CULTIVATING CREATIVITY IN AEROSPACE SYSTEMS ENGINEERING

TO MANAGE COMPLEXITY

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ABSTRACT

Cultivating Creativity in Aerospace Systems Engineering to Manage Complexity

Kenneth Lucas Dodd

In recent decades, complexity in aerospace programs has been increasing, leading to large budget and schedule overruns. Many of the risks of complex system development can be attributed to the inadequacy of linear methods when applied to nonlinear domains, i.e., oversimplification in a program amplifies the amount of risk produced when a system behaves unexpectedly. Effectively managing complexity involves responding to the various sources of complexity, whether it appears in the objective behavior of the system itself or in the subjective behavior of the people developing it. Thus, the engineering of complex systems requires nonlinear modeling methods of the system as well as nonlinear processes for developing the system. Much effort tends to be focused on addressing the objective sources of complexity and less is given to understanding and responding to the subjective sources of complexity. This present study examines how facilitating creativity in aerospace system development can serve as a potential strategy for managing complexity. Creativity is a kind of psychological process that integrates linear and nonlinear modes of thinking, and therefore systems engineering processes that reflect the creative process could reduce the risks of complexity. There are three primary results of this work: a novel application of creativity research to aerospace engineering processes;

the most comprehensive published review of existing research on creativity in aerospace known to-date; and the proposal of two new systems engineering methods for facilitating creativity to manage complexity. These two new methods designed to improve the Waterfall methodology are as follows: the formation of a Parallel Systems Engineering group that functions analogously to how linear and nonlinear information are coordinated in creativity; and a conceptual model wherein aerospace programs are treated as a series of interdependent creative processes, which can be used to trace the propagation of complexity through various phases of system development.

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Chapter 1

INTRODUCTION

This thesis is a response to both the current and perennial aspects of aerospace complexity. The research presented here is a thorough examination of the relationship between complexity, creativity, and aerospace systems engineering in light of historical trends toward developing increasingly advanced, complex systems. It can function as a comprehensive guide book for how creativity could be a solution strategy for managing aerospace complexity, and its methods are ready to be applied and tested in the work environment.

Much of the literature in complexity theory forwards many poignant examples of complex system behavior, yet tend to use inconsistent definitions, offer generic recommendations, and conflate political and scientific discussions about complexity. Granted, complexity is a complex subject matter. Even so, there is a need for consistent definitions, specific recommendations, and a scientific discussion of complexity. "We need a new paradigm for systems engineering. [Former NASA Administrator] Michael Griffin has suggested that Systems Engineering is a collection of heuristics that lacks a foundational theory" (Holt et al., 2017). Given recent changes in the aerospace industry, such a study is warranted. This thesis responds to the problem of complex aerospace system development in three main ways: (1) a novel application of creativity research to aerospace engineering processes; (2) the most comprehensive published compilation of existing research on creativity in aerospace known to-date; and (3) the proposal of two new systems engineering methods for facilitating creativity to manage complexity.

Chapter 2 is a discussion of complexity as it pertains to the aerospace industry. Complexity is defined and misconceptions are clarified in Section 2.1. Recent evidence of the increase of complexity in aerospace programs and the subsequent risk will be surveyed in Section 2.2. In Section 2.3, the difficulty of complex systems engineering will be examined, which will suggest that a paradigmatic change in complexity management strategy is necessary to improve upon the recent trend of cost and schedule overruns. The difference between objective and subjective complexity will be briefly looked at in Section 2.4, because it is important to recognize that objective and subjective sources of complexity call for different solution strategies. This builds up to Chapter 3, where creativity is discussed as a mechanism for addressing the paradigmatic challenge of complex systems engineering.

Chapter 3 applies creativity research to the aerospace system development process, something that is almost entirely unprecedented in the field. Section 3.1 is a literature review of creativity research, discussing what creativity is in the context of engineering, as well as clarifying common misconceptions that have import in understanding why fostering creativity could be used to respond to aerospace engineering complexity. Section 3.2 is a study of how the creative process consists of an interplay between convergent and divergent thinking modes and applies these ideas to conceptual design. This directly feeds into a discussion in Section 3.3 of how, specifically, creativity addresses complexity. Creativity is what is called a "tertiary process," because it integrates linear and nonlinear thinking. Creativity can bridge linear engineering methods with complex design domains. In this way, creativity could be used as a mechanism to more appropriately respond to complexity. Section 3.4 describes the motivational factors that facilitate or hinder creativity and relates these motivational factors to human behavior in aerospace programs. Section 3.5 first discusses the creative process in general, and then applies this creativity research to the phases of aerospace development programs. In Section 3.6, the Agile and Waterfall systems engineering methodologies are discussed and compared as strategies for facilitating creativity.

Chapter 4 brings together existing research on fostering creativity in aerospace engineering, as well as engineering as a whole. Various methods for fostering creativity are described. The methods bear special relevance in searching for how to improve the historically traditional Waterfall methodology, but are applicable under a variety of systems engineering strategies. First, there is an overview of the existing literature in Section 4.1, notably featuring the work of aircraft designer Darold Cummings, who is the primary forerunner in the topic of creativity in aerospace engineering. Some of his recommendations for facilitating creativity, which focus on stimulating creative brain activity, are discussed in Sections 4.2 and 4.3. Other recommendations and findings of his are brought up at other places throughout this chapter. Section 4.4 surveys engineering research on the motivational factors of creativity. Section 4.5 briefly compares the effects of leadership style and systems engineering on the motivational factors of creativity.

Section 4.6 references studies on creativity in engineering education and workplace training. Section 4.7 summarizes various methodological tools in aerospace engineering that can affect creativity: several tools for evaluating creativity, Multidisciplinary Optimization, and Model-Based Systems Engineering. Section 4.8 introduces Gabora's proposed approach for mathematically modeling the creative process. These methods outline the limited amount of existing research on creativity in aerospace.

Chapter 5 is the culmination of the research in this thesis. In it, I recommend two new systems engineering methods for facilitating creativity as a way to manage complexity. The first method is the introduction of a Parallel Systems Engineering group that functions similarly to how intuition and tertiary processing functions in the mind. The second method is a conceptual model for how modelling the creative processes in aerospace programs could make complexity traceable throughout the various phases of a program's lifecycle.

This thesis represents a comprehensive survey of existing research on how creativity relates to aerospace engineering as well as a step forward in the field. As mentioned, it can be used as a guide book for how to manage complexity in aerospace programs, especially large programs. The implications of the research presented here is ready for application and testing. This study may serve as a milestone for future research in the topic.

Chapter 2

COMPLEXITY

In this chapter, we will examine complexity so as to build an argument for why fostering creativity in aerospace programs could help in managing complex systems. First, we will look at a basic definition of complexity based on a literature review of the mainstream research. Then, we will look at how complexity has been affecting the aerospace industry in recent times. This is followed by an examination of a paradigmatic challenge of complex systems engineering. This will be followed by a discussion comparing between objective and subjective sources of complexity. Chapter 2 serves as background for how and why fostering creativity could address many of the challenges of complex aerospace system engineering.

2.1 A Basic Definition of Complexity

First of all, what is complexity? Throughout the literature, there are many competing definitions of complexity and proposed methods for addressing it. There is even argument over whether or not it is at all possible to make a general theory of complexity, since doing so might take the complexity out of complexity (Morin, 2008). It may seem like what is most definite about complexity is its indefiniteness, and that understanding complexity is itself a complex undertaking. The fact that complexity is not a well-defined problem does add risk to the process of developing a complex system. Nevertheless, it is possible to find consensus among researchers and form a definition of complexity adequate for practical purposes. A broadly accepted view is that *complexity* is the quality of a system having a large number of components with tight coupling between them, which results in the system exhibiting unexpected behaviors (Clearfield & Tilcsik, 2018). In simple terms, a complex system is one for which “the whole is greater than the sum of its parts” (Mitchell, 2009).

Complexity in this sense is a modern concept, but there is also a long history of complexity research. A quick glance at the etymology of complexity will shed some light on the definition used here. Complexity derives from the Latin verb *plectere,* which refers to the process of braiding or folding things together (Mitchell, 2009; Morin, 2008). Thus, a complex system is a system characterized by the intertwining between its parts. The interrelatedness of a complex system means that the whole system exhibits behavior that is inextricable from the sum of its components. Just as pulling on a thread can significantly affect an entire fabric, affecting any one component of a complex system can significantly affect the whole system. This interrelatedness can also happen over time, such that the system has the capacity to change itself over time. The properties of a complex system which emerge as a result of the assembly of components are often called *emergent properties*.

An excellent example of a complex system is a natural ecosystem. At Yellowstone National Park, the resident population of wolves became extinct many decades ago due to over-hunting. This absence of predation from wolves allowed the elk and deer population to grow several times larger than its normal amount. This led to deforestation of aspen groves near bodies of water, which the deer and elk like to consume. In turn, beavers could not gather enough building material for their nests and dams, and so they left the Yellowstone region entirely. Consequently, many species which depended on the ponds created by beaver dams, like algae, insects, frogs, fish, and waterfowl, also disappeared from the area. However, in more recent years, the wolves were reintroduced into Yellowstone, and their population was protected by law. This had a chain reaction on the food web: the deer and elk population decreased, the aspen groves replenished, the beavers returned to the park, and numerous species of aquatic organisms and waterfowl returned along with them (Hannibal, 2012). The nonlinear effects of the presence of wolves on the Yellowstone ecosystem are emergent properties that exemplify complex system behavior. The Yellowstone ecosystem is a complex system because the interdependencies between its many organisms are of great significance to how the entire ecosystem behaves.

An example of an aerospace system that meets the criteria for complexity is the National Aerospace Plane (NASP) program's X-30 vehicle design. The X-30's was intended to be a single-stage-to-orbit (SSTO) flight vehicle, using combined-cycle air-breathing engines to power the vehicle from subsonic to hypersonic speeds. This meant that the various flight systems were highly interdependent and sensitive to performance perturbations. The vehicle would have had a very large number of parts with tight coupling between them. Not only was the vehicle itself complex, the program behind it was also complex, relying on thousands of engineers in numerous civilian contractors and branches of the Department of Defense. The complexity of the X-30 system and program led to its eventual demise (Schweikart, 1998; Heppenheimer, 2007).

It is key to differentiate between what might be termed a colloquial notion of complexity and the more technical definition used here. Colloquially, complexity is often understood as the quality of something being especially hard to understand or control. In a technical setting, the colloquial version of complexity is inadequate, because it has the consequence of conflating complex systems with large linear systems. A large deterministic system, which may be hard to understand, is theoretically predictable. By comparison, a complex system, which is by definition nondeterministic, may also be hard to understand, but it is theoretically unpredictable. Unlike a large linear system, a complex system does not simply exhibit integration effects but actually behaves quite differently from predictive models. Emergent properties are opaque to deterministic prediction, and therefore pose risk to a program. The risk posed by emergent properties can be called *emergent risk* (DeTurris & Palmer, 2018). Although in practice it can be a good idea to try to minimize a program's complexity so as to avert unwanted emergent risk, the scope of this research is limited to the cases where the technological advantages of complexity are preferred to the benefits of minimizing complexity. Now that a basic definition of complexity has been established, we will proceed to examine the problem at hand regarding complexity in aerospace today.

2.2 Emergent Risk in Aerospace Today

On top of typical sources of uncertainty, complex system development programs come with the added challenges of emergent risk. In recent decades, large aerospace programs have become increasingly large, advanced, risky, and, consequently, increasingly costly and time-consuming. This rise in complexity is evidenced by the increase in such things as the numbers of subsystems, component interfaces, and lines of code (Arena et al., 2008). The fourth-generation F/A-18 has 15 subsystems, approximately 10^3 interfaces, and 40% of its functions managed by software. By comparison, the fifth-generation F-35 has 140 subsystems, 10^5 interfaces, and 90% of its functions managed by software (DeTurris, 2017). With such an increase in system complexity comes additional program risk. Numerous large aerospace programs have experienced major delays and schedule runovers due to risks associated with complexity. As mentioned, the NASP program sought to produce an air-breathing, hypersonic vehicle. Although the program enlisted NASA, DARPA, the Air Force, the Navy, the SDIO, Rockwell, McDonnell Douglas, General Dynamics, Rocketdyne, and Pratt & Whitney and at its peak had an annual budget of $320-million, the program ran for about ten years, completing only 17 out of 32 major technical milestones before it was cancelled (Schweikart, 1998; Heppenheimer, 2007). In the case of the Boeing 787, many technical and organizational risks were taken without prior experience of such risks. Boeing delegated responsibility for development risks across their supply chain, but this amounted to a 40-month delay and a cost overrun of about $10-billion (Zhao, 2016). The F-35 Joint Strike Fighter (JSF) development has been delayed by nearly a decade and gone over budget by roughly $20-billion (GAO, 2018), due to the enormous challenges of designing it for multiple design environments with differing technology requirements (Sprenger, 2013). The January 2020 GAO report states that the James Webb Space Telescope (JWST) "is one of NASA's most complex projects and top priorities. Problems discovered during integration and testing caused multiple delays that led NASA to replan the project in June 2018… The project's costs have increased by 95 percent and its launch date has been delayed by over 6.5 years since its cost and schedule baselines were established in 2009." The JWST has more than 300 single-point failure modes (GAO, 2020).

Similar problems have also been occurring outside the aerospace industry, with many technical fields recognizing the immense challenge of developing and maintaining large systems, and subsequently admitting the need for a thorough reframing of problem-solving strategies (Mak & Clarkson, 2017). To name a few, these fields include the supervision of large cybersecurity frameworks, global banking networks, metropolitan power grids, and nuclear powerplants. A hacker can penetrate a large cybersecurity framework more easily than a small one, making them more unsafe. The ripples of fraudulent banking activity or economic collapse can propagate much more quickly in a global, internet-based banking network than a series of independent, disconnected economies. Advanced power grids in metropolitan areas have more points that can set up cascading feedback in blackouts, the downed powerline in 2003 affecting over 55 million in the Northeast being a noteworthy example (Zolli & Healy, 2012). Nuclear powerplants can approach meltdown due to only a handful of minor glitches, like the Three Mile Island event in 1979 (Clearfield & Tilcsik, 2018). These system-level failure phenomena were all unexpected or overlooked during early phases of development – they were, functionally, unknown unknowns, originating from system complexity.

Over the last century, the maturation of aircraft and spacecraft design involved a gradual increase in complexity. However, in recent decades, the development of advanced digital systems has allowed a sudden spike in the number of interconnections within systems and systems of development (Becz et al., 2010). This brought with it an amplification in the number of unknown unknowns (Arena et al., 2008). Figure 1 shows how as the complexity of automobiles, integrated circuits, and aerospace vehicles has increased, the duration of design, integration, and testing has levelled off for the automobile and integrated circuit markets but has continued to increase for aerospace vehicles (Eremenko, 2010). To meet the rise in complexity, there should be a response in terms of management and systems engineering strategies. What would this look like?

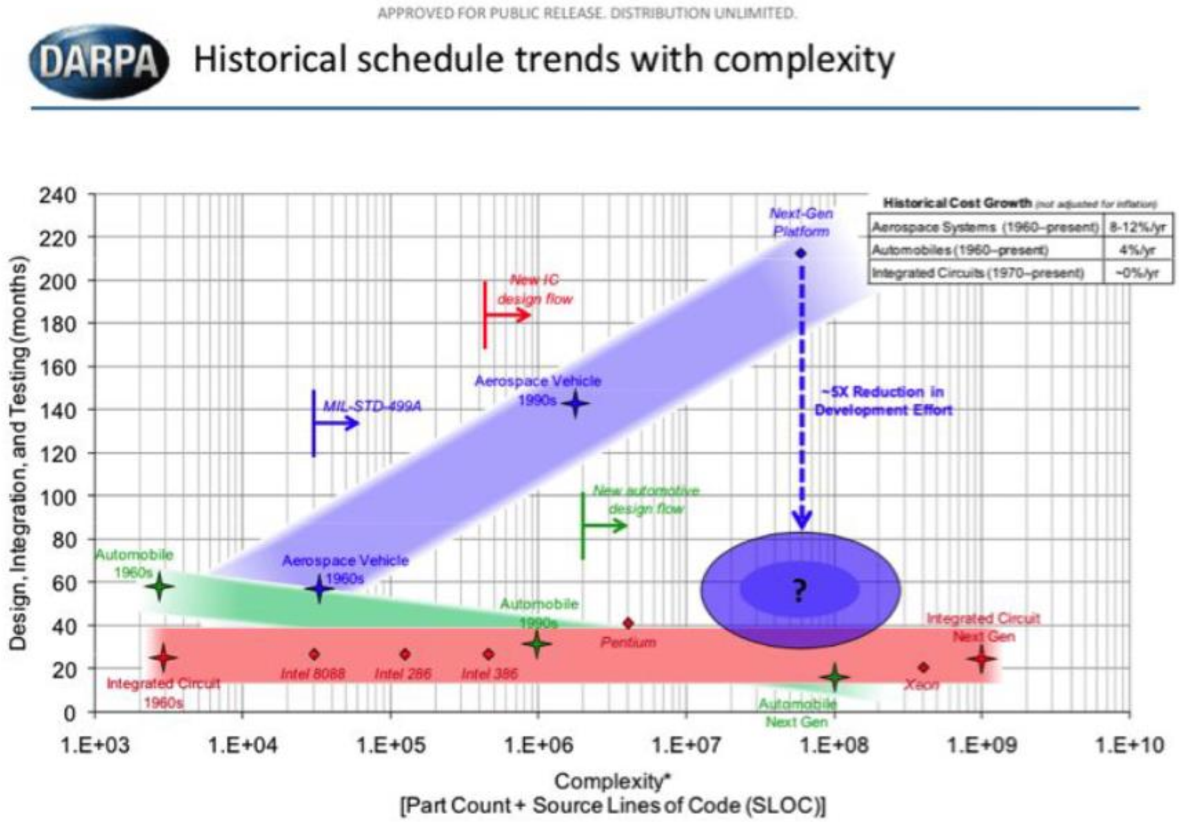

Figure 1. *Development time compared against system complexity in aerospace systems (violet), automobiles (green), and integrated circuits (red). (Eremenko, 2010)*

Complex systems offer the advantage of added capabilities and the disadvantage of added risk. Systems like the F-22 Raptor, which rely on advanced technology to execute their functions, are highly expensive to produce, operate, and maintain. Only 188 of 648 units were produced, their individual cost having raised from $149 million to $412 million and the program cost from $12.6 billion to $26.3 billion. Moreover, the advanced technologies onboard are expected to become inferior or obsolete within one or two decades of its entrance into service (Vartabedian & Hennigan, 2013). Even though the vehicles were functional, was it a worthwhile program? What does its cancellation say about large, complex aerospace programs relying on advanced technology? Some of the most effective and lasting aircraft systems in history, like the B-52, the C-130, the F/A-18, and the 737, have enduring longevity precisely because they were not particularly complex designs: they were simple enough to be adapted to new uses and robust enough to be operated and maintained for decades. Even complex aerospace programs that were arguably successful, like the SR-71, the Saturn V, and the B-2, were extremely costly and could not be used in quite so versatile a manner as other, simpler systems. With the highly sophisticated technology currently available to designers, should aerospace systems be developed for the advantages of complexity even if that means there is added potential for major unexpected risks?

Complexity is a feature of modern technology, though the risks it poses are closely related to how well complex systems are managed. Unknown unknowns characterize today's cultural backdrop to engineering: designs have a rapidly increasing number of interconnections and an accelerating ability to communicate around the world (Meadows, 2008). How will aerospace engineering adapt to the changing world? In recent news, the JPO program is now moving F-35 data into an Agile software development environment (Hudson, 2020). Another example is the sixth-generation fighter jet. The military is approaching the problem of a fighter jet from a different angle for the sixth-generation fighter. Rather than developing one platform with a long maintenance cycle, the program is being called "Penetrating Counter Air," and may involve short-run production of multiple systems that perform different tasks with a short operational life (DiMascio et al., 2020). Complexity is already producing responses in the aerospace industry.

Nevertheless, it could be argued that many complex aerospace programs have experienced budget and schedule overruns not because of system complexity but primarily because of poor planning and management. Furthermore, the development of large, complex systems tends to lead to enormous, complex programs. In this way, it can be hard to distinguish between the complexity of a system and the complexity of a program, making it difficult to identify where emergent risk originates and where it can be mitigated. Can complexity and its risk be attributed to excessive ambition and insufficient prudence? The emergent risks inherent in designing a complex system can easily balloon into nightmarish difficulty. Yet, complex systems can be alluring to develop because they appear to have the potential of becoming extremely sophisticated and simultaneously perform many valuable functions. In Section 2.3, we will look at why complexity poses such a risk for systems engineering and what should be done about it.

2.3 Complexity Poses a Paradigmatic Challenge for System Engineering

There is a major paradigmatic challenge for complex systems engineering: effective systems engineering depends on well-defined requirements and predictions, but complex systems are unpredictable. What can be done to reduce the impact of unpredicted events?

2.3.1 The Function of Systems Engineering

The discipline of systems engineering evolved as a response to large, advanced projects requiring coordination between many diverse teams (Johnson, 2006). In essence, its role is to coordinate the various roles within an engineering program. Systems engineers coordinate high-level program goals, detailed work packages, and everything in between, monitoring the various sources of risks and the program's process. Systems engineering serves as the linkage between the working-level engineers and those who oversee the program goals, and, as such, it exists to make sure clear communication and coordination of activities occurs between the program management, technical leads, design sub-teams, users, and stakeholders. Systems engineering acts as a hub amid the technical disciplines and as a bridge between the technical and business sides of a program. Systems engineers do not by themselves accomplishes these tasks, as many of their duties are shared with organization managers (Bay et al., 2009; Davis & O'Connor, 2005; Drake, 2018-19; Hirshorn, 2006; Parker, 2011). Effectively, systems engineering coordinates the creative activities of the entire engineering process.

2.3.2 The Challenge of Complex Systems Engineering

Essentially, the problem at hand boils down to a mismatch between the nature of engineering methods and the nature of complex systems. One of the founders of modern cybernetics, William Ashby, formulated a rule about how to control a system. Ashby's Law of Requisite Variety states that a control system has control over its controlled system insofar as it has access to a greater variety of states (Ashby, 1956). As an example, the Law of Requisite Variety would say that a pilot has control over their aircraft insofar as they can respond to a greater variety of flight conditions than they experience during flight. This concept can be applied to systems engineering. Systems engineering methods have control over their system insofar as they can address a greater variety of system behaviors than the system will exhibit. In the case of engineering complex systems, there is an unavoidable shortfall toward what can be known a priori about the system because the system has emergent properties, which are significantly different from the linear sum of its component properties and therefore are inordinately difficult to predict. In other words, the integration and environmental effects of a complex system are beyond the scope of conventional predictive methods. This is a lack of requisite variety between the engineering processes and the complex system. It means that the system engineers will more or less experience a lack of control over their system. To obtain control in a complex program, the engineering methods need to be able to address a greater variety of states than the complex system can exhibit. Although increasing prediction capabilities and planning detail might seem like appropriate responses, in the case of complex systems engineering, this approach misses the mark as to where the lack of control is located. Complex systems are by definition unpredictable and nondeterministic, and so increasing fidelity of engineering processes, protocols, and predictions does not fundamentally gain control over the source of emergent risk. To be more effective in managing complexity, systems engineers should adopt a different solution strategy.

2.3.3 The Cynefin Framework

Snowden and Boone's Cynefin Framework (pronounced ku-*nev*-in) addresses this paradigmatic challenge by classifying linear and nonlinear systems according to their degree of determinability and recommending appropriate courses of action for managing those systems (Snowden & Boone, 2007; Holt et al., 2017). There are five system domains: simple, complicated, complex, chaotic, and disordered. Simple and complicated systems are linear, whereas complex and chaotic systems are nonlinear. *Disordered* systems are simply those which have not yet been categorized into one of these four domains. *Simple* systems are in the linear domain of "known knowns." They can be practically understood in their entirety, allowing for full deterministic prediction. Simple systems call for the categorizing of a problem into an already known course of action. Managing a simple system involves a sequence of sensing, categorizing, responding. Data is taken of the system, it is categorized into a known course of action, and then direct action is taken. *Complicated* systems are in the linear domain of "known unknowns." They are linear and deterministic in nature, and have many more elements involved than simple systems, and therefore require more skill and understanding to operate. Multiple correct though not immediately obvious solution approaches exist, and different modeling schemes can all be valid. Complicated systems can be effectively managed by a priori knowledge, but doing so requires careful analysis in addition to the implementation of legacy knowledge. For example, repairing a car or operating a private single-engine airplane under normal operational conditions are complicated tasks. Cynefin recommends that complicated systems are managed with a sequence of sensing, analyzing, and responding. Empirical data is sensed from the system, that information is analyzed methodically, and then a response is implemented.

In the nonlinear domain, the possibility for deterministic models and solution methods starts to break down. A *complex* system, under the Cynefin Framework, is characterized by emergent properties, which are often called “unknown unknowns.” Addressing a complex system is more indirect. Nonlinear systems cannot be predicted deterministically, and therefore empirical data has to be taken into account before the system can be potentially understood and effectively controlled. When there is emergent behavior, it is difficult and even sometimes counterproductive to formulate a priori rules for the system. Interpretations tend to take the form of empirical studies and loose inferences from the a posteriori data collected. There is a greater emphasis on a posteriori empirical data in managing a complex system than there is for linear systems. The central role of uncertainty in complex systems means that managing complexity requires addressing both technical and nontechnical factors. This will be discussed more thoroughly in Section 2.4. For now, take note that although complex systems cannot be predicted, they can be studied and influenced. Cynefin recommends that the appropriate conduct of leadership in complex domains is not a command-and-control approach or the avoidance of failure at all costs, but the establishing of an inquisitive, creative, open-ended workplace environment. Complex problems should be examined with creativity, patience, open-mindedness, and a toleration of risk in order to first learn about the system before formalizing various means to manage it (Snowden & Boone, 2007). Cynefin teaches that complex systems should be managed in a sequence of probing, sensing, responding. First, information is gathered about the system from various points of view through an open-ended, intuitive approach. Next, information is contextualized and related to other areas of information as observable trends begin to appear. Then, responses are made with attention to what is known and what is uncertain.

Chaotic systems are nonlinear systems that are so dynamic and unpredictable that there has to be direct intervention into the system to obtain any knowledge about it. Outside of Cynefin, "chaos" is often used in reference to systems with erratic behavior, like turbulence or ripple-effects. In Cynefin, that kind of chaotic behavior is classified under complexity since it is more moderate than something like an emergency. Cynefin's chaos is extreme to the point where action must precede understanding. The recommended management sequence is action, sensing, responding. Acting provides a means of obtaining data that can be responded to. Chaotic systems in this context are not under consideration in this thesis.

Cynefin accords with Ashby's Law of Requisite Variety. For each kind of problem domain, there is a method with requisite variety for it. A simple system can be managed simply. A complicated system calls for orderly management strategies. A complex system requires nuanced management strategies. A chaotic system should be responded to swiftly and decisively. The problem-solving sequences Cynefin recommends are commensurate with their problem domain. This brings us to a key insight in this thesis. Increasing prediction capabilities and methodological detail is not an appropriate management strategy for complex systems because doing so does not get rid of emergent properties. Cynefin's research suggests that obtaining requisite variety over a complex aerospace system does not require abandoning prediction and planning but moreover involves adopting nonlinear systems engineering processes to complement the more linear aspects of a program. Complex systems are not inherently unmanageable but rather require a management strategy that is appropriate for complexity.

These are ideas well-supported by many researchers and leaders in the field of systems engineering. Former NASA Administrator, Michael Griffin, notes that engineers for the last fifty years have "repeatedly failed to prevent catastrophes along the boundaries or interfaces between elements, [which are] often due to uncontrolled, unanticipated and unwanted interactions between elements, in many cases between elements thought to be entirely separate." (Griffin, 2010). Instead, he argues, engineers have kept trying to fix the problem by fixing the process. For Griffin, increasing levels of procedural fidelity is not where the root solution resides. "We need to rise above process, to examine the technical, cultural, and political mix that is 'system engineering', and to examine the education and training we are providing to those who would practice this discipline." This claim was echoed forty years earlier by NASA Administrator, Robert Frosch, "We have lost sight of the fact that engineering is an art, not a technique; technique is a tool." (Griffin, 2010). A 2015 INCOSE white paper titled, "A Complexity Primer for Systems Engineers," reports:

> "Throughout its history, systems engineering has been the primary method for engineering in the face of complexity. As the complexity of systems and their contexts has grown, systems engineering methods and tools have increasingly fallen short of what is needed in the face of this reality. A common approach has been to seek clever ways to simplify, or reduce, the subjective complexity

> so that the problem and the system are understandable. Scientific advances have, in fact, often come from elegant simplifications that model the important variables or forces that dominate behavior. However, this is not always possible – complexity often cannot be simplified away without losing the essence of the problem or possible solutions. Further, this simplification leads to an inability on the part of the solution to be able to engage with the complexity that remains despite our preference to assume it away." (Sheard et al., 2015).

Holt et al. state,

> "A new paradigm is needed for systems engineering to account for the unpredictable nature of complexity. Standard systems engineering techniques used to create large modern products have resulted in an exponential growth in time and development cost due to complexity. Simply adding layers of modification to the existing paradigm will not work because complex problems today cannot be solved using deterministic or stochastic methods. As evidenced by the growth of integrated hardware and software for large aerospace systems, standard systems engineering is not obsolete, but it will not work for everything anymore." (Holt et al., 2017)

Foster, Kay, and Roe write in "Teaching Complexity and Systems Thinking to Engineers" that:

> "The notions of systems and complexity were developed as a response to dissatisfaction with the science that dominated in the early 1900s. In the systems literature such science is commonly referred to as 'Newtonian.' Reflecting this description the philosophical underpinnings of Newtonian science are seen as

including linearity, predictability, control, and the attainability of perfect knowledge." (Foster et al., 2001)

There is a strong case that much of the emergent risk observed in the recent decades of aerospace is a result of relying exclusively on linear processes in nonlinear domains. This is not to say that formally organized systems engineering methods are inherently opposed to managing complexity. It is to say that to effectively manage complex system development, there needs to be a management strategy that reduces the impact of unpredicted events.

2.4 Objective and Subjective Complexity

Engineering is performed by people, for people, and therefore there are many subjective factors in engineering programs that deserve systematic attention (McGowan et al., 2013). Engineering is not limited, strictly speaking, to the technical processes of design and development, but also encompasses a diversity of roles, disciplines, processes, perspectives, and cultural forms related to technological system development. Many of these subjective elements are latent in the industry as customs, such as: organizational leadership styles and hierarchies; program planning methods and tools; traditions of standards, procedures, protocols, documentation, assumptions, design methodologies, legacy knowledge, and empirical models; professional organizations and governmental bodies; language and broader cultural values; and engineering education paradigms. These customs evolved through many iterations of failures and successes of earlier programs and are therefore apt for addressing many aspects of engineering. These subjective aspects of engineering are important for complex system development.

Sillitto describes *subjective complexity* as the "inability of a human mind to grasp the whole of a complex problem and predict the outcome," and *objective complexity* as "technical or system characteristics that lead to the subjective complexity or difficulty" (Sheard et al., 2015). Sillitto's objective and subjective complexity are rather light and informal, yet they were presented in 2015 by leading members of the International Council on Systems Engineering (INCOSE). There is a lot of research to be done on defining complexity for systems engineering. For the sake of the present discussion, it is relevant to differentiate between objective and subjective complexity to show that there need to be management strategies that address complexity in human behavior and not merely technical details.

Objective complexity is the main definition of complexity given earlier: the quality of a system exhibiting emergent properties due to having many components with tight coupling between them. Objective complexity refers to the organization of a complex system. It can apply to everything from the specific hierarchy of each element in the system to the various feedback mechanisms which occur between those elements under differing circumstances. As mentioned, the X-30 design was objectively complex. The X-30 program was also subjectively complex, since it involved thousands of engineers working in tightly interrelated ways. The thousands of engineers are the many components to the program. The tight coupling comes from the program having thirty-eight advanced technical milestones to reach, which made the developers significantly dependent on each other's work. The objective complexity of the program produces subjective complexity. The mishmash of people working on NASP led to many emergent properties, such as the confusion over what exactly the program was attempting to develop as well as the discord in work expectations between the many players involved. Engineering programs involve people, and human behavior is complex, since people have many emergent properties in their individual and group behavior (Mitchell, 2009; Gleick, 2008; Clearfield & Tilcsik, 2018). This is subjective complexity.

Objective and subjective complexity come from different sources and therefore should be handled differently. Objective complexity can arise from factors like tightly coupled subsystems, large digital networks, nonlinear operational environments, integration effects, coupled failure modes, real-world factors, unplanned off-design conditions, and unforeseen stakeholders. Subjective complexity can arise from factors like advanced technology, excess uncertainty, miscommunication, scope creep, poor documentation, hasty planning and coordination, insufficient or late testing, concurrent technology development, tension between user needs or requirements, inadequate design tools and processes, and decision-making biases. In aerospace programs, complexity tends to correlate with such things as advanced technology development, excess ambition and inexperience, multiple flight regimes, multirole aircraft, high maneuverability, high speed, high altitudes, stealth, many communication pathways, and low redundancy. Responses to complexity should be grounded in a rigorous understanding of sources of complexity in general, which highlights features that would otherwise remain subtle or hidden. Appropriate response strategies would emphasize the respective origins of complexity. Objective complexity calls for attention to the system at hand. Subjective complexity calls for attention to the conditions of knowledge, both assumed in models and embedded in design methodologies. Responding to objective complexity is perhaps a more straightforward task than responding to subjective complexity, since the challenge of objective complexity comes from the objective system. Subjective complexity calls for taking into account the criteria embedded in knowledge about a system.

There can also be a subjective complexity that arises from an objectively complex system. This is the main kind of complexity that poses the paradigmatic problem of complex systems engineering. To address the subjective complexity of designing an objectively complex system, it is important to integrate nonlinear thinking into systems engineering strategies. Nonlinear thinking and behavior are better equipped for addressing objective complexity than more linear thinking and behavior because they provide a mechanism for obtaining requisite variety. A complex process can access similar varieties of states as a complex system, which is essentially what Cynefin teaches. This brings us to where creativity becomes important in complex systems engineering: as a mechanism for addressing the subjective complexity of developing objectively complex systems.

Chapter 3

CREATIVITY

At first glance, creativity may seem like a far-removed topic from aerospace engineering. On the contrary, engineering is fundamentally a kind of creative activity. Therefore, looking into how creativity works can help improve systems engineering methods. Moreover, creativity research addresses and offers resolutions to the paradigmatic problem of complex systems engineering. As such, fostering creativity in aerospace systems engineering could be used as a complexity management strategy. In this chapter, we will explore the relationship between creativity and aerospace engineering. In Section 3.1, a definition of creativity is formalized for the context of aerospace engineering so as to clear up misconceptions and set the stage for the subsequent discussion. In Section 3.2, we will look at how creativity in general brings together reasoning and intuition through convergent and divergent thinking, with some basic application to aerospace programs. In Section 3.3, we will more thoroughly examine why creativity is aptly suited for addressing the problem of complexity in aerospace. Section 3.4 pertains to the motivational factors in creativity in the context of aerospace. Section 3.5 applies research about the stages of the creative process to aerospace programs. Section 3.6 compares two systems engineering paradigms for facilitating creativity: first the paradigm of Agile, which formally loosens processes, secondly the paradigm of Waterfall, which aims at formalizing effective processes. This will serve as conceptual background for Chapters 4, which summarizes existing strategies for facilitating creativity, and for Chapter 5, which recommends new strategies for facilitating creativity.

3.1 Defining Creativity for Engineering

To make sense of how engineering is a creative process, we will first form a definition of creativity that makes sense for engineering. It is a common misconception that creativity is novelty produced by informal, artistic means. As David Cropley, a central figure in the research of engineering creativity, writes, "…creativity is often associated with lack of rigor, impulsive behavior, free expression of ideas without regard to quality, and similar 'soft' factors" (Cropley, 2015). On the contrary, the evidence and consensus among researchers is that novelty makes up only one half of creativity, the other half being practical skill. Creativity is not mere novelty but instead combines novelty with practical skill. This gives us the definition that will be used here: *creativity* is the capability to solve problems in novel and useful ways (Russ, 1993; Amabile, 1996; Csikszentmihalyi, 1996; Cropley, 2015). It is not merely the ability to produce novelties, which is *inventiveness*, nor is it merely the ability to make useful products, which is *technical skill* (Csikszentmihalyi, 1996; Lehrer, 2012). Being a creative engineer requires both a great deal of knowledge and enough cleverness to implement that knowledge well. This is clearly evidenced in famous engineers of history, like Nikola Tesla, the Wright brothers, Kelly Johnson, Jack Northrop, and Werner von Braun. They are not remembered for being either visionary or practical: they are remembered for the transformative impacts their systems left on society (Csikszentmihalyi, 1996). These individuals were not only deeply knowledgeable about their fields, they also could think outside-the-box to develop exceptionally effective solutions to the problems of their times. The fact that they were able to engineer creative technology meant that they had to be able to combine inventiveness with technical skill.

Undergirding every creative act, big or small, is this combination of novelty and technical skill. This is the broad consensus among creativity researchers. "Creativity means a person's capacity to produce new or original ideas, insights, restructuring, inventions, or artistic objects, which are accepted by experts as being of scientific, aesthetic, social, or technological value" (Vernon, 1989). "A product or response is creative to the extent that appropriate observers agree it is creative… [whenever it is] novel and appropriate, useful, correct or valuable…to the task at hand" (Amabile, 1996). "A product is creative if old facts are integrated in new ways, new relationships emerge from old ideas, or there is a new configuration. Novelty, however, is not a sufficient [criterion]" (Russ, 1993). Creativity does not belong to the arts and humanities any more or less than it belongs to the STEM fields (Cropley, 2006; Lehrer, 2012; Csikszentmihalyi, 1996).

"Creativity is really a form of problem solving" (Guilford, 1968; Russ, 1993), and it is a central aspect of engineering. Engineering is, fundamentally, the practice of creating technological systems that satisfy a set of user needs, and every engineer uses some amount of creativity in their work (Cropley, 2015; Cropley, 2020). Engineers can be creative as individuals or as teams, and many attributes of individual creativity can be effectively scaled up to group creativity and vice versa (Cropley, 2020). Creativity can be a personality trait or a learned quality, and it can be facilitated or hindered by environmental factors, culture, and team dynamics (Csikszentmihalyi, 1996). Creativity can also be ascribed to the object or idea created, as in when something is judged to be creative. So, creativity is both a process of developing a system and an attribute that a system can have (Russ, 1993). Here, we will be focusing on the creative process of engineering rather than creative products or creative personalities. It is the creative process that has the most relevance for aerospace systems engineering.

Engineering is a kind of creative activity, and therefore it is important for engineering processes to facilitate creativity. As mentioned, there is a common misunderstanding that creativity is the same as novelty. Once this misunderstanding is removed, it becomes more apparent that engineering is, ipso facto, a creative process. Engineers create things, and therefore engineering is a creative process. This observation opens up a new way of addressing problems in engineering methods. Problems in engineering can be addressed as obstacles in the creative processes of engineering. On its own, this is a good enough reason to study the relationship between creativity research and aerospace systems engineering. Yet, there is an even better reason for doing so, which will be espoused in Sections 3.2 and 3.3. Before proceeding to discuss this and how creative behavior works, there are additional clarifications which are useful to make. First, we will consider the generalized nature of creativity and its applicability to systems engineering. Then, we will address why "creativity" was selected as the present research topic rather than another similar topic such as "design" or "innovation."

In stating that engineering is basically a kind of creativity, this is not to reduce sophisticated engineering tasks to simple, generic behaviors. Although creative processes can appear in many forms – e.g., painting, architecture, city planning – creative processes never happen in a generic way, i.e., creativity always happens in a specific context. There is a longstanding debate over whether or not there are consistencies in cognition and behavior across different fields of creativity (Cropley, 2020). For instance, do painting and engineering involve similar thoughts and behaviors? Without settling the debate, it is widely agreed that creativity has aspects which are unique to a specific field and aspects which are generalizable. Insofar as creativity can be generalized, its generic aspects can be abstracted and applied to specific contexts. Yet the generalized creative process does not include all aspects of a specific field. For example, painting and architecture are creative activities even though learning about creativity does not teach one how to paint or design buildings. Learning about creativity does, however, improve one's ability to apply technical knowledge about painting and architecture. Likewise, creativity has relevance to engineering as a whole. Even though creativity research does not contain the specific, technical aspects of engineering, comparing the general processes of engineering against the general processes of creativity provides a useful means for evaluating and improving the quality of engineering methodologies. Those aspects of engineering processes which are consistent across programs, such as methodologies and modeling platforms, are general in nature, and can be compared to the creative process more directly than activities which are specific to a program. Systems engineering is a generalized discipline, so it can be compared against general principles of creativity.

There are numerous words similar to "create" that are sometimes used interchangeably, such as "design," "develop," "produce," "make," "invent," and "innovate." In this thesis, these words are used selectively even though in most practical circumstances it is not necessary to do so. It is worth giving a brief overview as to why "creativity" was selected as the main topic rather than "design" or "development." Some might argue that "create" is just a synonym for "design" or "develop," and therefore studying engineering creativity is a redundant reframing of design science. This viewpoint misunderstands the motivations and implications of engineering creativity. The study of engineering creativity looks at the subjective processes involved in the act of making systems, from a multidisciplinary perspective and often with a heavy reliance on psychological research.

Similarly, "creativity" is studied here rather than "invention" or "innovation" because the paradigmatic challenge of complexity in systems engineering is more a problem of cognitive dissonance than a lack of technical capabilities ("Invent;" Cropley 2015; Verganti 2008; Verganti & Oberg 2013; Cropley 2015; Burton et al., 2011). The ultimate goal of fostering creativity, as presented here, is not the invention of unique and innovative systems but the potential for obtaining a cognitive edge on complexity. Creativity emphasizes subjective elements more than other words with a meaning close to that of "create," even though in practice it is not strictly necessary to be precise about words related to "create."

Now that a definition of creativity has been formed and some common misconceptions have been clarified, we will proceed to look at how the creative process is composed of convergent and divergent thinking. This will set the stage for understanding how creativity is a viable solution strategy for managing aerospace complexity.

3.2 Creative Behavior Consists of Convergent and Divergent Thinking

The creative process involves an interplay between two processes called convergent thinking and divergent thinking, and for this reason facilitating creativity is a potentially viable strategy for addressing the paradigmatic problem of complexity in aerospace systems engineering. This section describes and compares convergent and divergent thinking in a general context and in the context of aerospace system development; several misconceptions about the creative process are addressed; and an introductory explanation is given for how and why creativity research applies to complexity in aerospace programs, which is expanded upon in Section 3.3.

Convergent thinking refers to the more organizational side of creativity: an analytical, logic-oriented, conceptual state of critical reasoning with "the ability to find a single, correct solution" (Cropley, 2020). *Divergent thinking* refers to a more intuitive, fluid, dynamic state of free-association, broad scanning, and idea-generation, "the ability to ride the associative currents" (Wallach, 1970). Divergent thinking is related to "transformation abilities," which includes thinking outside the box, being cognitively flexible, and using multiple paradigms (Russ, 1993). As mentioned, convergent thinking tends to be reductive and focused and divergent thinking tends to be holistic and defocused. Convergent thinking tends toward rational organization, whereas divergent thinking tends toward intuitive relationships. This duality maps onto the two-pronged definition of creativity: the usefulness of creative products comes from convergent processes and the novelty of creative products comes from divergent processes (Levi, 2017). Convergent states are more conceptual and linear in nature, whereas divergent states are more intuitive and nonlinear (Russ, 1993; Csikszentmihalyi, 1996). Note that "conceptual thinking" is organized by logical reasoning, whereas "affective thinking" is organized by feelings (Russ, 1993). Affect is important in making possible associative leaps of meaning, such as those involved in humor, figurative language, and idea-generation. Studies have shown that access to affective, intuitive states may facilitate the creative insight process (Metcalfe, 1986). It is thought that being more in tune with affective states entails being more in tune with non-conscious intuited patterns and, subsequently, the mental processes behind the flash of insight (Russ, 1993). Therefore, sensitivity to affect is closely related to the ability to be creative. To be closed to affect-laden thoughts is to be closed to creative processes. For the purposes here, it will be helpful to consider affect, insight, and intuition as linked together. When one of these terms is referred to in this present work, it is correct to think of the others as well. This also follows from alternative theories of neuropsychology (Taylor, 2009).

There is some evidence that convergent and divergent thinking are delegated in part to different hemispheres of the brain. In convergent thinking, the left hemisphere is more active than the right hemisphere, whereas in divergent thinking, the right hemisphere is more active. However, in both convergent and divergent thinking, the left and right hemispheres are both active, only varying in degree (Carlsson et al, 2000). In the context of this present work, observations about the neurophysiology of creativity are by no means critically important. Nevertheless, it is simply worth mentioning that neurophysiological research shows that creativity involves coordination between diverse brain activities. Just as creativity is not novelty or technical skill but rather their combination, creativity is also not merely a divergent behavior or a convergent behavior but both in coordination. This characteristic of creativity integrating different kinds of thinking plays an important role in this thesis that will be elaborated on later.

In the creativity research literature, these processes are usually referred to as convergent and divergent "thinking" so as to discuss them in terms of cognitive states. However, these processes do not always happen as an internal state but can appear as an outward behavioral pattern, so they can also be called "processes" rather than "thinking." It makes little difference in this context, and so "processing" and "thinking" will be used interchangeably. Creativity depends on the effective interplay between these convergent and divergent thinking states (Russ, 1993; Levi, 2017).

Recent empirical studies show that these two sides of the creative process are not mutually exclusive cognitive states. Convergent thinking is not exclusively conceptual and linear, nor is divergent thinking exclusively intuitive and nonlinear (Gabora, 2017). Rather, it is more accurate to understand the difference between convergent and divergent thinking as a narrowing or widening of focus between specific or general contexts. Convergent thinking is creative thinking with a tendency to specify thoughts to one context; divergent thinking is creative thinking with a tendency to generalize thoughts to an open-ended context. The ability to shift between these different contexts can be called *contextual focus* (Gabora, 2017). Creativity is contextual focus effectively applied to the forms and functions of systems. Contextual focus can also be interpreted as the capacity for systems thinking. Thus, creativity can be understood as a kind of systems thinking applied to the development of useful and novel systems.

The linear nature of convergent thinking and the nonlinear nature of divergent thinking can be attributed to the cognitive faculties most active in either state. Reasoning focuses on specifying information and organizing it logically, whereas intuition focuses on relating information and finding general patterns. In this way, convergent thinking is relatively more linear than divergent thinking, whereas divergent thinking is relatively more nonlinear than convergent thinking. Even though neither process is entirely linear or nonlinear, it is still appropriate and useful to think about convergent thinking as linear and divergent thinking as nonlinear when understood in this moderate sense.

Furthermore, it follows that the dichotomy between convergent and divergent thinking is not a difference between orderly and disorderly thinking. Both convergent and divergent thinking are focused, but in different ways. Convergent thinking focuses on specifying and organizing information, whereas divergent thinking focuses on making associations between diverse fields of information. This can be described in terms of conceptual design. Broadly exploring potential design spaces in a nonlinear way is divergent thinking. It may appear unfocused and disorderly even though it is purposeful and useful for the whole design process. Divergent thinking focuses on an open-ended problem domain. In this way, divergent thinking is orderly even though its nonlinear appearance can make it look unfocused and disorderly. On the other hand, focusing on a specific trade space is convergent thinking. Doing so may appear exclusively linear, analytical, and without affect. Yet, within the boundaries of the trade space there is broad scanning and associative thinking, such as in the many critical questions that are posed for evaluating a design's feasibility or compliance to requirements. Convergent thinking focuses on a well-defined problem domain and makes associations within it. In this way, convergent thinking is not diametrically opposed to divergent thinking. On the whole, convergent and divergent thinking are closely interrelated in creativity, which has the significant conclusion that linear and nonlinear thinking are closely interrelated as well, a point which is the topic of Section 3.3.

These findings contradict what has been called the Blind Variation Selective Retention (BVSR) theory of creativity. The BVSR model holds that divergent thinking is a probabilistic process of trial-and-error, where new ideas are generated through random perturbations of a mental state space. Although it has an obscure title, the BVSR model fits with the common misunderstanding of creativity mentioned earlier. Many people believe that being creative means randomly generating novel ideas without practical focus. In contrast, the more recently formulated Honing Theory (HT) of creativity builds on the aforementioned research. HT posits that creativity is a process of contextual focus motivated to hone in on mitigating what can be called "psychological entropy." *Psychological entropy* is an uncertainty which produces a sense of anxiety, dissonance, boredom, curiosity, or awareness of a problem. In the case of design programs, psychological entropy originates in the user needs. The entire design process is motivated by the user needs and functions as an effort to resolve them. This concept will come back into play in Section 5.2.

For the present discussion, there are some implications of HT that are important. HT presents empirical studies with strong evidence that divergent thinking is better modeled as a chaotic process than random. This research means there is a tangible exchange of linear and nonlinear information in creativity (Gabora, 2017; Sabelli & Abouzeid, 2003; Guastello, 2002), which has many significant implications. For one, creative processes could be modeled mathematically. Moreover, it is relevant to the research presented here as a justification: creativity bridges linear and nonlinear information, and therefore creativity could be used as a mechanism to better account for emergent properties, the unknown unknowns of complex systems. There are two primary ways this finding is applied in the recommendations of Chapter 5.

Convergent and divergent thinking are complementary aspects of engineering creativity. In engineering, divergent processes search for potential design solutions, operational conditions, potential interactions, while convergent processes make sense of what is found, analyzing and evaluating design performance. Oftentimes, these processes are operating simultaneously. During trade studies, there are efforts to find and understand various candidate designs at the same time as efforts to optimize and reduce the number of selections. Sometimes, one of the two processes is dominant over the other. Verification, validation, and design reviews are primarily convergent processes, checking to see if a design will perform as expected. In verification and validation, there is also divergent thinking involved, such as in coming up with operational conditions at which to test the design, but divergent thinking is subordinate to convergent thinking. In all, convergent and divergent thinking work together toward making designs that effectively satisfy the needs of the end user.

Depending on how difficult it is to develop a system that satisfies the user needs driving a program's requirements – which can result from many factors, such as how advanced the design space is, or the budget and schedule allotted for program completion – there is a range of potential designs for those user needs. There is an enormous variety of possibilities for how a design process can unfold. Sometimes, there are many feasible design solutions to the RFP. Sometimes, there are no feasible design solutions to an RFP. And there can be a whole spectrum of gray in between, a whole range of uncertainty about the user needs and the requirements formed to articulate them. For instance, here are some ways that can pan out. The customer can request a system with feasible goals and the designers work to meet them. The customer can request a system with infeasible goals and designers develop requirements which are attainable but do not meet the user needs exactly. The customer inadequately articulates their goals, and the designers develop requirements that better address the user's actual needs. There can be recognition of shortcomings in both the communicability of the user needs and the feasibility of designs to meet them. There can be ongoing tension and struggle regarding the articulation of user needs and the feasibility of designs intended to satisfy those goals. In practice, there could be any number of cases where a user need is not exactly captured by a set of requirements. The point in mentioning them is to emphasize that there is a divergence of many potential design spaces, and that there is a need to converge the design spaces to candidate configurations which can be prioritized and downselected. The necessary dynamic between divergence and convergence that arises even in the early phases of formulating requirements is an example of the creative process.

More broadly speaking, during conceptual design, design spaces are explored and examined through activities like the deriving of requirements and trade studies. First, there is a process of developing derived requirements, which starts out with many possibilities and is then refined. Once major constraints are established for the design, a design space is mapped, which excludes infeasible designs and opens up a range of potential configurations. This design space is optimized down to a set of candidate configurations. Then, more work is done to study each of these configurations so that they can be compared. This is followed by a process of downselection to find a conceptual design suitable to the user needs.

The processes of expansion – imagining possible derived requirements, mapping a design space, studying candidate configurations – are divergent processes. The processes of reduction – defining a design space with derived requirements, disregarding inefficient configurations, downselecting candidate configurations – are convergent processes. Divergent processes expand the set of candidate designs and relate aspects of different designs. Convergent processes reduce the set of candidate designs and organize aspects of a design toward the end user needs. Figure 2 represents this interplay between convergent and divergent processes in conceptual design.

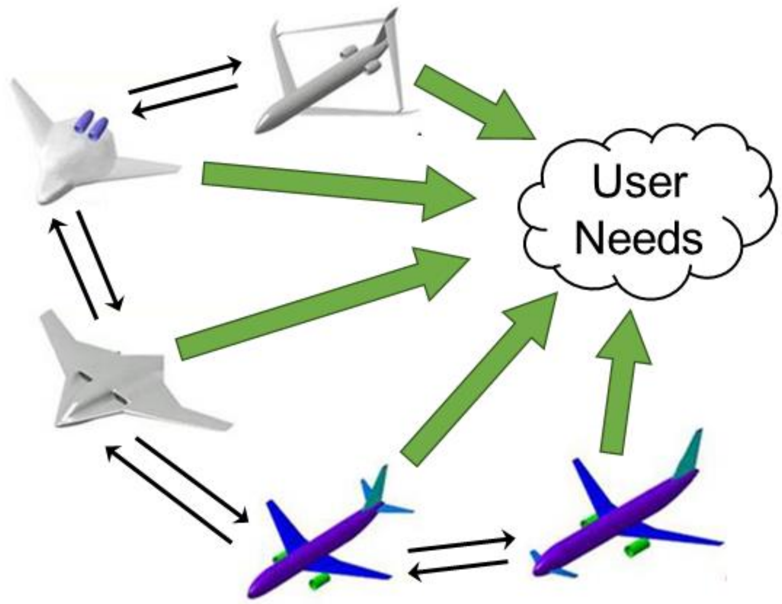

Figure 2. *Convergent and divergent interplay in conceptual design.* (Gipson, 2017)

Convergent and divergent processes occur throughout design and development, not just in conceptual design, such as in the design of a component, where many candidate designs are analyzed, synthesized, and evaluated. In analysis, there is a range of potential designs examined, then refined. In synthesis, the same happens on the level of integration. Then in evaluation, various test conditions are selected and then the system is verified and validated.

The interplay of convergent and divergent thinking in engineering is a synthesis of linear conceptual thinking and nonlinear intuitive thinking. Engineering is not only comprised of conceptualizing, analyzing, and linear organization. Engineering integrates affective divergent thinking alongside conceptual convergent thinking. This observation leads to a significant conclusion. Just as complexity in systems engineering presents an inherent dissonance between the linearity of reasoning and the nonlinearity of complexity, creativity presents a means for coordinating between convergent thinking and divergent thinking. Thus, the creative processes of engineering provide a mechanism for addressing the paradigmatic challenge of complexity in aerospace. This conclusion will be examined in greater detail in the following section.

3.3 Rationale for Creativity as a Complexity Management Strategy

Creativity involves an integration between linear and nonlinear thinking, which has the implication that facilitating creativity is a promising candidate for managing complexity. The majority of researchers of creativity agree that creativity integrates linear, conceptual thinking with nonlinear, intuitive thinking, although there is disagreement on how exactly that occurs. The research here by no means attempts to resolve the question. The prime importance of this finding is that creativity could be used as a mechanism to manage complexity. In this section, there are two areas of complexity that creativity has potential to address. There is the complexity that is perennial to all engineering programs, such as the objective complexity of unforeseen circumstances and the subjective complexity introduced by people working on a program. And there is the paradigmatic problem of complex system development, which is the main focus of this thesis.

3.3.1 Fostering Creativity as a Response to Common Sources of Complexity

Whether or not an engineering system is complex, there has always been some amount of complexity common to engineering programs. Here are four common areas of complexity in engineering programs that fostering creativity can address: the objective complexity of unforeseen circumstances, the subjective complexity of people involved in a program, the subjective complexity of user needs, and the complexity of efficiently designing to a set of user needs.

All engineering programs have some emergent properties, such as integration effects, unresearched flight conditions, and changes in the program budget or timeline. These can be considered as objective complexities. Although there will always be some unknown unknowns in any program, fostering creativity can help in mitigating the risk of these complexities by increasing the adaptability of the design organization. Creativity increases the likelihood of imagining unforeseen circumstances and developing effective responses to those emergent properties when they do arise (Cziksentmihalyi, 1996).

Even if an engineering system is not itself objectively complex, the development process involves people, and they can introduce subjective complexity into the program. With many employees working on a program, there becomes more potential for misunderstandings and diverging goals. A large engineering program is difficult to coordinate. Systems engineers have the responsibility of trying to coordinate between the different groups in a program to satisfy the program's requirements within allocated time and budget. Each engineering group and sub-group has its own emphasis, which means that they approach the system-level requirements program from different angles (Drake, 2018-19). This introduces subjective complexity into the program. When the vehicle under design is itself objectively complex, the challenge of coordinating and integrating the work of many engineers becomes that much more difficult. Fostering creativity through systems engineering methodologies can help provide balance between convergent and divergent thinking on an organizational scale, so that the complexity of managing the diverse teams is more intuitive and cohesive (Lehrer, 2012). For creativity, the challenge of making sense of many threads of highly interrelated information that is also constantly in flux is not an obstacle but rather acts as a positive motivator for problem solving (Csikszentmihalyi, 1996).

There is also a subjective complexity that emerges in the difference between user needs and formal requirements. Ultimately, requirements are determined from user needs. Requirements should be well-formed, clearly articulated, and verifiable (Drake, 2018-19). Essentially, program requirements should be linear. User needs, on the other hand, are by nature more nonlinear than the requirements developed to articulate them (Vincenti, 1990). As mentioned, there is a lot of gray area in trying to create and satisfy feasible requirements that adequately express user needs. There can be competing objectives in different requirements, requirements can misrepresent their corresponding user need, requirements can be poorly written, user needs can be impractical to begin with, etc.. User needs come from people, and so they are not guaranteed to be coherent. The challenge of formulating effective requirements for qualitative user needs is a subjective complexity. Fostering creativity can address this area of complexity by increasing the design organization's ability to create effective requirements. Moreover, enhanced creativity makes it easier to see how to satisfy apparently competing objectives or to address the user need behind the requirement in an unexpected way (Cummings & Hall, 2004). This transitions into the fourth area of complexity perennial to engineering programs.

Fourthly, the process of figuring out how to design a successful system is itself a subjectively complex undertaking. Overseeing an engineering program involves many interdependent, moving pieces, and coordinating the program toward making a system that fulfils the system-level requirements can be a serious challenge. The design and development process can take on coordinating between various hierarchies, groups, individuals, teams, organizations, etc. is by no means simple. Aerospace design is inherently a complex process. Despite this complexity, it is true that there are many successful systems in flight today. Although there have been numerous programs which ended in disorder as inefficient hairballs, some flight systems exhibit such a high degree of efficiency and sophistication that they are widely considered to be elegant systems. Creativity can turn the subjective complexity of aerospace design into an elegant system (Griffin, 2010). As a fundamentally creative process, improving the creativity of an engineering program can also mitigate some of the emergent risk inherent to any design process. This is by no means a new solution approach to the problem of complex systems engineering. Many best practices of systems engineering already function to facilitate engineering creativity.

3.3.2 Fostering Creativity as a Response to Complex System Development

Beyond addressing various areas of complexity that commonly appear in engineering programs, fostering the creative process through systems engineering can function as a mechanism for obtaining requisite variety in complex system development. As stated, the interplay of convergent and divergent thinking in creativity integrates linear and nonlinear types of information. In the creative process, reasoning and intuition are complementary cognitive faculties. Psychologists often consider intuition as *primary process* and reasoning as *secondary process*, because intuitive information is not abstracted from sense experience whereas rational concepts are abstracted. Creativity is sometimes classified as a *tertiary process*, in that it primary and secondary process (Runco, 2020). From this perspective, the paradigmatic problem of complex systems engineering is that there is a need for tertiary processes, since they integrate linear and nonlinear types of information. Creativity, as a tertiary process, can fulfill this role.

This idea is reinforced by research on creative personality traits, shown in Figure 3. Many of the traits, processes, and abilities important in creativity are also important for managing complex systems, such as tolerance of ambiguity, openness to experience, curiosity, preference for challenge, preference for complexity, and risk-taking. This supports that effectively managing complex domains and facilitating creative behavior are complementary aims.

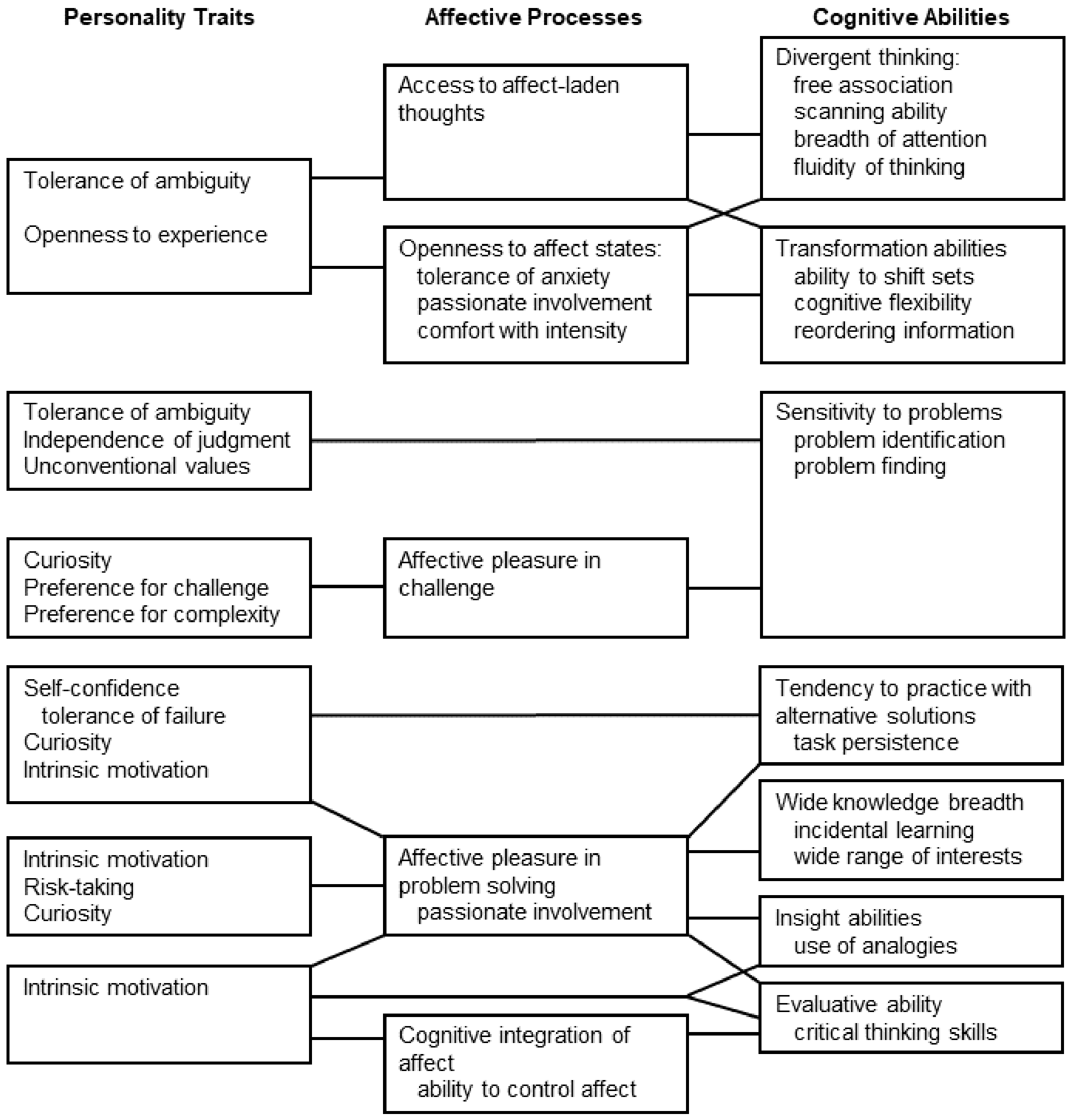

Figure 3. *Creative personality traits, creative affective processes, and creative cognitive abilities, arranged based on empirical studies (Russ, 1993).*

Facilitating creativity through systems engineering can function as a mechanism to account for the subjective complexity of developing objectively complex systems. Creativity is itself a complex process, a tertiary process, and for this reason it can be used to give engineers a cognitive edge on the challenge of working in a complex design domain.

In Section 5.1, this idea is represented as an actual systems engineering group that functions in a similar manner to creative tertiary process. For now, this information is a rationale for why creativity could be used to decrease emergent risk.

3.4 Motivational Factors in Creativity

Creativity is an affect-laden process, and, as such, emotions play a central role in being or not being creative. Creativity is highly dependent on motivational factors. Understanding these motivational factors is critical for the present study. Before going further, two clarifications will be made.

First, creative motivational factors tend to be consistent across scales. In other words, individuals and groups can be motivated to be creative in similar ways. The difference is that rather than facilitating the creativity of one mind thinking on its own, creativity is facilitated for a collection of minds interacting together. Many of the patterns of creative behavior can be abstracted in a way that is consistent across these scales, from an individual mind to small teams, all the way up to a large organization (Csikszentmihalyi, 1996).

Second, empirical studies have shown that everyone is creative, especially during childhood (Csikszentmihalyi, 1996). It is not true that creativity is an innate quality limited to some, where some are virtuosos, and some are not, even though it is true that there are definite personality traits associated with creativity (Russ, 1993). One's tendency to remain creative past childhood is facilitated through a combination of nature and nurture, i.e., one's biological predisposition and the environment in which one was raised (Csikszentmihalyi, 1996; Lehrer, 2012). In the vast majority of cases, when creativity is discouraged or not utilized, it becomes a forgotten skill. Yet, it can be relearned through practice under the right conditions (Lehrer, 2012). Now we will proceed to examine the motivational factors behind creativity.

3.4.1 Defining Intrinsic and Extrinsic Motivation

Intrinsic motivation facilitates creativity and extrinsic motivation hinders creativity. *Intrinsic motivation* is based on individual desire, a love for doing a task for its own sake and is characterized by a free-flowing state of focus known as “flow” (Russ, 1993; Csikszentmihalyi, 1996). On the other hand, because creative processes are sensitive to internal affective states, blocking attention from internal feelings can inhibit creativity. This tends to occur through the introduction of stressful external performance expectations on an individual’s internal thinking and feeling states. This is called extrinsic motivation. *Extrinsic motivation* is based on external performance goals and tends to involve stressful feelings and divided thoughts. Major creativity researchers Amabile (1996) and Hennessey (1996) give five “sure-fire killers of intrinsic motivation and creativity: expected reward, expected evaluation, surveillance, time limits, and competition.”

> “Over 25 years of investigation into these motivational orientations have led us to the Intrinsic Motivation Principle of Creativity (IMPC): Intrinsic motivation is conducive to creativity, and extrinsic motivation is almost always detrimental. In

its earlier incarnations, this proposed relation between motivational state and creativity of performance was advanced as a tentative research hypothesis. But investigators working in this tradition have gathered so much unequivocal empirical evidence that this proposition has been elevated to the status of an undisputed principle." (Hennessey, 2003).

Aerospace engineering's relationship with extrinsic motivation will be examined intermittently in the remainder of this thesis. For now, note that insofar as aerospace programs foster "expected reward, expected evaluation, surveillance, time limits, and competition," the creativity of aerospace engineers is hindered.

Formal mechanisms designed to foster creativity often end up restricting creativity unintentionally, because the motivational factors behind creativity are poorly understood (Lehrer, 2012; Csikszentmihalyi, 1996; Cummings & Hall, 2004). Creativity is a complex process that depends on many tightly coupled motivational factors. Attempting to deterministically cause creativity to happen through external constraints, such as hierarchies and protocols, can produce extrinsic motivation that, in turn, blocks off the affective states necessary for divergent thinking and tertiary processing. Creative endeavors become inflexible, intolerant of uncertainty, and productivity-focused when extrinsic motivation becomes dominant (Russ, 1993). Yet, even in spite of circumstances in aerospace programs where extrinsic motivation is dominant, creativity can still overcome the negative pressure (Cummings & Hall, 2004). The fact that many large, complex aerospace systems have been created attests to it.

3.4.2 External Systems Engineering Constraints Can Facilitate Intrinsic Motivation

Formal systems engineering methodologies can be used to facilitate creativity because external constraints are not the same as extrinsic motivation. In fact, external constraints, such as program timelines and detailed requirements, can be powerful intrinsic motivators of creativity. When constraints are treated in a purely technical manner, detached from notions of social standing, constraints can encourage engineers to rise to the challenge. External pressure can actually drive intrinsic motivation (Lehrer, 2012; Csikszentmihalyi, 1996). The difference between constructive constraints, producing intrinsic motivation, and obstructive constraints, producing extrinsic motivation, has largely to do with workplace culture. And as explained earlier, creativity is not a formless generation of novel ideas, because it involves both novelty and technical skill. Formless idea-generation "derives only from nonconformity, lack of discipline, blind rejection of what already exists, and simply letting oneself go… [it] has many of the elements of genuine creativity – such as a high level of fantasy – but only a tenuous connection with reality" (Cropley, 2006). Creativity has structure, meaning that external constraints can be constructive to creativity. Consequently, it is not necessary to abandon formal systems engineering methodologies in order to better facilitate creativity. This is elaborated upon in Section 3.6.

Requirements, schedules, and criticism in design reviews are likewise not inherent obstacles to creativity. Being creative does not require a lack of dissent and complete acceptance of novel ideas. On the contrary, there is strong empirical evidence that brainstorming – a process in which criticism toward diverse ideas is supposed to be withheld – can reduce team creativity. Creativity does not thrive in an absence of dissent, but in an environment of mutual respect amid cooperative friction (Catmull, 2014; Levi, 2017). "When the team is exposed to contradictory ideas from some members, the thinking of the majority is stimulated, producing ideas that are more creative. Dissent stimulates divergent thinking and encourages the team to view an issue from multiple perspectives." (Levi, 2017). A 2010 study showed that:

> "Both too little and too much task conflict can inhibit creativity. The most creative teams had moderate levels of task conflict that occurred during the early stages of the team's project. Novel ideas, which arise from task-related conflict during early team discussions, were more likely to be valued and used to develop creative solutions. To encourage creativity, team leaders need to recognize that some conflict is good and give team members time early in the project to voice their opinions. In addition, team leaders need to create a climate of psychological safety so team members feel safe bringing up new ideas." (Levi, 2017).

3.4.3 Balancing Convergent and Divergent Thinking to Produce Intrinsic Motivation

Honing Theory provides a concise formulation for conditions favorable to intrinsic motivation. Under HT, creativity is facilitated through the balance of two factors: (1) variety of information available and (2) the probability of associating that information. Creativity operates on the edge of chaos as a kind of critical transition state (Gabora, 2017).

Creative environments provide just enough variety of information and just enough probability of associating that information that convergent and divergent thinking can easily coordinate. When there is too little variety or association, the creative state is subcritical: there is not enough background information or imaginative recombination to develop anything novel. When there is too much variety or association, the creative state is supercritical: there is too much information and imaginative recombination to focus resources. The subcritical state is too convergent; the supercritical state is too divergent. Table 1 displays various combinations of states.

Table 1. *Conditions for a creative critical state.* (Gabora, 2017)

	Low Association	**Moderate Association**	**High Association**
Few Ideas	Subcritical	Subcritical-Critical	Critical
Moderate Ideas	Subcritical-Critical	Critical	Critical-Supercritical
Many Ideas	Critical	Critical-Supercritical	Supercritical

HT does not prescribe a methodology for obtaining creative criticality. Creative criticality can be achieved in many ways. There is an optimal range for intrinsic motivation when there is a balance between convergence and divergence. For instance, a highly formalized engineering program might decrease the variety of ideas and the likelihood of associative thinking. However, an engineering program with very little formality might err on the side of being so divergent that order cannot be made out of the chaos. There should be a cohesive combination of heterogeneity and flexibility such that a program can come up with novel ideas and put them to good use. A homogeneous team working on a program with very little formality could struggle to come up with many ideas, but the freedom their program has could give them high association, letting them be creative. Likewise, a heterogeneous team working on a highly formalized program could come up with many ideas with strong potential, and the regulated environment keeps them on track so that they can meet their program goals. An imbalance of variety of information or associative probability can lead to an uncreative program. A lack or excess of both these factors can also lead to an uncreative program. HT posits that there are many ways to achieve a balance for creative criticality. It should be the job of systems engineers to evaluate what their organization should do to work toward creative criticality. In Section 3.6, we will compare how Agile and Waterfall systems engineering methodologies attempt at producing creative criticality.

Creativity depends on intrinsic motivation. Trying to deterministically generate creative behavior risks imposing extrinsic motivation. Even so, external constraints – such as requirements, design criticism, and timelines – can facilitate intrinsic motivation. What differentiates external constraints that lead to intrinsic motivation from those that lead to extrinsic motivation is specific to a workplace environment. A concise way of evaluating if a workplace culture is favorable to creativity is through Honing Theory's notion of creative criticality. To be creative, there needs to be an optimal combination of diversity of ideas and probability of associating those ideas. Under this umbrella, there are many ways to facilitate creativity, and it is the responsibility of systems engineers to evaluate this on a program-specific basis. In the next section, we will look at how the entire development process is a creative process. This will ground an understanding of how systems engineering plays a role in shaping the creativity of an aerospace program.

3.5 Stages of Creativity

Engineering is fundamentally a creative process. The entire development process of an aerospace system can be understood as a creative process. Yet, a single program is not merely on process but is composed of many smaller creative processes. Engineering programs are often organized at different levels of detail, from a sequence of design phases that governs the whole program, all the way down to the work packages in Statements of Work. Similarly, there are natural stages that form the creative problem-solving process. In this section, we will build a concept of engineering as a series of intermediate creative processes; look at the stages of the creative process in general; and comparatively apply these stages to design phases. In Appendix A, the creative process is also compared to three other representations of the engineering process: analysis-synthesis-evaluation, the engineering "V," and Technology Readiness Levels. No similar work that compares the creative process to aerospace design phases has been found in the literature. What follows is a novel integration of findings from creativity research into the field of aerospace engineering.

3.5.1 Engineering is a Chain of Intermediate Creative Processes

In an idealized sense, the entire engineering development process consists of a series of interdependent, intermediate development processes. An engineering program begins with a set of user needs being formulated into system-level requirements. Then, the RFP containing the user needs and/or system-level requirements, is used as the basis for a program plan. The program plan is used to establish and coordinate an organization of engineers. Following this, the design process begins, and then the manufacturing process. Note: these processes can happen sequentially, concurrently, or recurrently, depending on the specific program; and, for simplicity, operation, maintenance, and disposal are excluded, since the focus of this thesis is on engineering creativity, not engineering maintenance. Each entity involved can be called an *intermediate system* and each process can be called an *intermediate creative process*. Each intermediate development is its own creative process, in which one intermediate system is used to create another. User needs are used to create an RFP. An RFP is used to create a program plan. A program plan is used to organize a program. An organization is used to design a system. A design is used to manufacture the system. The product of each intermediate development is the starting point for the next intermediate development. Although the contractor may evaluate and modify the system-level requirements to map better onto user needs, as well as derive other requirements from them, their work begins with requirements. From there, the engineers will expand the scope and detail of the program until the final end product meets (or does not meet) the user needs. From this point of view, the first intermediate process, the formulation of user needs into requirements, is a sort of inverse process to the remaining intermediate processes. The "user side" of development and the "design side" of development function having inverted goals. In Section 6.2, this model will be used to propose a method for modeling complexity throughout a program.

Of course, this model also simplifies away the various phases of design and the critical milestones throughout a program plan. The point here is to show that engineering consists of a series of interrelated developments with a variety of intermediate products rather than a single, linear work path ending with a single technical system. The quality of the coordination of earlier intermediate developments tends to cascade down through the subsequent processes; and since there are greater marginal gains for reducing risk the earlier along in the development process (Raymer, 2002), it is justifiable to consider nontechnical processes and deliverables as having critical importance to engineering programs. Many of these nontechnical processes are the responsibility of systems engineering. In the upcoming sub-sections, we will examine stages in the creative process and then relate these to aerospace design phases.

3.5.2 Stages of the Creative Process

The creative problem-solving process consists of stages of behavior loosely related in a sequence. Different formulations of the creative process exist in the literature, and the distinct details are less important than the general arc of how an idea is formed and brought to fruition. This sequence is generally outlined as (1) problem finding, (2) preparation, (3) incubation, (4) illumination, (5) verification, and (6) implementation (Wallas, 1926; Russ, 1993; Csikszentmihalyi, 1996).

In slightly fuller terms: (1) the problem at hand must be given constraints (problem finding); (2) the problem must be researched and evaluated (preparation); (3) the information must be allowed to incubate, “without the individual directly, logically working on the problem,” and to be filtered through complex mental processes, many of which happen “outside conscious awareness” (Russ, 1993) (incubation); (4) there is a moment of insight harmoniously synthesizing many lines of thought, often described as a “flash” (illumination); (5) an analytical working-through of the uncovered idea (verification); (5) and an out-working of the idea into practical application (implementation).

This series of stages is not a strict rule but rather summarizes the most important elements of creative development. It is often not followed in this exact order, since creative processes tend to involve concurrent threads of work. Others have outlined the creative process as generation, promotion, design, implementation, and evaluation (Thompson, 2007), but, again, the specific details that differentiates them are negligible. Do note that the creative act is not considered the moment of imagining a solution to a problem or the moment of finally implementing it. Creativity is really an ongoing activity that begins with a vague sense of an unformulated problem and ends with the problem being specifically addressed. Figure 4 shows the sequence with a color-coding that will be followed in later figures. Incubation and illumination are both colored green because the moment of illumination often happens spontaneously during incubation.

Figure 4. *Stages of creativity.* (Csikszentmihalyi, 1996)

3.5.3 Creative Stages of Aerospace Engineering Programs

This process can be easily mapped onto a typical timeline for aerospace system development. Aerospace programs historically tend to follow the "Waterfall" program structure, in which the work of conceptual design cascades into preliminary design, preliminary design cascades into detail design, detail design into manufacturing, then operation and maintenance, and finally disposal. Of course, this sequence of phases is not strictly necessary, it is a convention. Essentially, the design phases provide a meaningful structure that is useful for the customer and the supplier. Conceptual design provides time for the feasibility of the system to be evaluated without expending a lot of resources. It also makes it easier for the customer to select between multiple bidders. Preliminary design yields a more robust design than conceptual design and gives the customer a chance to step back from the contract before committing an even larger amount of resources to it. Detail design involves the finishing touches on the system and final verifications and validations before manufacturing begins and all its costs are incurred. Maintenance and disposal involve a much smaller workforce, and the engineering tasks pertain much less to design than to operational integration, upkeep, and updating. The fact this sequence is recurrently employed in aerospace programs shows its effectiveness.

As described in Section 3.5, every phase of design has some form of product as its goal, even though they are intermediate steps toward the final product. In this way, each phase of design follows its own creative process. The product of each intermediate design phase in turn leads to the creation of the next phase and its product. It is as if the set of user needs “unfolds” into an RFP, the RFP unfolds into a conceptual design, the conceptual design into a preliminary design, the preliminary design into a detail design, the detail design into an actual system. Each design phase creates the groundwork for the next design phase. The creativity sequence can be mapped onto individual phases or onto the entire series of design phases. In practice, the six stages of the creative process do not typically map linearly onto the engineering timeline but rather occur following a variety of orders: concurrently throughout design, recurrently in different phases, as well as incrementally in some aspects. First, we will look at how the creative process maps onto the entire design process (Figure 5). Then we will look at how the creative process maps onto the processes of developing an RFP, conceptual design, and preliminary design (Figure 6). Since there are greater gains to be made on emergent risk mitigation in earlier phases of design programs (Raymer, 2002), the later phases will not be considered here.

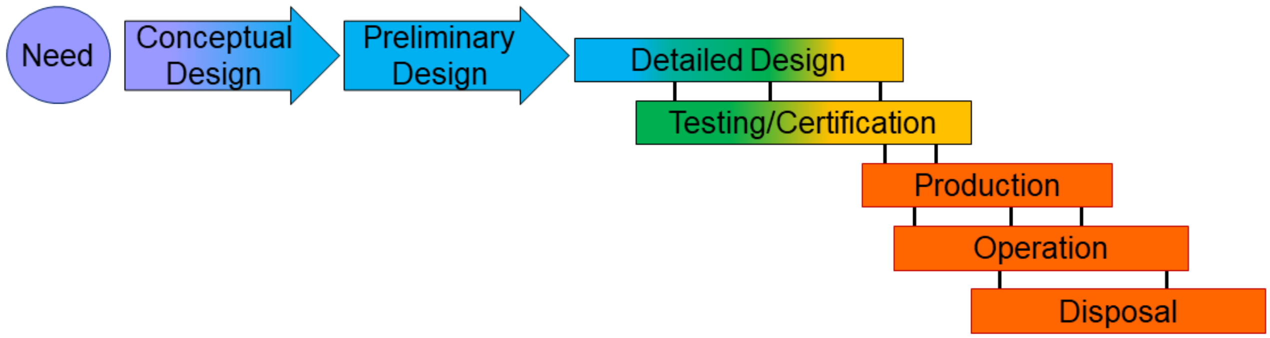

Figure 5. *Creative stages applied to a Waterfall development program.*

(1) Problem Finding: In the beginning, there is a user with some set of needs, and these needs are where the engineering design process originates. The customer representing the user will do work to understand their set of specific needs and formulate them into system-level requirements, publishing a Request for Proposal (RFP). They may collaborate with contractors and consultants during that process. A contractor may also first approach them with a formulated set of needs and the potential for a system to meet those needs.

(2) Preparation: After an RFP has been published with a set of system-level requirements, the early phases of contractor work begin, starting with program planning. Before committing to a program, a contractor will develop a program plan in order to evaluate whether the contract is worth pursuing. This plan will include a study of the required system capabilities, a Work Breakdown Structure (WBS) and Statement of Work (SoW), a corresponding budget and schedule, an estimate of risk, and other related activities. If the program seems feasible and worthy of investing resources, the contractor will move forward to designing and developing the system. The contractor may begin by evaluating the user and stakeholder needs, deriving requirements from those needs and

from the RFP, and consulting with experts and legacy knowledge. Various trade studies are performed so as to develop candidate configurations. Downselections occur. Cycles of analysis, synthesis, and evaluation refine the design.

(3) Incubation: Eventually, the detail design is tested and evaluated to see if it is predicted to satisfy performance requirements. If the system does not, redesign may occur.

(4) Illumination: Verification and validation demonstrate that the design is predicted to satisfy performance requirements. The design has converged. The customer agrees to purchase the system in a Critical Design Review, and/or makes final recommendations for redesign.

(5) Verification: Secondary checks occur after a final design review, final edits to the design are made. The system design is translated into a format that is suited for manufacturing. Legacy documents are established for operation, maintenance, and disposal.

(6) Implementation: The system is manufactured, operated, maintained, and eventually disposed. (Drake, 2018-19; Cropley & Cropley, 1999; Cropley, 2015)

However, this is a major simplification of the design and development process. As stated in Section 2.1, within each program, there are numerous intermediate development processes with their own products, such as an RFP, a program plan, an organization, the conceptual design, the preliminary design, various prototypes and articles of test hardware, the detail design, the instructions for manufacturing, the tangible end product. The whole engineering process consists of creative sub-processes. There is not one, incremental, linear creative process, but numerous, looped, nonlinear creative processes. Any engineering program consists of serial processes, parallel processes, and recurrent processes. Looking at the earlier phases of a program, a simplified representation of the creative process is as follows:

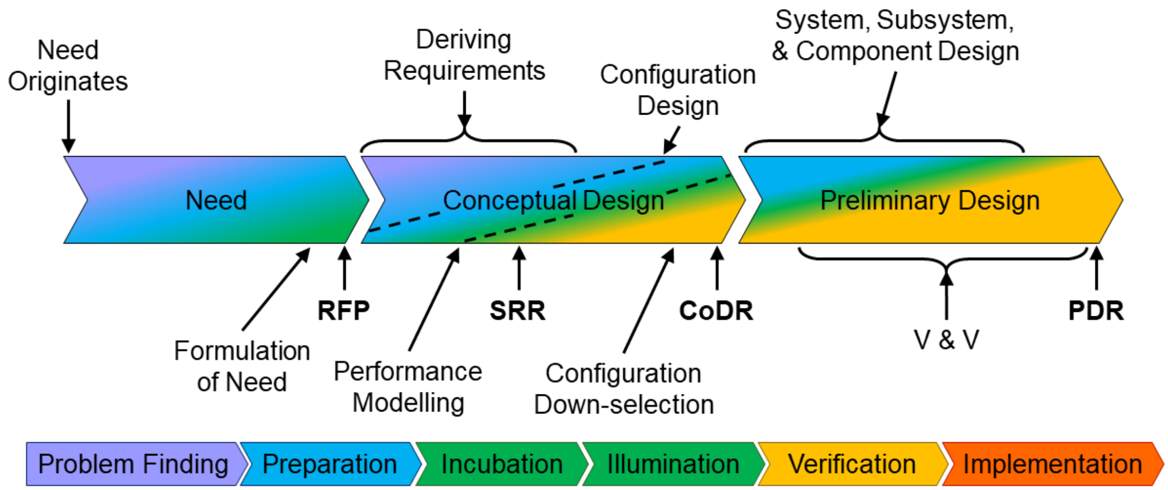

Figure 6. *Creative stages applied to the early intermediate development phases.*

From Need to RFP:

(1) Problem Finding: The user develops a need, though they may not yet be aware of it.

(2) Preparation: Around the same time, the customer or contractor performs research to understand the user's need for a potential system.

(3) Incubation: The customer reflects on the prior research.

(4) Illumination: The user's need is formulated into requirements and an RFP is written to formalize this.

(5) Verification: The verification stage is then handed off to the contractor, to derive requirements and see if there is a feasible system that can satisfy the required functions.

(6) Implementation: The implementation of the RFP follows as the remainder of the program.

From RFP to Conceptual Design Review (CoDR):

(1) Problem Finding: The RFP, user and stakeholder needs, and system-level requirements are identified.

(2) Preparation: A program plan is established. Requirements are derived from RFP and user needs. Research and trade studies are performed in the process of developing a candidate configuration

(3) Incubation: Various performance estimates begin as models s are sorted through, looking for solutions that converge on the user needs. Downselections occur.

(4) Illumination: Various trade studies and design optimization tools produce converged results.

(5) Verification: A System Requirements Review (SRR) is performed, evaluating the system-level and derived requirements to see if the required system is tenable. Verification and validation is performed on trade studies and configuration designs, leading to downselections. Candidate configuration is evaluated by contractor and customer in a CoDR.

(6) Implementation: Implementation of the conceptual design proceeds as the remainder of the program.

From CoDR to Preliminary Design Review (PDR):

(1) Problem Finding: The prior phases of the program largely serve to establish the preliminary design phase. Work packages for preliminary design are based on the outputs of the conceptual design phase.

(2) Preparation: Analysis proceeds on the various subsystems and components.

(3) Incubation: Models are synthesized.

(4) Illumination: Outputs converge.

(5) Verification: Verification and validations occur in anticipation of the Preliminary Design Review (PDR).

(6) Implementation: Everything after the PDR serves as the implementation of the preliminary design: detail design, manufacturing, operation, maintenance, and disposal.

3.6 Creativity in Agile and Waterfall Methodologies

Facilitating creativity takes on different forms depending on the structure of the design program. In the previous section, we described the creative process in terms of a historically conventional Waterfall methodology. Now, we analyze how the Agile and Waterfall methodologies approach creativity in different ways. Such an analysis has not been found in the literature on engineering creativity, so this section in itself is an attempt to open up an entirely new area of research.

3.6.1 Introduction to Creativity in Systems Engineering

Managing complexity can be a serious challenge. It is therefore important to understand the pros and cons of these systems engineering methodologies. By looking at how these strategies relate to creativity, we can develop a better picture of the leverage points for obtaining greater degrees of control over complex aerospace systems.

Before going on, we will acknowledge the limitations of systems engineering to facilitate creativity in general. As mentioned, creativity is itself a complex process of cognition and behavior. It is a nondeterministic process. Attempting to force people to be creative can actually produce extrinsic motivation that hinders creativity. Nevertheless, it is well-known that particular conditions do tend to be favorable for the affect states and intrinsic motivation essential to creativity. Increasing creativity requires an assortment of modifications to organizational practices grounded in a nuanced understanding of the organization's specific context, so that motivational factors are adequately accounted for (Lehrer, 2012; Csikszentmihalyi, 1996). Systems engineering can use creativity as a mechanism for managing complexity insofar as systems engineering methods can be made favorable to intrinsic motivation.

That being said, creativity involves so many external and internal factors that there is no set of clear-cut, surefire methods for facilitating it. By that same token, there is a great variety of possible ways to facilitate creativity. A general framework for creativity may be true to the complexity of factors involved in creativity, but it is not particularly practical. For now, we will focus on a general understanding of the goals and limitations of Agile and Waterfall. This can provide a sense of scope for what these methodologies are good at accomplishing. It would be the responsibility of systems engineers to adjust their methods of facilitating creativity for each specific program. In Chapters 4 and 5, we will focus on more applicable methods.

In a way, systems engineers oversee the creative processes of engineering. Systems engineers coordinate different disciplines and integrate high-level program goals with low-level work packages. This is very similar to how creativity coordinates different ideas, convergent thinking, and divergent thinking, integrating specific and general into a unified product. We will therefore be thinking of systems engineering as analogous to creativity, and systems engineering methodologies as being similar to different styles to being creative.

The primary difference between how the Agile and Waterfall methodologies foster creativity is in their approach toward formalization. Agile follows a more nonlinear, concurrent workflow, whereas Waterfall follows a more linear, serial workflow. First, Agile and Waterfall will be described, and then their relationship to creativity will be studied.

3.6.2 The Agile Methodology

Agile (Figure 7) divides a development program into a series of modules, in which separable elements of the system are developed from start to finish in a relatively short amount of time. Meanwhile, there is a concurrent process of integrating and testing the design. Agile emphasizes dynamic and open-ended development, prioritizing interaction over processes and tools, working products over exhaustive documentation, collaborating with customers over negotiating contracts, and action over planning (“Agile Manifesto,” 2001).

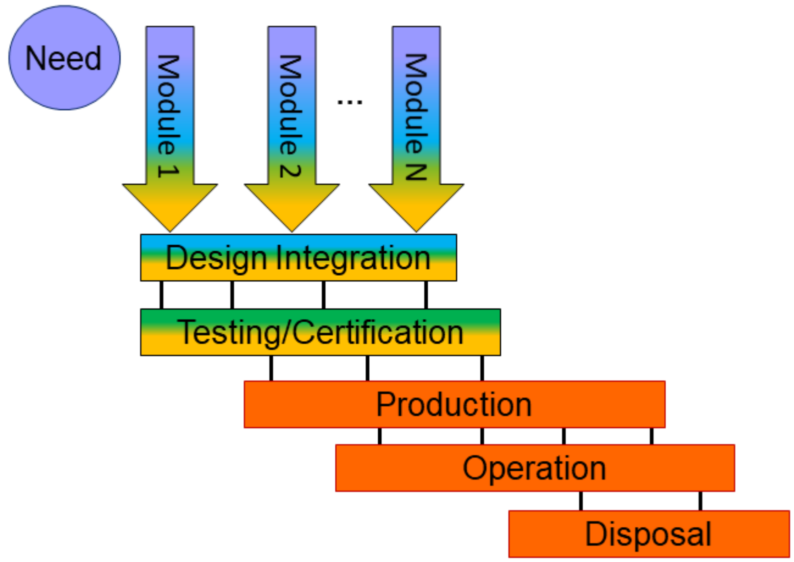

Figure 7. *Agile development process in colors of creative stages.*

Even so, "the Agile movement is not anti-methodology." ("Agile Manifesto," 2001). Instead, Agile methods aim to manage complexity by relying on human interactions and user-centered design. Rather than relying on formal methodology, Agile opens up the engineering process to be actively and spontaneously changed by the people working on a program. Agile relaxes on the side of systems engineering formality and focuses instead on being dynamic and active. Agile is becoming more common as a systems engineering strategy, and there are recommendations for how to integrate it into aerospace design, including the Agile decision support system (ADSS) for aircraft design (Li et al., 2015). The ADSS attempts "to reduce the adverse effects caused by a variety of subjective factors in the decision-making process and to promote human-machine collaboration" (Li et al., 2015).

3.6.3 The Waterfall Methodology

A more historical aerospace workflow (Figure 8) follows a mostly incremental process. It is often known as Waterfall for how each design phase cascades into the next. Waterfall divides a program into a series of phases in which the entire system is designed, each time to increasing levels of fidelity. This is not only convenient for the developer to avoid long rework cycles, it is also convenient for the customer to be able to identify a potentially successful system when it is less costly to commit additional resources to the program. Although a typical program following Waterfall is not formalized to an extreme, it is relatively more structured than an Agile program.

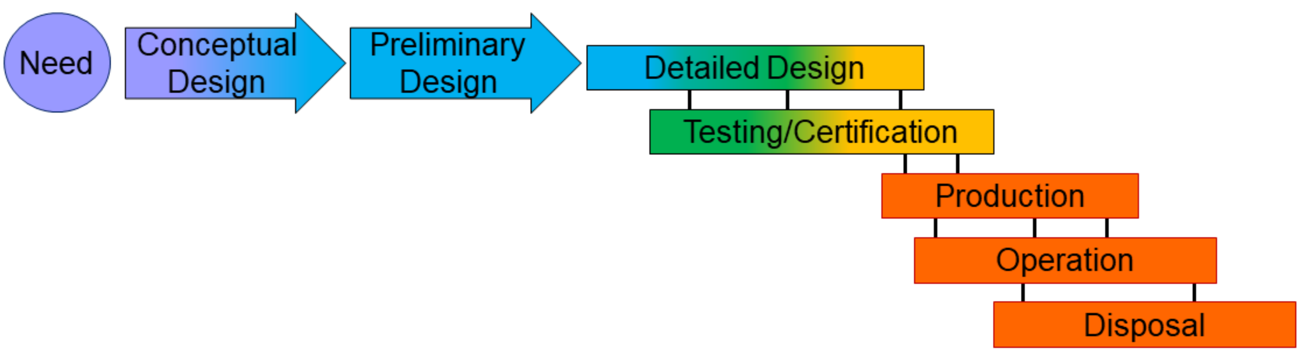

Figure 8. *Waterfall development process in colors of creative stages.*

3.6.4 Comparing Agile and Waterfall Creativity

Each of these methodologies place their focus on a different set of priorities, and as such have a different set of inherent benefits and risks. Agile tends to resemble divergent thinking, whereas Waterfall tends to resemble convergent thinking. The openness of Agile strengthens divergent behavior, which in turn helps manage a complex system. However, that divergence can also pose a challenge when working on a complex system that is large. A large program can become so sprawled out that centralization is important for success. The formality of Waterfall strengthens convergent behavior, which helps manage a large system. But, by being more convergent, it can be more difficult to adapt to a system's emergent behavior. Successfully implementing both approaches requires mechanisms to be put in place for achieving creative criticality.

3.6.4.1 Discussion of Agile and Creativity

Agile methodologies loosen the structure of the entire development process: schedules are more dynamic, organizations are more horizontal, employees are less compartmentalized, communication is faster, documentation is lighter. By decreasing the amount of "red tape" in a program, there are fewer constraints and expectations placed on engineers, allowing them to have a more open-minded attitude, giving them space to act with greater autonomy and experiment, decreasing the risk they face if they fail, and increasing the amount of interdisciplinary communication. Agile effectively makes the engineering process more intuitive. In this way, Agile improves upon conventional methods by increasing the number of interconnections in the program and tightens the coupling between program elements, making the program itself more complex. This agility is a way to increase the requisite variety of a program. By making a program more intuitively structured, Agile embeds a greater propensity to finding, storing, and interpreting nonlinear information. This, in turn, makes a program capable of managing a greater variety of tasks that a complex system must perform.

Although this gives Agile a greater degree of adaptability in a complex domains, there is a tradeoff. By deregulating a program, Agile assigns the responsibility of handling nonlinear information to the processes themselves. Individual agency and spontaneity are traded at the expense of lost traceability. It is worth noting that Agile was created by software developers, where the designs tend to be quickly iterable and any hardware testing and manufacturing tends to be modular. It is more difficult to develop large, non-modularizable systems using untraceable processes. Large aerospace engineering programs tend, due to their scale, to require a high amount of coordination and be conservative toward risk, meaning that traceability is often a high priority. It follows that Agile would tend to be less appropriate for the development of large aerospace systems. Since Agile defocuses on formality, as a methodology it theoretically places a limit on the scale of complexity that is manageable.

This does not mean it is impossible to use Agile methods effectively in aerospace programs. For instance, Aviation Week recently reported that the Joint Program Office (JPO) is integrating Agile into F-35 software management: “the JPO is using Agile software development tools that allow rapid updates and improvements like how Apple updates its iPhones, while Lockheed employs Waterfall development that allows for updates every 12-18 months.” (Hudson, 2020). Notably, Agile methods are being applied to the logistics operations of F-35 software, not its hardware. There are aerospace programs where Agile can be an excellent method. Smaller programs with fewer requirements and faster lifecycles are more suitable for Agile. Even components can be developed in an Agile manner, though perhaps at the risk of going countercourse to the need for central integration. Sometimes, Agile is suited for R&D projects, such as the development of the jet engine:

> "Success was not the result of 'skillful management of technology and organization,'…[but] stands rather as a shining example of non-linear, irrational, uncertain, multi-lateral, and profoundly passionate technological and business practice, yielding success not through planning but through dogged determination, a certain indifference to failure (which secrecy aided), and massive expenditures of public funds. The development of the early jet engines (in post-war America) is described as a 'messy, contingent, and intense process,' driven by passion, Cold War fears, and 'the challenges of mastery (in engineering and in organizational terms).' The development involved multiple technological areas, in which 'no one understood enough … about turbulent combustion, alloy metals, heat fatigue, or fluid dynamics to approach scientific certainty or reliable knowledge.' Designs did not always rely on theoretical science, but 'on empirical knowledge' that came from the systematic cycles of design, build, and test… 'Engineers often did not know why something worked, just that it worked'" (Young, 2007).

Space-X is another notable example of Agile being used successfully. The company is known for tending to follow Agile methods, such as using less hierarchy and documentation and pushing for test early. By limiting hierarchy and documentation to ensure that individuals can communicate freely enough to maintain a creative criticality, Space-X has effectively managed the complexity of creating orbital vehicles through thoughtful implementation of the Agile methodology (Berg, 2019).

It is generally more difficult to make improvements in fostering creativity by increasing formality than by loosening formality (Lehrer, 2012; Csikszentmihalyi, 1996; Cummings & Hall, 2004). There are numerous large aerospace programs that followed a methodology similar to Waterfall in which complexity caused major expenses and setbacks. The NASP and JSF programs had complex systems as their end product, and each program used a widely distributed hierarchy of thousands of engineers to account for their respective system's complexity. Yet both programs were riddled with major failures due to poor coordination of engineers and poor planning with respect to complexity. The requirements of these programs were far more nuanced and challenging than their conglomerated organizational hierarchy could efficiently control. The subjective complexity of developing these objectively complex systems led to large cost and schedule overruns. Such failures can be thought of as caused by obstacles in the engineering creative process. In practice, it tends to be extraordinarily difficult to successful create large, complex aerospace systems.

3.6.4.2 Discussion of Waterfall and Creativity

Despite the difficulty, there is still potential for improving the creative capacity of Waterfall methodologies, because being creative is not the opposite of having external constraints. Throughout the creativity research literature, practical recommendations for fostering creativity tend to be simple methods for flattening organizational hierarchy and informalizing processes. As mentioned, creativity has so many dependencies it is usually impractical to develop a systematic strategy for increasing creativity that is guaranteed to work in all cases. Formalizing mechanisms to generate creativity tend to inhibit creativity, precisely because there are so many motivational factors behind creativity that any attempt to control it is not grounded in sufficient knowledge (Lehrer, 2012; Csikszentmihalyi, 1996; Cummings & Hall, 2004). It tends to be easier to offer simple practical suggestions that coincidentally correspond to creativity than to take on the challenge of forming a process that resembles creativity. It is easier to facilitate creativity by using a process that resembles divergent thinking, as in the case of Agile, than by using a process that resembles convergent thinking, as in the case of Waterfall. As such, it can be easy to slip into the belief that creativity is the same as undisciplined idea-generation. However, creativity researchers are in consensus that this belief is a serious misconception (Cropley, 2006). Creativity is a complex behavior that uses a synthesis of divergent and convergent thinking to produce order. In other words, creativity is better understood as a tertiary process than an intuitive primary process. Creativity is not inherently disorganized. It follows that adhering to Agile principles is not the only methodological option for responding to complexity in aerospace; there is the potential to improve upon Waterfall. It may be more difficult to be creative in a formal environment than an informal one, but it is nevertheless possible. The research in this project uncovered a great deal of literature emphasizing Agile methods for creativity and found very little information on creativity by means of systems engineering formalities. This suggests there is potential for improving the creativity of

Waterfall that has yet to be capitalized. The two strategies given in Chapter 5 are designed as improvements on a conventional Waterfall methodology.

The research in this project suggests that Waterfall can be adapted to better facilitate creativity by considering the entire development process as a creative process, and then looking for areas where systems engineers can better associate and coordinate information. Although Waterfall as a whole resembles convergent thinking, just as Agile as a whole resembles divergent thinking, the work that successful systems engineers perform resembles divergent thinking and tertiary process.

Effective resource management is necessary for any system development, complex or not. In complex system development, resources should be managed with a greater degree of attention toward the potential for emergent behavior, in both the objective system and in the subjective processes implemented to develop the system. It is certainly possible for formal mechanisms to be put in place that give attention to unknown unknowns and the potential for complex interdependencies. For instance, in the case of the Apollo Program, the high amount of system complexity was dealt effectively with by dramatically increasing the formal hierarchy of the program’s organization. Although the program went beyond its expected resources, the high degree of formal coordination ensured that the program successfully created the end product (Johnson, 2006). Poor coordination of information is one of the root causes of emergent risk. Although emergent behaviors cannot be predicted, they can be searched for, reducing the risk that they can pose. The Apollo program had many systems engineering mechanisms for associating and coordinating information between organizational subdivisions, so as to address complexity before its risks snowballed. By providing many pathways for information to cross the organizational hierarchy, the systems engineers functioned like divergent thinking. By integrating the information of the program and focusing it toward the system-level requirements, they functioned like tertiary process. Given that the monumental program was, by many accounts, successful, it can be inferred that the systems engineering coordination achieved creative criticality: a balance of variety of information and likelihood of associating that information. If there were less coordination of information, i.e., if there were poorer communication, the Apollo program likely would have become tangled up to the point of crumbling under its own weight, as in the case of NASP. On the contrary, there was so much intelligently applied formality that the program managed to achieve its major goals. Effectively, the complex systems engineering of Apollo succeeded at facilitating program-wide creativity. Making the work of systems engineers resemble divergent thinking and tertiary process is a way to increase the creativity of Waterfall.

3.6.5 Summary of Comparison of Creativity in Agile and Waterfall

Facilitating creativity through formal systems engineering methods in aerospace programs is not a well-researched topic. On the other hand, how Agile methods increase creativity is a well-researched topic. Thus, there is the potential to make advances on the problem of managing complexity by way of altering protocols to better resemble creativity. The primary difference between facilitating creativity through Agile or Waterfall is in their resemblance to divergent thinking or convergent thinking.

In Agile creativity, systems engineering formalities are loosened enough that engineers can adapt freely to complexities that emerge throughout the development process. This freedom gives them an appropriate variety of information and an appropriate level of association. Yet there is enough structure that they do not lose focus from the major program goals. In this way, creative criticality is achieved in a dynamic manner. However, coincidentally facilitating creativity by loosening formality to resemble divergent thinking is perhaps not enough for developing large aerospace systems. It is important to address the root cause of the emergent risk of subjective complexity: poor coordination of information.

In Waterfall creativity, systems engineers function to coordinate between specific and high-level program goals. Formal hierarchies and processes are put in place so as to facilitate effective communication between the various engineers, managers, personnel, users, and stakeholders in the development process. Wise program planning, program managers, and systems engineers work to balance the need for enough variety of information and enough interchanges between that information. To the degree that Waterfall methods do not achieve creative criticality, the program will become disorderly and vulnerable to emergent risk. If, on the other hand, there is too much information available and too many interactions happening, the design process will become unmanageably large.

It is also possible for a single program to implement a combination of Agile and Waterfall methods, where the program leaders are seeking tradeoffs from each methodology to meet specific goals. Some areas of a program can be Agile while other areas are more incremental. It may well be that agility is preferable to traceability, or vice versa. The informal structure of Agile facilitates divergent thinking but poses the risk of being limited to smaller systems. Developing large systems may require too much coordination for less formalized methods to work efficiently. The advantage of Waterfall creativity is that by making formal techniques to facilitate creativity, it is better suited to developing large, highly sophisticated systems.

Either way, creativity depends on the interplay between convergent thinking and divergent thinking. The effective coordination of these thinking modes occurs through creative tertiary process. In Agile, tertiary process is coincidental and spontaneous, whereas in Waterfall, tertiary process is the intentional work of systems engineers.

Thus far, we have looked at theory about creativity in aerospace. In the following chapters, we will move in the direction of practical recommendations, beginning in Chapter 4 with existing methods for facilitating creativity and then proceeding to two novel methods for doing so in Chapter 5.

Chapter 4

EXISTING METHODS FOR FACILITATING CREATIVITY

In this chapter, we will take a look into existing recommendations for fostering creativity in aerospace engineering. Ironically, there is a distinct lack of research on aerospace creativity even though modern interest in engineering creativity was sparked in 1957 with the shock of Sputnik (Cropley, 2015). Various aspects and strategies for fostering creativity that appear in the literature are discussed, as briefed in the following paragraph. Of notable interest is the work of Darold Cummings and the father-son team of Arthur and David Cropley. The methods presented here bear special relevance in searching for how to improve the historical Waterfall methodology, even though they are applicable under a variety of systems engineering strategies.

Creative ideas form as intersection of various pools of information. Creativity involves a complex dynamic between different states of brain activity. Creativity can be cultivated by altering the workplace physically and psychologically. Leadership quality and systems engineering methodology seem to both have an affect on the conditions for creativity. College education and cognitive training can play into engineers' creativity, but it is insufficient. Several methodological tools, such as Model-Based Systems Engineering and forms of Multidisciplinary Design Optimization, are described in terms of how they affect creativity. A potential mathematical method for modeling creative logic is described. All of these strategies anticipate Chapter 5, in which some formal techniques for addressing the root cause of creative blockage in large aerospace programs are suggested.

4.1 Overview of Research on Aerospace Creativity

Although there is a great amount of creativity research in general, there is a distinct lack of research into how creativity relates to engineering (Kazanjian et al., 2000; Cropley, 2015) and especially how it relates to aerospace engineering. Ironically, "much of the modern interest in creativity in engineering resulted from the 'Sputnik shock' that followed the success of the Soviet Union in launching Sputnik 1 in 1957" (Cropley & Cropley, 1999); yet, inputting various search engines with terms related to aerospace engineering creativity reveals there is but a handful of papers on creativity and innovation in aerospace. In other words, modern interest in engineering creativity began in the aerospace industry and yet aerospace creativity has been an almost untouched topic since then. This lack of research in aerospace engineering creativity is significant, not only because engineering is fundamentally a creative process, but also because it is one of the most powerful and ubiquitous expressions of creativity in human society. David Cropley writes, "the process of engineering design bears a strong similarity to the more general process of creativity. However, with regard to engineering, while creativity research has articulated many of the key psychological cognitive, personal and organizational concepts, features and characteristics of this process, engineering design has largely ignored these. Instead, engineering design, and engineering more broadly, has remained defined largely in terms of key processes of logic, analysis and judgement" (Cropley, 2020). He goes so far to say,

> “In many ways…engineering design is the ultimate expression of creativity. For thousands of years humankind has depended on its ability to recognize problems, generate a diverse range of ideas for solving those problems, and the ability to evaluate and implement these ideas as practical solutions. This would seem to suggest that humankind, in the process of engineering design, has reached a pinnacle of creativity” (Ibid.).

Yet,

> “The engineering profession remains one that is seen principally in terms of the application of critical thinking skills, and the laws of nature, to the efficient use of raw materials. Engineering design is seen more as a matter of reapplying the known, rather than as a question of exploring the new. Engineering design is a good representation of creativity, but it is not yet the optimal representation of creativity. Not only are there weaknesses in parts of the process, in particular the application of divergent thinking, but there are also opportunities to improve engineering design by drawing on the considerable body of knowledge available from some 70 years of, largely psychological, creativity research.” (Ibid.).

Insofar as engineering processes are related to creative processes, it is beneficial to examine how various engineering behaviors, processes, and procedures can facilitate or hinder individual and group creativity.

Aircraft design consultant Darold Cummings is known for his presentations on creativity to cadets at the United States Air Force Academy and elsewhere. As an experienced aerospace engineer and knowledgeable teacher of creativity, his perspective is a major voice in the field and represents one of the few that are publicly articulated. Therefore, it is worthwhile spending some time examining his research. In light of the many consolidations that have occurred in the aerospace industry, as well as the ever-increasing amount of information involved in understanding industry trends, Cummings and Hall propose that exploiting the creative process can be a way to continue developing innovative design solutions. "In this emerging environment, individuals and groups are becoming 'cubicle entrepreneurs'; that is, developing new concepts in an engineering microcosm and then marketing them both internally and externally to achieve critical mass. This new environment has dictated an even greater need for creativity and innovation on a daily basis" (Cummings & Hall, 2004).

4.2 Meme Pools

Cummings advocates for understanding various cognitive aspects of the creative process and learning how to implement them. For instance, "the creative insight that inspires a new or unique pattern" is generated when meme clusters, "bits of information that form ideas or concepts," are combined in new ways. "An enriched meme pool (diverse experience) greatly enhances the ability to create unique patterns." The meme pool regarding the domain of aerospace engineering can be enriched by such things as engineering-related hobbies, personal hobbies, outside culture, and personal development. These non-domain meme pools can be sources for obtaining relevant skills and hands-on experience; for facilitating neural growth, stress reduction, and focused attention; for developing conceptual and intuitive knowledge about how to see design problems from an innovative perspective. Practices such as the “Brainernet” can be used to help generate unusual recombinations of meme clusters in the design process. Brainernet is similar to brainstorming: it involves an individual or group quickly coming up with many solutions to a design problem, on the premise that any idea is acceptable regardless of how bizarre or infeasible it seems (Cummings, 2018-19). This helps get the engineers out of their typical frame of mind. Conventional thinking is built around conventional designs, and so only minor, incremental innovations can happen by means of conventional thinking patterns.

4.3 Brainwave States

Furthermore, creativity can be described physiologically as brainwave states (Table 2), which can help engineers understand how to pace their workflow to be more conducive to creativity. Different activity levels in the brain, measured as electrical frequencies, correspond to different levels of attention. Higher frequency brainwaves correspond to higher attention activities, while lower frequency brainwaves correspond to sleepier, restful states. An understanding of some basic relations between these brainwave states affords valuable insight into engineering creativity.

Table 2. *Characteristics of different brain activity levels. (Cummings & Hall, 2004)*

Brainwave State	Frequency	Occurrence
Beta	16-28 Hz	Purposeful activity requiring alertness, such as planning, argumentation, or athletics.
Alpha	7-16 Hz	Alert relaxation, such as in silent contemplation or passive sensory awareness.
Theta	4-7 Hz	Falling asleep (hypnagogic state) and waking up (hypnopompic state), or daydreaming.
Delta	0.5-4 Hz	Sleeping state, in which body recovers from waking state.

Beta is a high energy state that allows for instantaneous action, reaction, communication, and judgment. In brainstorming, most people act in a beta state. Due to beta involving a high degree of attention and focus, it could be said that divergent thinking in the beta state happens in a convergent and rational manner: beta wave divergent thinking tends to involve quick critical thinking and is goal-oriented. In this way, convergent and divergent thinking can condition each other.

Alpha is a more patient state that allows for tranquil reflection and observation of general patterns and trends. Alpha can be activated in activities like reading a book. In high quality brainstorming sessions, the alpha state is activated alongside the beta state, allowing for calm observation to inspire judgments, decisions, and plans. Brainwave states can be layered and integrated together in diverse ways; this integration is key to creative processes in general (Lehrer, 2012; Csikszentmihalyi, 1996). Convergent thinking in the alpha state seems to happen in a nonlinear manner: alpha wave convergent thinking tends to involve open-ended questions, broad scanning, and intuitive leaps in the attentive periphery.

The theta state, also known as "liminal consciousness," for being the threshold state between waking and sleeping, mostly involves divergent thinking. It is open-ended and spontaneous. The theta and delta states are critical in the incubation and inspiration stages of creativity. When the brain slips into daydreaming or resting states, or when it rises from rest, various specified areas of attention are calmed down and brought together in nonlinear recombinations. In other words, the brain states related to dreaming have a critical role in enabling the complex cognition that is so characteristic of creativity. Of special significance is the interaction between beta and alpha. Since extrinsic motivation can close off awareness of affective states, beta state activity can speed past, overlook, or misinterpret alpha state activity. Since alpha is a more nonlinear, holistic, quiet state, overlooking it means inhibiting intuitive reflection.

Appreciating how different brainwave states function in creative cognition can help engineers understand how to behave more creatively at work. Perhaps going for a walk, daydreaming, or sleeping on an idea is a better way of solving a tricky design problem than frustratedly going in circles without making much progress. Focusing too heavily on deadlines can prevent an engineering organization from integrating brainwave states with a lower frequency than those in the alert beta state.

4.4 Effects of Environment on Motivation

It is possible to alter the physical environment of a workplace to facilitate creativity, such as by removing cubicles, personalizing them, and by providing software with intuitive user experience (UX) (Lehrer, 2012; Levi, 2017; Csikszentmihalyi, 1996; Catmull, 2014). “It is paradoxical that engineers are asked to think out of the box while spending most of their time confined to a very banal box!” (Cummings & Hall, 2004). In 2014, Northrop Grumman opened up their “FabLab,” short for Fabrication Lab, at their Space Park facility in Los Angeles. FabLab is a 5,500 sq-ft. facility to give employees “hands-on access to a range of tools, equipment and materials, and the freedom to turn their ideas into reality” (Defense & Aerospace Week, 2014).

Analogously, it is possible to alter the psychological environment of a workplace to facilitate creativity, such as by fostering a culture of tolerance toward ambiguity. It should be noted that it is much more difficult to change the culture of a workplace to facilitate creativity than it is to change the physical environmental, and that many of conventional practices in aerospace programs actually work to hinder the creative process. “In the Advanced Design arena, considered the creative front of the aerospace industry, the psychological environment can best be described as routine chaos. Budgets can fluctuate rapidly, and projects which often appear solid sublimate right in front of astonished engineers. The ability to function with a high level of energy and enthusiasm in an ambiguous environment truly sets people apart.” (Cummings & Hall, 2004). The “routine chaos” of many aerospace programs makes it difficult to implement major changes to systems engineering methodologies that facilitate creativity, since conventional workflows evolved in tandem with aerospace programs. To some extent, it is the responsibility of individuals to bring enthusiasm to the workplace, to act with intrinsic motivation in the face of uncertainty and ambiguity. “The environment within a large company is often not well suited to radical changes, yet radical change is required to develop successful products in a rapidly changing geopolitical world. James Albaugh, President and CEO of Boeing IDS, in a speech in 2002 said, ‘It is hard for big organizations – be they military or corporate – to embrace change. Mass – we know from physics – is the measure of inertia.’ Most ‘Cubicle Entrepreneurs’ succeed in large companies despite the system of entrenched checks and balances, and the panoply procedures.” (Ibid.) Innovation depends on creativity and yet engineering processes tend to inhibit creativity by requiring formality and negatively rewarding divergent thinking. Even so, creativity can still occur. Structure and constraint can be a catalyst or growth point creativity, just as it can snuff it out (Sandwith et al., 2017; Catmull, 2014; Cummings & Hall, 2004).

Groups can be organized to facilitate intrinsic motivation. This includes forming teams with an optimal balance of heterogeneity and homogeneity: new and experienced engineers, engineers of different disciplines, engineers with different personalities, engineers with different backgrounds, etc. (Lehrer, 2012). Forming cross-functional teams may prevent the inhibition of creativity that arises in the confusion of cross-team interactions; and in cross-team interactions in large programs, focusing on failures and crises may make it easier to foster the creative process (Kazanjian et al., 2000).

As stated earlier, facilitating the necessary motivation for engineering creativity is specific to a workplace. Young summarizes some of the major promoters and inhibitors of creativity in aircraft design, shown in Table 3.

Table 3. *Factors for promoting and creativity in aircraft design.* (Young, 2007)

Creativity Promotors	**Creativity Inhibitors**
Adversity	Limitations of computer simulation tools
Observation and curiosity	Absence of a creative environment
Races, contests, and inducement prizes	Fear of failure
Targets and grand challenges	Unwarranted or unsubstantiated criticism
Collaboration and concurrent engineering	Poor definition of success
Information technology, analysis tools, and knowledge base	

Essentially, "…each stage of engineering design, to be optimized, requires the right set of individual dispositions and qualities, coupled with the right environmental conditions for the particular convergent or divergent stage in question. If any of these three are misaligned – for example, an unmotivated, closed individual in a divergent process, or, a highly motivated, highly divergent team, with no time or resources to generate ideas – then engineering design, and creativity, will be blocked." (Cropley, 2020).

4.5 Leadership Style and Systems Engineering

There is disagreement over the extent to which creativity is determined by culture or methodology. Some swear by wise leadership and employee self-actualization, other swear by systems engineering. There is ambiguity over whether leadership style drives culture or methods drive culture, both in the creativity literature and in engineering practice. They likely feed into each other, and creativity can be facilitated both ways. Someone like Kelly Johnson can lead many successful programs without making major changes to conventional workflows. A program can lack systems engineering practices and still be well-ordered and successful. Yet, to leave implicit the capacity to facilitate creativity and develop complex systems has the consequence that those informal, intuitive methods cannot be generalized and repeated when such leadership is absent. Systems engineering can formalize the best practices of effective leadership. Moreover, on especially large programs, the acumen of an exceptional leader is harder to access, and so a plurality of leaders can be coordinated through something like systems engineering. This is no excuse for poor leadership but can help toward ensuring that an organization can be consistently successful in creating systems. As for what sorts of small practices are known to assist in facilitating engineering creativity, here is a brief list:

- Individuals should be given independent free time so that they can perform intuitive, nonlinear processes such as insight, incubation, and illumination.
- Groups should engage in free-flowing exchanges of ideas. Groups should collectively speculate, imagine, and critique their progress together, so as to facilitate project-wide intrinsic motivation.

- Individuals should not be rewarded negatively during postmortems.
- Imaginative activities should be performed, like premortems, root cause analyses, and preliminary syntheses of user and stakeholder needs. (Catmull, 2014; Lehrer, 2012; Csikszentmihalyi, 1996; Clearfield & Tilczik, 2018; Cropley & Cropley, 1999)

Cropley and Cropley recommend how to foster creativity at particular stages of the engineering process: "It is possible to state areas in the synthesis process where management functions should be employed to specifically foster the skills (both cognitive and non-cognitive) needed to ensure success. Some of these have already been suggested. They may be summarized as follows:

(a) Preliminary synthesis activities of engineers must seek to generate a wide and varied body of latent knowledge to feed the creative aspects of the synthesis process. Engineers must be given the means and opportunity to build this latent knowledge.

(b) Professional knowledge and ability contribute vitally to creativity. Engineers must build specialist knowledge on a continuing basis to feed creativity.

(c) Engineers must be made aware of cognitive skills. They must be trained in divergent thinking techniques. These may span a variety of 'creativity techniques'.

(d) Engineers must be able to apply these cognitive skills in a supportive, extrinsically rewarding environment. They must feel comfortable thinking divergently, and being seen to think divergently, at the appropriate time.

(e) Engineers must develop tolerance for ambiguity, openness and other similar non-cognitive characteristics.

(f) The system in which they work must support the feelings which drive many of the creativity phases. Thus the engineer's pride, excitement, curiosity, etc. must be nurtured at the appropriate phase of creativity." (Cropley & Cropley, 1999)

4.6 Engineering Education and Cognitive Training

Creativity can be facilitated in engineering through engineering college curricula that encourage ingenuity and collaboration and on-site cognitive training. Much of engineering education is structured to produce specialists with a conservative attitude toward novelty and has an absence of hands-on experience. Generalized, interdisciplinary coursework is often not permitted, setting up engineering students to not explore their interests and, consequently, to neglect divergent thinking. As John McMasters and Russell Cummings point out, "system talent (especially those who serve as system architects) is relatively rare in the general engineering population and special care is needed to cultivate and develop it in student and apprentice-level engineers" (McMasters et al., 2004). Open-ended design problems with hands-on collaborative experience are atypical for many engineering college programs. David Cropley's copiously cited "Promoting Creativity and Innovation in Engineering Education" is a superb essay on how to develop a creative engineering curriculum. He cites Sternberg's three main principles for promoting creativity: "First, students must have the opportunity to engage in creativity. This must be woven, holistically, throughout programs and courses in an integrated and mutually reinforcing manner. Second, students must receive positive encouragement as they engage in tasks requiring creativity. Third, students must be rewarded when they demonstrate the desired creativity" (Cropley, 2015).

Creativity can arise as personality trait, a learned behavior, a social tendency, and an environmental condition (Cropley, 2015). Thus, it can be taught and cultivated, albeit when attempts are driven by a reductive intent (Cropley & Cropley, 2000). Simply having occasional trainings or working sessions for engineers to consider problems from different perspectives, to problem-solve creatively, to reflect on their tasks with philosophical abstraction, to focus on user and stakeholders offers some potential for benefitting engineers, and to reflect on the effectiveness of their procedures is potentially beneficial for engineers.

4.7 Methodological Tools

Tools already exist for evaluating the creativity of engineering products, such as the Decision Tree for Originality Assessment in Design (DTOAD) (Kershaw et al., 2019), but these do not directly serve the goal of improving complexity management strategies. An organization's capacity to be creative is a more important metric for evaluating if they can manage complexity than the originality of a system. Cropley and Cropley's Innovation Phase Assessment Instrument (IPAI) questionnaire evaluates roughly how aligned various areas of an engineering organization are with the ideal conditions for creativity (Cropley, 2015). The IPAI gives a means of comparing where, relatively, creativity is more or less prevalent.

There are numerous methodological tools for complex systems engineering, and in so doing foster the information coordination required for Waterfall creativity. According to INCOSE, Model-Based Systems Engineering (MBSE) is "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (INCOSE, 2007). By making it easier for engineers to understand the state of the program and communicate with each other, there will be fewer external constraints, such as regularly checking specifications and tracking changes, that tend to yield creativity-inhibiting extrinsic motivation. Multidisciplinary Design Optimization (MDO) also facilitates creative information coordination by synthesizing the trade studies of different disciplines in one platform (Wang et al., 2014). Similarly, the up-and-coming field of Uncertainty-Based Multidisciplinary Design Optimization (UMDO) is "an advanced methodology to address competing objectives of aerospace vehicle design, such as performance, reliability, and robustness" as pertaining to the uncertainties of various system aspects (Yao et al., 2011). Like MDO, UMDO fosters creative information coordination, except through the explicit investigation of subjective complexity in a systematic and comprehensive manner. This is by no means an exhaustive representation of methodological tools that will assist in facilitating engineering creativity; these examples are selected to relate how such tools affect creativity. Future work in methodological systems engineering tools will help complex aerospace system development by enhancing the information accessibility needed for project-wide engineering creativity.

4.8 Mathematics for Creativity

The Honing Theory mentioned in Section 3.2 offers math for how to represent creative recombinations of information. Modeling creative recombination cannot be a process of linear superposition, since it is typically the case that creativity puts different ideas together in a way that results in emergent properties distinct from the properties of the component ideas, i.e., because creativity is a complex process. To deal with the complex, noncompositional nature of creative processing, HT proposes a quantum model would function. This “quantum model” has nothing to do with the phenomena of quantum mechanics, except for its logical operations. The noncompositional, probabilistic, potentiality-focused logic of quantum mechanics lends itself to describing the complex operations of creativity.

The potential of creative ideas can be represented as state vectors in Hilbert spaces, and the combinations between different states under different conditions yields different potentials for usefulness. The potential of a creative idea can be represented as follows:

$$\boldsymbol{p} = a_0\boldsymbol{u} + a_1\boldsymbol{w}$$

where $\boldsymbol{p}$ is a measure of the idea’s potential, $\boldsymbol{u}$ and $\boldsymbol{w}$ are orthogonal unit vectors denoting the usefulness or wastefulness of an idea, and amplitudes a_0 and a_1 are complex numbers that represent the probability of those two states. By representing the probability of usefulness with complex numbers rather than real numbers, nonlinear associations between different states, such as superposition, interference, and entanglement, can be composed together in a linear fashion.

Now, the potential of a creative concept varies depending on conditions. For instance, a different user might envision a different use case, or a different environment might make the same user deem the product ineffective. Thus, there is also a need for: "(1) its set of states Σ… (2) a set L of relevant properties, (3) a set M of contexts in which the concept may be relevant, (4) a function ν that gives the applicability or weight of a certain property for a particular state and context, and (5) a function μ that gives the probability of transition from one state to another under the influence of a particular context" (Gabora, 2017). Depending on the state and context, the creative idea has different valuations of its potential, corresponding to members of the sets and vectors given above. The vector basis of the creative idea is an eigenstate to all the particular conditions and contexts it can operate in. When one use-state is selected, the vector is projected into that Hilbert space. Although this could happen in a simple fashion, where there is a deterministic result to each state, it may be the case that there are several states, relevant properties, and contexts at work simultaneously.

There is also the function-first nature of creative products to account for (Sandwith et al., 2017), i.e., that different systems can satisfy the same use, as well as the possibility of more than one potential use-state happening in one context simultaneously. To deal with this, the Hilbert space operators can be arranged as projections of state vectors onto each other, with different dimensions corresponding to use-states. So long as each state vector is divided by its length, the potential usefulness of each state can be linearly added as a series of unit vectors. The dissipation of psychological entropy can be seen as how aligned the state vectors are with each other in the dimension of usefulness. Again, the HT mathematical method for representing creative recombination is not a way to evaluate the conditions for creativity; it is a way of expressing the complex nature of creative recombination.

There has not been a large amount of research done on engineering creativity, and much less on aerospace engineering creativity. Existing research in the field tends to concentrate on broad motivational factors or prospective areas for future work. The Agile community has done most in the area of bridging between motivational factors and systems engineering methods. However, is a lack of research on how Waterfall methods can be altered to facilitate creative motivation. Given that vertical hierarchy is important in complex aerospace systems engineering, such methods could be valuable.

Chapter 5

NEW METHODS FOR FACILITATING CREATIVITY

In Chapter 4, various existing engineering strategies were considered with regard to how they facilitate engineering creativity. In this chapter, two new strategies are proposed for using creativity as a way of addressing the paradigmatic challenge of complexity in aerospace. The first strategy is the formation of a new systems engineering group that performs divergent thinking and tertiary processing in an analogous manner to creative thinking in an individual. The second is a conceptual model for how to model tertiary processes throughout a development program to anticipate complexity earlier than is otherwise knowable. These strategies were developed with Waterfall in view.

5.1 Parallel Systems Engineering

"…To fully exploit [the elements of the creative process] they must be focused into techniques that provide free-thinking and successful problem solving" (Cummings & Hall, 2004). It would be helpful to systems engineering to scale up the creative interplay between convergent and divergent thinking, between reasoning and intuition, to a procedural level. This would help adapt the Waterfall methodology for complex design domains. Conventional systems engineering, as it stands, performs both convergent and divergent thinking, coordinating the various organizational disciplines, divisions, groups, and teams, as well as coordinating between program-level goals and individual work packages. It is necessary for systems engineers to perform the ideation, broad scanning, and associating of divergent thinking as well as the analysis, synthesis, and evaluation of convergent thinking. Systems engineers observe the program as a whole and in its components, intuitively make best judgments and connect various threads of information together, reason through the objectives of the program and develop formal processes and metrics for staying on track with system-level requirements. Although systems engineering has evolved in tandem with aerospace technology, conventional methods tend to fall short when it comes to complex system development. For large, high-stakes programs, the external expectations placed on systems engineers and placed on others by systems engineers can become a source of extrinsic motivation, making the creative interplay between reasoning and intuition difficult to manage. These external constraints are not bad, per se, because they are important means of effectively organizing a program and maintaining its productivity. However, in the context of complex system development, the need for linear organization and the need to follow a nonlinear process toward complexity are in conflict.

To account for this, it is possible to adopt the Agile approach to creativity: loosening procedures and flattening hierarchy so as to facilitate more intuitive, divergent thinking. However, this means that there is less regulation embedded in a program, making it more difficult to develop large, complex systems. On the other hand, it is possible to hold to the Waterfall approach to creativity, seeking formal techniques for facilitating creative motivation. This can be accomplished by forming a systems engineering group that performs the tasks that intuition and tertiary processing would in an individual's creative process. The conventional systems engineering group remains in their current capacity. However, instead of having to try and wrangle divergent processes away from the extrinsic motivation of a linearly organized program, such an ancillary group would complement conventional systems engineering groups by performing tasks that require a higher degree of openness to intuitive cognitive states than is practical for other engineers. They would perform tasks which tend to occur in parallel with the critical path, concurrently rather than incrementally, and yet are vital to complex system development. For this reason, they could be called a Parallel Systems Engineering group (PASE), not to be confused with the similarly oriented Program Systems Engineering (PSE) (Pfarr et al., 2009).

PASEs would not interface with the customer or perform tasks on the critical path, but would instead have a great deal of autonomy, acting as assistance to various engineers in connecting the dots of uncertainty, tying up loose ends, performing those tasks which are so divergent as to be impractical for other engineers and yet are important, and actively reflecting on how engineering complexity is affecting a design process. As systems engineers, they would coordinate between broader objectives and smaller work packages, but in a way that reports "downward," i.e., they are responsible to individual engineers rather than to upper management. This would free them from extrinsic motivation, since their constraints would not be determined by formalities but by the complex needs of the program. Their responsibility is to the program and to the engineers they are serving. Moreover, PASEs would function similarly to intuition in associating and recombining information, and to tertiary processing, in that they would be able to coordinate between specified and generalized tasks. In filling the missing role for divergent thinking and tertiary integration, openness and variety of information would be increased on an organizational-level scale, facilitating the creative process.

PASEs would not be a substitute for other engineers to engage in holistic or creative behavior. That would set up opposition between one small working group, which is supposedly “nonlinear and creative,” and all the other engineers who are, in comparison, “linear and uncreative.” It is unlikely such a scheme would lead to constructive collaboration, much less to improvements in complexity management. Moreover, instituting a PASE group by no means is to say that engineers are uncreative and opposed to nonlinearity. In many regards, aerospace engineers already see, appreciate, and understand the nonlinear aspects of engineering, as well as how to be creative. The fact that aircraft and spacecraft can function at all is a testament to the skillful communication and coordination between the engineers who designed them. However, there is a tendency for engineering processes to be noticeably reductive in complex domains. Providing clearer guidelines and more effective methods for catching problems associated with complexity would attend to this need. PASEs would function as a check-and-balance on organizational-level creativity in complex aerospace system development. Furthermore, PASEs would not substitute the existing work of systems engineers. PASEs act as an ancillary check on the areas where conventional systems engineering is prevented by practical demands from accessing more divergent processes. They have a complementary role of stepping outside the conventional process into a parallel process, in order to check on the flow of information, especially between components and across layers of system hierarchy.

In an individual's creative process, there are distinct roles that reasoning, intuition, and tertiary processing play. Yet, in systems engineering, the are blended together. Forming a PASE group would protect the openness needed for creativity under a Waterfall methodology. In doing so, the problems of complexity and emergent risk are addressed directly, systematically, and practically – all while making hardly any changes to the conventional workflow of aerospace programs.

Although Parallel Systems Engineering is a novel concept derived from the nature of creativity, it was discovered later that a similar goal has been suggested in a study of NOAA and NASA's $7-billion Geostationary Operational Environmental Satellites (GOES-R) program. In GOES-R, a Program Systems Engineering team (PSE) was formed, consisting of about twenty people belonging to one of three tiers: "systems leadership, an intermediary, or 'middle' tier of developing systems professionals with functional backgrounds, and functional experts" (Pfarr et al., 2009). The PSE was studied with regard to how it affects collaborative systems thinking for the entire program, i.e., how well it facilitated creative thinking. Since the middle tier systems engineers "act as an interface between the functional experts and the systems leadership," they became a locus of major problems related to:

1. Insufficient breadth of experience;
2. Common understanding of holistic system;

3. Unified PSE team culture;
4. Integrating goals of middle tier with those of technical experts.

Some of the proposed solutions to these middle tier problems include:

- "Using the senior systems engineer who has [breadth of] experience as a mentor and consultant, providing resources (books, online databases, other engineers at Goddard) so that the engineers get the data they lack, and to allow more time for tasks so that this data gathering process can happen." (Ibid.)
- "On the job training including rotational assignments, a curriculum of technical courses, and systems leadership training." (Ibid.)
- "Establish focus groups within the Engineering Directorate. These are small groups of 4 – 7 systems engineers working on areas with a common theme. For example, we can create a focus group for the Earth Science ground system engineering and a focus group for spacecraft systems engineering, etc. The primary purpose of these focus groups is to improve the systems engineering capabilities through knowledge sharing and problem solving among the group members. Additionally, they provide a measurement and feedback on how well the systems engineering processes were being applied on the various projects. They are non-confrontational assessments of the issues, successes and the challenges that were being faced each day by the systems engineers in the field. It may also be an excellent way to monitor the inner workings of the systems engineering processes without a formal assessment. People tend to be nervous about formal surveys and assessments and they will often hold back information or exaggerate performance under the scrutiny of such formality.

On the other hand, focus groups are less formal and less confrontational and engineers are more willing to open up on what the real issues are." (Ibid.)

Notwithstanding mentoring and training, introducing a Parallel Systems Engineering group would most likely fulfill many of these aims. PASEs would have additional space, time, and resources to obtain the needed breadth of knowledge. They would work toward common understanding of the holistic system, since their explicit goal is to focus on connecting various elements of a program. They would be non-confrontational, since they act to serve the needs of working level engineers rather than reporting to systems leadership. A PASE group would also prevent informal focus groups from being marginalized from formal scheduling. By being free from the critical path, PASEs function as a check on program-level intuition and tertiary processing. Figure 9 shows how PASE might fit into an organizational chart.

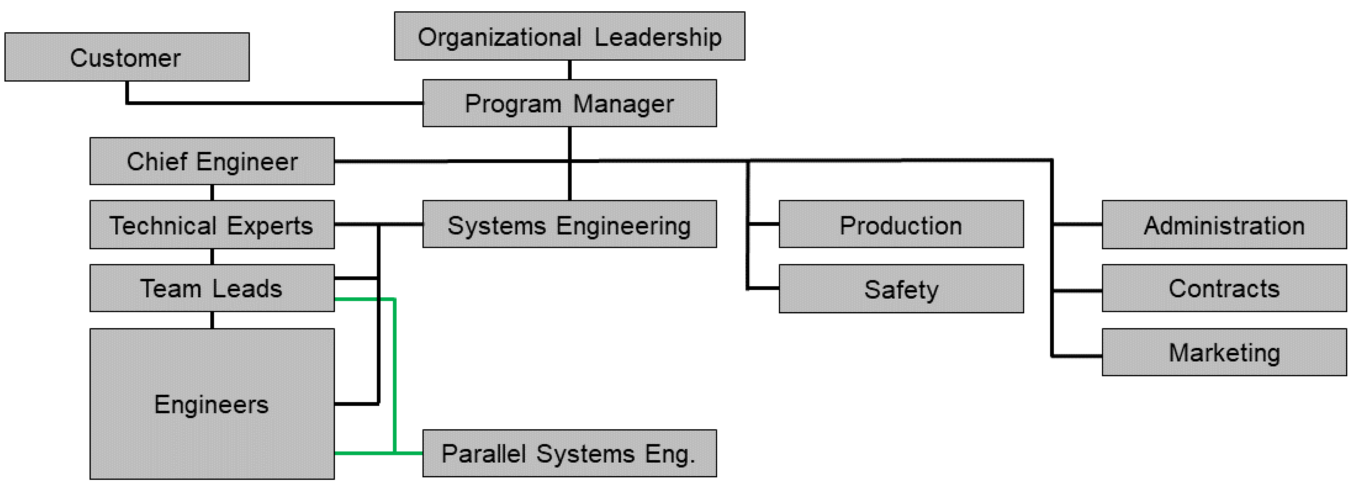

Figure 9. *Parallel systems engineering in an organizational chart. (Drake, 2018-19)*

5.2 Modeling Complexity in Intermediate Creative Processes

As mentioned in Chapter 3, the engineering development process consists of intermediate creative processes with intermediate products along the way. This can be understood to follow the chronological sequence of traditional design workflows or a logical sequence between various kinds of tasks. Chronologically, development might be decomposed as follows: user needs are formulated into requirements, requirements are translated into a conceptual design, a conceptual design is refined into a preliminary design, a preliminary design is refined into a detail design, then detail design is manufactured into the end product. Logically, development might be decomposed as: user needs are formulated into requirements, requirements are translated into a program plan, a program plan is translated into an organization, an organization is used to design the system, the design is used to make manufacturing plans, manufacturing plans are used to make the end product. Either way, the entire engineering development process can be understood as a series of interdependent, intermediate creative processes.

In each of the intermediate processes, the output product derives from the previous intermediate system. In a more simplified sense, the progression from user needs to requirements is a sort of inverse process to the progression from design methodology to design. The formulation of requirements begins with psychological entropy, a need for a system and ends with creating formal requirements for measuring system performance. The design methodology begins with those requirements and tries to create something that fulfills the user needs. Each of these are creative processes, and ideally, they form a closed loop, such that the user need corresponds to the requirements, and the requirements correspond to the end product. This idea is depicted in Figure 10, following the color code given earlier in Figure 4.

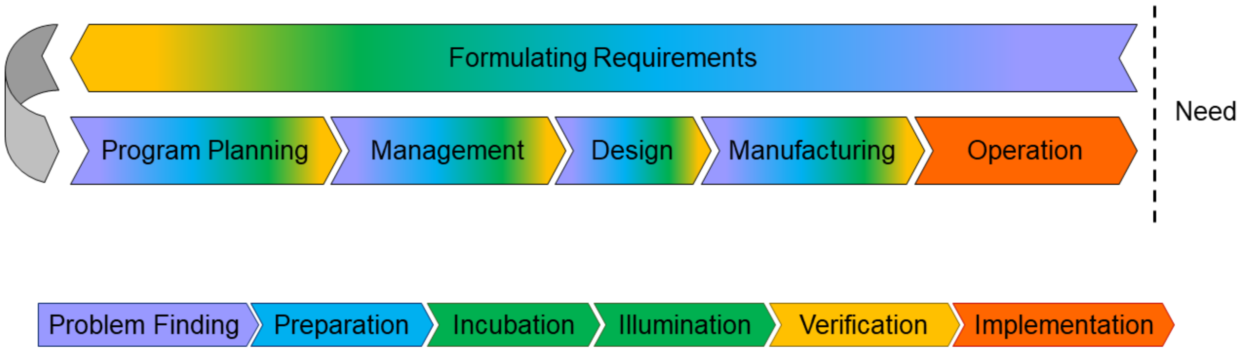

Figure 10. *Intermediate creative processes of aerospace system development.*

Since creativity integrates linear and nonlinear information in a tertiary process, then by modeling the creative process, complexity can become traceable. In engineering, tertiary processes would primarily appear in the development of an intermediate system. For instance, the complexity of a design could be anticipated by modeling the design process, or the complexity of an organization could be anticipated by modeling the management process. In general, modeling an intermediate creative process provides a mechanism for representing tertiary process information, making it possible to directly address many forms of engineering complexity. A central database, such as an MBSE platform, could be used to observe the flow of information and search for areas of tight coupling. This could provide a means of observing correlations between objective and subjective complexity across phases of a program. It could even be possible to study how complexity propagates through any of the intermediate creative processes, and to thereby evaluate whether or not an intermediate process has requisite variety for the intermediate product it is developing. This may make it possible to anticipate emergent risk well before synthesis, verification and validation, and in earlier program phases. The ability to anticipate areas of emergent risk would represent a major advantage in systems engineering.

Chapter 6

CONCLUSION

The present challenge of complex aerospace system development requires a paradigm shift in systems engineering methods. Mounting evidence of large aerospace programs exceeding their budgets and schedules suggests that conventional systems engineering methods lack sufficient control over the complex systems they are implemented to develop. Although it is important to address the technical challenges of developing objectively complex systems, it is also important to address the subjective complexity of developing objectively complex systems. To successfully manage complexity, systems engineering processes can adopt nonlinear processes that are appropriate for complex design domains. Creativity is a tertiary process that integrates linear and nonlinear thinking in a way that produces meaningful order. Thus, fostering creativity through systems engineering can be used as a complexity management strategy. Not only that, engineering is fundamentally a creative activity, and therefore applying the findings of creativity research to aerospace systems engineering has potential for improving complexity management strategies in general.

There has been a limited amount of research on creativity in aerospace, which means that this topic has unexplored potential in the aerospace industry. Future methods for fostering creativity in aerospace programs could consist of the strategies recommended in the literature review of Chapter 4. In addition to cataloging these methods, this thesis provides two novel methods for reducing emergent risk in complex system development. These methods were developed by comparing creativity research, complexity theory, and aerospace systems engineering. Strategies were sought for how to adapt the Waterfall methodology for large, complex aerospace systems.

The two methods presented in Chapter 5 represent the culmination of this work. First, a Parallel Systems Engineering group can be added to existing organizational hierarchies to compensate for the limitations of conventional systems engineering methods. Parallel Systems Engineers could perform divergent thinking and tertiary processing on a program-wide level, focusing on areas of complexity, as support for the working engineers. This could help facilitate the creative process for the whole program. Second, the flow of information through intermediate creative processes in a development program can be modeled. By tracking the flow of information in a central database, like MBSE, and observing areas of tight coupling, the propagation of complexity throughout a program could be modelled. This could provide a means for predicting areas that are likely to have emergent risk well before synthesis, verification, and validation. Facilitating creativity through systems engineering methods such as these could make complex aerospace development programs cheaper and more efficient.

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APPENDICES

A. ALTERNATIVE REPRESENTATIONS OF THE ENGINEERING CREATIVE PROCESS

There are several other well-known models of the standard engineering process. There is the “Analysis, Synthesis, Evaluation” model, which is better understood as a simple representation of engineering tasks in general than an outline of the entire engineering process. Analysis glosses over identifying user needs, deriving requirements, trade studies, and the actual designing of subsystems, components, subcomponents, etc. Synthesis likewise glosses over many steps of combining information in the engineering process, like configuration development, crosstalk between engineers about integration, and testing. Note that “in most systems engineering projects the most difficult phase is the system synthesis rather than the analysis. Systems synthesis requires the greatest ingenuity in finding promising new concepts and will ordinarily require both technological inventions as well as organizational innovations. This system synthesis phase also requires the use of judgment and good sense, so as to achieve a system which represents a major advance but is not hopelessly difficult or unreasonably expensive and time consuming to develop” (Cropley & Cropley, 1999). Evaluation also includes all forms of double-checking throughout the process. It is impractical to try to fit it into the six-stage creative sequence.

There is also is the “Engineering V,” where the first section of the engineering process that consists of designing the whole system down to the smallest level of detail is represented by the left side of the “V,” and the second section of the engineering process consisting of integrating the designs for the sub-levels, verification and validation, making modifications as necessary, combining levels of system hierarchy, all building up to a completed system design is represented by the right side of the V. This model does fit well with the six-stage creativity sequence. The left half of the V matches with the first four creative phases: problem finding, preparation, incubation, and illumination. Then, the system is evaluated and implemented, which corresponds to the right side of the V. Of course, the creative phases recur whenever there is rework to be done. These models are abstractions, intended to illustrate ways in which the creative process can map onto the engineering process. It is not necessary for there to be one-to-one correspondence to glean valuable information from the comparison.

The Technology Readiness Level (TRL) flowchart (see Table 4) does have a loose correlation with the creative process, in that lower TRLs indicate a concept that is developing, middle TRLs indicate a concept that has been formed and yet to be fully verified and implemented, and higher TRLs indicate a concept that is in implementation. Beyond this, the similarity is not rigorous. Yes, the problem of complex system development can be reframed in terms of being inventive enough to make advanced technology. Cultivating creativity in engineering would allow for greater access of advanced design spaces. So, in one sense, if complexity is associated with advanced technology, it is reasonable to think that enhancing engineering creativity would make challenging programs more feasible. However, as stated previously, the intent here is not to advocate for innovative technology but rather the behavioral process undergirding aerospace engineering in general.

Table 4. *TRL definitions* (Young, 2007)

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/pr characteristic proof of concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operations