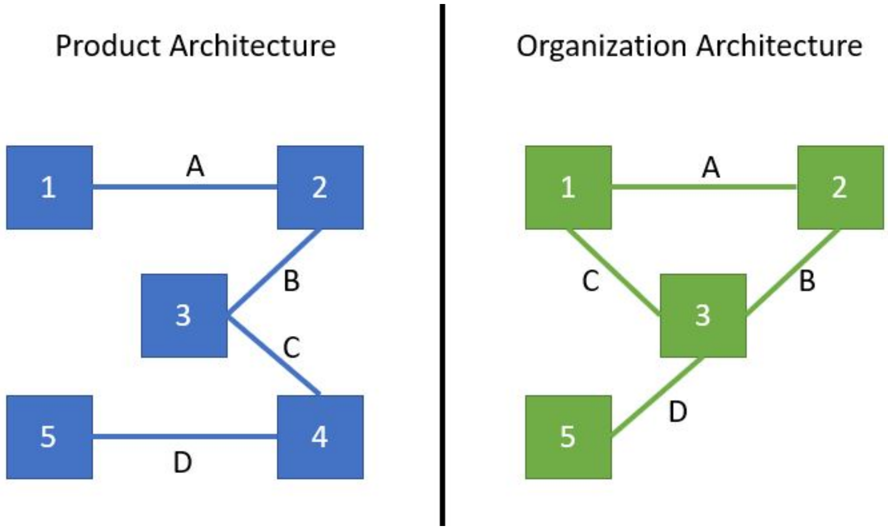


Figure 1.5: Example of a Partially Organization/Product Pair

Figure 1.6 presents each example as a spectrum ranging from the unmirrored system to the completely mirrored system. Each organization/product pair analyzed in mirroring literature exists somewhere on this spectrum. For the example problem used in this work, a completely mirrored and partially mirrored system's design solutions are compared.

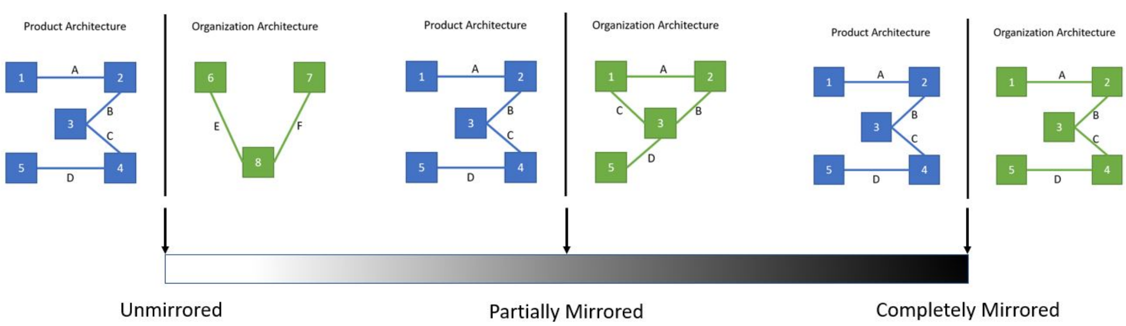


Figure 1.6: The Mirroring Spectrum

Where the organization/product pair is placed on the spectrum depends on the definition of the "match" between the organization and product architecture. There are varying definitions for what is considered a match between the organization and product architectures. For this research, the definition of match is similar to Colfer et.

al.s definition [4]. The match between the links and nodes include both their presence in the architecture and the metrics that compose them. What is considered a match between the links is more strict than that of the nodes. For example, the nodes of the organization and product are considered matching if the product architecture has a node that correlates to a node in the organization architecture that is responsible for the product node and that product node alone. A link is only considered matching if the information passed between the product nodes and the organization nodes have the same metrics (i.e. the same type of information is communicated in the links).

Mirroring hypothesis research falls into two categories: descriptive and normative. Descriptive research is performed to test the hypothesis of whether mirroring is present within an organization. Normative research is performed to test the hypothesis of whether the presence of mirroring has a positive or negative impact on the performance of an organization or product. Both descriptive and normative studies view mirroring as a natural phenomenon between an organization and product. Mirroring as a strategy is an emergent view within the literature and the studies describing the use of mirroring as a strategy are few and far between. The majority of mirroring hypothesis strategy research typically occurs after the production and distribution of a product and is used to implement corrective actions in an organization or product.

Literature critical of the mirroring hypothesis argue that with the existence of mirrored firms showing success, there also exists unmirrored firms showing just as much success. Puranam et. al. provides a good start for exploring arguments against the mirroring hypothesis [28]. This work recognizes the existence of this argument, but ultimately assumes the mirroring hypothesis is true. This assumption is necessary since this study is not descriptive or normative, but rather seeks to explore untested areas of the arguments supporting the mirroring hypothesis.

1.5 Mirroring Hypothesis Gaps

The gaps addressed in this study are the shortage of mirroring hypothesis literature studying its application in the design phase of a physical product life cycle and the lack of discussion on the mirroring hypothesis‘s effect on the diversity of design solutions if mirroring is implemented as well as on where mirroring would be appropriate to implement in the product life cycle.

While descriptive and normative studies are the majority of the mirroring hypothesis literature, this study does not properly fall into either category. Building off of work by Honda et. al. [8] and Austin-Breneman et. al. [9], this study does not intend to prove mirroring as an existing concept nor show its effect on performance, but rather discuss its effects on the computed solutions of a two-subsystem satellite optimization design problem described in chapter 2.

2. FIRESAT II EXAMPLE PROBLEM

This work demonstrates its goals by utilizing the FireSat II example problem from the Space Mission Analysis and Design (SMAD) textbook by Wertz and Larson [29]. This example problem is well-established in research literature [20] and additionally formed the basis for Hondas work in information passing [8]as well as Austin-Brenemans work in student design teams [9]. The FireSat II example problem in SMAD is intended to allow you to begin with a blank sheet of paper and design a space mission to meet a set of broad, often poorly defined, objectives at minimum cost and risk [29]. The FireSat II example in this work will utilize a small subset of the satellites subsystems to demonstrate mirroring as a design metric and provide the grounds for a discussion on how an organization-product architecture pairs level of mirroring affects its design solution diversity, and when mirroring as a design variable should be applied in the product life cycle.

2.1 FireSat II Overview

The objective of the FireSat II design is to identify and monitor forest fires. The requirements that are created from this objective fall into one of three categories: functional, operational, and constraints. The requirements applicable to this work are the functional requirements describing the required performance of the system, performance in this case is measured by the satellites instantaneous field of view (IFOV), and the constraint requirement describing the budget of the satellite. It is common knowledge in the space community that the total mass of a system is directly correlated to the cost of that system; therefore, the budget of the satellite in this work is measured by the total mass of the system [30]. After determining the objective and developing requirements, SMAD instructs the designer to characterize the system using the following parameters:

- Preliminary mission concept
- Subject characteristics (i.e. controllable or passive)
- Subject trade-offs
- Orbit characteristics
- Payload size and performance
- Mission operations approach
- Spacecraft bus design to meet system requirements
- Launch and orbit transfer system
- Deployment, logistics, end-of-life strategies
- Cost estimate

The preliminary mission concept is the mission objective to detect and monitor forest fires. Subject characteristics are defined by the characteristics of the phenomena detected by the satellite. Controllable phenomena are events generated by the system itself, such as experiments on-board the satellite. Passive phenomena are events monitored outside of the satellite. FireSat IIs subject characteristic is passive since forest fires are external phenomena to the satellite. The subject trade-offs when discussing mission characterization are the subjects and attributes of the forest fires that should be detected or monitored in order to fulfill the missions objective. These subjects include heat, fire, smoke, and atmospheric composition. The trade-offs are the identification of how these subjects can be detected or monitored and which systems are within the satellites budget. Heat can be detected by an Infrared (IR) detector, flame and smoke can be detected visually, and atmospheric composition can be detected through a light detection and ranging (lidar) instrument. The focus of this work is on the IR detection of heat through an observation payload. The preliminary mission concept, subject characteristics, and subject trade-offs were determined by the SMAD text and further refined by the focus of this work. The example problem utilized in this work determines the mission characteristics: orbit characteristics and payload size and performance. All other mission characteristic parameters are not considered in this study including the cost estimate since the cost estimate defined in SMAD encompasses development, production, and operation costs which extend beyond the scope of this work.

Equipped with an objective, requirements, and the broad characteristics of the system, the designers of the system must determine how well different system alternatives satisfy the fundamental mission objectives. In this case, how well can FireSat II alternatives detect and monitor forest fires and at what cost? For this work, we extend these questions to ask: Does the level of mirroring within an organization change how well the design alternatives satisfy the mission objectives?

The designers are tasked with building a satellite whose performance is measured by its observation payload. Observation payloads collect data. For this satellite, it collects heat data from Earths surface. There are two basic types of observation payloads: active and passive [31]. An active payload must supply its own light source to enable specific types of measurements. For example, the lidar instrument that can be used to measure atmospheric composition. This design will use a passive instrument or one that observes intrinsic emissions such as the heat data observed by the IR instrument. An example of a similar payload is the Thermal Emission Spectrometer (TES) on Mars Global Surveyor. One of the capabilities of TES is to measure the temperature of the Martian surface. The instruments characteristics are given in Table 2.1.

While the satellite designed in this study will be smaller since it is attempting to accomplish less objectives, these numbers are provided to give an industry example of similar numbers that will be produced by the simulated designers in this study.

Table 2.1: TES Instrument Specifications [32]

Instrument Weight	385	[kg]
Total S/C Weight at Mars Arrival	767	[kg]
Power	10.6	[W]
Instrument IFOV	7.5	[mrad]
Cross-track Ground Resolution at 400 [km] Orbit Altitude	9	[km]

The performance of the IR instrument used to measure heat for FireSat II can be measured by the observation payloads ground resolution (GR). The GR is defined as the size of surface area scanned by the instrument and is determined by the instantaneous field of view (IFOV) of the payload and the orbit altitude of the system [33]. The IFOV is defined as the solid angle in which the detector can detect radiation. There are two directions ground resolution is measured: along-track and cross-track. If a rectangle is drawn on the surface of the Earth, the along-track resolution measures GR along the width of the rectangle and the cross-track resolution measures along the length of the rectangle as shown by Figure 2.1.

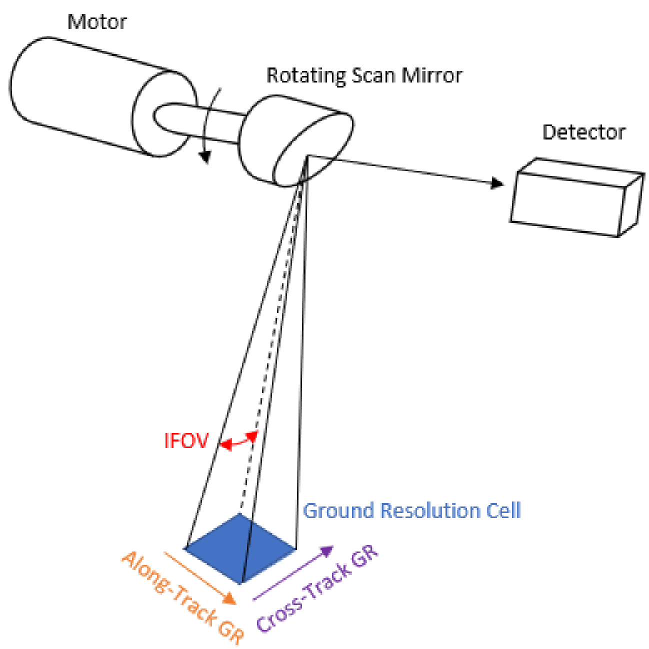


Figure 2.1: Ground Resolution Definitions [33]

For this study, the designers have selected to measure performance by the GR. SMAD specifically computes the GR for a multi-spectral IR instrument which is depicted in Figure 2.2.

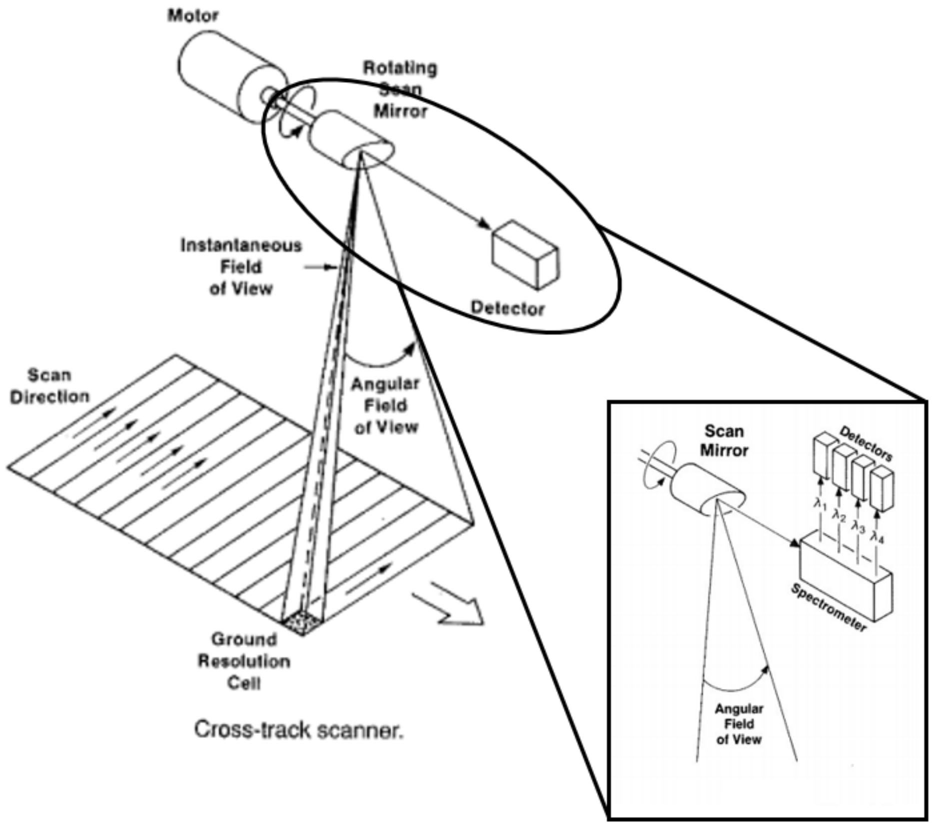


Figure 2.2: Cross-Track Scanner [33]

Figure 2.2 includes a visual depiction of the cross-track scan, IFOV, and GR of the instrument. For clarification, there is a difference between the ground resolution and spatial resolution of an instrument. To reiterate, ground resolution is the scan area of the instrument. Spatial resolution is the shortest distinguishable distance between two objects within the scan area or the amount of pixels in the scan area.

The objective of FireSat II is to detect and monitor fires; therefore, the designer will want to maximize the GR in order to increase the total area scanned by the instrument and maximize the heat data collected in each scan. The mission characteristics selected for this mission included not only the payload performance, but the payload size and orbit characteristics. The payload size and orbit characteristics determine the satellites total mass which correlates to the systems cost. The shared design variable between both the payloads performance and total system mass is the orbit altitude. The relationship between orbit altitude and GR and orbit altitude and the total system mass is shown in Figure 2.3.

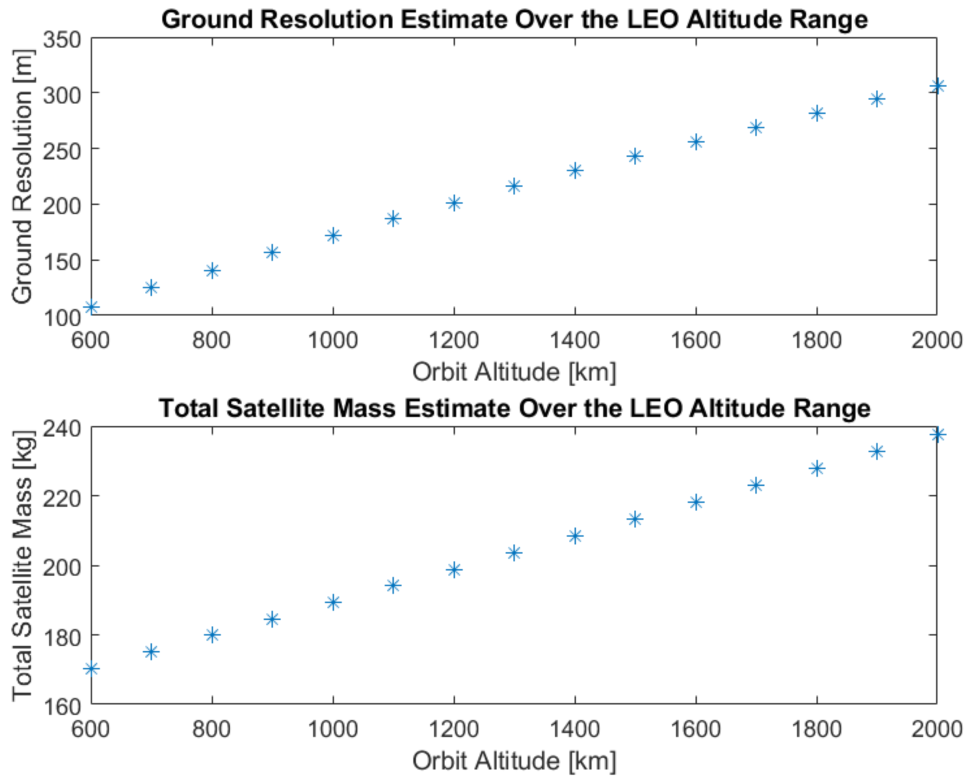


Figure 2.3: Design Variable versus the Design Objectives

Figure 2.3 shows that if the designers maximize the performance of the intended payload, it increases the total system mass and, therefore, increases the cost of the system.

The design objective trade-off is performance versus cost and forces a multi-objective design problem on the design teams. In addition, both objectives have a non-linear relationship with the design variable. The calculation of both design objectives are best estimates and are used to gauge initial values in the early design process. The equations used to compute the estimate of the cross-track GR and total system mass are described in sections 2.1.1 and 2.1.2, respectively.

2.1.1 Cross-Track Ground Resolution Calculation

The Cross-Track Ground Resolution is dependent on the orbit altitude of the satellite. There are several constants and design decisions that are used in this calculation that are described in Table 2.2.

Table 2.2: Cross-Track GR Calculation Constants and User-Defined Variables

Name	**Symbol**	**Type**	**Value**	**Units**
Earth's Radius	R_e	Constant	6378.1366	[km]
Earth's Gravitational Parameter	μ_E	Constant	398600.4356	$[\frac{km^3}{s^2}]$
Degree to Radian Conversion	D2R	Constant	$\frac{180}{\pi}$	$[\frac{deg}{rad}]$
Eccentricity	e	User-Defined	0	
Minimum Working Elevation Angle	ϵ_{min}	User-Defined	20	[deg]
Max Cross-Track Ground Sampling Distance	x_{max}	User-Defined	1.12	[km]
Number of Cross-Track Detector Samples at Nadir in One Pixel	N_{samp}	User-Defined	3	

The first step in calculating the Cross-Track GR is to compute the altitude at apogee:

$$h_a = (R_e + h) * \frac{1+e}{1-e} - R_e[km] \tag{2.1}$$

Equation 2.2 computes the semi-major axis of the mission orbit:

$$a = \frac{2 * R_e + h + h_a}{2}[km] \tag{2.2}$$

The semi-major axis is used to compute the period of the mission orbit in Equation 2.3:

$$P = 2 * \pi * \frac{\sqrt{\frac{a^3}{\mu_E}}}{60}[min] \tag{2.3}$$

The orbital period is used to compute the average ground track velocity of the satellite in Equation 2.4:

$$V_g = 2 * \pi * \frac{\frac{R_e}{P}}{60}[\frac{km}{s}] \tag{2.4}$$

Equation 2.5 calculates the maximum Earth angular radius:

$$\rho_{max} = D2R * \sin^{-1}(\frac{R_e}{R_e + h})[deg] \tag{2.5}$$

The maximum Earth angular radius is used to compute the maximum nadir angle of the satellite in Equation 2.6:

$$\eta_{max} = D2R * \sin^{-1}(\sin(\frac{\rho_{max}}{D2R}) * \cos(\frac{\epsilon_{min}}{D2R}))[deg] \tag{2.6}$$

The maximum Earth central angle is calculated using the maximum nadir angle in Equation 2.7:

$$\lambda_{max} = 90 - \eta_{max} - \epsilon_{min}[deg] \tag{2.7}$$

The slant range equation is a function of both the maximum Earth central angle and the maximum nadir angle and is calculated using Equation 2.8:

$$R_s = R_e * \frac{\sin(\frac{\lambda_{max}}{D2R})}{\sin(\frac{\eta_{max}}{D2R})}[km] \tag{2.8}$$

The swath width, or the angular width of the observable area on the ground, is calculated using the maximum Earth central angle in Equation 2.9:

$$SW = 2 * \lambda_{max}[deg] \tag{2.9}$$

Finally, the cross-track GR is a function of the orbit height and the cross-track instantaneous field of view. The cross-track instantaneous field of view is calculated by Equation 2.10:

$$IFOV_x = \frac{x_{max}}{R_s} * \frac{D2R}{N_{samp}}[deg] \tag{2.10}$$

The cross-track GR is calculated by Equation 2.11:

$$GR_x = IFOV_x * N_{samp} * h * \frac{1000}{D2R}[m] \tag{2.11}$$

2.1.2 Satellite Total Mass Calculation

The Satellite Total Mass is dependent on the orbit altitude of the satellite. There are several constants and design decisions that are used in this calculation that are described in Table 2.3.

Table 2.3: Satellite Total Mass Calculation Constants and User-Defined Variables

Name	**Symbol**	**Type**	**Value**	**Units**
Earth's Tilt Angle	TA_E	Constant	23.44	[deg]
Earth's Gravitational Parameter	μ_E	Constant	398600.4356	$[\frac{km^3}{s^2}]$
Earth's Radius	R_e	Constant	6378.1366	[km]
Degree to Radian Conversion	D2R	Constant	57.2958	$[\frac{deg}{rad}]$
Parking Orbit Altitude	h_{park}	User-Defined	200	[km]
Parking Orbit Inclination	i_{park}	User-Defined	55	[deg]
Mission Orbit Inclination	i_m	User-Defined	55	[deg]
Mission Duration	MD	User-Defined	8	[years]

Drag Parameter	C_D	User-Defined	2.3	
Payload Cross-Sectional Area	A	User-Defined	2.6	$[m^2]$
Deorbit Perigee	P_d	User-Defined	75	[km]
Payload Mass	M_{pay}	User-Defined	150	[kg]

The first step in calculating the Satellite Total Mass is to compute the total Delta-V over the mission lifetime. This calculation is described in the next section.

Delta-V over the Mission Lifetime Calculation

The calculation of the total Delta-V over the mission lifetime begins with a calculation of the initial velocity of the satellite by Equation 2.12:

$$V_i = \sqrt{\frac{\mu_E}{h_{park} + R_e}}[\frac{km}{s}] \tag{2.12}$$

The final velocity of the satellite is computed by Equation 2.13:

$$V_f = \sqrt{\frac{\mu_E}{R_e + h_m}}[\frac{km}{s}] \tag{2.13}$$

The orbital period of the mission orbit is the same as Equation 2.3 in the Cross-Track GR calculation in section 2.1.1. Using the orbital period, the orbits per year is calculated by Equation 2.14:

$$OpY = 365.24 * 24 * \frac{60}{P}[\frac{orbits}{year}] \tag{2.14}$$

The ballistic coefficient of the spacecraft is computed using the payload mass, payload cross-sectional area and drag coefficient by Equation 2.15:

$$\beta = \frac{M_{pay}}{C_D * A}[\frac{kg}{m^2}] \tag{2.15}$$

The maximum atmospheric density, ρ_A, is used to compute the solar max of the orbit to determine the total Delta-V of the satellite in LEO. The maximum atmospheric density is approximated by the SMAD provided table below [20]. Any values not provided by Table 2.4 are interpolated or extrapolated.

Table 2.4: Maximum Atmospheric Density

Altitude (km)	**Atmospheric Density (kg/m^3)**
0	1.20
100	5.67E-07
150	2.21E-09
175	9.21E-10
200	3.84E-10
225	2.12E-10
250	1.17E-10
275	7.17E-11
300	4.39E-11
325	2.85E-11
350	1.85E-11
375	1.25E-11
400	8.43E-12
450	4.05E-12
500	2.03E-12
550	1.05E-12
600	5.63E-13
650	3.08E-13
700	1.73E-13
750	9.95E-14
800	5.88E-14

850	3.57E-14
900	2.25E-14
950	1.46E-14
1000	9.91E-15

The first orbit transfer is a Hohmann transfer from the initial, circular parking orbit to the satellite's final mission orbit by Equation 2.16:

$$OT = 1000 * \sqrt{V_i^2 + V_f^2 - 2 * V_i * V_f * \cos(\mid i_{park} - i_m \mid)}[\frac{m}{s}] \tag{2.16}$$

An object is considered orbiting in LEO if its mission orbit is between 600 and 2000 [km]. While in this orbit, altitude maintenance may be necessary due to external forces moving the satellite out of its designated path. The altitude maintenance required for maintaining an altitude in LEO is calculated by first computing the solar max of the mission orbit by Equation 2.17:

$$SM = (\frac{\pi}{\beta} * \rho_A * (R_e + h_m) * 1000 * V_f * 1000) * OpY[\frac{\frac{m}{s}}{year}] \tag{2.17}$$

If the orbit is not in LEO, the solar max is zero. The altitude maintenance for LEO is then calculated by Equation 2.18:

$$LEO = SM * MD[\frac{m}{s}] \tag{2.18}$$

The satellite is designed to stay in LEO for its mission duration. At the end of its mission lifetime, the spacecraft will need to be disposed of in order to not accumulate debris in the LEO orbits. The Delta-V required to dispose of the spacecraft is calculated by Equation 2.19:

$$Disp_{sc} = 1000 * V_f * (1 - \sqrt{2 * \frac{(R_e + P_d)}{2 * R_e + P_d + h_m}})[\frac{m}{s}] \tag{2.19}$$

The total Delta-V of the spacecraft mission is a summation of the orbit transfers, altitude maintenance, and spacecraft disposal by Equation 2.20:

$$\Delta V = OT + LEO + Disp_{sc}[\frac{m}{s}] \tag{2.20}$$

Satellite Total Mass Calculation

Once the total Delta-V over the mission lifetime is computed, it is used to compute the estimated Satellite Total Mass Calculation. It is assumed the specific impulse, ISP, of the satellite's propulsion system equals 300 [s] and Earth's gravitation constant, g, is 9.8 [m/s]. The Satellite's Total Mass is computed by Equation 2.21:

$$M_{sc} = M_{pay} * e^{\frac{\Delta V}{ISP * g}} \tag{2.21}$$

2.1.3 FireSat II Example Problem Summary

This work uses the SMAD FireSat II example problem in order to demonstrate the mirroring hypothesis as a design parameter and facilitate discussions about how mirroring affects the product design, the design solution diversity, and the application of mirroring as a design parameter in a product life cycle. FireSat II is an appropriate design example to build from because it provides a straightforward and practical design problem to test this work's objective in that all the equations are not only outlined in the SMAD text, but are typical of those used in industry to approximate actual satellite design alternatives. Additionally, SMAD is well established in the aerospace industry and has been used throughout various research literature including in studies closely related to this work. The FireSat II example's practicality, similarity to this work's objectives, and history in aerospace and research literature make it an ideal example problem for this study.

3. OPTIMIZATION MODEL

3.1 Description of the Objective Functions

The goals of this thesis are to demonstrate mirroring as a design metric, understand how this mirroring example affects the diversity of the design solutions, and describe the mirroring hypothesis‘s applicability in the product life cycle. The optimization problem helps to fulfill these goals by using the FireSat design example to demonstrate mirroring as a design metric and understand its effects on the diversity of the design solutions. As described in chapter 2, the objective of the FireSat design is to maximize performance, i.e. ground resolution, while minimizing cost, i.e. total satellite mass, by changing the design variable, i.e. orbit height. The relationship between the design variable and the objectives is continuous, constrained to a LEO orbit, and nonlinear;therefore, the type of optimization algorithm used to solve this multi-disciplinary problem will need to be able to handle continuous, nonlinear objective functions.

How is optimization used in design?

Optimization was chosen as the solution method due to its use across multiple disciplines and its ability to locate solutions using a systematic process. Similar to mirroring hypothesis research, optimization is used in fields such as business, computer science, public service, technology, and engineering which is advantageous for solving a problem that is looking at both the organization and product. Additionally, optimization algorithms provide the user a means of locating an optimal solution through a systematic process using design constraints and criteria and is argued to be an essential skill-set for emerging designers in technology and engineering fields [34].

The importance of optimization to the design field and its wide-spread use in design are the reasons for pursuing an optimization method for this example problem.

3.1.1 Complete versus Partial Objective Functions

For this example, picture two teams within an organization working to design the FireSat II. One team‘s main objective is the product performance and is tasked with designing a product that maximizes the ground resolution. The other team‘s main objective is the product cost and is tasked with minimizing the satellite‘s total system mass. When evaluating the mirroring in this example, the organization is represented by the objective function of the optimization formulation (i.e. maximize ground resolution and minimize total system mass). The product is represented by the results of the optimization problem (i.e. the final values for ground resolution and total system mass). The completely mirrored system is depicted in Figure 3.1.

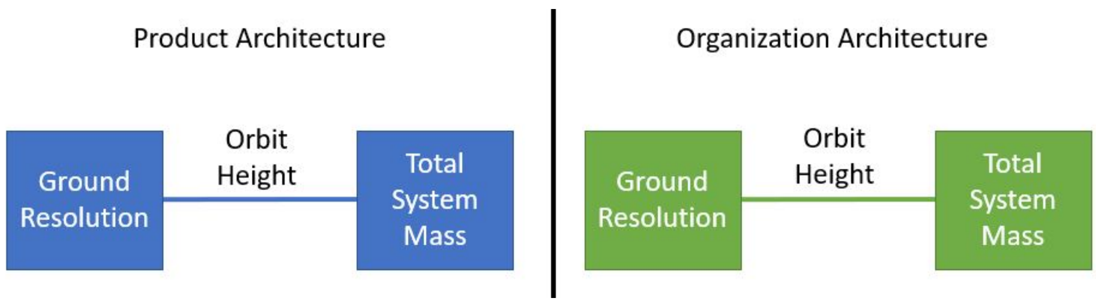


Figure 3.1: FireSat II Completely Mirrored System

The organization for the completely mirrored organization/product pair is represented by the weighted objective function in equation 3.1 with objective functions cross-track ground resolution (GR) and total system mass (M_{tot}) as a function of the orbit height (h):

$$\begin{aligned} \min \quad & w * \frac{-f_{GR}}{f_{GR}(x^*_{GR})} + (1-w) * \frac{f_{M_{tot}}}{f_{M_{tot}}(x^*_{M_{tot}})} \\ \text{s.t.} \quad & 160[km] \leqslant h \leqslant 2000[km] \\ & \Delta V > 0 \end{aligned} \tag{3.1}$$

Since this work is applying a mirroring perspective to the Honda et. al. problem, like Honda et. al., this work's design problem will be composed of objective functions using derivatives of the SMAD design [8] to represent the partially mirrored pair. The partially mirrored organization/product pair is depicted in Figure 3.2.

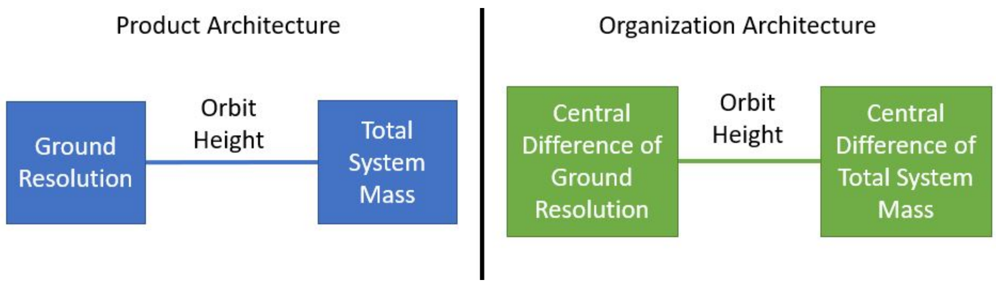


Figure 3.2: FireSat II Partially Mirrored System

The partially mirrored system objective functions are the gradient of the cross-track ground resolution (Δf_{GR}) and the gradient of the total system mass ($\Delta f_{M_{tot}}$) with respect to the orbit height (h) shown in equation 3.2.

$$\begin{aligned} \min \quad & w * \frac{\Delta f_{GR}}{\Delta f_{GR}(x^*_{GR})} + (1-w) * \frac{\Delta f_{M_{tot}}}{\Delta f_{M_{tot}}(x^*_{M_{tot}})} \\ \text{s.t.} \quad & 160[km] \leqslant h \leqslant 2000[km] \\ & \Delta V > 0 \end{aligned} \tag{3.2}$$

The gradients are computed for the partially mirrored system using the central difference approximation shown in equation 3.3, where "x" is a small difference in the orbit height (h).

$$\Delta f_{GR} = \frac{f_{GR}(h+x) - f_{GR}(h-x)}{2 * h} \tag{3.3}$$

The following subsections further describe the use of a derivative objective function within design and optimization as well as how this problem set up addresses the overall goals of this work.

Derivatives in Design and Optimization

The derivative of a function is a rate of change or the amount by which a function is changing at a single point. The gradient of a function is a directional derivative or the amount by which a function is changing in a specific direction. Product design aims to create the best product possible to fulfill a need. Derivatives and gradients are tools in design, often used in optimization, to find the minimum or maximum way of fulfilling that need [35]. By using the derivative or gradient of the function as the objective function in an optimization problem, the objective of the optimization problem is reframed to state: Find the maximum or minimum value of this function by finding the maximum or minimum amount of change in the desired direction of the optimization objective. For example, in this work‘s FireSat example problem, the designers want to achieve the maximum cross-track GR and the minimum total system mass. When optimizing the derivative objective function, the designers want to achieve the maximum change in the positive direction of the cross-track GR with respect to the orbit height in order to achieve the maximum cross-track GR. For the other objective, the designers will want to achieve the maximum change in the negative direction of the total system mass with respect to orbit height in order to determine the minimum total system mass. While other methods could be used to demonstrate mirroring, this method was used because of its similarity with that of the design problem in Honda et. al. which formed the foundation of this example [8].

The method used to demonstrate the complete and partial mirroring provides a simple problem with enough dissimilarity to demonstrate mirroring‘s effect on design as well as discuss the diversity of solutions between the two mirroring examples. While this example is sufficient to address the goals of this work, increasing the complexity of the example in future work is discussed in Chapter 6.

3.1.2 The Use of a Genetic Algorithm

The example problem necessitates an optimization algorithm that can optimize a nonlinear, multi-objective formula. Genetic Algorithms are an example of an optimization method that can solve nonlinear, multi-objective problems. Genetic Algorithms are a randomized, heuristic search strategy meaning this algorithm does not require a defined starting point. It works from a population of candidate solutions from which it evolves to determine the strongest solution for the provided objective. This algorithm does not use derivatives which allows for the use of derivatives in the objective function described earlier in this section. Additionally, genetic algorithms are commonly used across disciplines including business and engineering, making this problem a believable example of what would be used in industry. Multi-objective optimization is an exercise similar to those that would be used to evaluate trade-offs in the early design phase of an industry product. The early design phase is described in Chapter 5. A con of the algorithm is the number of iterations it requires to find a solution. The genetic algorithm method tends to avoid local minima, but the amount of time it takes to converge is unpredictable and is often computationally expensive. Since the focus of this work is mirroring and not optimization, the genetic algorithm‘s pros outweighed its cons and the algorithm was deemed sufficient to demonstrate the goals of this work.

Research in multi-disciplinary optimization traditionally focus on either the organization side, such as logistics, or the product side, such as system design. What distinguishes this study from other multi-disciplinary optimization research is the comprehensive look of both the organization and product. My problem does not only ask how can we make the product better or how can we make the organization better but rather merges the two to ask, how can the organization and product be made better given their inherent mirroring dependencies?

4. RESULTS AND DISCUSSION

The optimization formula derived a solution for an orbit altitude range of the LEO altitude range (i.e. 600 - 2,000 km). The algorithm used a weighted objective function between maximizing the cross-track GR and minimizing the total system mass with a solution computed for weights ranging from 0 to 1 with an increment of 0.1 for each objective (e.g. 0 weight on cross-track GR and 1 weight on total system mass to determine the first solution, 0.1 weight on cross-track GR and 0.9 weight on total system mass to determine the second solution, etc.). Figure 4.1 presents all of the design solutions across all objective function weights.

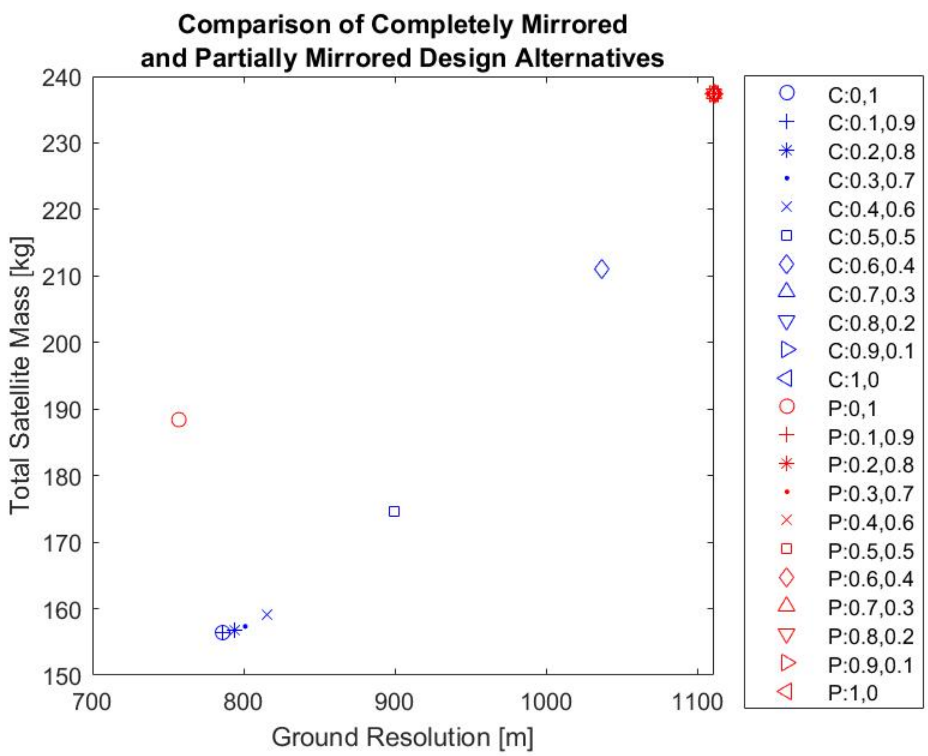


Figure 4.1: Design Solutions for All Objective Function Weights

The graph is depicted by distinguishing the design alternatives from the differently mirrored systems by color and by distinguishing the different objective formula weights by symbol. The blue colored symbols, represented by the letter "C" in the legend, are the design solutions produced by the completely mirrored organization/product pair. The red colored symbols, represented by the letter "P" in the legend, are the design solutions for the partially mirrored organization/product pair. The completely mirrored organization/product pair produced design alternatives in which the majority of alternatives cluster around a 800 m ground resolution with C:0.5,0.5 at GR = 900 m, C:0.6,0.4 at GR = 1150 m, and C:1,0 at GR = 1100 m as outliers. Whereas, the partially mirrored organization/product pair produced design alternatives in which the majority of alternatives cluster around a 1100 m ground resolution with P:0,1 at GR =750 m as an outlier. Figure 4.2 depicts selected individual solutions to better show the differences between the complete and partial mirroring structures of the example design problem.

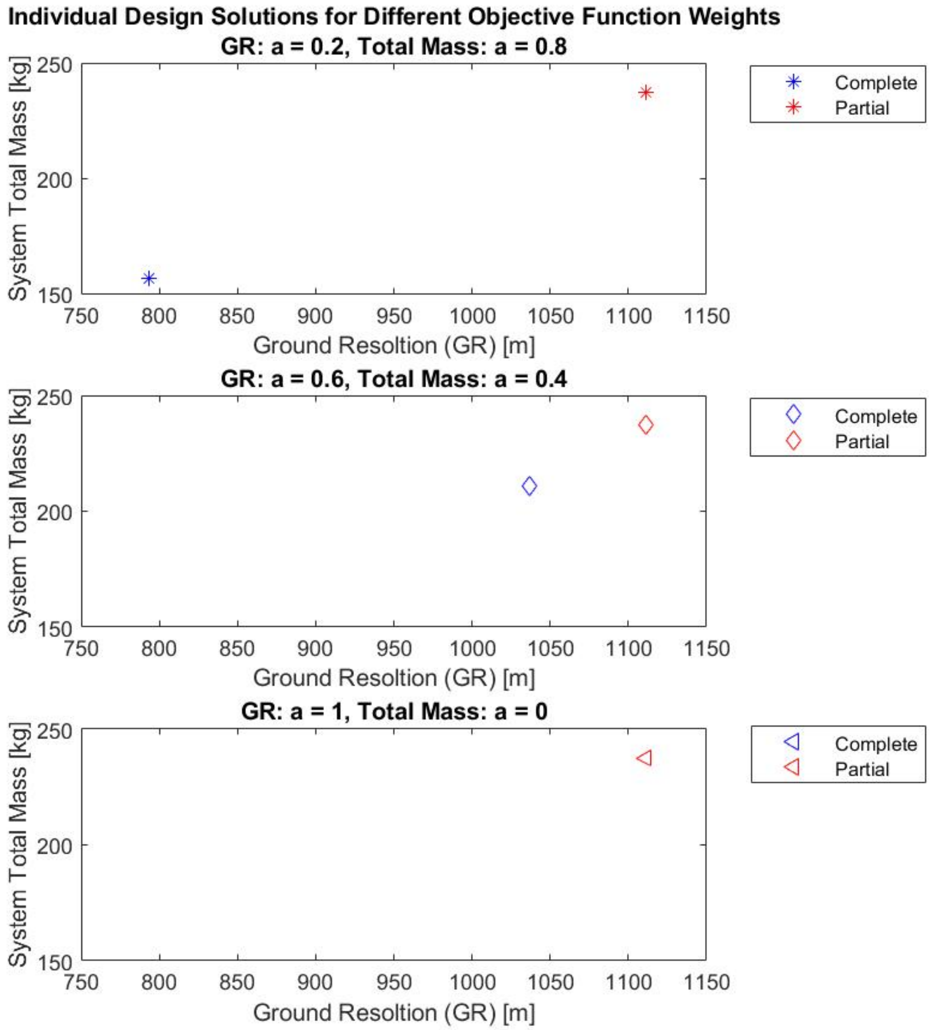


Figure 4.2: Design Solutions for Different Objective Function Weights

When the ground resolution weight is 1 and the total satellite mass is 0, the completely mirrored organization/product pair and partially mirrored organization/product pair produce the same design alternative at GR = 1100 m. This is the only case where the completely and partially mirrored pairs produce the same design alternative. The majority of discrepancies follow the pattern shown in the top graph with a ground resolution weight of 0.2 and a total satellite mass weight of 0.8. The graph where the ground resolution has a weight of 0.6 and total satellite mass has a weight of 0.4 was included to show an additional example of the different completely mirrored versus partially mirrored discrepancies identified in this example problem.

The results appear to lean towards the completely mirrored organization for a higher performance and towards the partially mirrored organization for a lower cost. The reason for this trend is ultimately unknown in this study. Speculating on these results, the normative hypothesis states that a more closely mirrored organization/product pair will produce a higher performing product. The results of this work support that hypothesis in that the completely mirrored (i.e. more closely mirrored pair) have a higher number of design solutions with a higher performance. An investigation into the definitive answer of why the different mirrored organization/product architecture pairs produce different results would be better informed by expanding this study to either include additional subsystems or perform this same study on different example problems as described in Chapter 6.

In this FireSat II example, mirroring does change the design of the final solution and it changes the diversity of the solutions. The design of the final solution are the design solutions that are produced with each iteration of the objective function weights. The diversity of the solutions are the unique design solutions that are produced over the entire swath of design solutions. The completely mirrored architecture produced 7 unique design solutions over the 11 weights; whereas, the partially mirrored solution only produce 2 unique design solutions over the 11 weights.

The goals of this thesis are to answer the questions:

- Does mirroring have an effect on the design of this problem?
- Does mirroring have an effect on the design diversity of this problem?
- If mirroring does have an effect and could be used strategically, where in the early design phases of a product life cycle should mirroring be used?

The sole intention of the optimization problem is to address the first two questions for this specific example. Mirroring is used as a design metric in the example through the comparison of the completely mirrored and partially mirrored architectures. Designers could use the trade-off of the differently mirrored systems to determine which organization and product architecture pair is preferred for their design needs. As stated in Chapter 1, mirroring hypothesis research shows that closely mirrored organizations, on average, perform better than unmirrored organizations [4]. It should be noted there exists a bias in the nature of the research to more deeply investigate successful firms rather than unsuccessful firms, causing the data to skew in favor of mirroring. Should this research prove to be true when the bias is eliminated, and having a mirrored organization proves to increase product performance, product design could be improved by co-designing the organization and product to closely mirror each other, therefore, producing a product better aligned to the organization‘s desires. This example problem simply demonstrates that a completely mirrored and partially mirrored organization produce different design solutions. Future work to eliminate past research biases and conduct industry research into mirroring during the design phase would be necessary to make firm conclusions on mirroring‘s benefit to the resulting product solution.

5. MIRRORING HYPOTHESIS APPLICATION IN THE PRODUCT LIFE CYCLE

After demonstrating mirroring as a design parameter in the early design phase of a product design trade study and discussing its affect the product diversity, the third and final goal of this work is to discuss in depth its application within a product life cycle. In literature detailing product life cycles, the ideal product life cycle is extensively described in government ”best practices” documentation. Additionally, the U.S. government operates a large fleet of satellites for Earth observation, navigation, and communications. Due to the large amount of government documentation on product life cycles and applicability to the FireSat II example problem, the Department of Defense (DoD) acquisition life cycle will be the focus of this work.

5.1 The Department of Defense Acquisition Life Cycle

The Department of Defense acquisition life cycle, while heavily documented, is difficult to generalize. Every acquisition program in the Department of Defense is unique. This uniqueness is an advantage since military branches do not want to duplicate programs or capability when vying for government funding and resources. Each program aims to fulfill an identified capability or mission with the objective of its product design to successfully execute that capability or mission. This forces the Department of Defense life cycle standards to be adaptable to match the need of the product but consistent enough to be replicated and create lessons learned. When researching the government acquisition life cycle, papers either contain a chart similar to Figure 5.1.

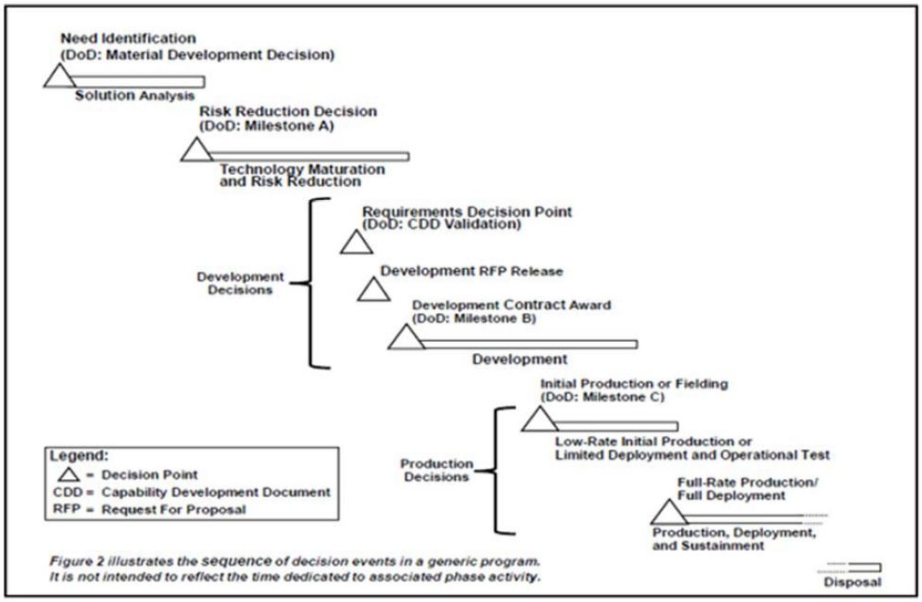


Figure 5.1: Department of Defense Key Acquisition Phases and Decision Points [36]

... or similar to Figure 5.2.

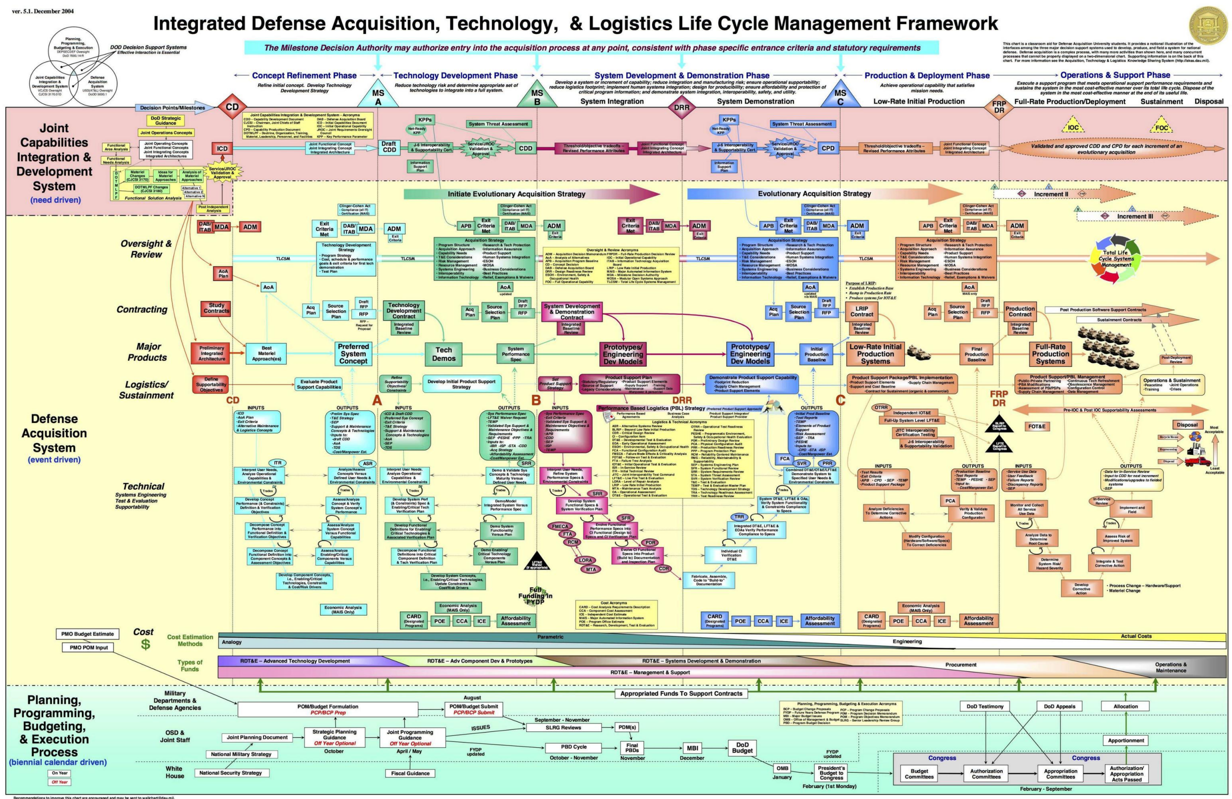


Figure 5.2: Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System [37]

Figure 5.1 is a high level view of the Department of Defense acquisition life cycle. It contains a flow down of the major milestones within the acquisition life cycle as well as critical documentation and phases that build up to the milestones. The problem with using this depiction of the life cycle when discussing the mirroring hypothesis is it does not have high enough granularity to understand the full picture of the organization and product development within the life cycle. The mirroring hypothesis requires the ability to evaluate the architectures of the organization and product at each step within the life cycle in order to understand where it would be best used as a design parameter in its early design phases. This depiction of the life cycle is too general for that type of evaluation.

Figure 5.2, on the other hand, is too granular for the purposes of this discussion. While more detail about the organization and product at different phases within the life cycle allows for greater accuracy when constructing the organization and product architectures, too much detail introduces more confusion than it does understanding. In order to properly evaluate the mirroring hypothesis‘s place within the Department of Defense acquisition life cycle, a middle ground between Figure 5.1 and Figure 5.2 is required.

Figure 5.3 seeks to improve communication of the common steps in the early design phases of the Department of Defense acquisition life cycle and was constructed by combining Figure 5.1 and Figure 5.2 with supplemented information from Department of Defense acquisition life cycle documentation.

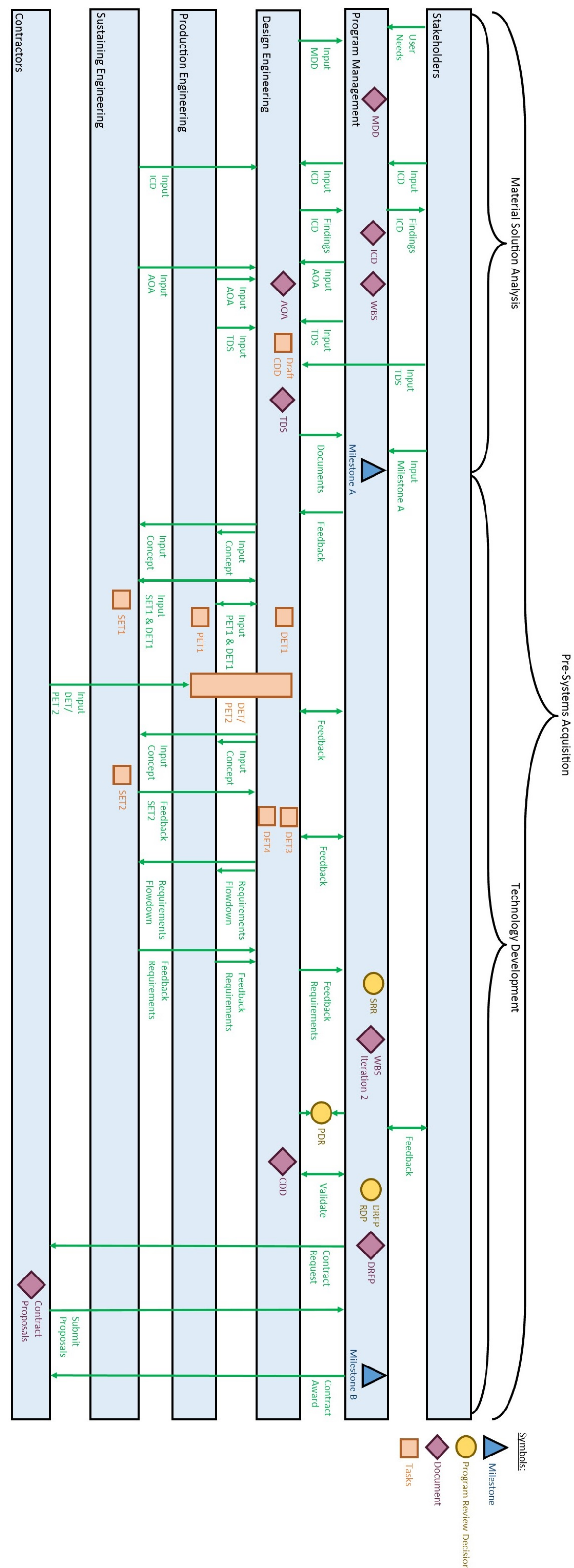


Figure 5.3: The U.S. Government Product life cycle

Table 5.1: Product Life Cycle Acronyms

Acronym	**life cycle Event or Product**
AOA	Analysis of Alternatives
CDD	Capabilities Development Document
DET	Design Engineering Task
DRFP	Development "Request for Proposal"
ICD	Initial Capabilities Document
MDD	Material Development Description
PDR	Preliminary Design Review
PET	Production Engineering Task
RDP	Release Decision Point
SET	Sustaining Engineering Task
SRR	System Requirements Review
TDS	Technology Development Strategy
WBS	Work Breakdown Structure

The Department of Defense system acquisition life cycle depicted in Figure 5.3 details the Department of Defense system acquisition process as a swim lane model from the inception of acquisition to Milestone B. The symbols in each swim lane are a part of four categories: Milestones, Program Review Decisions, Documents, and Tasks. Milestones, Program Review Decisions, and Documents have specified names and processes in the Department of Defense literature. Program Milestones represent the culmination of each phase where a Program Review Decision determines if the program is ready to move onto the next phase. The activities and activity conclusions are extensively recorded in Documents throughout the phase. Tasks were created to capture necessary steps in the life cycle that are not given a formal titles in Department of Defense processes, but were valuable enough to the proceeding discussion to include in this depiction of the Department of Defense acquisition life cycle. The tasks are described in Table 5.2.

Table 5.2: Product Life Cycle Tasks

Task Name	**Task Description**
DET1	Evaluate program integration and potential risks based on Milestone A results
PET1	Evaluate potential production needs based on Milestone A results
SET1	Evaluate potential support and maintenance needs based on Milestone A results
DET/PET2	Perform competitive prototyping
SET2	Define support objectives based on competitive prototyping results
DET3	Develop system architecture
DET4	Develop technical architecture

The swim lanes represent the actions and interactions between the Stakeholders, Program Management, Design Engineering, Production Engineering, Sustaining Engineering, and Contractors. All swim lanes except Contractors are actors within the Department of Defense. Stakeholders are the customers of the product. This would traditionally be a specified branch of the military such as the Air Force or Army. Program Management are the upper level decision makers of the product design, production, and operation, such as the Milestone Decision Authority who is the designated Department of Defense authority to proceed to the next phase of the life cycle. The team titled Design Engineering focuses on developing and refining the type of product necessary to meet the needs of the Stakeholders. Production Engineering focuses on developing the needs and requirements to build the product concepts by Design Engineering. Sustaining Engineering focuses on what is needed in operations and sustainment of the product concepts after they are out of production. Contractors are organizations hired to design, produce, operate, and sustain the final product. Each swim lane designation encompasses several actors within the Department of Defense which were grouped based on their functions and responsibilities described in Department of Defense Instruction (DODI) 5000.02 [37], Defense Acquisition University's Integrated Defense Life Cycle Management System chart in Figure

5.2, and the Department of Defense Key Acquisition Phases and Decision Points in Figure 5.1. This swim lane model is primarily built from the DODI 5000.02 whose purpose is "to update established policy for management of all acquisition programs" and "authorizes Milestone Decision Authorities (MDA) to tailor the regulatory requirements and acquisition procedures" [37]. Additionally, this swim lane model is not representative of time between documents or tasks. It is meant to convey the flow through documents and tasks during the detailed phases of the life cycle as defined in Department of Defense life cycle documentation.

While deviations from the specific steps, or the order of those steps, can and will occur, this product life cycle represents life cycle best practices and demonstrates what should generally be done when designing a Department of Defense product. With the knowledge that mirroring does have an effect on a product's design and diversity, where is it appropriate to use mirroring strategically within the Department of Defense acquisition life cycle?

5.2 The Mirroring Hypothesis Applied to the Product life cycle

The design phase of a product life cycle is critical to the success of the product. A well defined problem with clear, concise requirements prevents detrimental life cycle burdens such as requirements creep, schedule delays, and misalignments between the needs of the Stakeholder and the product provided to the Stakeholder [38]. Additionally, the cost to change a product greatly increase as time and milestones progress in the product life cycle; therefore, it is more cost advantageous to design the product successfully during the design phase rather than to fix a misdesigned product later in the life cycle [39]. Based on Chapter 1, the mirroring hypothesis argues that organizations who more closely mirror their organization and product architectures will increase their product's performance. To implement mirroring as a design parameter in an early design phase, mirroring requires a mature enough architecture to measure the nodes and links within the organization and product architectures and then quantify their differences. The design also cannot be overly mature otherwise "mirroring" becomes an improvement to an existing product rather than a design parameter. With this in mind, mirroring most appropriately belongs in the activities within the Pre-Systems Acquisition phase of the Department of Defense life cycle.

5.3 Pre-Systems Acquisition

The Pre-Systems Acquisition phase of the Department of Defense acquisition life cycle begins at the formation of a need and ends at the award of a contract. It is composed of two sub-phases: Material Solution Analysis and Technology Maturation & Risk Reduction. The sub-phases are described in Subsection 5.3.1 and Subsection 5.3.2, respectively.

5.3.1 Material Solution Analysis

The Material Solution Analysis phase determines if a new product is required to fulfill the product stakeholder's need(s) and analyzes the possible alternative solutions. This phase includes the documents: MDD (Material Development Decision), ICD (Initial Capabilities Document), AoA (Analysis of Alternatives), and WBS (Work Breakdown Structure). The MDD identifies whether or not a new product or a modification of an existing product is necessary to satisfy the stakeholder. This decision assists in scoping the forward work in establishing the first set of requirements within the ICD and performing the AoA. The completion of the MDD starts the activities to analyze alternative solutions. The MDD is traditionally led by the Director of Cost Assessment and Program Evaluation (DCAPE), or similar Department of Defense component, in tandem with the Milestone Decision Authorities (MDA). While an organization architecture is established to perform the work needed for the MDD, at this point in the life cycle, the product architecture is non-existent. With the sole purpose of the MDD being to make the decision of whether or not to create a new product, the product architecture does not exist beyond knowing whether or not it will exist. This causes the MDD to be a poor decision point to implement mirroring as a parameter.

The ICD works towards creating a well defined problem statement and solidifying the requirements stemming from the problem statement. The importance of well defined requirements and their impact on the final product is widely discussed in product development and life cycle literature. This step is crucial to starting the program on the right path with achievable goals and a well-scoped budget. While this step ultimately contributes to the construction of the product architecture, the product architecture is still too immature to properly implement mirroring as a design parameter in this step. This step assists in defining the functionality of a product (i.e. what the product needs to accomplish) but does not, and should not, contain the design of the product. Requirement standards traditionally do not define the design of the product. In a mirroring context, the design of a product, or at the least an idea of the design alternatives, is necessary to define the nodes and links that make up a product architecture. Due to these reasons, the ICD is not the proper point at which to implement mirroring as a design parameter.

The AoA identifies potential alternatives, guided by the ICD, to fulfill the defined requirements."An AoA is an analytical comparison of the operational effectiveness, suitability, and life cycle cost (or total ownership cost, if applicable) of alternatives that satisfy established capability needs" [40]. In other words, the AoA asks: out of a list of alternatives, which alternatives best meets the stakeholder's needs? The AoA serves to help organizations understand their product tradespace and quantify the performance qualities of the product options. The staffing of an AoA study traditionally consists of a study team scoped to the level of effort, length of time, and cost of the study. An AoA is initiated by a lead command or study director who is tasked with assembling the AoA study team, determining its size and composition. The Government Accountability Office (GAO) is the oversight body for Congress in order to ensure the funding awarded to government entities is used appropriately. In

2014, the GAO released a list of 24 best practices for performing an AoA [41]. One best practice related directly to the composition of the team:

"The team includes members with diverse areas of expertise including, at a minimum, subject matter expertise, project management, cost estimating, and risk management" [41].

This sentiment is repeated and further detailed by the AoA Handbook released by the Office of Aerospace Studies in the U.S. Air Force [40]. Both sources agree, the AoA lead command‘s role in addressing the expertise needs within their AoA study team is crucial to the success of the AoA. Additionally, the GAO guidelines state several best practices which speak to the influence the AoA study team has over the resulting product including the screen of all alternative, selection of the success criteria, and the weight, or importance, of each success criteria when considering the alternatives. While the team is instructed to enter the study without predispositions towards alternatives, the background and competencies of the individuals inherently introduce bias into the study [42]. It is at this point in the life cycle where the organization and product architectures are not only mature enough to begin using mirroring as a design parameter, using mirroring as a design parameter could assist in ensuring the product alternatives evaluated and selected reflect the product characteristics desired by the stakeholders by selecting an organization to perform the study that is predisposed to those characteristics.

This work posits that the AoA lead command could use the mirroring hypothesis as a design parameter for determining the best assemblage of people on their team in order to create the best swath of alternatives to fulfill the capability and functionality defined in the MDD and ICD. This application of mirroring is uni-directional and flows from the organization architecture to the product architecture. Assuming the mirroring hypothesis is true, the product alternatives‘ architectures will reflect the architecture of the AoA study team; therefore the selection of those participants will direct impact the types and composition of the alternatives within the study. Armed with the knowledge that the organization and product architectures will align, mirroring could ultimately be used by the AoA lead command to influence the creation of the product architectures through the deliberate design of the study team architecture.

The WBS created at this stage in the life cycle scopes the resource cost (i.e. amount of people) necessary to proceed through Milestone A and the Technology Maturation and Risk Reduction phase [37]. At this point in the life cycle, the AoA study team should have an alternative, or a short list of alternatives, to pursue in the next life cycle phase. While creating the WBS is an organizational architecture design activity, the product architecture to be pursued was confirmed by the previous activity. The products the WBS is scoping for are the groundwork for developing the stakeholder's end product. While mirroring could be used to align the future workforce with the life cycle products going forward, this discussion focuses on the stakeholder's end product architecture rather than the product architectures of the life cycle artifacts. From the perspective of the stakeholder's end product architecture, the WBS is not an opportune document to use mirroring as a design parameter.

5.3.2 Technology Maturation & Risk Reduction

The Technology Maturation & Risk Reduction phase involves cost and performance trades, an analysis of risk reduction, completion of the requirements for preliminary design, development, and production as well as a proposal for commercial bids. The documents involved in this phase are: draft two of the WBS (Work Breakdown Structure), CDD (Capabilities Development Document), DRFP (Development Request for Proposal), and Contract Proposals. There are three program review decision within this phase: SRR (System Requirements Review), PDR (Preliminary Design Review), and DRFP RDP (Release Decision Point). This phase concludes with Milestone B. Milestone B is the critical decision point in an acquisition program because it commits the organizations resources to a specific product, budget profile, choice of suppliers, contract terms, schedule, and sequence of events leading to production and fielding [37]. Where the Material Solution Analysis worked towards establishing a need or capability, the Technology Maturation & Risk Reduction phase aims to ”reduce technology, engineering, integration, and life-cycle cost risk to the point that a decision to contract... can be made with confidence in successful program execution for development, production, sustainment” [37].

The SRR ”assesses the system requirements captured in the system specification and ensures that the system requirements are consistent with the approved materiel solution, ICD, enabling concepts, and available technologies identified in the Materiel Solutions Analysis (MSA) phase” [43]. This is the last review of the product requirements before handing them to the awarded Contractor to begin production of the product. The requirements have a large impact on the product‘s performance, cost, and schedule; therefore, this review is very important to the product‘s success so the Contractor builds what the stakeholder needs in an efficient manner. While the SRR holds great significance to the progress and success of the Department of Defense acquisition life cycle and influences the end product architecture, it does not have a direct correlation to the design of the relationship between the organization producing the product and the product itself. Therefore, the SRR is not a good candidate for using mirroring as a design parameter.

The second iteration of the WBS is similar to the first iteration in that it prepares for the next phase in the life cycle by estimating the necessary man power and work breakdown. The difference between the second iteration of the WBS and the first iteration is this WBS must also take into consideration the contracts that will be awarded at Milestone B. Similar to the first WBS, the second iteration of the WBS addresses the life cycle events and not the end product architecture [44]. While the life cycle events have influence on the end product architecture, this discussion focuses on mirroring as a design parameter of the stakeholder‘s end product architecture; therefore, the WBS is not a good candidate for mirroring as a design parameter in this work.

PDR establishes the functional and allocated baseline of the product architecture and evaluates whether that baseline has a reasonable plan forward to satisfy the program requirements within the designated cost and schedule [37]. The PDR is the accumulation and review of the product development thus far in the life cycle before awarding a contract. It is the turning point from a DoD driven life cycle phase to a Contractor driven life cycle phase. There should be no major design changes to the product at this point in the life cycle since it is a review of the baseline of the product the program is attempting to produce. Since the baseline design is under review at this point in the life cycle, mirroring as a design parameter does not make sense to use during this event.

The CDD is one of the key transition points from design to operations during the Department of Defense acquisition life cycle. The CDD specifies the product‘s operational requirements which strive to meet the performance specifications detailed in the ICD. This document is the first concrete definition of operational objectives and performance threshold in the program [37]. This work focuses on the design of the product, rather than the operation rules between the user and the product as dictated by this document; therefore, the CDD is not a good candidate for using mirroring as an early design phase parameter.

The contract award at the end of the Technology Maturation & Risk Reduction phase takes place in three steps: DRFP RDP, DRFP, and Milestone B. The DRFP RDP and DRFP is the two step process of releasing the requirements to potential contractors in order to receive contract bids on the program. The release decision point of the DRFP is the DoD decision that the documentation accumulated thus far in the life cycle is sufficient enough to properly evaluate contract bids and select a contractor who will build what the stakeholder needs. The DRFP RDP acts as a final decision point to ensure an affordable and reasonable schedule has been drafted for the contractor of the program. The DRFP is the actual release of the program documentation to contractors.A Source Selection Authority (SSA) and Source Selection Advisory Council (SSAC) are responsible for analyzing the received proposals and making the Milestone B decision (i.e. the contract award). A key question in this evaluation is: out of a list of contractors, which contractor could best fulfill the vision of the product?

Similar to using mirroring as a design parameter in the AoA phase, the DRFP and Milestone B present an opportunity to co-design the structure of the organization through contractor selections and, in turn, the resulting product architecture of that award. The Department of Defense is no stranger to Multi-Award Contracts (MACs). In 2018 alone, the Navy awarded 1,870 MACs to organizations occupying 46 out of the 50 United States [45]. Going into Milestone B, theoretically the program has defined the requirements driving the proposal through SRR and PDR program review decisions [37]. As the SSAC pursuing a MAC, using mirroring as a design parameter provides the opportunity to align the awarded organizations to the product envisioned in the baseline. While the product baseline is mature, the possibilities for the product are still open as the Department of Defense design phases simply perfects the proposal of a need, not a product. The SSAC defines the contract structure and responsibilities of those who will create the product which provides an opportunity to co-design the organization and the vision of the product and use their alignment to benefit the end product. If the mirroring hypothesis is assumed true, this alignment during the contract awards would improve the overall performance of the product.

The conclusion of Milestone B and the Technology Maturation & Risk Reduction phase is also the conclusion of the early design phases of the Department of Defense acquisition life cycle. Tables 5.3 and **??** summarize the conclusions of whether mirroring should be utilized as an early design parameter for each program review decision, milestone, and document. The strongest cases for using mirroring as an early design parameter are during the AoA and from the DRFP to Milestone B. The AoA is a promising opportunity to use mirroring as a design parameter if you are the AoA lead command since you can shape the AoA study team to have the architecture that is desired in the product architecture. The time frame between DRFP and Milestone B is another promising opportunity for the SSAC to use mirroring in order to award contracts to create an organizational architecture the produces a desirable product architecture. While this work speaks theoretically and generally towards the Department of Defense acquisition life cycle, the extensive background research that contributed to this work into the Mirroring Hypothesis and the Department of Defense Acquisition Life Cycle creates a compelling argument for where it could be successful in Department of Defense product design.

Table 5.3: Mirroring Conclusions for the Department of Defense Acquisition Life Cycle

Acquisition Life Cycle Event	**Mirroring Conclusion**
MDD	Mirroring should not be used as a design parameter.
ICD	Mirroring should not be used as a design parameter.
AoA	Mirroring should be used as a design parameter.
WBS, 1st Iteration	Mirroring should not be used as a design parameter.
SRR	Mirroring should not be used as a design parameter.
WBS, 2nd Iteration	Mirroring should not be used as a design parameter.
PDR	Mirroring should not be used as a design parameter.
CDD	Mirroring should not be used as a design parameter.
DRFP RDP DRFP Milestone B	Mirroring should be used as a design parameter.

Table 5.4: Mirroring Conclusions Justifications for the Department of Defense Acquisition Life Cycle

Acquisition Life Cycle Event	**Mirroring Conclusion Justification**
MDD	The product architecture is not mature enough during this decision.
ICD	The product architecture is not mature enough during the development of this document.
AoA	The co-design of the AoA study team and the product alternatives‘ architectures presents a promising opportunity for using mirroring as a design parameter.
WBS, 1st Iteration	The focus of the WBS is outside of the focus of this discussion which is mirroring as a design parameter of the stakeholder‘s end product, not as a design parameter of the life cycle artifacts leading up to the end product.
SRR	This event, while has great impact on the overall program architecture, does not directly design the relationship between the organization and product architecture.
WBS, 2nd Iteration	The focus of the WBS is outside of the focus of this discussion which is mirroring as a design parameter of the stakeholder‘s end product, not as a design parameter of the life cycle artifacts leading up to the end product.
PDR	PDR is the review of the established baseline for the program‘s product; therefore, there should no design occurring at this time.
CDD	Mirroring as an early design phase parameter of the end product does not scope to cover the operational requirements of that end product.
DRFP RDP DRFP Milestone B	Mirroring as a design parameter could be used to co-design the contract award architecture and the product architecture to ensure a higher product performance, assuming the mirroring hypothesis is true.

6. CONCLUSION

The goals of this work were to demonstrate the mirroring hypothesis as an early design parameter through the use of a specific example problem, discuss its effect on the design solution and its diversity, and examine its place as a design parameter within a product life cycle. This research focuses on a specific satellite design problem in order to compare the design results of a mirrored and a partially mirrored organization/product pair. This research does show that for the specific example, mirroring has an effect and affects the solution in the following ways: The difference in design solutions and the diversity of the design solutions of the FireSat II show that mirroring makes a difference in the design alternatives. If the mirroring hypothesis is assumed true, mirroring as a design parameter could be used strategically to achieve a higher performing FireSat II. Mirroring requires a maturity in the architectures of the organization/product pair to be able to quantify the mirroring between them, but not mature enough to where design is no longer taking place. In the early design phases of a government acquisition life cycle, based on the analysis of the life cycle and the necessary pre-conditions of using mirroring as a design parameter, it is suggested that mirroring be used as a design parameter during the AoA as a design parameter in the co-design of the AoA study team and the product alternatives‘ architectures and in the evaluation of contracts during Milestone B in the co-design of the contract award architecture and the stakeholder‘s end product architecture. This work utilized literary analysis of the mirroring hypothesis and Department of Defense government acquistion life cycle to present arguments that mirroring could be used as a design strategy to improve a product if exploited during choice events within the design phase of the product’s life cycle.

While this work cannot speak beyond the example problem it builds its foundation on, future work into investigating the validity of the mirroring hypothesis could open doors to expanding the research into how it can be used as a strategy rather than a remedy or an observation. This could be done by increasing the complexity of the design problem to see how the effect of mirroring evolves with the complexity of a product. Additionally, different nodes, metrics, and levels of mirroring could be evaluated to determine if for other example problems, does the difference of design and diversity of design hold true or do they differ from the results of this example problem?

The mirroring hypothesis is only a hypothesis, but there are still opportunities to use mirroring as a strategy. While using mirroring as a strategy at an industrial scale is not recommended, using it as a design parameter in a smaller scale study such as a student team design problem could inform both research into the validity of the mirroring hypothesis and into using the mirroring hypothesis as a strategy. Austin-Brenneman investigated student team's design practices and approaches by taking teams of graduate students to complete a complex design problem in a controlled environment. This mirroring hypothesis discussion could lead into research that builds on Austin-Brenneman's student design teams and factors the mirroring hypothesis as a metric into the design process of student teams to further investigate its relevance to the performance of design.

Other future work could include research on a life cycle starting from the beginning of the life cycle, rather than evaluating the past, and investigate how mirroring plays a role in the development of the product. By performing the study at the start of a product life cycle, it could eliminate the inherent bias to almost exclusively study high performing organizations as well as give the flexibility to collect real time data rather than relying on past records. This study could be taken further by performing an in-depth research initiative to see how differently mirrored organizations in the design phase of the life cycle comparatively perform.

Most of all, future work could also include investigations into the strategic uses of the mirroring hypothesis. If proven to be more than a hypothesis and research finds organizations and products do reflect each other, what are the ways this knowledge could be used to improve the design of products?

This work is unique in that it introduces the concept of mirroring as a design strategy rather than as a research metric or remedy to a struggling product. While the example problem in this work is specific, real world designers could use this analysis to contemplate mirroring in their own design problems and ask themselves, how does my organization affect my product and vice versa? How can we use mirroring to improve the organization/product relationship? In the end, the motivation behind this work is to spark questions within industry designers to evaluate from a high level how the mirroring hypothesis plays into their roles and how they can use the mirroring hypothesis to create a better product.

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