A QUANTITATIVE HUMAN SPACECRAFT DESIGN EVALUATION MODEL FOR

ASSESSING CREW ACCOMMODATION AND UTILIZATION

by
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Crew performance, including both accommodation and utilization factors, is an integral part of every human spaceflight mission from commercial space tourism, to the demanding journey to Mars and beyond. Spacecraft were historically built by engineers and technologists trying to adapt the vehicle into cutting edge rocketry with the assumption that the astronauts could be trained and will adapt to the design. By and large, that is still the current state of the art. It is recognized, however, that poor human-machine design integration can lead to catastrophic and deadly mishaps.

The premise of this work relies on the idea that if an accurate predictive model exists to forecast crew performance issues as a result of spacecraft design and operations, it can help designers and managers make better decisions throughout the design process, and ensure that the crewmembers are well-integrated with the system from the very start. The result should be a high-quality, user-friendly spacecraft that optimizes the utilization of the crew while keeping them alive, healthy, and happy during the course of the mission.

Therefore, the goal of this work was to develop an integrative framework to quantitatively evaluate a spacecraft design from the crew performance perspective. The approach presented here is done at a very fundamental level starting with identifying and defining basic terminology, and then builds up important axioms of human spaceflight that lay the foundation for how such a framework can be developed. With the framework established, a methodology for characterizing the outcome using a mathematical model was developed by pulling from existing metrics and data collected on human performance in space. Representative test scenarios were run to show what information could be garnered and how it could be applied as a useful, understandable metric for future spacecraft design.

While the model is the primary tangible product from this research, the more interesting outcome of this work is the structure of the framework and what it tells future researchers in terms of where the gaps and limitations exist for developing a better framework. It also identifies metrics that can now be collected as part of future validation efforts for the model.

DEDICATION

I would like to dedicate this thesis to the men and women (and dogs, monkeys, rodents, and one-eyed bunnies) that have made the journey to space possible and to those that continue to push the frontier evermore.

Ad astra.

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ACRONYMS

BBN –Bayesian Belief Nets
C3PO –Commercial Crew and Cargo Program Office
CFM –Contributing Factors Map
CHSF –Commercial Human Spaceflight
COMSTAC –COMmercial Space Transportation Advisory Committee
COTS –Commercial Orbital Transportation Services
CREAM –Cognitive Reliability and Error Analysis Model
EMU –Extravehicular Mobility Unit
ESM –Equivalent System Mass
EVA –Extra Vehicular Activity
FAA –Federal Aviation Administration
FAA AST –Federal Aviation Administration Office of Commercial Space Transportation
FKA –Russian Federal Space Agency
GCRs –Galactic Cosmic Rays
HCD –Human-Centered Design
HITL –Human-in-the-loop
HPM –Human Performance Model
HPSF –Human Performance Shaping Factors
HRP –Human Research Program
ICE –Isolated, Confined, Extreme Environment
IMPRINT –IMproved Performance Research INtegration Tool
IPME –Integrated Performance Modeling Environment (IPME)
ISS –International Space Station
LEO –Low Earth Orbit
MIDAS –Man Machine Integrated Design and Analysis System
NEA –Near Earth Asteroid
NASA –National Aeronautics and Space Administration
PSF –Performance Shaping Factor(s)
RKA – ROSCOSMOS

CHAPTER 1. INTRODUCTION

1.1 BROAD RATIONALE

When considering complex systems, design has a considerable influence on the performance and behavior of the users. From the most mundane applications to the most complex, poor design can confound or even harm users. This problem has been demonstrated in many industries spanning from aviation to nuclear power plant operations. Multiple examples can be found where poor consideration of the operator's interactions with the system have led to fatalities (Shappell and Wiegmann, 2004; Shayler, 2000; Bureau d'Enquetes et d'Analyses, 2012; Fuqua, 1986; Puente 2015; U.S. NRC, 2014). These failures have pushed these industries to better understand human-machine interactions. In an analogous fashion, the crewed commercial space industry, though still in its infancy, already has encountered these problems and will likely see more. Space is an extreme environment where the actions of the crew can directly determine their survival and safety. Given the minimal number of crewmembers typically onboard a spacecraft and the multitude of complex systems they must operate each crewmember must perform at the highest level. Often mission success is contingent upon their ability to successfully complete tasks. In turn, their success rate is greatly influenced by the design and operations of the spacecraft. Understanding how the design impacts the crew's performance can provide valuable insight for assessing the system and identifying improvements. Unfortunately, no rigorous, comprehensive methodology exists to help designers make these assessments. Therefore, *the goal of this research is to investigate this problem and develop a quantitative method for evaluating how the design of human spacecraft will affect the crew's performance.* Ultimately, this methodology could serve as an assessment tool for improving spacecraft design and operations.

1.2 Overview: The Changing Landscape of Human Spaceflight

Historically, human spaceflight in the United States has been solely conducted by the National Administration for Space and Aeronautics (NASA). But today, a new era of human spaceflight is just on the horizon.

With the retirement of the Space Shuttle in 2011, NASA has transferred its Low Earth Orbit (LEO) domain to new commercial companies for delivery of crew and cargo to the International Space Station (ISS). New contracts have been established through NASA's Commercial Crew and Cargo Program (C3PO), which "employs a different strategy where industry creates privately owned and operated space transportation systems, with NASA serving as a lead investor and customer of transportation services" (NASA, 2012). By relinquishing LEO activities to commercial companies, it allows NASA to focus on exploration-type missions to the moon, Mars and beyond (National Space Policy, 2010).

Meanwhile, commercial spaceflight tourism has been gradually growing since the highly-publicized Ansari X Prize competition in 2004, which some regard has having "reignited the waning spaceflight interest of the general public" (Dubbs, 2011). An article in the Chapman Law Review describes the X Prize competition much like the early aviation contests, where it "demonstrated that travel beyond what were the assumed upper boundaries for private parties was not only possible, but could also be extremely profitable" (Parsons, 2006). Since then, several new spacecraft developers, investors, and entrepreneurs have begun their own enterprises, expanding the reach of the commercial spaceflight market.

These three classifications of the human spaceflight industry (1) *government, 2) government-industry partnership, and 3) private corporations*) bring a versatile set of new missions, destinations, operators, users, developers, participants, and customers. A review of each of these categories is done to describe the diversity of this new landscape and how each industry approaches human spaceflight. The most critical objective for the industry, as a whole, is to ensure the safety of the astronauts (or spaceflight participants), though how this is achieved varies with the goals of the particular organization.

1.2.1 Government: NASA's Human Spaceflight Missions

Leveraging over 50 years of human spaceflight experience, NASA has re-affirmed their goal to engage in long-duration and long-distance human space exploration missions in cis-lunar space, Near Earth Asteroids (NEA), and on Mars (NASA, 2014d) Figure 1 shows the variety of destinations and versatility of missions being envisioned by NASA. These type of missions must overcome technical and scientific challenges of humans living and working in space for more than 500 days. It is anticipated that any mission to Mars will be highly demanding on the crew and the spacecraft system.

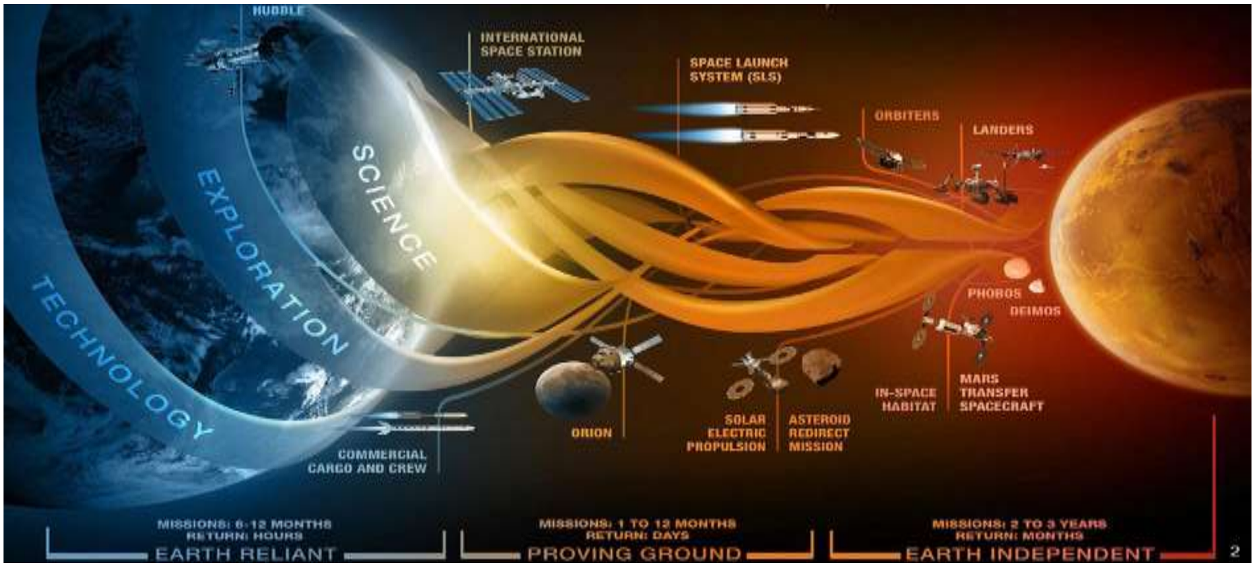


Figure 1. Future destinations and human spaceflight missions for NASA (NASA, 2014).

1.2.2 Government-Industry Partnership: The Replacement of Space Shuttle

As NASA focuses on more distant destinations past LEO, there is still a need for space-related research that can be done on the International Space Station (ISS). The retirement of the Space Shuttle has currently left the United States dependent on the Russian Space Program for rides up to the ISS. Consequently, NASA has contracted with commercial spacecraft developers, SpaceX and Boeing, to build the follow-on human transport vehicles to the Space Shuttle.

Relying on private companies to build spacecraft is not a new concept for NASA as they have been used since NASA's incipience in 1958, albeit under a different model as contractors, not the current public-private partnerships. More recently, NASA has essentially handed over routine space cargo operations to commercial companies. With the Commercial Crew and Cargo Program Office (C3PO), services for cargo transport to the ISS are now being conducted by commercial providers, SpaceX and Orbital ATK (NASA, 2014a). The strategy is to have these "routine" flights performed commercially to allow NASA to focus on beyond LEO flights.

1.2.3 Private Corporations: The growth of Commercial human spaceflight

Commercial human spaceflight (CHSF) is anticipated to be a fast growing industry in the coming decades. The Tauri Consulting Group published a market analysis that forecasted the expected growth of demand for a 10-year period assuming it starts when the first commercial human spaceflight occurs (Tauri, 2010). They compared three scenarios representing potential global economic situations using: 1) a 2010 baseline, 2) a constrained environment, and 3) a growth scenario. The major difference between these three scenarios is the initiation of lunar missions. The baseline scenario assumes lunar missions begin a few years after the ten-year period while the growth scenario assumes lunar missions start immediately, and the constrained scenario does not include any lunar missions. Figure 2 shows an increasing demand in all three scenarios over the 10-year timeframe. Year 1 is defined as the first year in which a commercial human spaceflight is conducted. The predictions for the first year demand were extrapolated using a number of surveys collected from individuals with varying net worth.

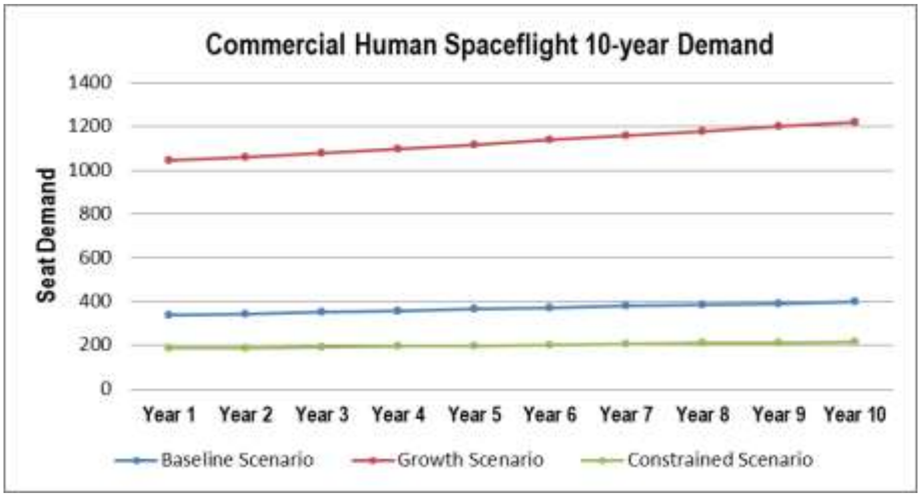


Figure 2. CHSF market demand re-plotted from the Tauri Group Analysis (Tauri, 2010).

While the demand for human spaceflight continues to grow in anticipation of this new market, the supply is also increasing. A number of companies are rising up to meet the expected demand for commercial space tourism. Table 1 shows a representative list of new spacecraft developers that have appeared in the last 20 years vying to fill the market. To set themselves apart from each other, the companies provide a variety of unique services, vehicle types, and different experiences ranging from private high altitude balloon flights, to suborbital flights, to lunar fly-bys, to ultimate Mars excursions. It can also be seen that the majority of the companies on the list are less than 10 years old, which is highly unconventional for aerospace-related fields. The combination of these aspects indicates the dynamic, fast-pace, and pioneering nature of the industry.

Even local governments have recognized the potential business opportunity of the new CHSF market. To capture the fringe benefits from the market, various states have sought to establish spaceports from which the spacecraft developers could launch, land, and operate their vehicles. To date, there have been ten spaceports officially licensed by the Federal Aviation

Administration (FAA) across the United States as illustrated in Figure 2 (FAA, 2013). While no flights have been launched with paying customers as of 2016, the industry is poised to make big strides in the next few decades.

Table 1. List of new companies developing human spacecraft in the last 20 years.

Name of Company	Founding Year	Estimated # of Occupants	Anticipated Destination(s)	Source
1 Bigelow Aerospace	1999	6	Space Station, ISS	www.bigelowaerospace.com
2 Blue Origin	2000	3	Suborbital, Orbital	www.blueorigin.com
3 Copenhagen Suborbitals	2008	1	Suborbital	www.copenhagensuborbitals.com
4 Excalibur Almaz	2005	3	Suborbital, Orbital, ISS	www.excaliburalmaz.com
5 Golden Spike	2010	2	Lunar Surface	goldenspikecompany.com
6 Inspiration Mars	2013	2	Mars Flyby	www.inspirationmars.org
7 Mars One	2010	4	Mars Surface	www.mars-one.com
9 Rocketplane Global, Inc.	2001	5	Suborbital	www.rocketplane.com
10 SpaceDev (Dream Chaser)	1997	6	Suborbital, Orbital, ISS	www.sncorp.com
11 SpaceX	2002	4	Orbital, ISS	www.spacex.com
12 STAR Systems	2011	4	Suborbital	www.hermesspace.com
13 Virgin Galactic	2004	6	Suborbital	www.virgingalactic.com
14 World View Enterprises	2013	8	Suborbital	www.worldview.space
15 XCOR Aerospace	1999	2	Suborbital	www.xcor.com

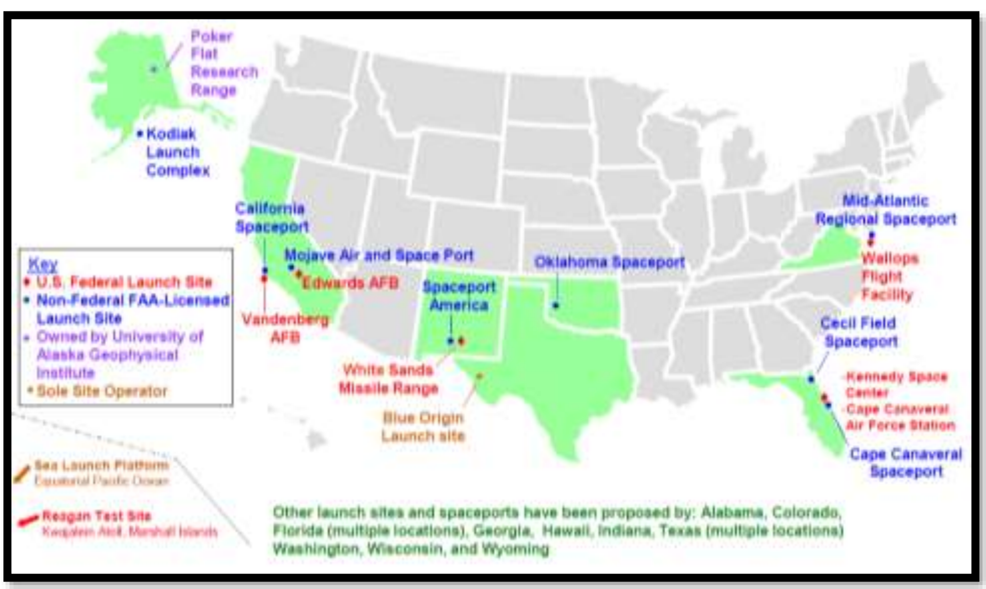


Figure 3. Map of U.S. launch sites and spaceports (from FAA, 2013).

The human spaceflight industry is not only growing very quickly, but also facing a very different landscape than its prior 55 years of history. With brand new companies and developers who have never been in the aerospace field prior, new users and customers, and inexperienced operators, oversight of this new landscape of human spaceflight needs to be carefully considered when establishing regulations, yet cautiously enough as to not smother the burgeoning new industry.

1.3 Concern for Spacecraft Safety and Operability

With the inevitable expansion of the human spaceflight industry in both commercial and government domains, there have been ongoing concerns regarding how to ensure newly designed spacecraft effectively protect, accommodate and utilize the crew members onboard, as well as minimizing risk to the uninvolved public. The three major segments of the industry (government, government-industry partnerships, and private corporations) have specific concerns that are expressed in their documentation or process requirements. Each of their areas of concern are discussed in the following sections.

1.3.1 Government Concerns: Human Research Roadmap Risk Identification

NASA is in the process of capturing and characterizing the anticipated risks for these missions under the Human Research Program (HRP). The program has developed the Human Research Roadmap (HRR) which identifies risks and gaps that need to be addressed as humans look to venture beyond Earth's orbit (NASA, n.d). Out of the thirty-three listed high-level risks four can be traced to specific issues relating to spacecraft design and its integration with the human operators. The following list identifies the most relevant risks from the HRR that are specific to spacecraft design:

1) Risk of Incompatible Vehicle/Habitat Design
2) Risk of Inadequate Mission, Process and Task Design
3) Risk of Inadequate Design of Human and Automation/Robotic Integration
4) Risk of Inadequate Human-Computer Interaction (NASA, 2014b)

An evidence report published by NASA cites how poor vehicle design which does not accommodate nor consider the human's capabilities and limitations "could lead to injuries, crew frustration, and/or mission failure" (NASA, 2013). The risk for both inadequate critical task design and poor human and robotic integration is that "[…] tasks, schedules, and procedures will be developed without considering the human condition, resulting in increased workload, flight and ground crew errors and inefficiencies, failed mission and program objectives, and an increase in crew injuries" (NASA, 2014c). Another concern is that "poorly designed human interfaces can result in a loss of situation awareness compromising mission safety and efficiency" (NASA, 2014c). It is clear that NASA recognizes the relevancy and importance of understanding the interaction and interplay between the crewmembers and the spacecraft and has directed resources towards further investigation of these issues.

1.3.2 Government-Industry Partnership Concerns: Using Human-Rating Certifications

With the new contracting method between NASA and the commercial providers, NASA has had to establish a more generalized spacecraft design compliance process called Human-Rating Certification. This process is described in the document called Human-Rating Requirements for Space Systems, also known as NPR 8705.2B. The document provides insight on what it means to 'human-rate' a spacecraft. The term 'human-rating' or similarly 'man-rating' has historically been difficult to define. Through the years it has evolved from focusing solely on the spacecraft's safety and reliability to include the human element (Klaus, 2012). In NPR 8705.2B, NASA defines a ‘human-rated’ system as one that ‘accommodates human needs, effectively utilizes human capabilities, controls hazards and manages safety risk associated with human spaceflight, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations’ (NASA, 2011b). The emphasis here is on three distinct qualities of the spacecraft: 1) protecting the crew, 2) accommodating the crew, and 3) utilizing the crew. While safety is a critical element, it is clear that there are two other critical factors that must be included which center around the system’s ability to accommodate and utilize the crew. The establishment of these human-rating requirements by NASA is a big step in making transparent the concerns regarding human spacecraft development for commercial companies developing their own vehicles and ensures that spacecraft developers focus on all considerations for the human element not just safety.

1.3.3 Private Corporations: FAA Oversight

To cope with the growing CHSF industry, the United States government has designated the FAA’s Office of Commercial Space Transportation (FAA AST) as the regulatory entity for commercial human spaceflight activities. A 2006 Federal Registrar summarizes the authorizing legislation for the role of the FAA as:

> “...establishing requirements for human space flight as required by the Commercial Space Launch Amendments Act of 2004, including rules on crew qualifications and training, and informed consent for crew and space flight participants. The requirements should provide an acceptable level of safety to the general public and ensure individuals on board are aware of the risks associated with a launch or reentry.” (51 U.S.C. Ch. 509, §§ 50901-21, (2011))

The FAA currently has limited regulatory control purposely in place with the idea that industry needed a 'learning period' without a heavy regulatory environment that might stifle their business (Smith, 2014). As the industry continues to move forward, the FAA has shown its interest and concern with developing regulations that will be sensitive to the industry concerns but also allow for responsible development of a safe and successful commercial operation (Foust, 2014).

While not officially allowed to enforce new regulations until 2015 with an extended moratorium until 2023 (U.S. Commercial Space Launch Competitiveness Act, 2015), the FAA has been proactive about gathering insights from the industry through a series of teleconferences with the Commercial Space Transportation Advisory Committee (COMSTAC) specifically addressing occupant safety. The FAA's latest draft of their "Established Practices for Human Space Flight Occupant Safety" document was released to illustrate the type of concerns they hope to address (FAA, 2013).

While each industry segment documents their human spaceflight concerns differently, they understand that the human is an integral part of the safety and success of the system. Safety is the underlying concern for all space missions, and the risks highlighted here are safety considerations that result from the human-system interaction. Ultimately, human spaceflight, whether commercial or government sponsored, is centered about the human element and ensuring that the spacecraft accommodates and uses the crew optimally in an effort to develop safe and useful systems.

1.4 Rationale for Improvements to Human Spacecraft Design Practices

As human spaceflight systems become more complex, versatile, and interconnected, the need to better understand interactions between the human and spacecraft increases. The following sections illustrate the need for a more thorough understanding of human interactions with the spacecraft and why this type of research can elucidate and improve development of future systems whether as safety improvements, or greater mission success, or cost reduction.

1.4.1 Crew Integral Part of Human Spaceflight

Crew are an integral part of the spaceflight system and their actions are not only critical for accomplishing mission tasks but have also been crucial for salvaging dangerous mission critical issues. For example, the safe landing of Apollo 11 can be attributed to Neil Armstrong's quick assessment of the landing situation and taking manual control of the lander (Jones, 2016); while not life-threatening, the rover on Apollo 17 encountered a broken fender that would have prevented the astronauts from accomplishing parts of their mission and was saved by astronaut Jack Schmitt's make-shift fender (Smithsonian, 2015); and the oxygen canister fire on Russian's Mir Space Station was put out by both cosmonaut Valeri Korzun and astronaut Jerry Linenger (NASA, n.d.a). While these incidents can be blamed as a result of having astronauts onboard a spacecraft making it more dangerous, the benefit to having astronauts in space cannot be denied in regard to the accelerated pace of science done in space which could not have been accomplished solely by automated systems. What is important to consider is how astronauts and the spacecraft can work together in concert to achieve even greater scientific discovery.

Integrating humans with complex systems has been a growing area of research as technology has gotten more advanced and sophisticated. Several fields have been created to formally address this area of research and have evolved from measuring specific human characteristics like anthropometrics or biomechanics to inclusion of interface design issues, such as, human systems integration (HSI), human factors engineering (HFE), human machine interface (HMI). The growing list of human systems integration methods shows that there is a strong acknowledgement of good practices and research needed for integrating humans into complex systems. If the humans are not accounted for appropriately in the design it can result in severe accidents as has been witnessed in the course of history. Understanding how crew are impacted by the spacecraft design is not only a rational step in ensuring mission safety and success, but is also a proactive step for preventing future catastrophic accidents in space.

1.4.2 Need for Predictive Capability of Crew and Spacecraft Performance

Launching humans into space is an expensive endeavor with long design, development, and manufacturing timelines. Once the spacecraft is launched into space there is minimal capability for repairs or maintenance. Therefore, tests and system validation are done on the ground to ensure minimal risk. Failure of a spacecraft system could result in loss of the mission (LOM), loss of the vehicle (LOV), and more tragically, loss of the crew (LOC). To reduce the risk of failure designers have begun to rely more heavily on simulations or models to help predict and analyze the performance of the spacecraft prior to manufacturing. Computational models and simulations are powerful tools for spacecraft designers and help elucidate concerns prior to launch of the system. This section describes the need for robust and predictive models to ensure compatible crew performance in spacecraft.

In addition, there is value in doing these analyses quickly and cost effectively. Quantified analyses of human performance for specific spacecraft designs may be beneficial for designers when doing conceptual trade studies between the crew's performance and spacecraft metrics like mass, volume, or cost. A clear grasp of the crew's performance provides an objective method for comparing design modifications and understanding whether they hinder or improve the overall system performance.

1.4.2.1 Minimal Capability for On-Orbit Repairs

Due to the high cost of spaceflight missions, crew time is a limited commodity on orbit. From a cost perspective, it would be beneficial to overload the crew with numerous tasks to receive the most 'bang for the buck', but high workload is often associated with high levels of stress, and higher error rates and decreased task performance. Researchers have shown that there is an optimal level of stress applied on the human before it becomes too overbearing and results in reduced performance (Hancock, 1989). Generally, there is limited time for crew to be working on repairs or maintenance tasks, as they would also have science-related payloads to attend. Because of the crew's tight schedules there is little time to be used specifically for maintenance of hardware.

Another limitation is the amount of mass that can be brought up with the spacecraft. Due to the limited mass, not every tool or machine can be sent up to do repairs on hardware, nor can multiple replacement parts be sent. For long duration missions to a distant destination, there would be minimal ground support available. The combination of limited resources and support drives two design considerations where the system must be reliable and robust, or if it fails, must be easily repaired or maintained by the crew. As the hardware system performance degrades through its lifetime, there should be accurate models that can identify and predict the failure conditions as well as the ability of the crew to handle them.

1.4.2.2 Human Spacecraft Development Costs

Human space missions have historically been a costly endeavor. The total cost of the Apollo Program was equivalent to about $98 billion in 2008 dollars across 14 years (Stine, 2009). The Space Shuttle Program cost estimates have shown $170 billion across 30 years of operation with an average cost per flight around $1.5 billion (Pielke, 2007). The expense can be attributed to a number of reasons, but one method that has been shown to reduce development and operations cost is to minimize re-design burdens late in the program (Laughery et al., 2013). This often means more thorough and rigorous design work is done early in the program development phase to minimize the need for re-work.

In the Systems Engineering Process, the early work consists of architecture trade studies, conceptual design studies, simulations and models of various designs. This early phase is meant to explore the design space given the mission requirements and constraints. As the process progresses, more hardware, time, and resources have been applied to the project. Often with human systems development, analyses and testing are done far along in this process. These tests are constituted as prototypes, or simulated environments to examine numerous scenarios. If a design flaw is discovered during testing and requires major hardware changes, it can be very costly at this stage. Large complex systems that had not sufficiently tested human integration early in the process have been shown to incur greater costs during operations and maintenance due to the re-design or operational workarounds. Reviews of complex military projects have shown evidence of significant cost savings with the use of human modeling tools and simulations early in the design process (Booher, 1997; Clark, 2002; Rouse, 2010). Predictive models and simulators for complex systems have been beneficial for a number of military acquisitions and are anticipated to provide similar benefits for human spaceflight programs.

1.4.3 Current Methods Are Insufficient

Currently, the method for integrating humans in the spacecraft is through requirements-based documentation and guidelines that provide detailed component level design considerations. NASA documents human-specific design requirements in two volumes of NASA-STD 3001 (NASA, 2007a and NASA, 2011a). These documents are the foundation from which designers create requirements specific to their vehicle and mission needs. A requirements-based process is important for the systematic definition, verification and validation of the design. Using only requirement verification as an assessment method, however, has limited capabilities for predicting design impacts on crew performance for a number of reasons outlined below:

1) Requirements dictate functions and not specific design choices
2) Requirements are meant to be static and not used as a modelling tool
3) Downstream impacts of requirements are difficult to identify and track

Requirements are necessary for specifying design selection criteria but they are not able to answer the question of how well a given design accommodates and utilizes the crew. Additionally, methods for evaluating the impacts from spacecraft design on the crew are often applied late in the design process, where the ensuing redesign incurs significant costs. As documented by Gansler and Booher in the aviation industry “often times, prototypes are built and tested late in the design process and can result in expensive redesigns” (Gansler, 1987; Booher, 1997; NASA, 2014). As a result of these high costs, numerous models and methods have been developed to address early design issues with regards to hardware and vehicle integration, but few have incorporated human impacts, and more specifically, few exist for human spacecraft models.

This methodology, while useful, is not able to provide a comprehensive evaluation at the spacecraft level and often times a prototype is built to identify issues with human-in-the-loop operations, but getting to this stage requires a detailed design of the system, and if testing reveals major issues, it can be quite costly to change. A higher-level abstraction of spacecraft design may provide a less costly and more systematic approach for designers to evaluate their design and employ objective assessments for comparing designs.

1.4.3 Summary of Needs in Human Spacecraft Design

Predicting crew performance is a desirable capability for designers as a guide for more definitive feedback regarding design impacts on the crewmembers. Additionally, quantifying crew performance predictions can provide a more robust analysis when doing trade studies to compare against the system mass, volume, and power measures. The stakes of human spaceflight are high and there is minimal ability to fix vehicles once launched, therefore early performance prediction can help improve mission success, lower cost, and improve safety. The current methods for predicting crew performance are insufficient to capture the versatility of new spacecraft or the dynamic nature of the spaceflight system where the human 'subsystem' changes in response to the environment.

Given these assertions, the goal of this research is to investigate the impacts of spacecraft design on crew performance, and to develop a quantitative framework for helping designers assess and evaluate the quality of the spacecraft from the perspective of the crewmembers. The framework is intended to serve as an evaluation tool for improving spacecraft design and operations, and bridges the gaps between the engineering design process and the human element. It also opens the door to explore crew performance from a novel yet integrative perspective in an effort to answer more of the qualitative aspects that have plagued spacecraft designers for decades.

1.5 Dissertation Overview

This document is divided into five main chapters. This preceding Chapter One provided the introduction and rationale for better assessment methods for human spaceflight. Chapter Two presents background information that points out the complications of integrating humans into spacecraft, and examines the multitude of methods that are currently used to evaluate complex human-system interactions while identifying specific methods that have. Chapter Three presents the framework components for developing a quantitative human-spacecraft model, including definitions, characteristics, and relationships between design factors and crew performance. Chapter Four aggregates the components into an overarching framework model that maps design choices to crew performance predictions. Various design reference missions are used as test scenarios to validate the use of the model and the results are presented in Chapter Five. Finally, Chapter Six describes the limitations and future considerations required for improving the model.

CHAPTER 2. BACKGROUND

"*Machines would not exist without us, but our existence would no longer be possible without them*" (Pierre Ducasse, from Bruno Munari's *Design as Art* (1966)).

Designing a vehicle capable of safe, crewed-spaceflight presents a difficult challenge for the engineers, designers and human occupants involved. Spaceflight is often classified as an Isolated, Confined, Extreme (ICE) environment in which the astronauts are isolated from friends and family, and because of the inhospitable surroundings outside of the spacecraft, the vehicle is the only oasis for human life. The spacecraft must provide everything: a pressurized environment, atmospheric and thermal control, food provisions, hygiene needs, places to exercise, and transportation to name a few. If any of these needs are not met, the internal environment can vary anywhere from uncomfortable to fatal for the occupants.

In order to increase robustness and redundancy within the vehicle, the capabilities of the crewmembers are typically considered and designed into the vehicle's planned operations. The crew is expected to make repairs, help navigation computers perform difficult maneuvers, and diagnose any unexpected problems occurring during daily operations. This integrated design approach helps to reduce overall system complexity and development time, however, it requires careful consideration of the human-machine interaction to be robustly implemented.

Careful consideration of the vehicle-crew interaction is not an easy task for designers. In addition to the inherent difficulties associated with simply keeping the crew alive, crewmembers can vary widely in skills and demeanor. The optimal design for the human user may not be a feasible solution in terms of the constrained spacecraft mass and volume requirements. And while human integration is recognized as an important consideration, programmatically, the basic engineering requirements of the vehicle are often considered earlier and with higher importance than the needs of the crew. There are a variety of reasons as to why this occurs. The National Research Council (2007) identified fifteen reasons as to why system designs fail to appropriately integrate the human element and are reposted in Table 2. Reasons 2, 4, 5, 7, 9 point to a lack of methods or tools to help adapt Human Systems Integration (HSI) practices into practical applications. As a result of not having usable tools or methods, it is difficult for stakeholders to incorporate HSI effectively into the design process.

Table 2. Identified reasons for minimal Human Systems Integration(HSI) incorporation into complex system designs (National Research Council, 2007).

1	Failure to introduce human factors considerations early enough
2	Lack of effective methods and tools to predict direct impacts and ripple effects of envisioned future systems early in the design process
3	Tendency to focus on people as the error-prone weak links that need to be 'automated away'
4	Failure to apply known good/recommended methods routinely in practice
5	Lack of ability to abstract generalizable concepts and principles as well as transportable models, across application contexts
6	Lack of synergy between research and practice
7	Lack of adequate HSI metrics to support progress monitoring pass/fail reviews and system-level education
8	Inadequate or poorly documented data on human task performance
9	Lack of effective use of methods and tools to support the HSI process
10	Difficulty of cost-justifying resource allocation for HSI issues
11	Inadequate education and training of system developers to sensitize them to HSI issues
12	Limited opportunities for the education of HSI specialists
13	Failure to assign resources to HSI
14	Conflicting requirements of various stakeholders in system development process
15	Insufficient advocacy for HSI at top level of organizations

Having the ability to quickly assess impacts of engineering design choices on the crew early in the process could greatly increase the chances of design choices being made that best accommodate and utilize the crew. This in turn will increase the crew's performance which can directly feedback into the overall robustness and success of the mission. It is therefore critical for crewed-spaceflight to have a human-design centered metric for assessing and evaluating the impacts of design choices on the performance of the crew. Unfortunately, as mentioned, no methodology exists to date that can provide a comprehensive and quantitative assessment of how well a spacecraft accommodates and utilizes the crew. While computational human performance models do exist and are helpful, they tend to be more focused towards terrestrial scenarios and therefore provide an incomplete description when applied to human spaceflight.

This chapter provides background on these various models and discusses their limitations. To understand these limitations, and where the difficulties arise when developing a human spaceflight performance metric, the elements that should compose a comprehensive model are described.

First the large number of variables that can affect the crew's performance are discussed. These variables range from the crewmember's internal emotions and the surrounding space environment to the required spacecraft operations. These variables are generally consolidated under the name of performance shaping factors (PSFs) and fully identifying and characterizing them is a major challenge that may never be fully accomplished.

Second, the roles and tasks required of the crew are discussed. These tasks can be highly versatile, ranging from mechanical maintenance to performing surgery. While system automation can help with many of these tasks thereby reducing workload for the crew, it can also create unintended consequences. The crew may develop system mistrust or they may misdiagnose problems due to faulty sensors, while highly automated navigation and control may reduce situational awareness during critical maneuvers or emergencies. However, task oriented design is not limited to automation as it must also account for the changing attitudes of the crewmembers and how they might handle being overworked, faced with failing systems, or subject to extreme boredom.

From this foundation of crew performance elements (PSFs, and crew roles), various human performance integration methodologies are described. A cursory overview of over 400 different methodologies were collected and analyzed for their applicability and use for human spaceflight crew performance analysis. Their advantages and limitations are discussed.

Finally, from the overview of previous works and background presented in this chapter a clear set of objectives for the model framework are identified and outlined.

2.1 Factors that Affect Crew Performance

The spacecraft provides the living and working environment for the crew. Everything the crew interacts with influences the crew's performance in some way. A poorly designed system can degrade performance, while a well-designed one can enhance or ease the crew's job. There are many areas of spacecraft design that can impact the crew's performance from noise levels to the air flow. But before delving into the details of the spacecraft design, it is important to understand the external space environment and how it can constrain and motivate certain design choices. In actual operation, two environments exist for the spacecraft: the inescapable natural space environment and the artificial environment created by the spacecraft design and chosen operational elements such as launching, orbit trajectories, and re-entry. The following sections provide some background regarding these environments and what a spacecraft designer should be aware of when designing for different mission types.

2.1.1 Natural Space Environment

Space presents a unique and formidable environment characterized as an extreme environment. Overlooking the dangers of launching into space, landing, and re-entry, the natural space environment itself presents several hazardous conditions that threaten the health and productivity of the astronauts. Five major space environment concerns can be classified as the following (Klaus, 2009):

1. Micro-Meteoroids and Orbital Debris (MMOD)
2. Lack of pressure and/or atmosphere
3. Thermal Extremes
4. Radiation exposure
5. Microgravity

Depending on the spaceflight mission, there could be other natural environment hazards that must be considered, for example, on the moon, lunar dust is a danger to both hardware and human health (Larson, 2000).

2.1.1.1 MMOD

The Earth travels through a number of natural debris sources from the universe including comet tail debris, or micrometeorite fields. These natural sources are often hard to predict and can be found in various sizes. The larger items are better tracked, but smaller items may not be so easily observed. The debris travels at high velocities and can puncture spacecraft hull, or degrade surface coatings that provide functional use such as on solar panels or thermal shielding material.

There are also a growing number of man-made objects that have created orbital debris. “It is known that there are over 20,000 unwanted satellite debris items in low Earth orbit, and the number is increasing in many altitudes” (Nock, 2013). With every launch often other non-functional objects are inadvertently sent into space either from the launch vehicle itself or items that come loose from the spacecraft due to the dynamic launch environment. Traveling at high velocities, even small particles 1-10mm in diameter can penetrate space suits and structures (Larson, 2000). When astronauts are sent outside of the spacecraft to do extravehicular activities, it is important to consider MMOD as a major hazard that must be well-monitored and mitigated through safe operational practices and robust spacesuit design.

2.1.1.2 Lack of Pressure and/or Atmosphere

Space is a vacuum with little to no atmosphere. The spacecraft must be designed to provide a pressurized environment for the human occupants at a comfortable level. Additionally, the lack of atmosphere makes it difficult to reject heat from the spacecraft. Material properties exposed to a vacuum also become distorted and degraded. If optical surfaces are needed, such as windows, it is important to maintain their surface properties for effective operations in space (Larson, 2000).

2.1.1.3 Thermal Extremes

Spacecraft face extreme thermal regimes throughout a mission. Around Earth orbit, spacecraft will receive 1367W/m^2 of energy from the sun on one side, while being exposed to a near 0K temperatures in the shadows (Gilmore, 2002). The spacecraft and space suit must be able to accommodate these large temperature ranges and keep the astronaut at a comfortable working environment to prevent health hazards such as heat stroke or frostbite.

2.1.1.4 Radiation Exposure

There are two major sources of radiation in space that impact human spaceflight. The first source of radiation is any energetic ionized particles that come from the sun due to its solar activity. This type of radiation can often be shielded with enough layered and dense material to protect the human occupants. The second type of radiation source is from Galactic Cosmic Rays (GCRs). These come from deep space objects that radiate high energy particles that can disrupt the human body's DNA. Radiation dangers occur either as large dose events which causes immediate radiation poisoning, or as an insidious long-term accumulation that result in various cancers.

Radiation protection is still a major concern for long-duration space missions. The current mitigation strategy is to follow the required ALARA (as low as reasonably achievable) (Buckey, 2001).

2.1.1.5 Microgravity

Microgravity effects on the human body are still being studied especially regarding the long-term effects. The human body undergoes a number of physiological changes due to the lack of gravity. Without preventative measures in space, bone density is reduced dramatically at alarming rates, muscle mass is loss and becomes weaker, and the vestibular system ceases to function properly. In addition, the stressors of the spaceflight environment such as variable day/night cycles, cabin noise and vibrations, and unpleasant odors also impact the crews' well-being. There is also evidence of immuno-suppression in crew members during extended space missions, which could threaten crew health if exposed to contagions (Buckey, 2001).

2.1.2 Internal Spacecraft Environment

While the space environment naturally provides external hazards, there are also dangers associated with getting to space as well as the operational environment internal to the spacecraft. Depending on the mission, there could be additional risks due to the chosen launch profile, such as high acceleration due to specific. These induced environments are not a direct factor of the space environment and do not always present an immediate danger, but must be considered when designing for various missions.

2.1.2.1 High Acceleration

As the rocket lifts off from the launch pad carrying human cargo, it can achieve launch accelerations upwards of 3-8 times the force of gravity, while re-entry accelerations can be upwards of 12 g's as with the Mercury missions (NASA, 1963). Proper orientation of the astronauts can help alleviate potential problems of having blood pooling in the wrong places in the body, when the heart is unable to overcome the acceleration forces. Having the acceleration forces transverse to the axis of the body (applied from the front to the back), it can help reduce the stress of high acceleration loads. "In this position the gravitational force is not acting on the long hydrostatic columns of blood that exert heavy pressure on the heart. […] With the acceleration forces acting in the transverse direction, the astronaut can withstand about 20 g for short periods of time" (Hammond, 2001).

2.1.2.2 Vibration

During the launch of the spacecraft, not only does the rocket produce high accelerations, it also induces a variety of vibrations throughout the vehicle. The vibrations can occur along any axis during flight (Hammond, 2001).

2.1.2.3 Noise

The noise level in the crewed compartment will range throughout the mission from launch to landing. Noise must be well monitored and maintained within certain frequencies and amplitudes as not to cause permanent damage to the astronaut's hearing. In addition, during critical periods the noise level must be low enough to allow for emergency sounds to be audible (Hammond, 2001).

2.1.2.4 Artificial Gravity

In some scenarios there may be a desire to create an artificial gravity environment to help mitigate the detrimental physiological effects caused by the microgravity environment. While no spacecraft currently have had this ability, future space explorers may encounter this type of vehicle.

Concerns regarding the artificial gravity include the required rotation and how variations of acceleration laterally (from head to toe) may impact the crew's performance and adaptations (Hammond, 2001).

2.1.2.5 Isolation

While the physical distance of space is merely 100km above the height of Earth's surface, the ability for the astronauts to interact with other people beside their crewmates are highly limited by the communication links to Earth. In LEO, astronauts communicate with the ground on a frequent basis, but as missions extend further from Earth, communication becomes more difficult. The amount of data exchanged will be both limited and infrequent. Time delays become a major frustration for operations. The extreme isolation from the earth in a completely foreign and unusual environment can cause psychological stresses in the crew (Manzey, 2004).

2.1.3 Performance Shaping Factors (PSFs)

While the space environment is clearly important in establishing the mission constraints, another equally critical impact on crewmembers is the living environment of the spacecraft. The interface the crewmember sees is the internal design as well as the environment (atmosphere, pressure level, humidity etc) generated by the spacecraft. While exterior design will impact the crewmember's ability to do operations and repair on the spacecraft, this work will limit the scope by focusing solely on the internal environment design and for now 'ignore' the exterior design. The assumption is that the foundation developed in this thesis will be flexible enough to include the external design as an additional design parameter for future work.

It is clear that several factors affect crew performance ranging from organizational demands to specific illnesses. In fact, a list of 172 Performance Shaping Factors (PSFs) for astronauts have been documented (Mindock, 2014), capturing the large variety of factors that could influence the astronauts' performance. The contributing factor map, shown in Figure 4, categorizes the factors in a socio-technical hierarchy which starts at the individual level and extends upwards to organizational impacts that could affect the astronaut.

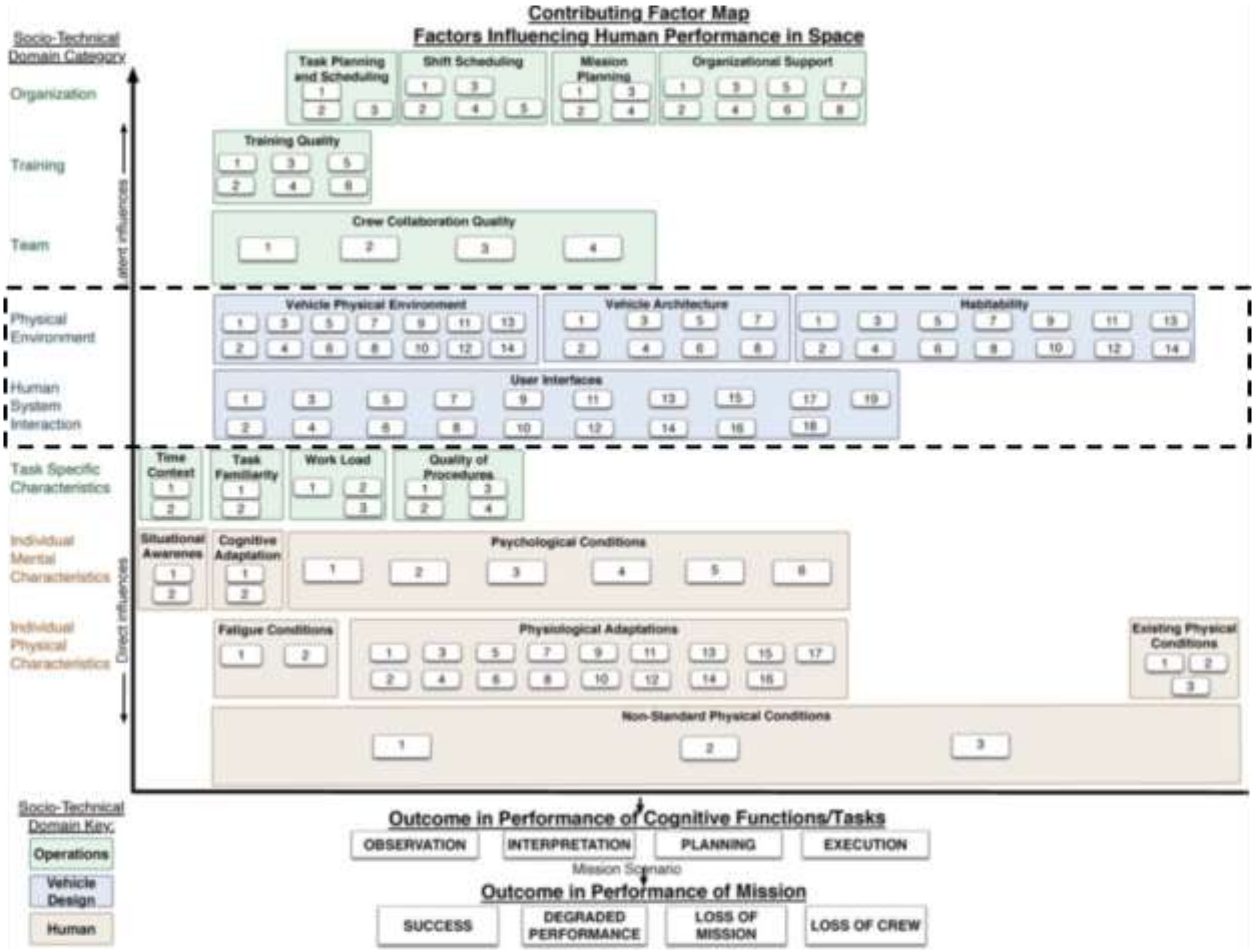


Figure 4. Map of contributing factors to human formance in space (Mindock, 2014) (dashed box show the design specific PSFs (C) that can be controlled by designers).

More specifically, the factors are grouped into the following six categories: (1) Individual Physical Characteristics, (2) Individual Mental Characteristics, (3) Task Specific Characteristics, (4) Human System Interaction, (5) Physical Environment, (6) Team, (7) Training, and (8) Organization. These six categories can further be classified into, (A) Human or Individual Specific PSFs (Mental and Physical Characteristics), (B) Operations or Group Specific PSFs (Team, Training and Organization), and (C) Vehicle Design Specific PSFs (Physical Environment, Human System Interaction, Task Specific Characteristics).

While it can be argued that all of these factors must be considered when identifying performance issues with astronauts, it is clear that the designer can only directly impact category (C) Vehicle Design Specific PSFs. Therefore, the scope of this work focuses on the design choices that the designer can specifically control to achieve the intended crew performance. The Vehicle Design Specific PSFs are listed in Table 3.

Table 3. Vehicle design PSFs (modified from Mindock (2012)).

VEHICLE ENVIRONMENT	VEHICLE ARCHITECTURE	HABITABILITY	USER INTERFACES
Natural and induced environment factors	***Factors that create the physical environment surrounding crew***	***Human needs of the system***	***Interface design between human and system***
Noise Level	Décor	Microorganism Virulence	Identifiability
Vibration Level	Anthropometric Accommodations	Inventory management Capability	Information Displays and Decision Aids
Humidity Level	Habitable Volume	Confinement	Standardization
Lighting (ambient)	Location and Orientation Aids	Level of Sensory Stimulation	Control Panels/Input Devices
Temperature	Translation Paths	Availability of Personal Items	Hardware Tool Availability
CO2 Level	Hatches and Doors	Availability of Medical Care	Situation-specific Lighting
Air Flow	Windows	Cleanliness of Environment (microorganism, gunk etc.)	Hardware Ease of Use
Oxygen Level	Lighting (Ambient)	Food System	Software Ease of Use
Odor		Nutrition	Information Management Support
Atmospheric Particulates		Availability of Private Space	Human/Vehicle Automation Integration
Acceleration/Gravity Level		Availability of Recreation/Personal Activities	Work Station Anthropometric Accommodations
Toxic Substance Level		Décor of Environment	Mobility Aids and Restraints Availability and Quality
Atmospheric Pressure Level		Hygiene Support	Orientation of User Interfaces
Radiation Exposure Level		Water System	Suit Design
		Countermeasures	Caution and Warning Functionality
Modified from Mindock (2012).			Human/Robotics Integration

In this model configuration, the designer assumes that the crew will perform to the best of their ability given the design of the vehicle and intended mission goals. This limits the job of the designer to ensuring that their design provides everything the crew needs to optimally execute the mission while the crew's job is to perform those functions at their highest ability.

2.1.3 Summary of Factors Affecting Crew Performance

As shown in this section, there are numerous factors that affect the crew's performance. While the classification schema presents the PSFs as an organized list of individual elements, it is clear that they are interconnected and can be highly influenced by one another. For example, microgravity environments can exacerbate high CO2 levels in which they form pockets of 'dead air' directly in front of the astronauts' faces, but can be alleviated with appropriate amount of airflow. The dependencies across design choices are not all well-understood and require much more data collection to define. In the meantime, the list of PSFs provide an easy starting point for understanding impacts of design choices on the crew.

2.2 Role of Crew in the Spacecraft

Due to the extreme environment of space it is vital that both the astronaut and spacecraft can perform their required functions in any situation that arises throughout the mission. While having humans in a spacecraft add the need for life support systems, the unique capabilities of the human can increase the overall reliability and functionality of the system. In addition, the crew functions in a variety of roles including being a human test subject for space medicine, doing tasks that are too difficult to automate, being able to adapt quickly when unexpected issues arise, and more philosophically, they act as a representative for their country. The following section describes how the human occupant interacts with the spacecraft and can be classified in two modes: (1) passive or (2) active crew. In the passive state, the spacecraft works to provide the basic necessities of life with little interaction from the crew. In certain cases, such as space tourism, there might be a demand for more than just the basics and may require more comfortable settings or even elements of luxury. For active crews, this requires continued interaction with the spacecraft that not just meets the minimum accommodation requirements, but requires systems to be usable and functional. The role of the crew in spacecraft can be highly varied and understanding the different roles crew can play is critical when considering the design of the spacecraft.

2.2.1 Crew as a Passive Participant

The spacecraft is designed to protect the crew from the hazards of space, in addition it must also provide basic necessities to keep them alive including oxygen, water, and food. The basic consumables required for each crewmember are well-documented with considerations regarding the intensity of activity and variations in temperatures. The figure below illustrates a diagram of a human's inputs and outputs during a nominal day. Humans also generate waste products, which the spacecraft must be capable of removing including carbon dioxide, fecal material, urine, trace contaminants (hair, skin, gases), and excess humidity and heat produced as a byproduct of metabolism. The amount of waste produced per crewmember per day is also well-known (NASA, 2004). These basic provisions must be provided to keep the human alive and healthy.

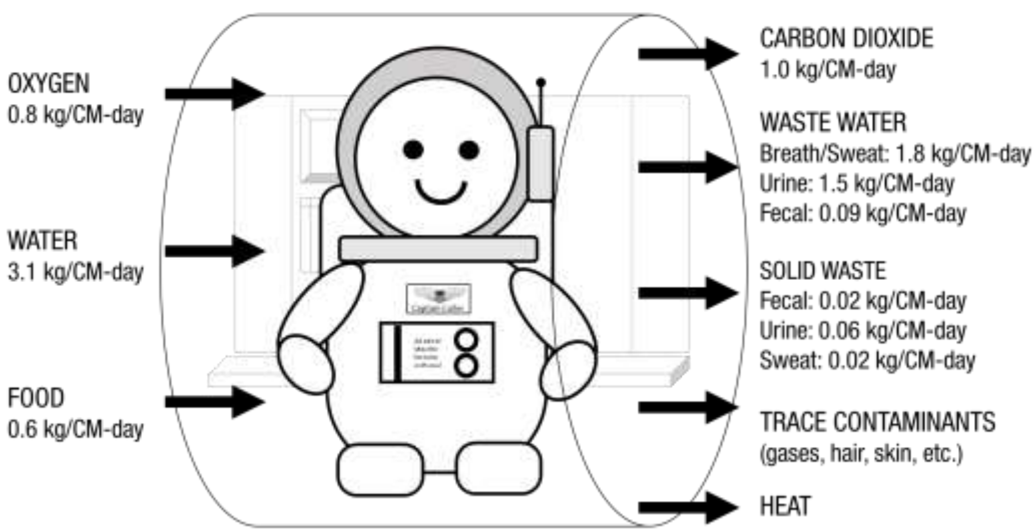


Figure 5. Input and outputs to keep human alive in space.

Humans cannot survive the extreme space environment and require the spacecraft to at minimum provide a healthy environment for life. Not meeting the basic accommodation demands of the crewmembers can lead to dangerous conditions for the human. Even at this most basic level of necessities requires thoughtful design considerations.

2.2.1.1 Maintaining A Healthy Spacecraft Environment

The assumption used here is that even if the crew are passive members of the flight there is an implicit requirement to keep the crew's health up or near their pre-flight baseline and that there are basic tasks that the crew must do to keep themselves alive (i.e. eating, hygiene activities, or emergency operations). Maintaining a healthy crew requires, at minimum, a clean atmosphere, uncontaminated drinking water, standard pressure and temperatures, comfortable humidity levels, and reduced noise and vibration.

A number of crew have been sickened during spaceflight due to toxic leaks inside the cabin forcing missions to be cut short, while greatly endangering the crew's lives. There have been at least 12 documented cases in which the spacecraft environment had environmental control issues causing sickness the crew members and at least three of the incidents resulted in early mission termination (NASA, 2010).

Temperature extremes can also cause reduced performance, but in more severe cases can affect crew health. In the early phases of high-altitude flight testing, the cabin temperatures exceeded 100ºF and the pilot's speech began to slur. The pilot's internal body temperature began to rise as well. Luckily, he was able to land the vehicle and extract himself without further harm (Shayler, 2000).

A noisy spacecraft environment also endangers the crew's health due to potential hearing loss. High amplitude and high frequency sounds can also create an uncomfortable living environment. Certain levels of vibration are also of concern to crew survival. As noted by NASA (2013), "Vibration may directly cause injury via mechanical stress to internal organs and musculoskeletal structure or limb flail resulting in impact with cabin equipment and adjacent crew. […] Severe and unexpected vibration may also have a cognitive impact."

Appropriate accommodation of the crew in the spacecraft is an important foundation in providing the crew with a suitable living and working environment. Without considering these accommodations in the design it will adversely affect the crew's health and ability to execute any required tasks.

2.2.1.2 Degradation of Crew Performance Due to Poor Accommodation

Basic crew accommodations allow the human to survive in the spacecraft. The environment in which the crew lives and works in will have a direct impact on the level of their well-being. A number of environmental choices can influence the crew's comfort level from the temperature of the cabin, the ambient lighting, the airflow, or the humidity levels. While there are clear guidelines for many of these choices, it is important to recognize them as choices made by the designer to ensure the ideal level of comfort while maintaining a low mass and efficient volume usage.

The process of designing human spacecraft is made difficult by numerous factors including: the dynamic role of the crew, the range of possible mission scenarios, and the hazardous environment of space. Ensuring the crew is appropriately and efficiently integrated within the spacecraft can be a difficult process as seen by the number of incidents that have occurred either in the history of spaceflight which have been tied to human error.

2.2.2 Crew as an Active Participant

The first flight in space by Russian cosmonaut, Yuri Gagarin, had proven that humans were indeed able to survive and function in microgravity. During the Mercury Program, a committee was established to focus on the study of human factors and training related to human spaceflight. The report published by this committee addressed the need for determining man's capabilities in space:

> "The ultimate and unique objective in the conquest of space is the early successful flight of man, with all his capabilities, into space and his safe return to earth. Just as man has achieved an increasing control over his dynamic environment on earth and in the atmosphere, he must now achieve the ability to live, to observe, and to work in the environment of space." (Link, 1965)

Follow-on flight experiments focused on understanding how astronauts live and work in the unique space environment. To this day, astronauts continue to be test subjects for space medicine, where their bodies are used for studying the effects of microgravity on human physiology. Their continued presence provides enormous amounts of data regarding pre-, during, and post flight physiological changes throughout the mission.

2.2.2.1 Crew Roles and Capabilities

Besides being just the 'guinea pig' of spaceflight, astronauts perform a wide range of activities from piloting the vehicle in the case of the Space Shuttle Orbiter to the very technical and intricate maneuvers for science payloads. Debates decrying why send humans at all, don't truly grasp the range of tasks that are done by the humans during spaceflight which currently no robot is capable of. But in an era of rapidly improving robotic and computer design, there is great value in identifying the advantages of having both incorporated with the crew. A recognition of this clear distinction between human and machine dates back to the 1950's with Dr. Paul Fitts who developed a list allocating the functions that "men-are-best-at" and "machines-are-best-at" (MABA-MABA) (Fitts, 1951).

Table 4. Fitts MABA-MABA list (Fitts, 1951).

What Men Are Better At (MABA)	What Machines Are Better At (MABA)
1) Sensory Functions	1) Speed and Power
2) Perceptual Abilities (superiority in stimulus generalization)	2) Routine Work (fewer errors and more uniform responses)
3) Flexibility (ability to improvise)	3) Computation
4) Judgement and Selective Recall	4) Short-term Storage
5) Reasoning (inductive reasoning)	5) Simultaneous Activities

It is important to note that the goal of the list is not to delineate and delegate one task over another to the human or robot, but rather it provides designers a better understanding of where the human and machine could collaborate. In the event of a failure of either component, the other would need to execute the same function, but not necessarily to the same efficiency or accuracy. A large body of research has been developed in this area of human-robot cooperation and continues to generate better guidelines for the interactions to be considered between humans and their future robot companions.

2.2.2.2 Crew Performance Degradation Endangers Missions

As crew members are responsible for a variety of critical tasks, an injured or underperforming crew member will reduce the overall mission performance and possibly endanger the safety of the team. Degradation in performance can mean a variety of things from minor errors committed by a crew member (e.g. typos, misreading), to physical inability due to reduced musculo-skeletal capability, to injuries caused by the vehicle, or possibly psychological breakdown either between teammates or at the individual level.

There have been several documented reports regarding the variety of crew degradation incidents that have led to dangerous situations. The following table lists the types of performance degradation that are of concern as noted in several reviews aggregating the impacts of space-related performance issues (Nicogossian et. al., 1993; NASA, 2013; Manzey, 1993; NASA, 2010).

Table 5. Performance degradation categories and example concerns

Physical Degradation (NASA, 2015; NASA, 2012)	Mental Degradation (Morphew et al., 2001; Kanas and Manzay, 2008)	Psychological Degradation (McPhee, 2009; Kanas and Manzay, 2008; Holland et al.,2009)
Fatigue	Fatigue	Depression
Postural Imbalance	Errors	Ataxia
Nutritional Deficiency	Slow Reaction Time	Asthenia
Radiation Exposure	Limited Cognitive Capabilities	Frustration/Anger
Orthostatic Intolerance	Sleepiness/Alertness	Mood and Mood Disorders
Skeletal Muscle Atrophy	Spatial Disorientation	Anxiety
Cardiovascular Deconditioning	Poor Decision-Making	Psychosomatic Reactions
Bone Loss	Sensory-Motor Discordance	Salutogenic Responses
Visual Impairment/Intracranial Pressure (VIIP)	Impaired Working Memory Function	Poor Psychosocial Adaptation

2.3 Current Human Integration Methods For Spacecraft Not Sufficient

Designing a spacecraft is a complex task in itself, the addition of the human element makes it even more challenging to predict and ensure a vehicle that accommodates and utilizes the crew effectively. As new missions are being envisioned for the future, there is a wider range of human capabilities and preferences to accommodate. Woolford (2010), a space human factors and habitability manager at NASA, describes the recognition by NASA to investigate strategies "for quantifying the critical nature of human factors requirements." While NASA is currently aware of the need for quantifying these requirements, a clear and comprehensive methodology is still missing. As reported in NASA's Human Research Roadmap, one of the gaps includes the lack of: "[m]ethodologies and metrics for integrated vehicle/system level evaluations leveraging multiple, complementary tools/methods such as digital modeling, [human-in-the-loop] HITL evaluations, and population analysis." (NASA, 2013).

2.3.1 Current Human Spacecraft Design Methods

2.3.1.1 NASA Systems Engineering Process

NASA uses the systems engineering process to iterate through design and development as a systematic process for ensuring a good design. The figure below shows the systems engineering process used by NASA, and shows where system analyses are done across the lifecycle (NASA, 2007b).

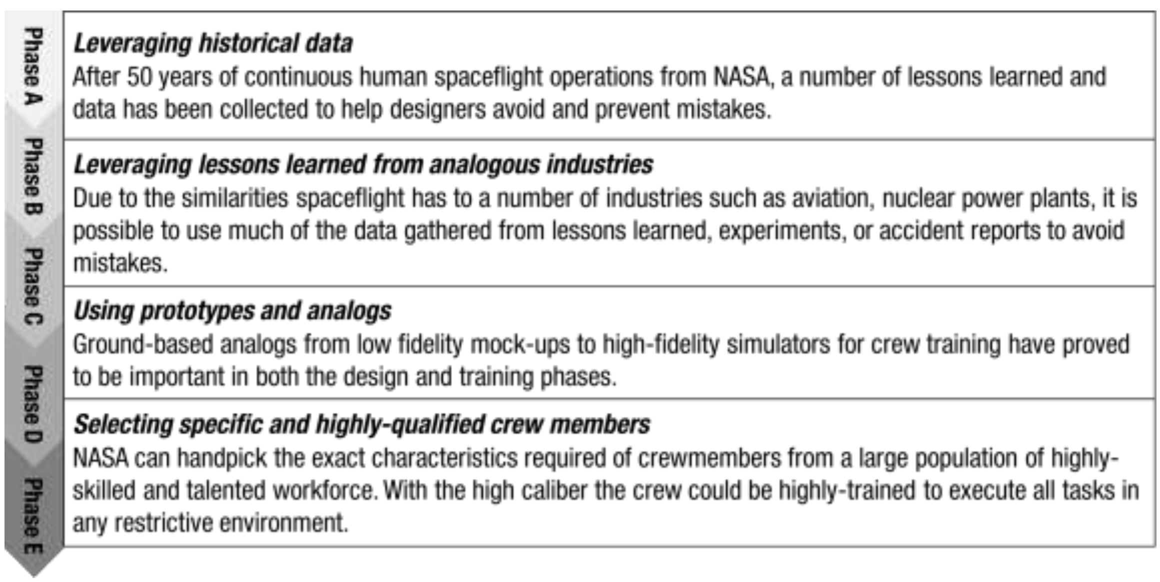


Figure 6. Current methodologies for evaluating human performance in a system mapped to systems engineering phases.

Analysis and evaluation is done at every step of the systems engineering process. The purpose of having the number of analysis and evaluations is to ensure comprehensive consideration of all design choices and their implications on mass, budget, and performance of the system. Human system integration into a complex system has been difficult as many of the analyses and evaluations fall much later in the design process.

2.3.1.2 NASA Guidelines and Documentation

There are a number of guidelines and requirement documents for how to design a human spacecraft. The main documents that are used currently as standards for spacecraft design are listed in Table 6. While having guidelines and standards are useful for understanding the concerns and provide guidance for design constraints, it can be difficult to evaluate and verify that these requirements are met.

Table 6. List of human spacecraft design documents, guidelines, and standards.

Document #	Document Title	Date
NASA-STD-3001 Vol 1	NASA Space Flight Human System Standard Volume 1: Crew Health	2007
NASA-STD-3001 Vol 2	NASA Space Flight Human System Standard Volume 2: Human Factors, Habitability, and Environmental Health	2011
NPR 8705.2B	Human-Rating Requirements for Space Systems	2009
NASA/SP-2010-3407	Human Integration Design Handbook (HIDH)	2010
JSC 63557	Net Habitable Volume Verification Method	2009
JSC-65995	Commercial Human-Systems Integration Requirements (CHSIR)	2011
JSC-64367	Exploration Life Support Baseline Values and Assumptions Document	2010
NASA/TM-2003-210785	Guidelines and Capabilities for Designing Human Missions	2003

2.3.1.3 ESM Method Provides Subsystem-Level Quantification and Prediction

Another method that NASA uses to compare hardware choices in the conceptual design phase of the development is using a technique called Equivalent System Mass (ESM) comparisons. ESM is calculated as the sum of the mass equivalencies of the following parameters: Mass, Volume, Power, Cooling, Crew Time (NASA, 2003). ESM can be applied to evaluate trade study options across various life support systems, and can be used to identify which of several options that meet all specified requirements have the lowest launch cost, as related to the specified parameters.

2.3.2 Using Human Integration Methods from Analogous Industries

While the tools are limited for human spacecraft integration, there are analogous industries that parallel the spaceflight environment with its highly complex systems and human operators working in risky environments. These industries also face similar challenges of human integration issues, and have their own number of methodologies that have been adapted. This section describes a large review of around 400 methodologies that exist in the literature across various industries in which human systems integration methods are used. The purpose of this work was to analyze the different methods and identify any potentially useful methods that could be applied to better evaluate human spacecraft designs.

2.3.2.1 Analysis of Other Human Performance Methods

The method for collecting began with finding various disciplines that had similar attributes to human spaceflight. The following table lists the disciplines that were investigated for human integration methods and their similarities to human spaceflight.

Table 7. Other industries analogous to human spaceflight.

Unique Human Spaceflight Attributes	Commercial Aviation	Naval Operations	Industrial Engineering	Nuclear Power Plant	Robotics/ Automation
1 Small cramped living/working quarters	X	X	X	X	
2 Limited people	X	X	X	X	X
3 People stay or get exchanged a few times	X		X	X	X
4 Highly selected people	X	X		X	
5 Dangerous outside environment	X	X			
6 Live/work inside 99% of time		X			
7 Highly-esteemed work	X			X	
8 Highly-technical work	X	X	X	X	X
9 Lots of training required for crew	X	X	X	X	
10 Environment fully controllable	X	X			

From each of these five analogous industries a number of methodologies were reviewed and analyzed to see how well they could be applied to human spaceflight.

2.3.2.2 Analyses on Human Systems Integration Evaluation Methods

With the collection of about 400 human systems integration evaluation methodologies a handful of queries and filtering were done to describe and characterize the types of methodologies that exist. The goal of the analyses was to filter for specific attributes of the method that could be applied to human spacecraft design which requires a quantitative and predictive evaluation methodology.

The aggregation of the data was a tedious process of reading documentation about each methodology and cataloguing 17 characteristics of interest including: "FAA Human Factors (HF) Tool Category", "FAA HF Tool Subcategory", "Specific Method/Tool Name", "Description", "Adaptable for Human Spaceflight (Yes (Y)/No (N))?", "Process/Tool", "Fields of Use (Aviation, Space, Nuclear..)", "Outputs", "Fidelity Level Required (High (H)/Medium (M)/ Low (L))", "Outputs Quantitative (QN)/Qualitative(QL)?", "Who Created?", "Number of Resources Required (H/M/L)", "Time Required to set-up? (H/M/L)", "Computer Skills Required?", "Still in Use?", "Validated?", "When Used in Systems Engineering (SE) Design Process?". The process itself was done solely by the author with the assumption that the author had some knowledge in these areas to make educated and accurate interpretations of the methodologies. It is noted here the information captured in the database leverages much of the data that exists in the FAA Human Factors website.

The first analysis done was classifying the various types of methods. An FAA Human Factors website for educating practioners, provided an initial starting list of method types. The list included: Human & System Performance Assessment, Modeling & Simulation, Knowledge Elicitation, Human Factors Knowledge, Human Factors Program Planning, Physical Ergonomics, and Human Computer Interfaces (HCI). As the 400 methods were analyzed, the categories were tweaked to include Safety and Data. The reasoning for these updates was because the FAA website did not include more recent probabilistic and computationally driven methodologies that have developed quickly in the past years and not yet captured in the FAA website which is listed as having only been updated since 2000. The methods generally fell into nine categories as shown in the figure below.

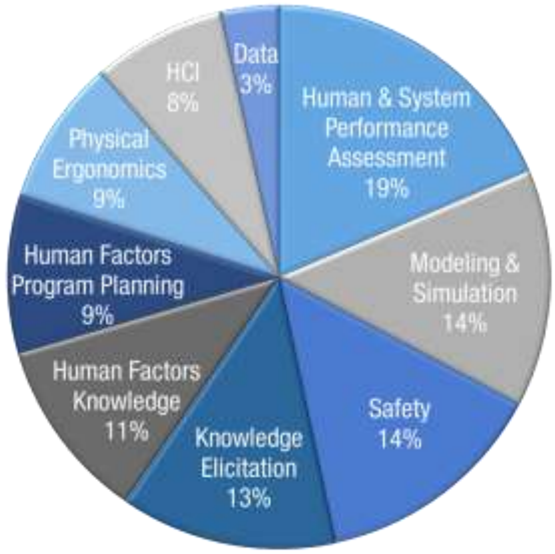


Figure 7. Classification of human integration evaluation methods and tools.

A quick definition for each of the categories is described below in order of the category with the most methodologies as seen in Figure 7.

Human & System Performance Assessment: These types of methods include cognitive testing, function allocation, generic performance measurements, physiological tools, secondary task evaluations, situation awareness, stress, and workload specific tools.

Modeling and Simulation: These methods leverage any type of model or simulation that has been created to analyze human performance.

Safety: These methods are pulled from literature for evaluating accident investigations, human errors, human reliability, and risk assessments.

Knowledge Elicitation: These methods are used during usability tests in which the information can be elicited from the user in a variety of ways. These include cognitive task analysis, interviews, observation, questionnaires, and task analysis.

Human Systems Knowledge Tools: This category captures any documentation that has been generated to help guide designers, including databases, guidelines, glossaries, standards, and technical reports.

Human Systems Program Planning: This category holds any methods and tools that are useful for managing a large and complex human system including cost/risk benefit analyses, data item descriptions, decision-making tools, economic cost analyses, and project management methods.

Physical Ergonomics: This set of methods is specific to any ergonomic or anthropometric models meant to help the designer appropriately size and place items for ease of use with minimal strain and injury. They include empirical models, postural analysis tools, various software and standards specific to anthropometric data.

Human Computer Interaction: This category is for methods that are specific to the human computer interface. It includes information regarding design as well as methods for analysis of good computer interactions.

Data: This category is for any type of methods and tools that can help sort through various types of data sets and organize or analyze them specific methods include data mining tools and data analysis tools.

Another query that was run to better characterize the various methodologies was to filter for how many methodologies produced quantitative outputs as opposed to qualitative. Table 8 shows an even split between methodologies with quantitative and qualitative outputs, while Table

9 provides a more detailed breakdown of the quantitative and qualitative methodologies with the list of their classification type as well.

Table 8. Number of quantitative versus qualitative methods.

Output Type	# of Methodologies
Quantitative	201
Qualitative	202

Table 9. Detailed breakdown of quantitative vs qualitative methods.

Methodology Classification	Qualitative Output (% Total)	Quantitative Output (% Total)
Human & System Performance Assessment Tools	7.4	11.2
Modeling & Simulation	0.0	14.1
Safety	2.0	11.9
Knowledge Elicitation Tools	8.7	4.2
Human Factors Knowledge Tools	10.9	0.0
Human Factors Program Planning Tools	7.7	1.7
Physical Ergonomics	5.5	3.2
Human Computer Interaction Tools	7.9	0.0
Data Tools	0.0	3.5

The equal division between the quantitative and qualitative method outputs could be an indicator of the multidisciplinary field in which there is a mix between the ‘softer’ social sciences and the more data driven engineering and medical disciplines. For example, many of the methodologies with quantitative outputs can be traced to computer models and simulations while the methodologies with qualitative outputs rely on subject matter experts to make recommendations for design changes.

Another analysis was done to indicate when these methods and tool were often applied. The figure below shows the spread of methods and where in the systems engineering lifecycle in which they are most often used.

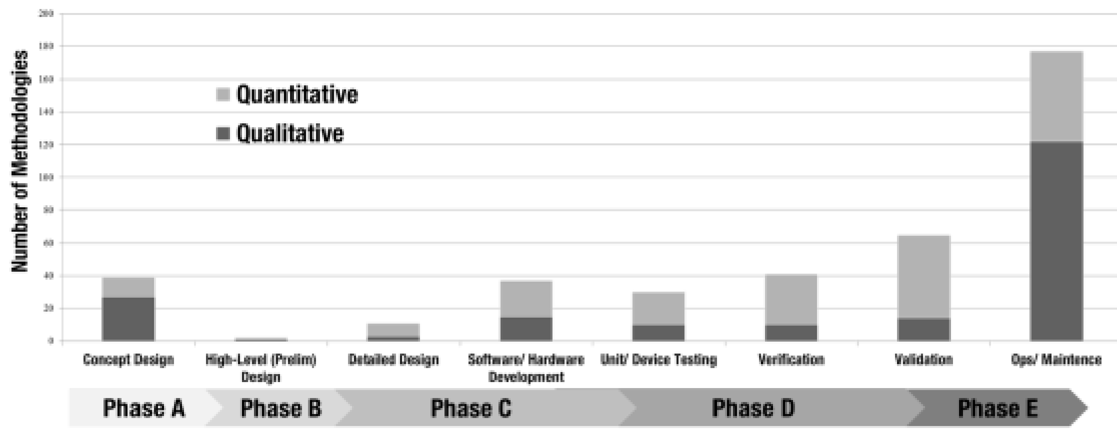


Figure 8. Methodologies and when they are used in the systems engineering lifecycle.

From the chart it can be seen that the majority of the methods and tools are used later in the systems engineering lifecycle. Intuitively, this can be understood as doing evaluations with users in the loop of some type of prototype or simulation of the system.

The first filter was for the Models and Simulation class of methods. And within this classification, another filter was selected for the ones that output quantitative values and was used early in the development lifecycle. This filtering process left a list of 15 specific methods as listed in Table 10.

2.3.2.3 Detailed Analysis of Qualified Methods

To determine which of the 15 methods left could potentially be applicable for human spacecraft design, a list of useful attributes of the method was identified. Five general attributes were intuited from observed trends, information flow, and application of human factors modeling, specifically: the phase in which it is used during the design process, the characteristics of the outputs, the characteristics of the inputs, the structure of the model, and the scope of what the model captures. For each of these attributes, the specific needs for a potential human spacecraft design evaluation model are identified and listed below with a brief rationale.

1) **Early Design Phase:** Due to the high costs of spaceflight, having an evaluative methodology early in the process will help to reduce downstream costs. The analysis shows a lack of methodologies in this early design phase (NRC, 2007; Clark, J. J. and Goulder, R. K., 2002).

2) **Quantitative Output:** Having a quantified value for crew performance is necessary to make objective comparisons across various designs similar to what is done with metrics like mass, volume or power (NASA, 2016).

3) **State-Driven:** With the variety of upcoming human space missions whether for commercial or government, the model should be able to handle a range of mission types, human occupants, and task requirements. A state-driven methodology is one that can be updated with a number of different mission profiles, users, and various tasks that could be performed. The methodologies that have this type of state-driven capability appear in the models and simulation type classification (Baron, 1990).

4) **Flexible Architecture:** Since human spaceflight is fairly young, there are unknown unknowns that are still to be discovered, therefore having a flexible architecture is crucial in adapting to new information that is learned with each new mission. A methodology that has a flexible architecture is one that can adapt to new information or poorly understood information (Leiden et. al., 2001).

5) **Comprehensive**: Each subsystem can be well-optimized for their required task or need, but when they are integrated into a full system, it is important to understand how each subsystem might impact others. The total system performance needs to be considered as an aggregation of subsystems which must perform well as a whole. A comprehensive methodology integrates different aspects of the human spacecraft

> interactions. The purpose of the evaluation is to provide a high-level concept design comparison; it must encompass all aspects of how the spacecraft design might influence the crew performance. Therefore, such a methodology should include the quality of the habitation environment as well as the controllability of the spacecraft. It would entail understanding how the space is properly used as both a workspace and living area. To evaluate methodologies for "comprehensiveness" required a deeper understanding of each methodology and what information and foundational knowledge it contained (Whitmore, et. al., 2013).

Filtering for all five characteristics left no potential models to work with, so instead any methodologies with at least 2 of the 5 attributes were identified which generated a list of fifteen methodologies as listed in Table 4. After reviewing each of the filtered methodologies, five stood out as adaptable for a potential comprehensive human spaceflight evaluation methodology, and have been identified on Table 4 with a thick dashed line. Each of the five methods is described with more detail in the following sections with the recommended extensible aspects that would be needed to create a more standardized method of evaluating human spacecraft design.

Table 10. Model selection from the five spacecraft design model attribute requirements.

#	Method	Detailed Classification	Early Design	Quantitative	State-Driven	Flexible	Comprehensive
1	Micro Saint (in MIDAS)	Task Network Model		√	√	√	
2	IPME	Task Network Model		√	√	√	
3	WinCrew	Task Network Model		√		√	
4	IMPRINT	Task Network Model	√	√	√	√	
5	ACT-R	Cognitive Models		√	√	√	
6	MIDAS	Cognitive Models		√		√	
7	D-OMAR	Cognitive Models		√	√		
8	SAMPLE	Cognitive Models		√	√		
9	Soar	Cognitive Models		√	√		
10	GLEAN	Cognitive Models		√	√		
11	Epic	Cognitive Models		√	√		
12	APEX	Cognitive Models		√	√		
13	CREAM	Error Models		√	√	√	
14	Bayesian Belief Nets	Error Models		√	√	√	
15	PARADyM	Error Models	√	√	√		

2.3.2.3.1 Integrated Performance Modeling Environment (IPME)

IPME is a simulation and modeling tool for replicating and measuring complex human systems interactions. It combines both the top-down approach of task network modeling with bottom-up approaches for simulating human behavior. IPME has a user-friendly graphical user interface, and provides a full-featured discrete event simulation environment built on Micro-Saint modeling software. The following are specific functions it can perform:

- Allows the user to select from two different workload models
- Supports performance shaping function (PSF) approaches and built-in micro models
- Uses built-in micro model functions that represent basic human actions and behaviors such as the rate at which text is read or the time to reach or move a motor control.

The tool "calculates times for very detailed activities, such as walking, speaking, and pushing buttons" (Pew, 1998) allowing designers to measure specific times for operational tasks. Because it is a commercial tool, getting access requires monetary investment. There are also five-day training courses available from time to time in Boulder, CO. This seems to be a flexible and extensible platform, but requires more contact with the company for access to software. The IPME tool provides more help in the later stages of the design in which task operation times are critical to understand, but has difficulty extending to the early design phases where not much detailed design has been set or is known about the spacecraft.

2.3.2.3.2 Improved Performance Research Integration Tool (IMPRINT)

IMPRINT is an embedded discrete event task network modeling language (Micro Saint) that uses task-level information to construct networks representing flow and performance time and accuracy for operations and maintenance missions. Workload profiles are generated so that crew-workload distribution and soldier-system task allocation can be examined. Manpower requirements estimates can be generated for a single system or Army-wide. Additionally, outputs can be used as basis for estimating manpower lifecycle costs (U.S. Army, 2010).

2.3.2.3.3 Man Machine Integrated Design and Analysis System (MIDAS)

MIDAS is a dynamic, integrated human performance model (HPM) environment that facilitates design, visualization, and computational evaluation of complex human-system concepts in simulated operational environments. It uses symbolic representations of mechanisms that underlie and cause human behavior and combines them with graphical equipment prototyping to create a dynamic simulation. This process is intended to reduce design cycle time, support quantitative predictions of human-system effectiveness, and improve design of crew stations and their operating procedures (“MIDAS”, n.d.). But similar to the IPME and Micro Saint it requires fairly detailed design choices to be in place before a simulation is run.

2.3.2.3.4 Cognitive Reliability and Error Analysis Model (CREAM)

CREAM is a human reliability analysis approach for probabilistic safety assessments. It is a stand-alone method that can be used for accident analysis and for larger design methodologies for more interactive systems. CREAM allows for the designer to do particular tasks including:

“• identify tasks that require human cognition and therefore depend on cognitive reliability

• determine the conditions where cognitive reliability and ensuing risk may be reduced

• provide an appraisal of the consequences of human performance on system safety which can be used in PSA.” (Hollnagel, 1998)

The methodology and approach of CREAM is a particularly relevant one for space systems as many designers are familiar with probabilistic risk assessment (PRA). CREAM uses this same approach but applied to the human ‘subsystem’. The difficulty with this approach is identifying accurate failure rates for the human. Because the human ‘subsystem’ is highly interconnected and dependent on the surrounding environmental factors, their failure rates will be dynamic values that vary over the life of the mission. These dependencies and dynamic aspect are not yet captured with the CREAM model.

2.3.2.3.5 Performance and Reliability Analysis via Dynamic Modeling (PARADyM)

PARADyM is a model developed by Draper Laboratory to analyze human-in-the-loop performance. The model uses Matlab® and Simulink ® to model different components of a system capturing individual dynamics, failure modes, and any dependencies. One of the unique aspects of this tool is its use of Markov modelling to determine the systems reliability over a given mission timeline. Initial probabilities are set for various Markov states and are propagated to other states over the systems lifetime via specified transition rates based on the failure rates of the components (Bortolami, 2009).

The limitation for this system for adding the human-in-the-loop is similar to the CREAM model in that it lacks real data from human spaceflight mission failure rates. While error probabilities and failure rates of the human can and has been adapted from error rates found in nuclear power plant operations, it has not been thoroughly verified in the spaceflight environment.

2.3.3 Summary of Current Method Limitations

There are a number of tools, methods, and frameworks available focused on human and complex system integration efforts. It is important to note that while a number of methodologies were gathered for this analysis, it does not represent a comprehensive list of every human performance evaluation methodology that exists or ever existed.

Through the process of collecting the methodologies, it became clear that there are no systematic or standard processes readily available to help find, much less, characterize and understand the methodologies that currently exist outside of intensive literature searches. In general, there is a need for a better database and collection of these various methodologies to be helpful for future designers of complex human systems.

Besides the process itself, the meta-analysis from the collected data also provided a number of interesting insights on the type of methodologies available. The first analysis grouped methodology type into a specific classification. While useful as an exercise and as an early analysis tool, it can greatly vary depending on the definition and creation of different classifications. There may be another set of classifications that could help better distinguish the type of tools, methods, or frameworks in a more useful form such as field of application (aviation, nuclear power plant operations, or military operations.). Future analysis needs to include more meaningful ways to classify the methodologies.

The analysis also shows that there are few methodologies that exist or are used early in the concept design phase of the systems engineering process. The number of methodologies currently in use might be an indicator of both the difficultly of creating an early concept design methodology or that designers have not found them particularly useful for this early phase. Both these considerations must be addressed for adoption of future approaches.

Also evident from this work is that while there are a number of methodologies for human performance evaluation in complex systems, there still doesn't seem to be one that supports all the attributes that would be required for human spacecraft design. For example, the CREAM approach helps designers quantify error probabilities for one design, but it lacks flexibility in changing efficiently to another design without having to re-map errors and any coupling of factors.

Another option besides adapting and modifying existing methodologies is to create a new one from scratch. The creation of a new methodology can be a completely new framework, or it could be a merger of various other methodologies. The considerations for each must be thoroughly weighed, as it could be largely useless to add another methodology to the over 400 existing ones, but if it proves to be more beneficial and well-targeted to the human spacecraft designer, then the effort could be worthwhile.

2.4 Research Objectives

The performance of the crew is greatly influenced by the design of the spacecraft. To achieve optimal mission performance, it is important to understand how the design influences the human's ability to perform various tasks. The current models and methods are not comprehensive enough nor are they flexible to provide the right evaluation and analysis needed early in the concept design phase. Without such a tool early in the systems engineering design phase, it becomes difficult to evaluate between various designs. **The goal of this work is to create a framework which can be used early in concept design phases that quantitatively evaluates how well the spacecraft accommodates and utilizes the crew.** To achieve this goal, a detailed list of objectives is identified below.

Objective 1: Develop a framework establishing a quantitative model for human systems integration into a spacecraft

Output(s): Framework that (1) establishes standard definitions for relevant terms for crew performance and human-rating; (2) characterizes the terms with specific and measurable inputs and outputs, and (3) maps relationships between the spacecraft design, crew, and operations.

Objective 2: Build a computational model using the developed framework

Output(s): A computational model that integrates the framework concepts to generate quantitative values for how well the crew is accommodated and utilized for various spacecraft designs and missions.

Objective 3: Analyze and demonstrate model capabilities with various spacecraft design scenarios

Output(s): Analysis of the model outputs using randomized parameter runs and historical human spaceflight missions.

The intention of this research is to present a model for quantifying crew performance and demonstrate how the model can be applied through the design process to identify and uncover issues that specifically impact crew performance.

A major presumption of this thesis is that the current state of understanding of human performance can be captured in a computational model and that by updating various values and relationships a prediction of potential human behavior in a specified environment can be achieved. But to be clear, this model is not intended as the culminating edifice for all human-machine interaction models, rather the goal is to lay the foundations for the framework for how we can use human performance measures as a metric for design quality and start to weave the various threads and pieces together. The very act of creating the model provides just as many insights as the outputs of the model, especially in the early development of the model.

CHAPTER 3: ESTABLISHING A FRAMEWORK FOR THE MODEL

3.1 APPROACH AND PHILOSOPHY FOR FRAMEWORK

In Chapter 1 a rationale was provided for needing a crew performance metric in spacecraft design. In Chapter 2 an overview of performance shaping factors and the overarching processes for spacecraft design was discussed along with discussion of current and previous works in the field. At the end of the chapter, three objectives were presented to guide the remainder of this work. In this chapter, objective one is addressed where the terminology and basic framework for the model is developed.

This chapter seeks to answer the overarching question: How can we measure spacecraft quality in the context of crew performance? This is accomplished through an elemental resource breakdown based upon translation of the human performance definition to the spaceflight environment, ultimately developing a framework for evaluating crew performance.

The first step in developing a framework is examining its infrastructure from broad considerations. The method for defining a framework is described through four development steps posed in the form of the following questions: (1) What is the purpose and scope of the model, (2) What is the relevant terminology, (3) What are the relationships between the terms, (4) What are the relationships between the final crew performance metrics and the vehicle design process? This chapter discusses each of these questions in detail. Having answered these questions, it pulls together the pieces and concludes with a descriptive framework for assessing spacecraft design in terms of crew performance.

3.2 Step 1: Identify Purpose and Scope of Model

3.2.1 Fundamental Axioms of Human Spaceflight

As part of the process in defining and understanding the purpose and scope of the model, a philosophical foundation for the model was first established. This was accomplished axiomatically as the philosophical foundation cannot be mathematically proven, only stated as self-evidently true. A total of three axioms were identified in the course of this work. The first two axioms focus on the purpose of human spaceflight and were identified, in part from discussions in bioastronautics (Klaus, 2009).

The purpose of this axiomatic discussion is to provide motivation for human spaceflight therefore some background discussion is required before stating the axioms. The fundamental assumption of human spaceflight is that humans are somehow directly involved in the process whether as passengers or pilots. This therefore requires that the crew be alive and in a state that would be considered reasonably fit. From these assumptions, the human spaceflight axioms can be stated as follows:

Axiom 1: The purpose of human spaceflight is to provide a means for humans to explore space.

Axiom 2: For crew to optimally perform they must be alive, healthy, and happy.

These axioms only address the overall roles of humans in human spaceflight, albeit nebulously, they do not directly describe the required interactions between the vehicle and the crewmember.

In order to address the spacecraft-human interaction, a third axiom is identified which extends the philosophy of the first two axioms onto specific considerations of the spacecraft design and its impacts on the crewmembers. This axiom is developed by examination of the literature. As explained in NASA's Human Rating Requirements document (8705.2B) (NASA, 2012), the purpose of the human space vehicle is to ensure the crew are *protected*, *accommodated* and *utilized*.

From this statement, a fundamental assumption is made: protection is reflected by whether the crewmembers are alive and healthy. If the crewmember is not alive or is injured in some way, the spacecraft has not ensured adequate crew protection. Therefore, from this assumption, it is then argued that the impact of the spacecraft design appears in how well the design accommodates and utilizes the crew. This naturally leads to the crew performance axiom which is central to this work.

Crew Performance Axiom: Measures of crew performance indicate how well the crew are accommodated and utilized within the spacecraft.

These axioms act as a guidance for a human-centered approach to spacecraft design while the philosophy they establish sets the stage for describing the scope and purpose of the crew performance model.

3.2.2 Inquiry Based Approach to Model Development

To fully define the scope and purpose, an inquiry based technique often applied in design-thinking processes, is used. This approach utilizes a series of questions and answers to define the model's purpose. These questions were aggregated from a number of project scoping methodologies and can be compiled into a set of eight high-level questions to elicit information about the intended model.

Upon answering each question in this inquiry based approach to identifying the scope and purpose of the model, a clear framework is set from which the following sections will build upon.

Question 1: Who is this model for? (Audience/Customer)

Human spacecraft designers and managers who make decisions on the overall design of the spacecraft.

Question 2: What does the model include and exclude? (Scope)

The model focuses specifically on the crewmembers inside the spacecraft. It assumes there are surrounding support systems that allow the spacecraft to function (including data sent to and from the spacecraft from earth or surrounding support systems like telecommunication satellites). These supporting systems act as black box interfaces in which the spacecraft can use to achieve the intended operations. For example, if the mission was to Mars, an architecture is assumed that includes various communication links that would be needed for the crew if a 30-minute communication delay was required. While the choice of the infrastructure clearly impacts the overall system design and architecture due to cost, re-supply or maintenance of such systems, the model does not consider these factors in determining the overall quality of crew accommodation and utilization.

Figure 9 provides an illustration of the scope of this investigation. While there have been significant documented impacts due to Earth-based factors such as mission control's influence on Skylab-4's crew revolt (Compton, 1983) and the delay of informing a cosmonaut on Salyut 6 about the death of his father for fear of performance impacts (Kanas, 2016), this particular work does not focus on these factors as mentioned earlier in Chapter 2 because it is not within the control of the vehicle designer.

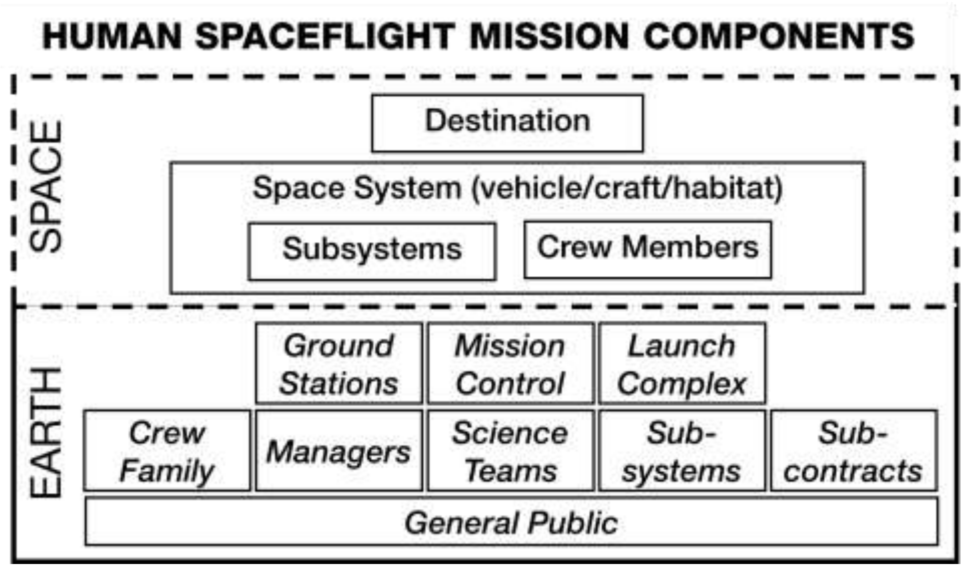


Figure 9. The dashed (top) box highlights the scope of the investigation, which is focused on the interacting components in space, although many Earth-bound factors indicated in the lower box also influence the outcome.

Question 3: What information is needed for the model? (Inputs)

The information or inputs needed for the model are the pre-determined factors, such as a design reference mission, that dictate destination, duration, and crew make-up. Additional inputs will be used throughout the process by the designer to make specific design selections using documented specifications, reasoning, or assumptions.

Question 4: What information will be produced by the model? (Outputs)

The outputs of the model must ultimately tell the designer how well a particular design accommodates the crew and how effectively they are utilized. To be useful, the output must be tied to specific design considerations, therefore allowing the designer to know what design adjustments can be tweaked to improve the design.

Question 5: How will the model be used? (Concept of Operations)

The framework has three main uses: 1) to see how various changes to design impact the outputs while providing insights regarding the sensitivity of certain design choices, 2) to allow the designer to assess different choices and make adjustments to improve the design, and 3) to identify areas that need more research in regards to design and performance interactions.

Question 6: How much background must the users have to use the model? (User Background)

In the ideal case, the user is a highly-experienced spacecraft designer that already has an inclination of what specific design choices will improve the outcomes for crew performance. But this may not be the case, therefore straightforward implementation of the model by inexperienced human spacecraft designers is also required.

Question 7: What are general characteristics of this model?

There are numerous types of model that can be produced for specific outputs. But in general, Human Performance Models (HPMs) can be categorized with five contrasting characteristics identified by the "Panel on Human Performance Modeling Committee on Human Factors" (Baron et al., 1990) and re-listed in Table 11. Given the purpose and scope of the model, the five characteristics that are desired for this model are listed on the left column of the table. It is expected that this model provides useful outputs, predicts outcomes, includes multiple tasks, provides idealized system behavior, and is applied from a top-down perspective.

Table 11. General characteristics of HPMs as summarized by Baron et al. (1990).

Model Characteristics		
OUTPUT Models the system as a black box focusing on accurate outputs rather than validating the process	vs	**PROCESS** Describes a theory for how humans perform tasks
PREDICTIVE Predicts outcome(s) of the system or subsystems prior to data collection	vs	**DESCRIPTIVE** Fitting model by adjusting free parameters to conform to existing performance data
MULTITASK Models multiple tasks	vs	**SINGLE-TASK** Models a single task
PRESCRIPTIVE (Normative) Predict ideal rationale behavior, given human and situational limitations	vs	**DESCRIPTIVE** Describe how a human is likely to perform a task
TOP-DOWN Begins with system goals, then progressively elaborates sub-functions primitives that are not explained further	vs	**BOTTOM-UP** Begins by defining a set of primitive elements at both the human performance and the engineering levels

Question 8: At what point in the design process will this model be used?

The model is intended to be used across the spacecraft design process, starting from the mission design to concept development, and out through testing and validation. But the main goal is to help mission designers make design decisions early in the process to help improve human-system integration.

3.3 Step 2: Identify and Define Relevant Terms

There are two categories of terminology that must be clarified, the first set of terms relates to the development of the conceptual infrastructure including distinguishing the differences between ‘framework’, ‘method’, ‘methodologies’, and ‘model’. The second set of terms relates to the model itself and its constituent parts. Having clear definitions for these terms provides the basic foundation from which their general characteristics can be further discussed.

3.3.1 Conceptual Infrastructure Terminology

The terms used in the previous chapters regarding the infrastructure of this thesis are defined here to provide more clarity and structure to the concepts being developed throughout this work.

Framework is the basic underlying structure of a concept. In regards to this work, a framework is developed to describe how spacecraft design can be quantified through the perspective of crew performance. In other fields, such as computer science, this is known as the program architecture.

Method is a systematic procedure for an approach or application. In this case, the method is a mapping of human spaceflight data and relationships into the framework.

Methodology is a collection or system of methods that are used as an approach to a framework. Methodologies are used here to describe the variety of methods and tools that either are standalone methods (just one process or measure) or an aggregation of several methods.

Model is the actual representation and application of the method onto a framework. There can be several other representations for a model, but this particular work focuses on the use of a computational model in which the method of application is through mathematical relationships.

An illustration of the relationship between these terms is shown in Figure 10.

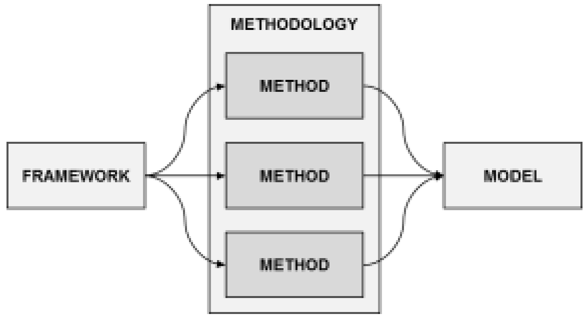


Figure 10. Mapping of the relationship between the terms framework, methodology, method, and model.

3.3.2 Terminology for Constituents of the Model

Specific to spacecraft design considerations, four other terms have been deemed highly relevant and necessary to clarify due to their frequent use in the human spaceflight literature as well as their applicability to this work: human-rating, crew accommodation, crew utilization, and crew performance. Establishing standard definitions aids in accurate characterization, quantification and application of the terms. As a starting point, the definitions were derived from existing sources of literature and used here as a baseline for identifying suitable metrics.

3.3.2.1 Defining Human-Rating

The term "human-rating" historically known as "man-rating" has evolved since its inception during the suborbital X-Plane program when humans were first launched into space and later through the Apollo Space Shuttle eras. The evolution of the term 'human-rating' brings insight to the priorities of spacecraft design where it initially focused on the safety of the astronaut and has now expanded to include the astronaut's performance as missions become more complex (Klaus, 2012). NASA has captured this more inclusive definition of human-rating of spacecraft design in their Human Rating for Space Systems document (8705.2B) where a human-rated vehicle is described as one that "accommodates human needs, effectively utilizes human capabilities, controls hazards and manages safety risk associated with human spaceflight, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations." (NASA, 2012)

While system safety and reliability has been measured historically with techniques like Probabilistic Risk Assessment (PRA) where failure rates are predicted for various subsystems, there has not been a similar standard technique for modeling, much less quantifying, accommodation or effective utilization of the astronauts. It is important to note that while the term human-rating also includes vehicle safety as a critical component to the system design, this work specifically views safety from a human-centric perspective, therefore safety is captured as ensuring crew health rather than a hardware reliability concern.

3.3.2.2 Defining Crew Accommodation and Crew Utilization

In previous work by Klaus et al. (2014), an overview of human-rating considerations for implementation led to informal definitions of crew accommodation and crew utilization, where accommodate was defined as: "what the vehicle provides to support the humans, beginning with life support and extending to human factors/ergonomics" and utilize as: "what the humans can operate to support the mission, including optimization of human-machine interfaces."

Crew accommodation can be specified as everything the spacecraft provides to support the humans, starting with life support, also considered the non-negotiable requirements, and extending to human factors and ergonomics, which are design choices in the trade space (Klaus et. al., 2014). Accommodation also consists of the environmental design of a spacecraft from the atmosphere composition and pressure choices to the temperature and humidity. A well-accommodated crew is one that can live comfortably within a spacecraft.

Crew utilization is specified as everything the humans can operate and use to support the mission, including human machine interfaces, restraints, and tools (Klaus et al., 2014). Considerations for crew utilization include the design of any components that are used beyond those needed for basic crew survival. These components may include control display interfaces, restraints and handholds, mechanisms for operating science payloads, or location and placement of windows.

To provide a more precise description of the two terms, the definitions are slightly modified and presented here where crew accommodation is defined as "system provisions for supporting human life, health, and happiness", while crew utilization is defined as "system provisions for supporting the system's use and operations." The added descriptor of "system provisions" helps to formalize the definitions, and adding "system's use" when defining crew utilization opens the definition to include not only operations of the spacecraft but any other tasks that could be done by the crew that are not directly related to operating the vehicle, such as observing, investigating, monitoring or supervising.

Ambiguous areas exist where the design both accommodates and utilizes the crew member. For example, removing CO2 is a critical crew accommodation required for keeping the astronauts alive, but high CO2 levels also affect the ability for crew to think clearly, and can subsequently be listed as an impact to both crew accommodation and utilization. In this case, it is evident that the lowest threshold for CO2 level should be based on human health and anything above would benefit crew cognition. In a contrasting scenario, lighting levels around the cabin can be highly variable as it does not immediately endanger the crew's mortality, but if the lighting is meant to be used for executing a critical task, then the appropriate amount of light must be provided. In this case, the minimum threshold for lighting is dictated by the critical task that requires light, which would be considered a utilization provision. Further characterization of these differences is needed to help designers assess the driving requirement for certain design choices.

3.3.2.3 Defining Crew Performance and Crewmember Performance

Before defining crew performance an important distinction must be made between "crew" performance vs "human" performance. Crew implies that there is more than one crewmember, while human is synonymous with just one crewmember. This is an important distinction because with multiple crewmembers each has a distinct role, and a measure of performance reflects the interactions between crewmembers rather than each individual. Therefore, crew performance can be defined as the aggregated performance across all crewmembers and their interactions amongst one another to achieve a required activity. On the other hand, crewmember or human performance is a reflection of that particular crewmember's own performance.

Now to define crew performance, the generic term of performance is used as a basis in which the dictionary defines as "the act or manner of performing", whereby perform is defined as "to carry out a task or assignment". (Macmillan, 1984) By simply inserting "a crew" as the object and combining the two parts, the term crew performance can be defined as "the act of a crew carrying out a task or assignment." The same can be applied in the singular case for human or crewmember performance as defined: "the act of a crewmember carrying out a task or assignment."

Because crewmember performance is central to this work, a more in-depth look at the definition is needed. A more detailed definition of human performance comes from Bailey (1996) where human performance (which is used throughout this work interchangeably with crewmember performance) is defined as: "the pattern of *actions* carried out to satisfy an *objective* according to some *standard*."

What this definition alludes to is the interactive nature of performance in which it requires an understanding of the interaction between various components. This can be explained as the human performing some activity or objective that has a particular standard that is defined by the context of the situation (Bailey, 1996). The following figure below captures the three components that constitute human performance.

Figure 11. Human performance componets (Bailey, 1996).

Similar categorizations for performance components can be seen with the SHEL model adopted by the International Civil Aviation Organization, which stands for Software, Hardware, Environment, and Liveware (humans). (ICAO, 1996) In this case the Environment maps to the Context, and Software and Hardware describe the interfaces through which the human performs the activity.

Since the purpose of this work is to relate spacecraft design (hardware) to human performance, making the distinction between software and hardware is not important. As a result, the three component Bailey model is selected for the framework development.

3.3.3 Summary of Relevant Terms

The preceding sections identified and defined the relevant terms encompassing this work. These terms are listed and summarized in Table 12 and will be referenced throughout the remainder of this work.

Table 12. Summary of relevant terms for crew performance.

Terms	Definitions
Framework	Basic underlying structure of a concept
Method	A systematic procedure for an approach or application
Methodology	A collection or system of methods that are used collectively as an approach to a framework
Model	The actual representation and application of the method or methodology onto a framework
Human-Rated (System)	(A system) that accommodates human needs, effectively utilizes human capabilities, controls hazard and manages safety risk associated with human spaceflight, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations
Crew Accommodation	What the vehicle does for the crew (i,.e. system provisions for supporting human life, health, and happiness)
Crew Utilization	What the crew does for the vehicle (i.e. system provisions for supporting the system's use and operations)
Crew Performance	The process of a crew carrying out or accomplishing an action, task, or function
Crewmember (Human) Performance	The pattern of actions carried out to satisfy an objective according to some standard. It is defined by the interaction between the crewmember, the activity, and context in which the activity is performed.

3.4 Step 3: Characterize Terms and Their Relationships

The next step in developing the model is characterizing the relationships between these terms. The relationships dictate the interactions between each model component as well as the data flow for the entire framework. In developing these relationships, three main terms are examined more closely: ***crew accommodation***, ***crew utilization***, and ***crew performance***.

3.4.1 Characterizing Crew Accommodation and Crew Utilization

The established definitions describe crew accommodation and utilization as specific system provisions that support the crew each in their own manner. The purpose of the framework is to help clarify and then measure these particular provisions. In the case of accommodation and utilization, the specific measurable outcome is to distinguish whether the crewmembers are alive, healthy, and happy, and if they are being used effectively. A larger value for crew accommodation indicates a better design for maintaining the crew's health and happiness, and similarly a larger value for crew utilization indicates a more efficient design that better engages the crewmembers. In some instances, crew accommodation qualities may directly conflict with crew utilization, for example, a scenario can be imagined in which quality of sleep, which relates to a crewmember's physiological capacity, may be reduced for the sake of performing more science experiments. In such an example, crew utilization increases but degrades crew accommodation. The expectation is that these minor infractions on crew accommodation in an effort to increase crew utilization will emerge as reduced crew utilization in the long-term as crew health decreases. While short term missions may not see the impacts of these trade-offs, but for longer missions, tracking and monitoring of these variables are critical as a design and operations assessment tool.

3.4.1.1 Characterizing Crew Performance

Using the definition of crewmember performance as the interaction between the human, activity, and context, each of these components are translated into a spaceflight equivalent. For spaceflight, the human element is represented by the crew onboard the spacecraft, the activity is represented by the tasks that are performed by the crew throughout the mission, and the context is the spacecraft environment and design. Figure 12 provides a general schematic for the architecture of the human spacecraft design evaluation model.

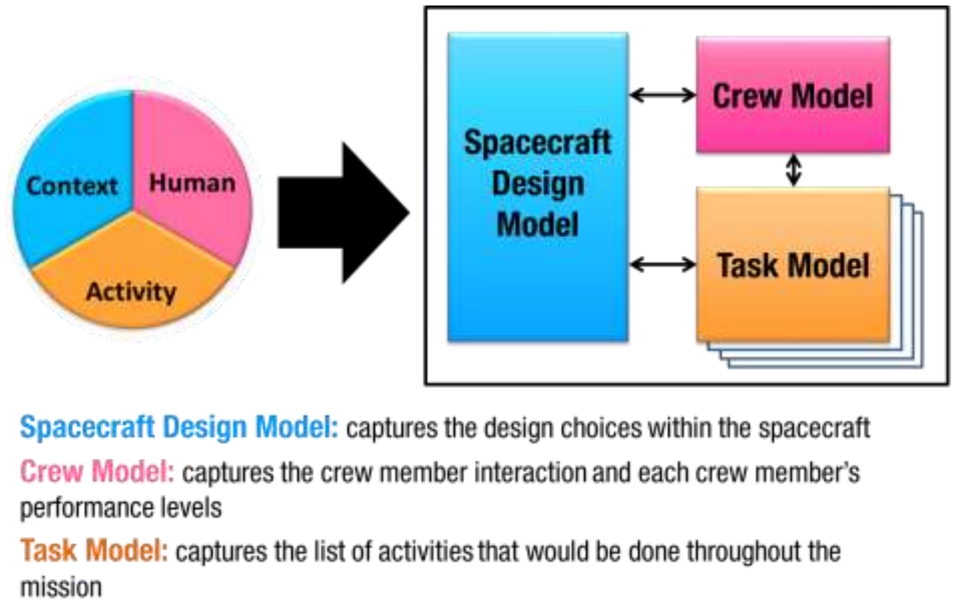


Figure 12. Mapping of human performance elements in the context of human spaceflight.

Each of these three components are described in more details to clarify their relationships and lay the foundation of the framework. In order to examine each of these components more closely, a specific method was employed called the Elemental Resource Model (ERM). Details of the model and its application to human spacecraft design and evaluation are described in the following sections.

3.4.1.1.1 The Elemental Resource Model (ERM)

The ERM framework describes how a human can be divided into several elemental resources that comprise their various capabilities. The idea of using an element-by-element decomposition model of the system originated from Dr. George Kondraske's work in 1988 where he was looking for better ways to measure and judge the clinical status of rehabilitation patients with neurological disorders. To understand the patients' progress, he wanted more fidelity in the measurement, but also a more structured approach to quantify and compare how well each task or function was executed from week to week (Kondraske, 2000). He decomposed each high-level task into more basic functional task elements. Each of the elements was then measured independently for each person and given a rating of how well they performed that function. These task elements can be mapped back into the high-level task to determine whether the task is achievable by a particular person. The work by Dr. Kondraske has been applied successfully to a handful of other human interface tasks such as driving, education, and training (Kondraske, 2002; Dillion, 2000). This same methodology can be applied to the decomposition of each crew performance component (crewmember, task, and spacecraft) as well as quantifying the resultant capabilities for each of the components.

3.4.1.1.2 Crew Performance Element Decomposition

To apply this methodology, the crew is decomposed into constituent elements. The first level of decomposition begins with the crew which earlier was described as being comprised of more than one crewmember. The next level is to separate a crewmember into his/her constituent elements of performance.

A bit of complexity arises as much of the literature uses a variety of definitions for the term "performance" where it has been associated with physical strength to psychological well-being (Kring, 2003; Williams et al., 2008; Schmidt et al., 2009; Nelson, 1998; ASAS, 2002; Ravinder et al., 2007). Examining the plethora of performance-related literature resulted in the identification of three main categories of human performance:

1) Physiological Performance (●): of or related to the physical capabilities of the limitations of the human body
2) Cognitive Performance (▲): of or related to the mental capabilities of the human such as decision-making, situation awareness, response times, workload, and general mentally-oriented tasks

3) Psychological Performance (■): of or related to the psychological well-being of the human.

Each of these three elements are represented by arbitrary geometric shapes for easy graphical representation and can further be decomposed into more basic resource elements of performance. These basic resource elements are chosen by the availability of measurable metrics. As suggested in Chapter 2, one of the main difficulties of developing a human spacecraft model is the lack of available data. Using metrics that already exist and in some cases have already been collected in spaceflight help to ensure the model can be validated in the future. The following sections describe in more detail each of the basic resource elements, how they were chosen, and what they represent.

Physiological Resource Elements

Physiological resource elements were chosen by a careful consideration of the Individual Performance Shaping Factors (PSFs) identified by Mindock (2012). The PSFs specific to the individual denote factors internal to the human that affect their performance. This list provided a comprehensive starting point for physiological resource elements of individual crewmembers. Additionally, the ones characterized in Mindock (2012) have also been identified as factors that are relevant in the context of human spaceflight. The full list of the physiological resource elements is listed below with an associated variable and subscript:

1) $P_B(t)$ = Bone Strength (●)
2) $P_C(t)$ = Cardiovascular System (●)
3) $P_D(t)$ = Digestion (●)
4) $P_F(t)$ = Fine Motor Control (●)
5) $P_H(t)$ = Hearing (●)
6) $P_R(t)$ = Hormones (●)

7) $P_I(t)$ = Immune System (●)

8) $P_M(t)$ = Muscle Strength (●)

9) $P_N(t)$ = Nervous System (●)

10) $P_P(t)$ = Proprioceptive Posture (●)

11) $P_V(t)$ = Vestibular System (●)

12) $P_E(t)$ = Vision (●)

13) $P_X(t)$ = VO2 Max (●)

A unique colored circle provides a graphical representation of each variable. The circles are colored a shade of blue for easier indication that it is within the family of physiological resource elements, but does not provide any significant importance aside from easier graphical representation purposes.

Each of these physiological resource elements play a critical role in determining the crewmember's overall health. While it is clear that they have some influence on one another the current iteration of the model does not take this into account for reasons of simplicity.

Cognitive Resource Elements

A similar process can be utilized for the decomposition of cognitive elements. A series of measures have been devised in the cognitive psychology and research community, specifically targeting functions and abilities that an astronaut might encounter. The following list of ten cognitive measures have been developed and validated by Basner et al. (2015) to track cognitive capabilities that are specifically needed for spaceflight:

1) $C_R(t)$ = Abstract Reasoning (▲)

2) $C_B(t)$ = Abstraction (▲)

3) $C_E(t)$ = Emotion Identification (▲)

4) $C_D(t)$ = Risk Decision Making (▲)

5) $C_T(t)$ = Scanning & Visual Tracking (▲)

6) $C_S(t)$ = Sensory-Motor Speed (▲)

7) $C_L(t)$ = Spatial Learning & Memory (▲)

8) $C_P(t)$ = Spatial Orientation (▲)

9) $C_V(t)$ = Vigilant Attention (▲)

10) $C_M(t)$ = Working Memory (▲)

As these capabilities may not be immediately clear, a brief explanation is provided for each of the cognitive abilities, alongside current testing methods.

Abstract Reasoning (also known as Fluid Intelligence) is defined as problem solving ability of the individual. It is often tested using increasingly difficulty pattern matching tests (Basner et a., 2015).

Abstraction is defined as "the ability to use information to group stimuli in some meaningful way" (Glahn et al., 1999). The ability to abstract information and maintain cognitive flexibility is considered a reliable way to assess the functionality of the frontal lobe in the brain (Basner et al, 2015).

Emotion Identification is the ability of an individual to correctly identify emotional facial expressions. Having a good emotion identification ability is important for long-term social interactions, especially important for future astronauts that rely on this ability to ensure camaraderie amongst the crew.

Risk Decision Making is the ability to make decisions to ensure safety of the individual as well as the crew. This ability requires mental analysis and objective consideration of presented data.

Scanning & Visual Tracking is the ability of the individual to scan and track an object visually. This ability for visual search and scanning task is important when docking spacecraft, or landing a spacecraft on varied terrain, or looking for display and control information within the cockpit.

Sensory-Motor Speed is a measure of the speed which information can be transferred from the form of some sensory stimuli (i.e. noise, visual display, temperature or pressure changes etc.) into a motor controlled execution task. This task is often measured as reaction time when shown an image and how quickly the individual can click a mouse button in response.

Spatial Learning & Memory is the ability to memorize complex figures. This is an important skill for astronauts comparing landscapes or navigating terrain, but also for managing inventory in tight spaces and knowing where items are located around the spacecraft.

Spatial Orientation is the ability for the individual to discern orientation of objects. It can be measured by the Line Orientation Test (LOT) in which the individual must rotate a line in a specific orientation to match a stationary line's orientation. The ability is important when maneuvering objects, recognizing the alignment of other vehicles, and piloting of the spacecraft (Basner et al., 2015).

Vigilant Attention is characterized as the ability of the individual to see or recognize certain stimuli often in the form of a visual stimulus. Low vigilant attention often appears as an effect of chronic sleep deprivation or circadian misalignment. Missing cues from displays and control panels can have serious consequences for spaceflight.

Working Memory is the short-term mental storage capability of an individual. It is widely viewed as an important cognitive function for several abilities including planning, problem solving, and reasoning.

Psychological Resource Elements

Psychological performance is defined here as the human's state of mind which allows for optimal task execution. There are a number of contributing factors to psychological degradation including high workload, fatigue, low morale, high pressure, under or over stimulation (Kanas et al., 2009), (Carrere and Evans, 1994), (Stuster, 1996), (Rasmussen, 1973).

The assumption used in this work is that crewmember's internal psychological state can be measured by levels of happiness and motivation. But there are other external psychological motivators such as levels of trust between crewmembers, ground, and even with the automation. These are difficult to characterize but have been included as other variables that would also need to be considered for measuring and quantifying psychological performance. Generally, there are several psychological metrics and many more ways to categorize them. To make it simple, this work selected a particular publication by Rasmussen et al's (2006) which reviewed teamwork and psychological factors across various industry and literature sources and broadly categorized psychological variables into three areas: behavioral, attitudinal, and emotional. These three variables can be represented as elements of psychological resources:

1) $Y_B(t)$ = Behavior (■)
2) $Y_A(t)$ = Attitude (■)
3) $Y_M(t)$ = Mood/Emotion (■)

The assumption is that these various psychological measures represent summations of all elements within their respective categories to provide an overall value of the crewmember's psychological well-being. A brief description of what these resource elements entail is described.

Behavioral metrics capture the actions taken by the crewmember. Some examples of behavior elements include creativity, autonomy, integrity, neuroticism, trust, and conflict management.

Attitude is a measure of the crewmember's internal perception of the situation. Some examples of attitude elements include perceived cooperation, organizational commitment, shared vision, and job satisfaction. While attitudes are hard to measure, it can often be an indicator for later conflicts or long-term behavioral deviance.

Mood/Emotion is an instantaneous state of emotion. Different tools are currently available such as Profile of Mood Status (POMS) and Positive and Negative Afffective States (PANAS) which are validated measures in the psychology literature. These measures give a snapshot in time of the crewmember's state of mind. Some example moods and emotions include stress, anger, frustration, happy, sad, and complacent.

3.4.1.1.3 Summary of Resource Element Decomposition

The overall decomposition of crew performance can be aggregated and represented in Figure 13. A summary chart of the subdivided performance elements are listed in Table 13. The last column of Table 13 provide a list of existing measures for the particular crew performance resource element. While this work does not focus on the specific measurement methods, this is an indication that several of these measures do exist and in fact can be used to collect astronaut data as validation.

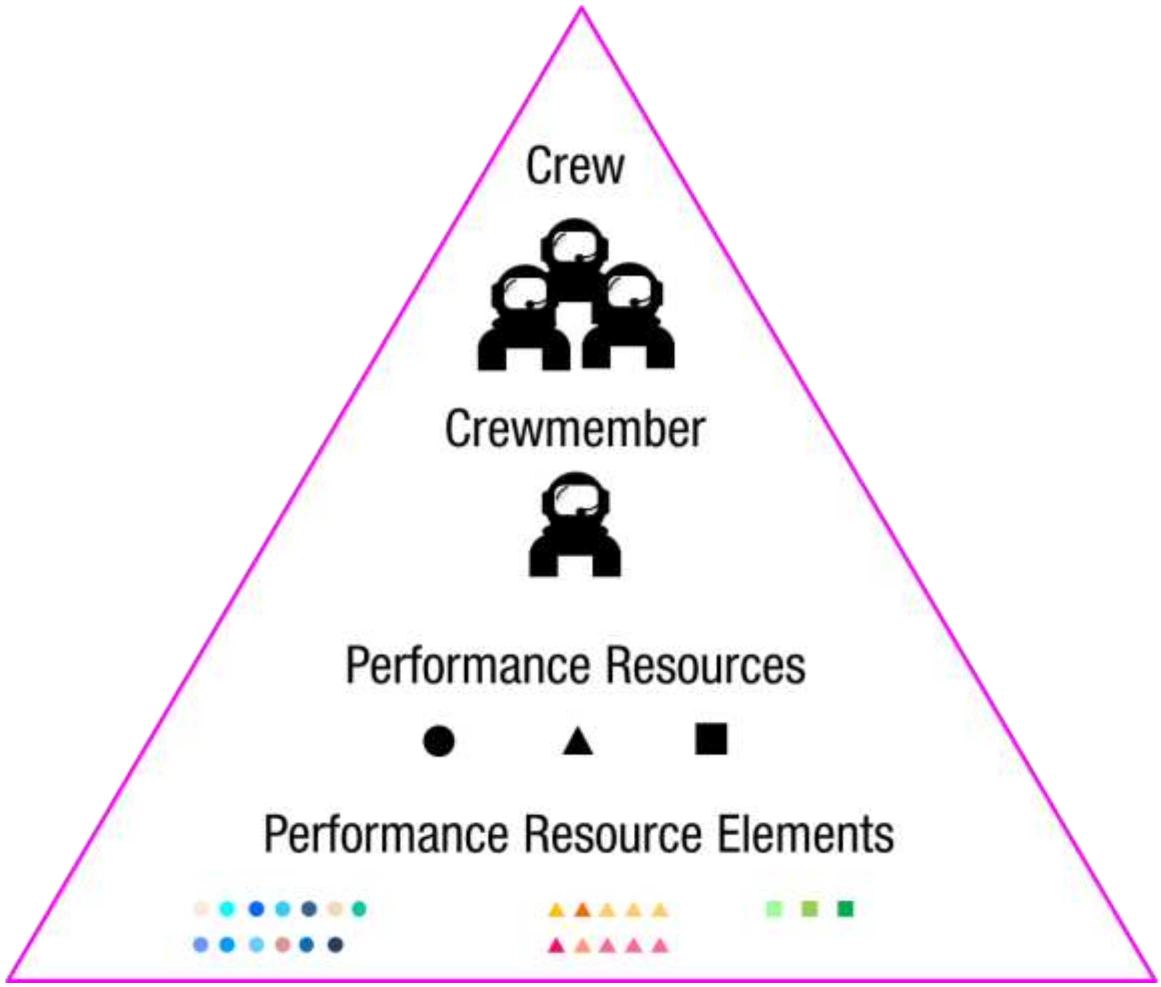


Figure 13. Crew decomposition to resource elements.

Table 13. Summary table of crewmember performance resource elements.

		Resource Element		Description	Existing Measurement Methods
Physiology	$P_B(t)$	Bone Strength	●	Quality of bone strength	Bone Mineral Density, Nutrient Levels
	$P_C(t)$	Cardiovascular System	●	Cardiovascular health	Heart Rate, Cholesterol, Blood Pressure, Age, Weight, Height
	$P_D(t)$	Digestion	●	Digestion ability	GI Absorption
	$P_F(t)$	Fine Motor Control	●	Ability for fine motor control	Finger Tapping, Spiral Drawing, Precision Grip/Lift, Coin Rotation
	$P_H(t)$	Hearing	●	Ability to hear	Audiogram Test
	$P_R(t)$	Hormones	●	Balance of hormone levels	Blood Glucose, Nutrient Levels
	$P_I(t)$	Immune System	●	Quality of immune system	% of White Blood Cells or Immunoglobulins in Blood
	$P_M(t)$	Muscle Strength	●	Quality of muscle strength	Muscle Mass, Muscle Volume
	$P_N(t)$	Nervous System	●	Quality of nervous system function	Heart Rate Variability, Ewing Battery Tests
	$P_P(t)$	Proprioceptive Posture	●	Ability of proprioception	Threshold to Detection of Passive Motion (TTDPM), Joint Position Reproduction (JPR), Active Movement Extent Discrimination Assessment (AMEDA)
	$P_V(t)$	Vestibular System	●	Quality of balance and orientation	Electronystagmography (ENG), Rotation Tests
	$P_E(t)$	Vision	●	Quality of visual system	Visual Acuity, Visual Range
	$P_X(t)$	VO2 Max	●	Quality of breathing	Respiration Rate, Max Lung Capacity
Cognitive	$C_R(t)$	Abstract Reasoning	▲	Problem solving ability	Matrix Reasoning (MRT)
	$C_B(t)$	Abstraction	▲	Abstract thinking	Abstract Matching (AM)
	$C_E(t)$	Emotion Identification	▲	Ability to identify emotions	Emotion Recognition (ERT)
	$C_D(t)$	Risk Decision Making	▲	Ability to make decisions	Balloon Analog Risk (BART)
	$C_T(t)$	Scanning & Visual Tracking	▲	Ability to scan and track objects visually	Digit Symbol Substitution (DSST)
	$C_S(t)$	Sensory-Motor Speed	▲	Speed of translating sensory stimuli into motor response	Motor Praxis (MP)
	$C_L(t)$	Spatial Learning & Memory	▲	Ability to memorize complex figures	Visual Object Learning (VOLT)
	$C_P(t)$	Spatial Orientation	▲	Ability to discern orientation of objects	Line Orientation (LOT)
	$C_V(t)$	Vigilant Attention	▲	Ability to recognize stimuli	Psychomotor Vigilance (PVT)
	$C_M(t)$	Working Memory	▲	Short-term mental storage capability	Fractal 2-Back (F2B)
Psychology	$S_B(t)$	Behavior	■	Actions, and task execution	Self-report, Rating Scales
	$S_A(t)$	Attitude	■	Internal perception of situations	Likert Scales
	$S_M(t)$	Mood/Emotions	■	Instantaneous state of emotion	POMS/PANAS

This elemental resource breakdown framework is used as a method for tracking the varying resources of the crewmember through the mission. The amount of resources available for each individual changes throughout a mission based on his/her activity level, health, and the influences from the environment. Figure 14 illustrates an example of the resource level status, per crew member at a given time point. Notice that crew members do not have the same maximum resource levels due to differences in their initial baseline health and cognition (e.g. some crewmembers can be stronger than others). The maximum resource levels for each individual can also change throughout a mission, for example one can improve muscle strength and overall health, but they are all measured against each individual's own baseline.

While currently there is no effort to aggregate these internal crew member resources (physical, cognition, psychological) as one comprehensive metric, there are metrics in existence for each individual resource element listed.

Figure 14. Snapshot at time, t_1, of crewmember resource status.

3.4.1.1.4 Spacecraft Design Element Decomposition

The spacecraft design can also be divided using the ERM approach. The decomposition of spacecraft design elements can be seen in Figure 15.

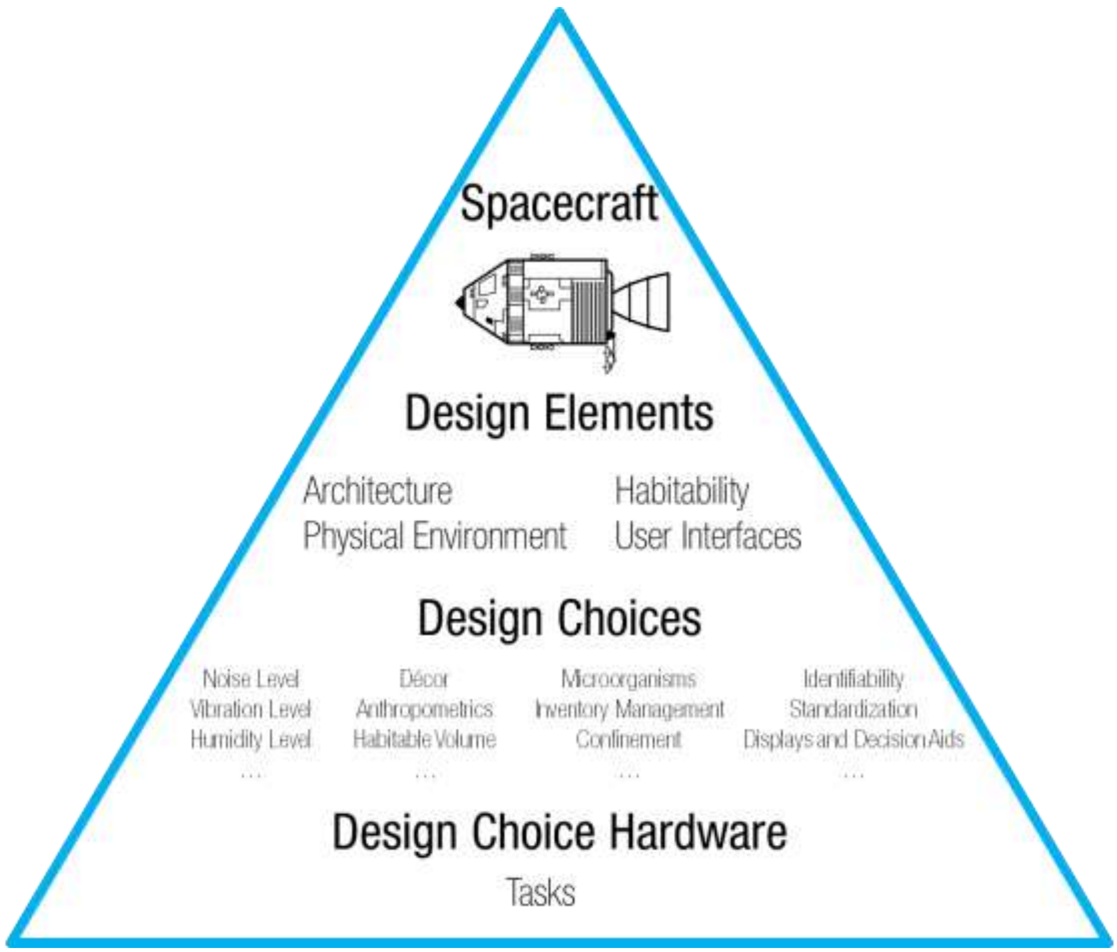


Figure 15. Spacecraft design element decomposition.

Spacecraft Design Architecture and Choices

Once again, the breakdown of the spacecraft elements leveraged the list of PSFs specific to the vehicle design from Mindock (2012). The spacecraft can be divided into four high-level design elements: 1) Physical Environment, 2) Habitability, 3) Architecture, and 4) User Interfaces. These can further be subdivided into 57 specific design choices, which were listed earlier in Chapter 2, but is repeated here as Table 14 for ease of reading. The specific design choices are thoroughly documented in Mindock (2012), and it is noted here that two more choices were added to this list (water system design and countermeasures) as they were deemed important aspects to include for a comprehensive spacecraft design.

Table 14. Performance Shaping Factors (PSFs) relevant to human and spacecraft interacations.

VEHICLE ENVIRONMENT	VEHICLE ARCHITECTURE	HABITABILITY	USER INTERFACES
Natural and induced environment factors	*Factors that create the physical environment surrounding crew*	*Human needs of the system*	*Interface design between human and system*
Noise Level	Décor	Microorganism Virulence	Identifiability
Vibration Level	Anthropometric Accommodations	Inventory management Capability	Information Displays and Decision Aids
Humidity Level	Habitable Volume	Confinement	Standardization
Lighting (ambient)	Location and Orientation Aids	Level of Sensory Stimulation	Control Panels/Input Devices
Temperature	Translation Paths	Availability of Personal Items	Hardware Tool Availability
CO2 Level	Hatches and Doors	Availability of Medical Care	Situation-specific Lighting
Air Flow	Windows	Cleanliness of Environment (microorganism, gunk etc.)	Hardware Ease of Use
Oxygen Level	Lighting (Ambient)	Food System	Software Ease of Use
Odor		Nutrition	Information Management Support
Atmospheric Particulates		Availability of Private Space	Human/Vehicle Automation Integration
Acceleration/Gravity Level		Availability of Recreation/Personal Activities	Work Station Anthropometric Accommodations
Toxic Substance Level		Décor of Environment	Mobility Aids and Restraints Availability and Quality
Atmospheric Pressure Level		Hygiene Support	Orientation of User Interfaces
Radiation Exposure Level			Suit Design
			Caution and Warning Functionality
Modified from Mindock (2012).			Human/Robotics Integration

Design Choice Hardware Mapping to Tasks

The lowest spacecraft design element is described here by "Tasks". The argument here is that design as its lowest component can be represented through a series of tasks or activities that are performed to interact with the design. For example, there can be two designs for fulling the "Flight Control" Task. Design A requires the astronaut to use a touchscreen flight control panel.

Design B requires the astronaut to use a manual yoke flight control system. While these designs both achieve the "Flight Control" task, they require different resources from the astronaut and when the task is accomplished it replenishes different resources. Design A, is a visually demanding task that requires a high cognitive load, while Design B relies on more manual inputs and less on cognition, it does require other resources from other sensory elements (not just vision).

In regards to hardware, Design A requires a good visual display and intuitively conveyed information, while Design B requires an appropriately design yoke that provides accurate and intuitive sensory feedback (i.e. harder to push as resistance in flight increases). These differences can be captured as "resource required" from the individual crew member. Figure 16 depicts how each Design comes with a "Resources Required" and a "Resources Refilled" value for each individual performance element.

Figure 16. Comparison of resources needed and provided by different designs that fulfill the same function.

The resources required and refilled for the crewmember (physical, cognitive, and psychological) are somewhat similar for both designs. In this case, an inferred subjective analysis points to Design B as providing slightly more psychological satisfaction due to the interaction. While the resource requirement and replenishment are arbitrary in this case, this example demonstrates how a design comparison can be done by mapping a specific design by its resource usage and refilling.

For this simple example, it is clear that the details of the design are still desirable to make a good assessment of the impacts. Collecting this information can be highly cumbersome and is also highly subjective. The danger is that the resources "required" and "refilled" for a particular design can be dictated subjectively which strongly impacts the crewmember's performance outputs. But the intention is that the designers describe their rationalizations for the design's influence on each resource, which can be supported by the use of real data.

3.4.1.1.5 Task Element Decomposition

The Task Model can also be decomposed using the same ERM approach. Tasks are dissected from high-level mission goals into specific functions that are done by an individual crewmember. Figure 17 provides a graphical representation of the breakdown.

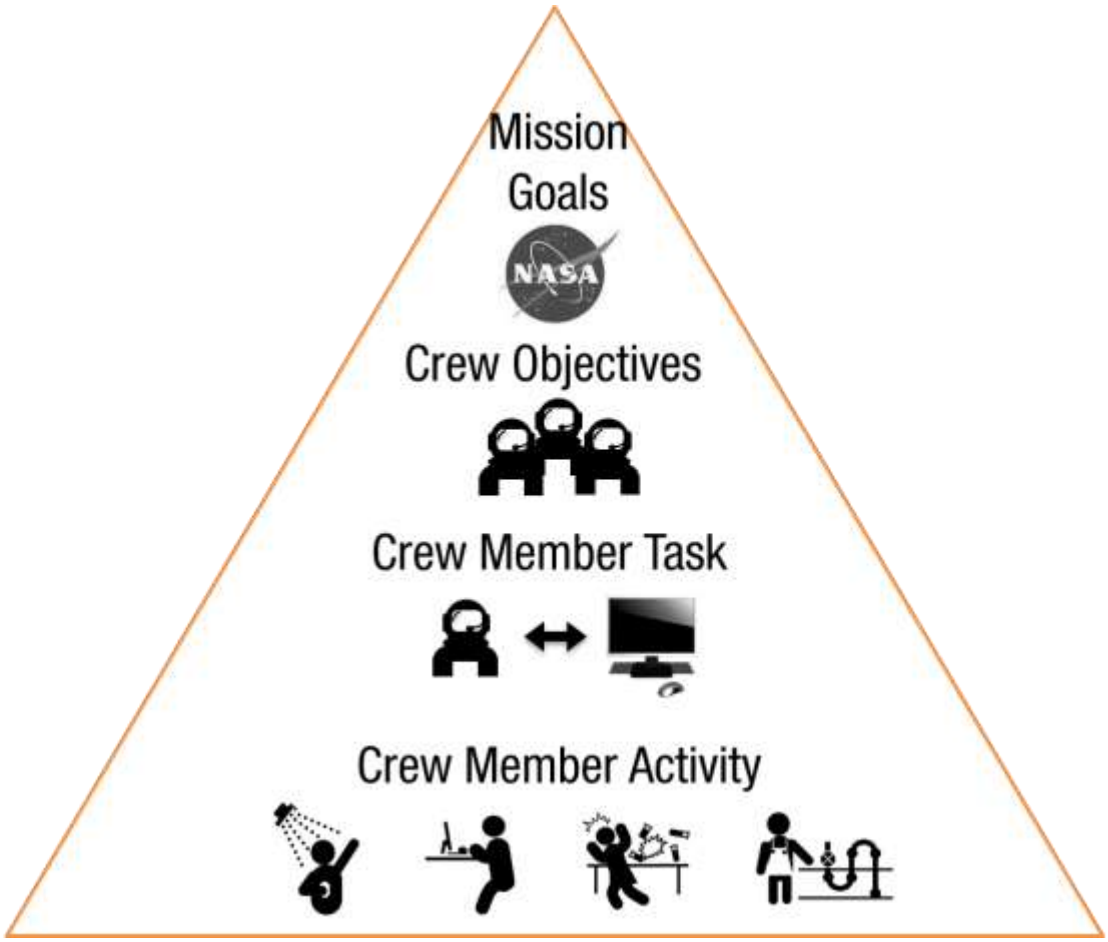


Figure 17. Decomposition of task elements.

It is important to note the terminology distinctions used here, where mission goals and crew objectives are accomplished by the collective crew, while tasks and activities are conducted at the individual level. This distinction plays a role in understanding how to aggregate the data at each level of fidelity. It also has implications for future development of the model to allow for flexibility at every stage of design fidelity.

Another important distinction is the difference between task and activity. In this context, task is considered an aggregate of several activities, while an activity is a singular action. The tasks are categorized into four high-level task types three of which are provided in Pranke and Larson (1999): self-sustenance, operations, payloads, and the fourth task type that was deemed missing was housekeeping tasks such as maintenance and repair of subsystems. These tasks can be further subdivided into specific activities.

Activity Lists

The various activities were defined, again, from Pranke and Larson (1999), with the addition of housekeeping tasks. The activities are defined as generic spaceflight activities historically conducted by astronauts throughout a mission. While numerous other activities can be defined, the goal was not to create a comprehensive list, rather a representative set is sufficient for the framework set-up.

Table 15. Categories of modes, their definitions and associated task lists.

Self-Sustenance	Breathing
	Drinking
	Eating
	Exercise
	Hygiene Activities
	Leisure Activities
	Sleeping
Operations	Contingency Operations
	Emergency Operations
	Flight Control
	Mission Planning & Scheduling
	Robotic/Habitat Operations
	Systems Monitoring
	Spacecraft Navigation
Payloads	Execute Experiments
	Manage Science Experiments
Housekeeping	Cleaning Spacecraft
	Maintain Operational Hardware
	Maintain Science Hardware
	Repair Operational Hardware
	Repair Science Hardware

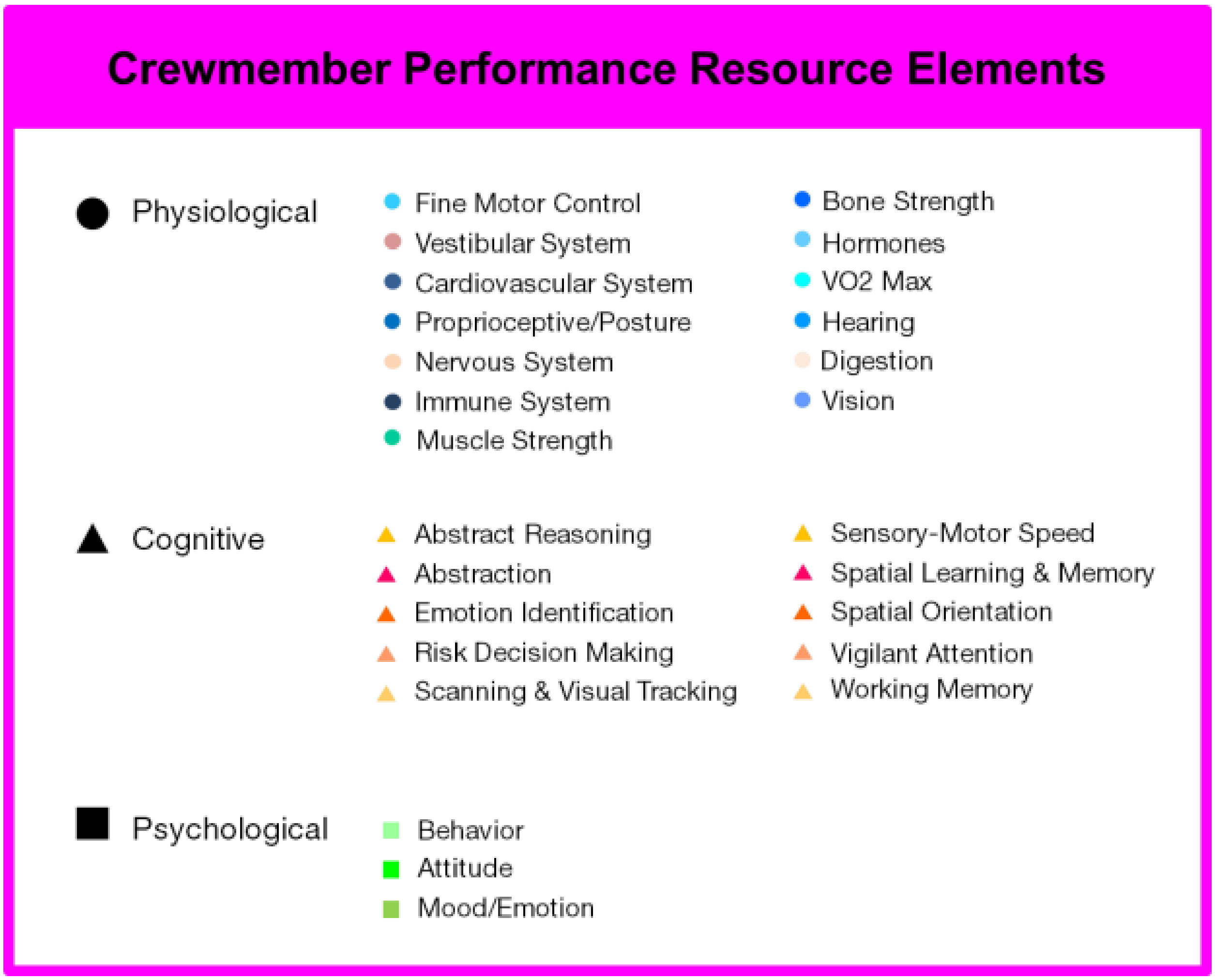
Tasking List

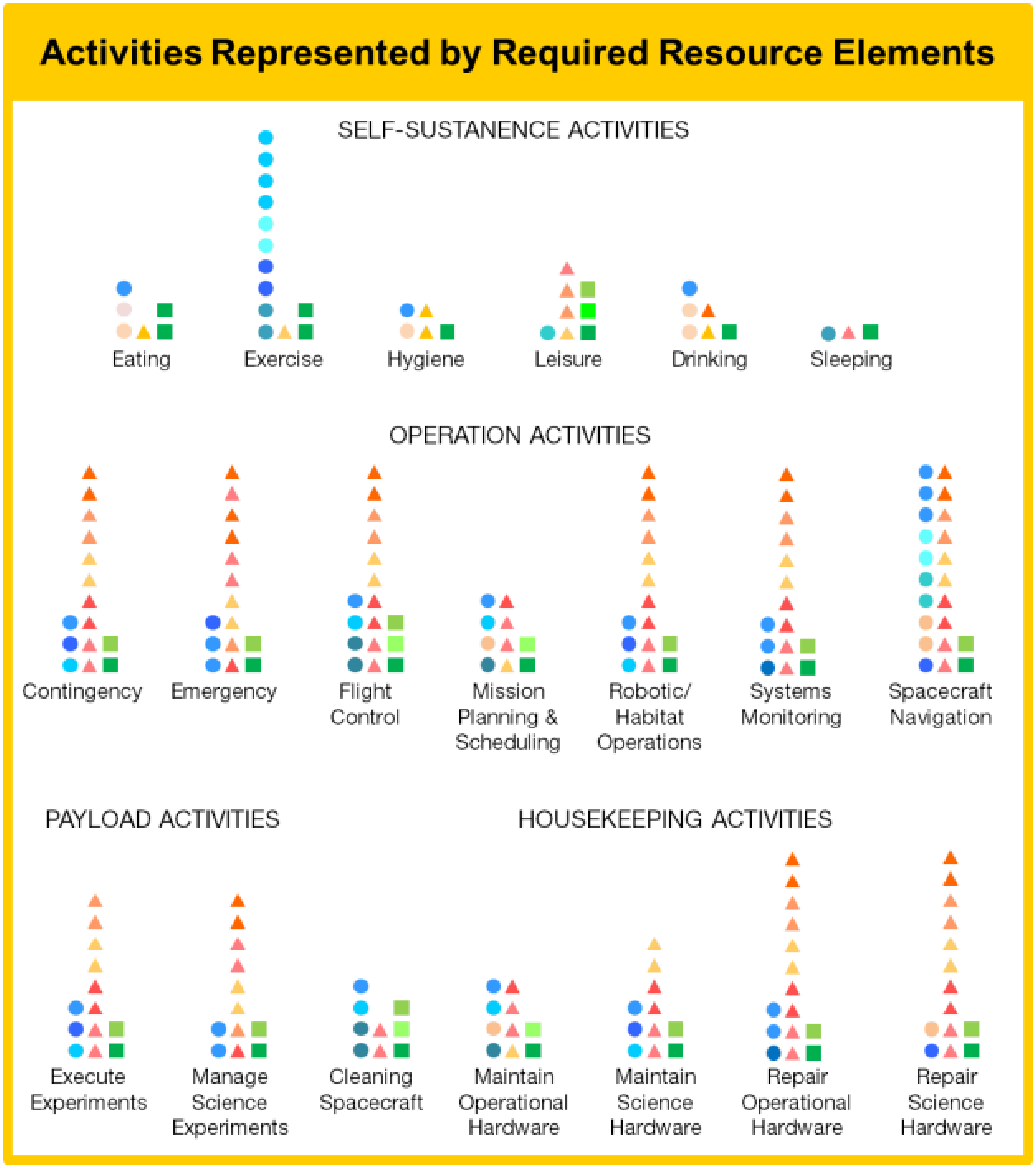
Within the framework, the Task Model is meant to provide a set of tasks for each crewmember also called here a task list. The task list is a set of activities that a crewmember performs over the mission timeline. A variety of task lists can be created by combining and re-arranging various activities.

To capture the range of task lists, the three representative levels of activity are defined: 1) No Tasking, 2) Some Tasking and 3) High Workload. The “No Tasking” task list only include activities that involve the self-sustenance activities. These are solely activities in which the crewmembers must perform to keep themselves alive. “Some Tasking” involves a generic set of activities that would be a reasonable and productive day onboard a spacecraft. A representative “Some Tasking” task list involves a selection of activities that include all the self-sustenance tasks along with a handful of operations, payloads, or housekeeping activities. It represents a normal 8-hour work day with appropriate breaks throughout the work day. A “High Workload” task list specifically tries to exacerbate the number of activities that the crewmembers must perform to mimic a high workload environment. The activities include all self-sustenance tasks but with fewer hours of sleep and a series of difficult operation activities with few breaks in between. More details of the selected task lists are explained by a case-by-case basis in Chapter 5 through representative case studies.

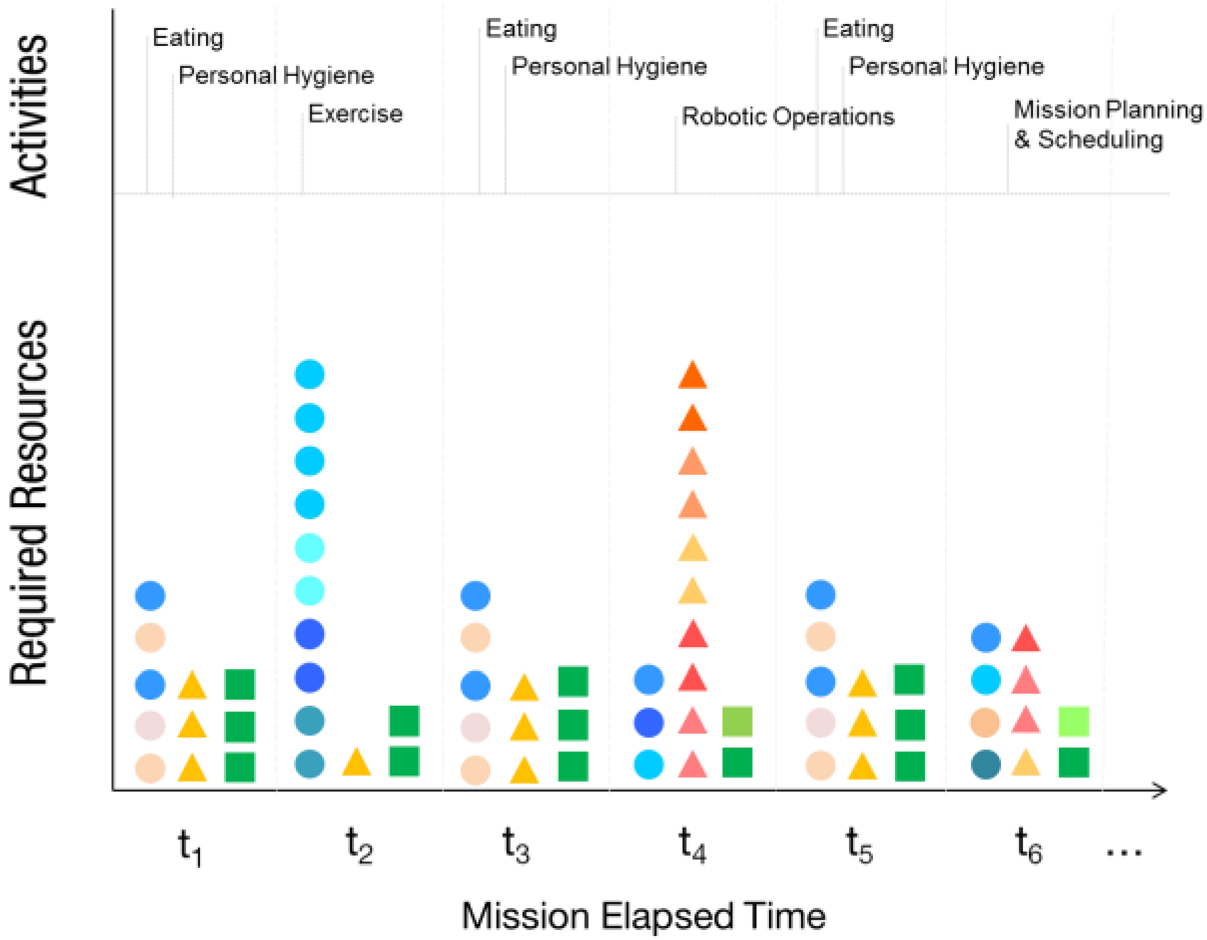
3.4.1.1.6 Framework Relationship Development

This section brings back together the three components of the framework (crew, spacecraft design, tasking) that were analyzed and recombines them to identify the relationships between each one of them to ultimately define crew performance. As mentioned earlier, the backbone of this model is the element breakdown of the crew member into specific resource elements. These resource elements are then used to map and qualitatively quantify the other two framework components: vehicle design and tasking. A graphical representation of the relationship mapping between these three components are shown in the following figures.





Activities Represented by Required Resource Elements
SELF-SUSTANENCE ACTIVITIES
Eating
Exercise
Hygiene
Leisure
Drinking
Sleeping
OPERATION ACTIVITIES
Contingency
Emergency
Flight Control
Mission Planning & Scheduling
Robotic/ Habitat Operations
Systems Monitoring
Spacecraft Navigation
PAYLOAD ACTIVITIES
Execute Experiments
Manage Science Experiments
HOUSEKEEPING ACTIVITIES
Cleaning Spacecraft
Maintain Operational Hardware
Maintain Science Hardware
Repair Operational Hardware
Repair Science Hardware



The figures depict how the crew resources can be applied to the various activities that a particular crewmember is executing. A list of activities can be strung together to form a mission timeline and identify when each activity is executed by that crewmember and what resources are affected at that time step. The underlying relationships are the fundamental building blocks for this framework.

3.4.1.2 Characterizing Crew Utilization

In the previous sections, the performance of the crewmember has been characterized through the mapping between the design and environment in which the crewmember is executing the specific activity. Now the second component to evaluating a spacecraft's design quality includes the utilization of those particular crewmembers. Using the definition of crew utilization established earlier: “what the crew does for the vehicle” several metrics were identified as possible measures for crew utilization. Leveraging *Human Spaceflight Axiom 1*, the goal of a human spaceflight is to allow the human to do the exploration work, therefore, the measure for utilization for such missions must include the total activities that the human(s) accomplish related to space exploration. The extent of utilization of the crewmembers must also run the gamut of the mission from launch to Earth return. And lastly, another requirement for such a metric includes the ability to capture the quality of work done, which relates to probability of errors and mistakes that occur as well as the difficulty of the tasks. These requirements for a crew utilization metric can be summed into two main measures which must capture:

1) total number of activities done by the crew throughout a mission
2) quality of executed activity.

It is noted here that the quality of the executed activity may be a challenging value to capture at this time due to the lack of human spaceflight data. Attempts have been made previously to capture activity quality by various metrics including speed or accuracy of finishing the task. There can also be merit in capturing the complexity of the task such as evaluating rock samples for signs of life, but at this time the data is difficult to capture and normalize between a variety of tasks. The framework described here provides the ability to capture some of these aspects by comparing resource usage for each activity as shown earlier in Figure 16. Additionally, the timeline of activities can be summed for the total number of activities done throughout the mission.

3.5 Step 4: Map Relationship to Spacecraft Design Process

Once the fundamental components of the framework have been laid down, the next consideration is in how this framework maps to the systems engineering process. As described briefly in Chapter 2, the spacecraft design process using systems engineering breaks down the phases from A-E with specific activities that mapped to those phases. As the process is performed, details of the design are refined. The information that is uncovered from the design process is aligned to the steps in the model. Figure 18 depicts how the spacecraft design process maps to the specific steps. The goal of this process is to help refine the design and identify the major questions associated at each step. In this case, the interest is in the early design process and therefore ends the process around what would be considered the "Critical Design Review" (CDR) during the Systems Engineering process. This is the phase where the design is approved for manufacturing and build.

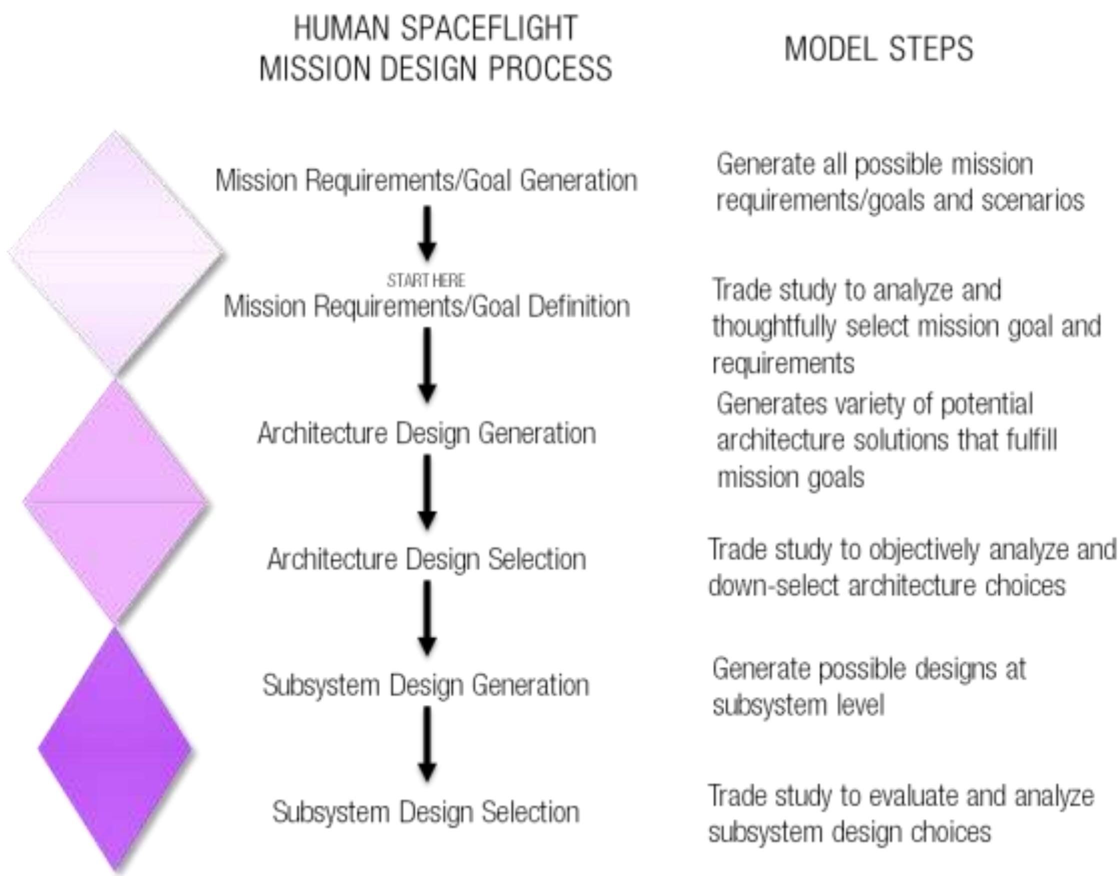


Figure 18. Mapping of human spaceflight mission design process to critical steps for the model.

The mapping process shows what information is provided at each step of the design process, and how those outputs affect the next level. Using a similar technique from human-centered design, the process alternates between diverging and converging idea phases in which ideas are either being generated (diverging), or are undergoing critical analysis (converging) (IDEO, 2016). The triangles in the left column of Figure 18 provide a visual indicator to the type of activity that occurs in each state -whether it is generative (diverging) for brainstorming of a multitude of ideas (upright triangle - ▲) or analytical (converging) for decision-making, assessment, and filtering of choices (upside-down triangle -▼). After each phase, the design becomes more constrained with increasing fidelity. This process is highly iterative whereby new information that is revealed in the process must be used to re-evaluate previously held assumptions. Information about the design is also revealed with a certain hierarchy in the design process. For example, selection of a food system is not appropriate until after the mission duration is defined.

No comprehensive documentation was found to provide a detailed guideline for specific prompts at each phase of the design process, therefore a list was created through the aggregation of several documents, reports, and rationalization. The next sections detail the hierarchy of parameter choices that drive detailed design decisions.

3.5.1 Framework Information Flow

The flow of the information is also vital to understand. From a designer's perspective, modeling occurs in a top down approach where the high level mission design and goals identification are completed first followed by architecture selection, the determination of large scale vehicle design choices (i.e. lunar descent modules, three body vehicles etc), and finally detailed subsystem selection and integration.

The framework was structured to be easily integrated into this top down design philosophy whereby the model is implemented during each phase of the top down approach with increasing numbers of variables. This scalability can be understood as follows.

In the high level mission design phase, the designer focuses on things like external vehicle geometry and materials. This in turn sets internal habitable volume and baselines solar radiation protections. These two variables are then mapped as an impact to individual crewmembers' performance resource elements. These three mission parameters begin to set the stage for various downstream design choices. Following the three parameter identification a handful of other high level mission parameters are identified:

1) Number of Crewmembers?
2) Expected Gravity Regime?
3) Launch Vehicle Constraints or Requirements?
4) Risk Posture for the Mission?
5) Funding Posture for the Mission?

The answers to this set of questions begins to narrow down possible design solutions. By selecting the number of crewmembers, the range of life support system needs can be bounded

In the architecture design, the vehicle geometry and shell materials have already been set however the designer can start looking at the internal floorplan design. This internal floorplan will then map to another set of astronaut resources and the crew member performance rating determined. Finally, the subsystem design is selected and relevant variables identified to produce a third and final crew member performance rating. In each design phase the procedure can be iterated to determine an optimal design within that specific phase. This ideal design propagates down and helps to dictate the subsequent design choices.

And finally, the same process occurs at the subsystem design level, in which the design selections made at this lower level are fed back into the framework to determine the crewmember impacts.

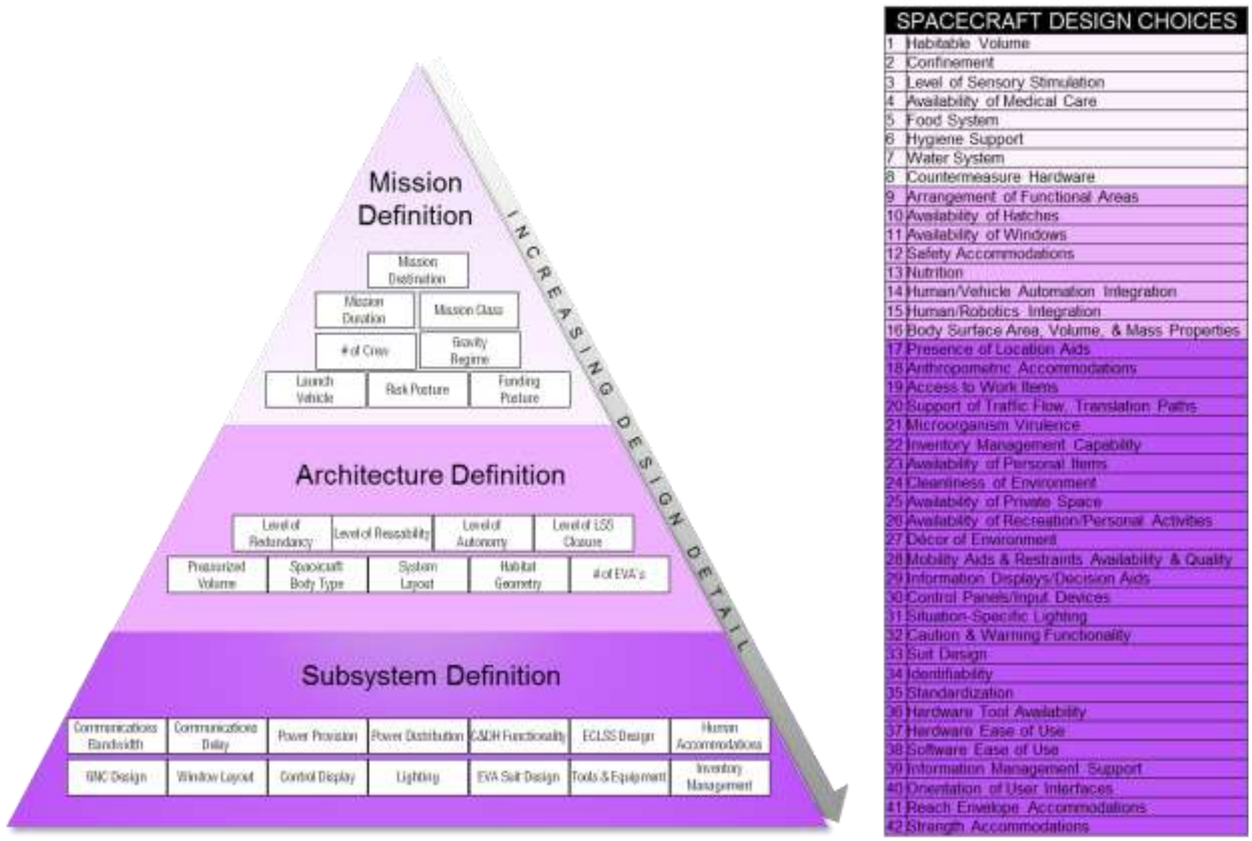


Figure 19. Mapping of design process to spacecraft design elements.

3.5.2 Defining Mission Goals and Objectives

Defining mission objectives is the first and most critical step conducted before initial spacecraft design. The mission objectives are defined which answer the top three mission parameters regarding destination, duration, and anticipated mission activity (also known here as the mission class). Figure 20 depicts various historical and upcoming flight profiles that span the range of these three mission design parameters.

3.5.3 Mission Profile Definition

Internal to the model the first step is to define the mission profile as dictated by the type of human mission. To define the profile, the following four parameters: mission class, destination, duration, and gravity regime are identified as the four main categories of mission parameters that serve as major drivers of the spacecraft design.

Mission Class: This identifies the type of mission that will be executed, which drives the type of mission tasks that will need to be done through the entire mission.

Mission Duration: This identifies how long the spacecraft must sustain the crew and maintain their health and well-being. As duration lengthens, the spacecraft environment and design becomes a more critical influence on the crew's performance.

Mission Destination: This drives many of the external environment concerns from radiation exposures to planetary dust mitigation needs. It also has implications on the required medical protocols where the farther the mission destination, the more self-reliant the crew must be for medical operations and procedures thus prompting the need for additional medical supplies.

Gravity Regime: Planetary surfaces offer some respite to the rapid physiological degradation that occur in microgravity. Various gravity regimes will also impact the architecture and layout of the spacecraft and how the crew can use various spaces.

The following table identifies the variations within each parameter that can be chosen for defining an overall mission profile. And Figure 20 shows how these various mission parameters can be used to characterize the variety of human spaceflight missions both historical and planned.

Table 16. Mission parameter choices for defining an overall mission profile.

MISSION PARAMETERS			
Mission Class	**Duration**	**Destination**	**Gravity Regime**
Exploration (X)	Hours (<24 hrs)	Suborbital (<160 km)	Microgravity (0g)
Set-up (S)	Days (1 day-1 week)	LEO (160-2000 km)	Partial Gravity (<1g)
Habitation (H)	Weeks (1 week -1 mo.)	MEO (2000-35786 km)	Artificial Gravity (Ag)
Transport (T)	Months (1 mos.–6 mos.)	GEO (35786-42164 km)	Gravity (1g)
Adventure Tourism (A)	Part. Year (6 mos.–1 yr.)	Moon	Hypergravity (>1g)
Operations (O)	Years (> 1 yr.)	Mars	
		NEA	

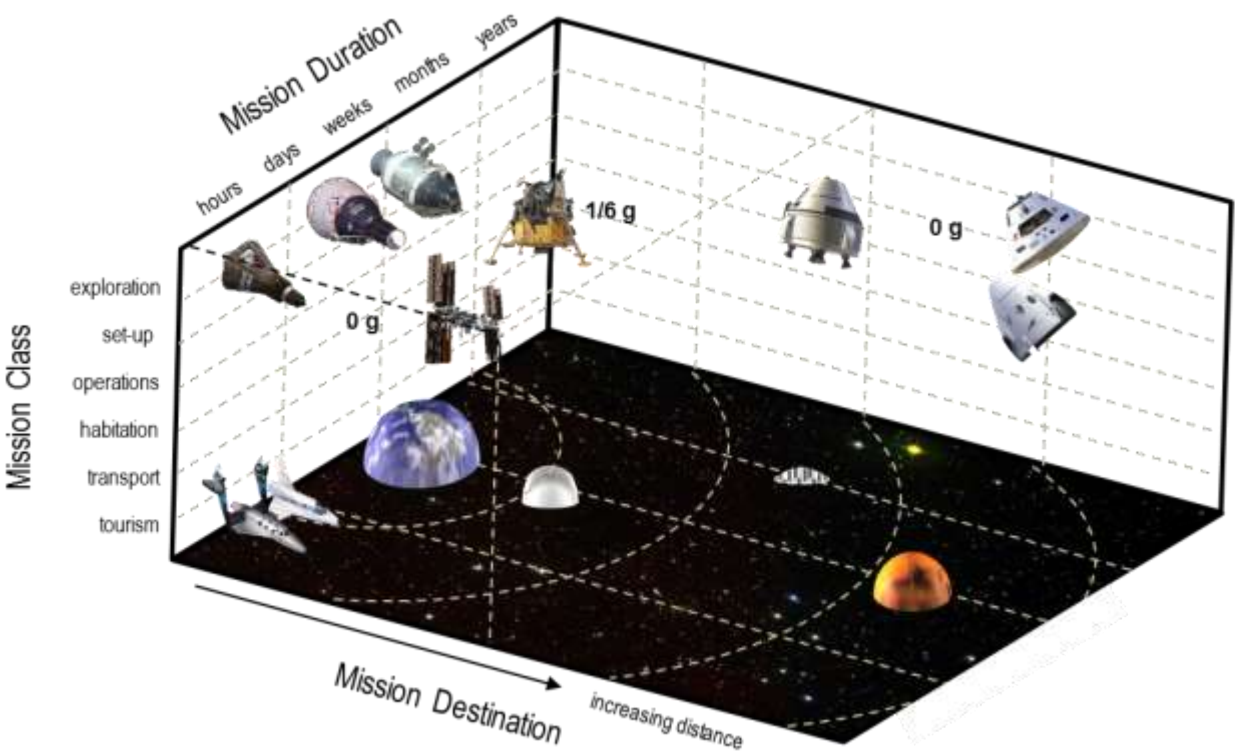


Figure 20. Comparison of various missions across the top three mission parameters: destination, duration, and class.

CHAPTER 4: MODEL DEVELOPMENT FROM ESTABLISHED FRAMEWORK

In chapter three the framework of the model was discussed in detail. This framework described the inputs and outputs and cast the crew metrics into Physiological, Cognitive, and Psychological resource elements that were then applied as measures of vehicle design and tasking impacts.

The procedure for utilizing this model framework was discussed in great detail, describing how the model could be applied at differing levels of design. Unfortunately, as discussed in Chapters 1 and 2, a major problem of crew performance modeling for spacecraft design stems from the lack of experimental data. So while Chapter 3 outlined a framework for casting the ideal crew performance model, the lack of data provides some significant restrictions on the implementation of that framework.

In Chapter 4 the focus is on applying the idealized framework described in Chapter 3 to the experimental data and rule-of-thumb type qualitative knowledge currently available for human spaceflight. As such, this chapter develops a semi-quantitative model relying upon the principles discussed in chapter three. In more specific terms, this semi-quantitative model utilizes experimental data when available from NASA. When no data is available, the model development relies upon scaling arguments, based upon relative orders of magnitude between terms, and a simplified hierarchical weighting scheme to designate, low, medium and high impact effects. As such, the semi-quantitative model assumes linearity between variables, unless experimental data is available to the contrary. The goal is not to create an exact working model, but rather present a simple mathematical model that sufficiently captures the basic premise of the framework and provides insight as to how crew performance is connected to the design and operations of the spacecraft.

4.1 Converting Data into Mathematical Representations

Before data can come out of a model a detailed characterization of the intended outputs is needed. Pulling on the definition of Crew Accommodation and Crew Utilization, the two basic questions that they fundamentally address are: “Are the crew alive, healthy, and happy?” and “Are the crew effectively utilized?”. In the context of the element based resource framework established in Chapter 3 these outputs can be restructured into specific measures regarding the crew performance impacts. To determine Crew Accommodation, the three resource element status are analyzed. The percentage of resources still left in the crewmember tells the designer how the crewmember is faring. If the resource level falls to 0% for physiological resources, then the crewmember is dead; 0% of cognitive resources means the crewmember is in a mental vegetative state; and 0% of psychological resources means the crewmember is despondent or in extreme psychological distress.

Crew Utilization is represented in a similar vein, but instead represents the efficiency of performing a task. The more efficient a task can be accomplished the fewer resources the crewmember would have used. In this case, crew utilization takes an aggregated task approach, where the elemental resource reduction amount is divided by the total number of tasks done by the crewmember. The value represents an average resource usage per task. The fewer resources used per task, the more efficient the design. While this measurement is not an exact reflection of the crew’s utilization, it provides a related measure that is sufficient for the purpose and scope of this work. Table 17 shows a summary of the outputs of interest.

Table 17. Measure of Crew Accommodation and Utilization outputs.

Crew Accommodation Metric	
Are they alive, healthy, and happy?	
Physiological Status	*% remaining*
Cognitive Status	*% remaining*
Psychological Status	*% remaining*
Crew Utilization Metric	
Are the crew used effectively?	
Design Efficiency - Ratio of Resources Used per Task (over total mission)	
Use of Physiological Resources	*Resources Used/Total Number of Tasks*
Use of Cognitive Resources	*Resources Used/Total Number of Tasks*
Use of Psychological Resources	*Resources Used/Total Number of Tasks*

Working backwards from the intended outputs, it is clear the metrics that are needed must measure the physiological, cognitive, and psychological state of the crewmember. The implication is that at the beginning of a mission, the crewmembers starts with 100% of their baseline resources and the resources are depleted throughout the mission in various ways. The following section focuses on converting the elemental resources into a measurable equation. An important consideration to note is the limited threshold detection difference between the real world and the mathematical quantity that can be achieved with these equations, for example, while mathematically there is a difference between 80% and 90%, the crewmember may not be able to distinguish such a difference in their psychological well-being at that resolution nor do any monitoring equipment or methodologies that currently exist to measure changes at that resolution.

4.1.1 Measuring Crew Performance through Change Functions

Looking at these three human performance measures (physiology, cognition, and psychology) with more detail, each of the measures can be decomposed into relevant factors that compose the metric. Figure 21 presents a graphical representation of how the resource elements are decomposed from the overarching systems perspective.

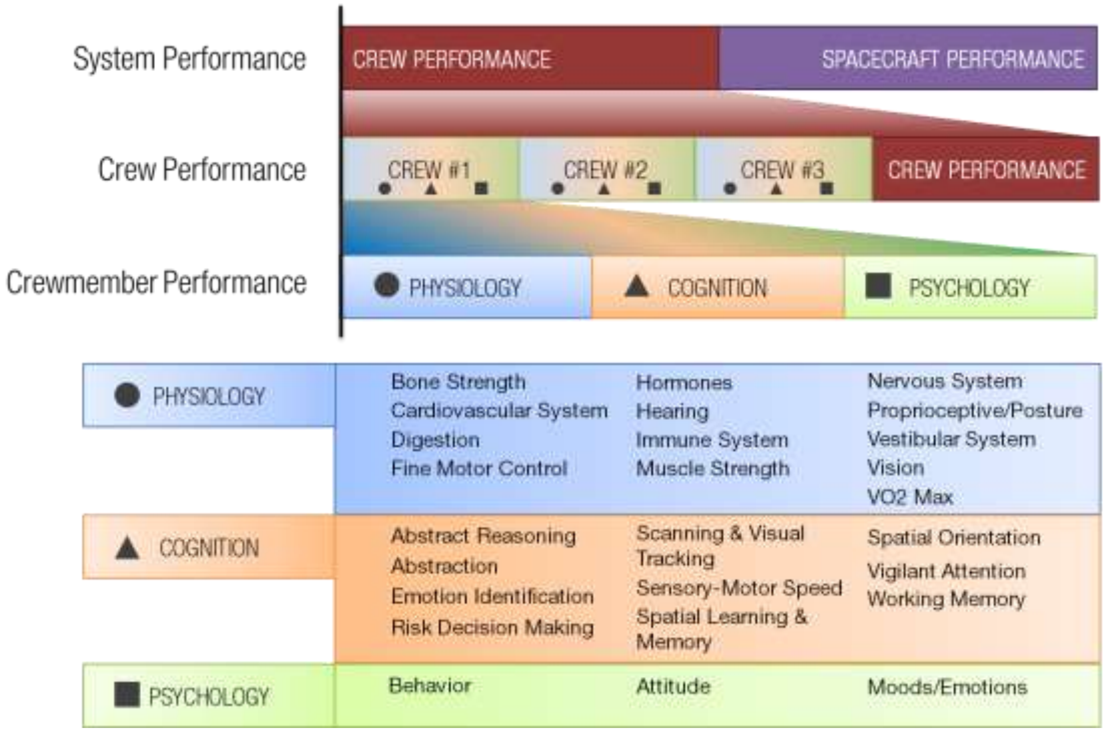


Figure 21. Breakdown of system performance components.

Furthermore, the measures can be mapped to a rate of impact or change over the mission duration. The impact for each component can be evaluated with existing metrics as follow-on work for modeling or quantification of these values.

4.1.1.1 Physiological Performance Change Function (P(t))

The purpose of the physiological change function is to provide a quantitative representation of the changes in physical ability of each crewmember. Physiological performance is defined here as all of the physical and bodily functions of the human body. It ranges from the performance of the basic physical senses to the health and state of the body. To understand how physiological performance can change over a space mission, various physiological performance issues were identified using previous work from Mindock (2012).

The physiological impact rate is a function of these physiological variables. They can be summed for an overall physiological change rate as defined in the following equation.

$$\boldsymbol{P(t)} = \frac{P_B(t)+ P_C(t)+P_D(t)+ P_F(t)+ P_H(t)+ P_R(t)+P_I(t)+ P_M(t)+ P_N(t)+ P_P(t)+P_V(t)+ P_E(t)+ P_X(t)}{13}$$

Equation 1

Each physiological variable here is assumed as independent of one another. This is chosen as the simplest possible representation of the framework. The purpose being to demonstrate how the mechanics of the framework could be applied to produce a mathematical model. However, it is clearly recognized, that a linear implementation will not capture the rich interactions existing between these variables as has been identified in numerous literature studies. If more quantitative data can be collected to better characterize these interactions, the same basic framework approach could be applied to produce a more realistic model. This early stage of model development is meant to show that the framework can capture all the correct components, and is not meant to be a high-fidelity computational simulation. This linearity assumption is carried through all three resource change functions.

The flexibility of this particular linear representation of physiological change allows for each crewmember to have a change function associated with their specific attributes. For example, some crewmembers may have more resilience to illness while others may come with pre-existing medical conditions. This early implementation of the model does not include astronaut variability; it can be added for future improvements.

4.1.1.2 Cognitive Performance Change Function, C(t)

The purpose of the cognitive change function is to provide a quantitative representation of the reduction in cognitive skill level of each crewmember as it pertains to critical task performance and its potential to increase errors and mistakes. Here, cognitive performance is defined as the information processing ability of the human. It starts at the interface between the sensory systems to how that information gets translated into information into the brain and how the human reacts or behaves with that information.

$$\boldsymbol{C(t)} = \frac{\boldsymbol{C_R(t) + C_B(t) + C_E(t) + C_D(t) + C_T(t) + C_S(t) + C_L(t) + C_P(t) + C_V(t) + C_M(t)}}{\boldsymbol{10}} \qquad \textbf{Equation 2}$$

4.1.1.3 Psychological Performance Change Function, S(t)

The purpose of incorporating the psychological change function is to provide a quantitative representation of the changes in psychological well-being of the crew member. This could provide a strong indicator for psycho-social issues that could appear amongst the crew if not dealt with during the mission.

$$\boldsymbol{Y(t)} = \frac{\boldsymbol{Y_B(t) + Y_A(t) + Y_M(t)}}{\boldsymbol{3}} \qquad \textbf{Equation 3}$$

The set of three equations (Equation 1-3) sets the stage for a quantifiable measure for crew performance.

4.1.2 Characterizing Crew Accommodation and Utilization Metrics

The information provided by the crew performance metrics can now be applied to spacecraft design specific outputs, in this case, measures of crew accommodation and utilization. Metrics for accommodation ensure the crew's basic needs are provided for and their comfort considered, while metrics for utilization ensure the crew can complete a task without unnecessary hindrances, strain, or injury. Hence, a high crew accommodation measure means the crew has been well-accommodated in the system and similarly, a high crew utilization measure indicates the crew is effectively used by the system. Various scenarios for crew accommodation and utilization are laid out in Figure 22.

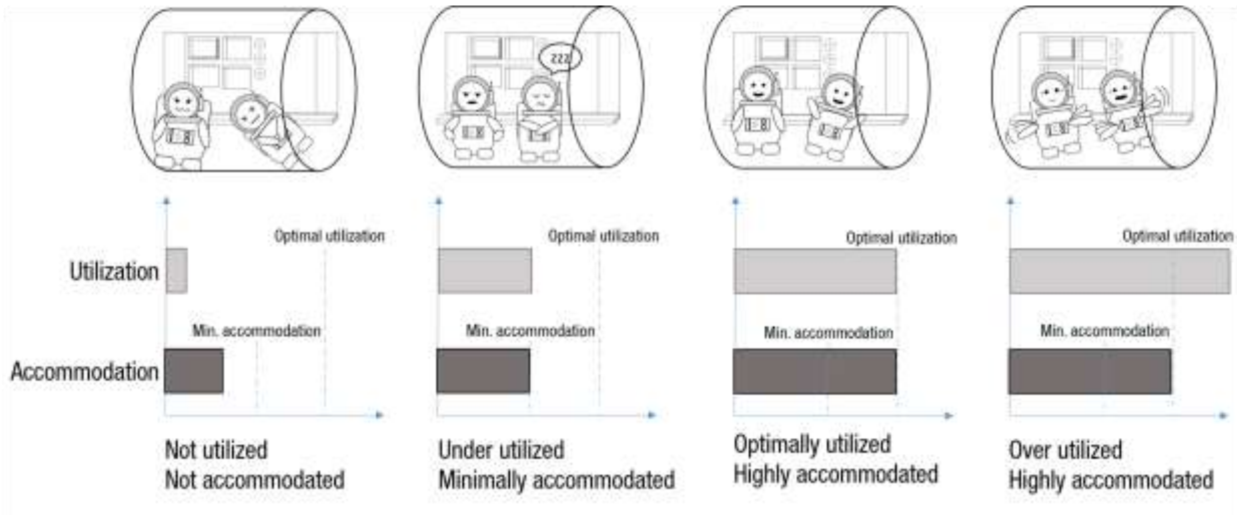


Figure 22. Various scenarios representing potential spacecraft deign accommodation and utilization measures.

Measures that describe whether crew are 'well-accommodated' or 'effectively utilized' can be refined further leveraging the definitions provided for accommodation and utilization. While the thresholds for optimal utilization and minimum accommodation of the crew sound like reasonable and intuitive boundaries, they are not easily defined or quantified without further investigation. To apply a methodical process, the first step is identifying what components of the spacecraft design that could impact the utilization or accommodation of the crew.

Measuring and monitoring the crew's performance is challenging due to the variability of human behavior as well as the large number of influences, which are often termed performance shaping factors (PSFs). The 57 PSFs have been characterized as pertaining to crew accommodation or utilization and aggregated into the Appendix A2. The tables provide a qualitative recognition of the different issues that arise between accommodation and utilization needs. While additional work is needed to thoroughly examine and scrutinize the components of each equation, this provides a starting point for bridging the gaps between the spacecraft design and its impact on crew performance.

These tables provide concise, useful examples as a reference for designers to better understand how a given design choice can impact crew performance at a qualitative level. For more interactive use, the tables can be incorporated into questionnaires when eliciting feedback from a prototype or mock-up as a way to parse the information between accommodation issues or utilization issues. Taking it a step further, the tables provide a starting point for translating spacecraft design choices into human performance impacts. The letters in parenthesis refer to specific crewmember resource elements that are impacted by the design choice. The list of elements that are impacted by each design choice, were identified by a subjective review using expert knowledge. To identify the impacts with a more objective approach would require a finer resolution of how the specific performance is impacted. An example of how a finer resolution could be done with a specific design example is shown below where symbols of "**(↓)**" or "**(↑)**" are used to indicate how it changes the baseline performance of the crewmember, indicating a reduction in this particular resource available to the crewmember or an in increase respectively. The general size of the arrow provides a comparative indicator for how much of the resource element is impacted the larger, the bigger the impact. No value in front of the variable indicates no change to the baseline.

Example of Noise Level Management and Design

Design Choice: Noise Level

Accommodate Issue(s): Too noisy causes hearing loss (P_H) or become highly irritating which affects your behavior, attitude and mood (Y_B, Y_A, Y_M)

Utilize Issue(s): Can't hear task feedback or critical alarms (C_D, C_S, C_V)

Note that lower values for physiological change, cognitive change, and psychological change are indicators of good design because there are fewer changes to the astronaut's original baseline state, which is considered at pre-flight.

Design Choice 1:

Noise level is high and can cause hearing damage in long-duration exposure.

$P(t) = P_B(t) + P_C(t) + P_D(t) + P_F(t) + (\downarrow)P_H(t) + P_R(t) + P_I(t) + P_M(t) + P_N(t) + P_P(t) + P_V(t) + P_E(t) + P_X(t)$

$C(t) = C_R(t) + C_B(t) + C_E(t) + (\downarrow)C_D(t) + C_T(t) + (\downarrow)C_S(t) + C_L(t) + C_P(t) + (\downarrow)C_V(t) + C_M(t)$

$Y(t) = (\downarrow)Y_B(t) + (\downarrow)Y_A(t) + (\downarrow)Y_M(t)$

There would be a large physiological impact to the crewmember's hearing, in which it reduces the ability of the astronaut to perceive alarms or irregular noises. With hearing damage, it is hard to imagine one's mood would be particularly improved.

Design Choice 2:

Noise Level below the damage threshold but not quite a library.

$P(t) = P_B(t) + P_C(t) + P_D(t) + P_F(t) + (\downarrow)P_H(t) + P_R(t) + P_I(t) + P_M(t) + P_N(t) + P_P(t) + P_V(t) + P_E(t) + P_X(t)$

$C(t) = C_R(t) + C_B(t) + C_E(t) + (\downarrow)C_D(t) + C_T(t) + (\downarrow)C_S(t) + C_L(t) + C_P(t) + (\downarrow)C_V(t) + C_M(t)$

$Y(t) = (\downarrow)Y_B(t) + (\downarrow)Y_A(t) + (\downarrow)Y_M(t)$

Having too much background noise, while not harmful, could impact the crew's ability to communicate with one another and also reduce the crew's attention and focus.

This is just one example of the application that can be derived using the tables to understand the impacts of the different design choices and their correlation to specific crew performance metrics.

These metrics are versatile and mutable depending on the stage of the design process. More resolution can be added into the equations as more design details are chosen. The complexity of the equations can be increased to provide relational data across the three performance categories, where for instance, components of psychology could influence changes in the astronaut's physiology. A number of potential quantification schema's can be generated, but this work ultimately focuses on presenting a possible framework in which to relate spacecraft design with crew performance.

4.2 Mapping Spacecraft Design and Crew Performance

As discussed in Chapter 2, the literature has identified performance shaping factors (PSFs) to describe which spacecraft design choices impact crew performance. These performance shaping factors were then grouped into three categories (A) Individual Specific PSFs (Mental and Physical Characteristics), (B) Group Specific PSFs (Team, Training and Organization), and (C) Design Specific PSFs (Physical Environment, Human System Interaction, Task Specific Characteristics).

Chapter 2 listed the set of fifty-seven vehicle design choices comprising category C. While the literature describes the impacts of these fifty-seven PSFs on crew performance, the studies are often not quantitative. Additionally, the quality of description can range anywhere from anecdotal information provided by astronauts, to analogous studies, or actual experimental data in space. Understanding this mapping will be the focal point for the remainder of this thesis.

In this section, the impact on crew performance is described for each spacecraft design choice. The ascribed references are chosen using a hierarchal classification for quality and consistency of the research, where an attempt was made at choosing primary data sources such as surveys or experimental data whenever possible. While some of the references are direct studies in space, others are chosen due to its similarity to spaceflight (especially the analogue studies for the psychological impacts). Additionally, it is noted that there are a few impacts listed that only have anecdotal references and would need additional data for support, in such cases, the impact is still identified and the reference source listed. The mapping of these impacts will continue to evolve as more research is done in space. This mapping is considered an organized means of identifying the relationship between the spacecraft design choices and their impacts to the crew.

The table Appendix 3 shows the mapping between the 57 PSFs and the 26 resource elements of an individual crewmember. (Note that the size of the table was too large to put in the body of this work, and therefore in consideration of the reading flow, the table is placed in the Appendix.) The identified impact is specific only to direct impacts as caused by the particular design choice. To understand an indirect impact, consider the case of elevated humidity levels. It could be anecdotally characterized that high humidity causes an indirect impact on crew abilities, such as in Florida when trying to work on the beach but the sand sticks to everything because of your sweat. However, this anecdotal impact is not highly significant in the astronaut's life. The sections below describe how each design choice impacts which resource element and identifies various literature sources that have found evidence for the correlations.

Ideally, each correlation is verified with a strong set of evidence from associated research, but because of the vast array of experiments needed, limited human spaceflight experiment times, and limited scope of this work, a thorough mapping could not be done. Instead this document notes the quality of the evidence cited, whether it has been drawn from a reputable peer-reviewed primary source or a published report from NASA, or from anecdotal references. The more convincing evidence that is discovered, the tighter the uncertainty bounds, while factors with less evidence that it impacts certain performance elements have larger uncertainty bounds. The following key is used for mapping the correlation strengths.

Documented Effect (D) -These are well documented relationships between elements with strong supporting evidence from peer-reviewed papers or NASA report.

Probable Effect (P) -These relationships are supported by a singular documented evidence report or by mixed data implicating a possible relationship.

Informal Effect (I) -No compelling evidence yet except from anecdotal or cursory acknowledgement. These effects are given an impact arbitrarily at this time of -0.001 with a -0.001 increase for increasingly negative impacts caused by the design. For example, anecdotally, noisy environments affect human mood negatively and therefore it is given an impact value of -0.001 for the Mood/Emotion resource, but an extremely noisy environment with potential for hearing damage will impact mood even more, thus the impact amount is set as a linear increase to -0.002. Many of these values have no set value and are not normalized against any particular data set, but are rather act as a starting point for indicating a perceived effect of specific design choices on crew performance. More experiments are needed to populate the database of effects and quantify the impact of each design choice on crewmember performance. But in lieu of not having the data, these arbitrary indicators lay the groundwork for demonstrating intuitive relationships between design and human performance metrics.

There are also design choices that would cause complete loss of a particular resource element and those are documented in the mapping table as -100 as a 100% degradation of that particular resource element. For example, a large noise level can cause permanent hearing damage, in which the hearing resource element is marked as degraded by 100%, but no other resource element would be affected (though anecdotally there would be some notable decrements in crewmember behaviour, attitude, and mood). Additionally, a design choice can be fatal to the crewmember and those are represented as an entire row of -100 in which the crewmember loses all resource elements because the design choice caused a fatality.

A "0" value listed in the mapping indicates that there was no literature found to show evidence of a relationship between that particular design choice and the performance element. This does not mean that a relationship does not exist or that there is no impact, but rather that it was not found in the course of this work. Having a "0" impact means it does not affect the baseline performance of the crewmember. A whole row of "0" for a spacecraft design choice indicates that the particular spacecraft design choices is equivalent to a normal work/living environment that the crewmember would normally encounter on earth.

The criteria for identifying correlations between spacecraft design choices began with NASA's Human Integration Design Handbook (NASA, 2014) in which the document systematically outlines spacecraft design choices and their impacts on specific human performance metrics. Once identified which human performance metrics are impacted further evidence was sought for each correlation.

Oftentimes the metrics used in various studies do not align perfectly with the performance metrics identified here, and in such cases, interpretation of the information is provided to fit the most closely associated metric. The mapping identifies the systems that are affected due to the extremes of the design. For example, extreme noise levels are either complete silence or extreme loudness.

The next sections provide detailed descriptions of the values put in place for each spacecraft design and the impact each choice has on the listed performance metrics. At this stage, the majority of the data consists of Informal Effects (I) due to the limited data. Where appropriate, citations are listed to validate specific impacts that have been documented.

4.2.1 *Vehicle Physical Environment*

The design of the spacecraft's physical environment can be configured in infinite ways, but constraints from the external space environment, government budgets, and schedules confine the design space into more finite choices. In addition, NASA has strict guidelines as to what should be permissible for ensuring healthy crew members and much of what is required now was learned from over 50 years of human spaceflight data. The recommendations and requirements are listed in a handful of documents and reports including NASA's Spaceflight Standard 3001 Vol 2 and NASA's Human Integration Design Handbook (NASA, 2011; NASA 2014).

4.2.1.1 Noise Level

Noise occurs in the spacecraft cabin due to various mechanical devices from fans to motors to propulsive manoeuvres. Several studies have documented the dangers of high-noise levels and its impacts from more severe hearing damage to annoyance and perturbation of sleep. These studies are identified and map to specific human resource elements. Noise comes in a variety of forms from loud startling sounds to high frequency pitches to irritating disharmony or in more positive forms as music and harmonious tones, or for denoting important information as warnings and alarms. Repko et al. (1974) suggested that there are "three relevant variables involved in determining the effects of noise on performance: a) length of the work period, b) characteristics of the noise, and c) type of task employed."

Four levels of noise have been defined as:

1) Quiet (normal baseline) minimal sound conditions
2) Meeting NASA-STD-3001 noise level requirements
3) Exceeding NASA-STD-3001 to damaging of auditory organs
4) Fatal in which the pressure levels can cause death

Acoustic silence was not considered here due to the impractical nature.

The following human resource elements that are impacted by these design choices are listed below grouped by the respective crew resource element (physiology, cognitive, psychology).

Physiological Impacts: ***Hearing***: *Documented*. Roller and Clark (2003) reviewed hearing loss and impacts to Space Shuttle crew members and concluded that the space shuttle environment was perceptibly loud for the crews and did have both short and long term hearing sensitivity shifts. In general, there is clear causality between loud noises and hearing loss, known as noise-induced hearing loss (NIHL). There have been several cases that document hearing loss as a result of noise. A review by Sliwinska-Kowalska and Davis (2012) review publications from 2008-2011 that document NIHL in various industries. NIHL a well-known issue where thresholds for noise limitations have been set by the U.S. Department of Health and Human Services to mitigate exposure of workers to damaging noise (NIH, 2015).

Cognitive Impacts: ***Abstract Reasoning, Abstraction, Emotion Identification, and Vigilant Attention***: *Probable.*

Noisy environments have been shown to decrease worker attentiveness (Hancock and Pierce, 1985). Even at levels defined in NASA's design documentation and previously operating Space Shuttle, there were recorded instances of crewmember headaches, "constant gritting of teeth and furrowing of brow, and indicated that noise was very difficult to deal with all day and night." (Goodman, 2003)

Psychological Impacts: ***Behaviour, Attitude, Mood/Emotion:*** *Documented.* Annoyance due to noise has been indicated in surveys of the STS-50 crew (Koros et al., 1992, Koros, 1993) Noisy environments also make it difficult to engage in conversation thus reducing social interaction, and in cases where clear communication is required between crewmembers or ground control potentially resulting in dangerous situations.

4.2.1.2 Vibration Level

Vibration can be caused by various spacecraft manoeuvres the most notable are launch and landing loads. Vibration can be generated by machinery on-board the spacecraft as well causing constant vibration or sporadic bursts from time to time which can affect the astronauts in different ways depending on its amplitude, and timing.

Physiological Impacts: *Bone Strength, Cardiovascular System, Fine Motor Control, Vision:* *Documented*. Bones are sensitive to vibration but this is dependent on the acoustic properties of the vibration. In some cases, low dose vibration at a low frequency have been shown to help prevent bone degradation and have been offered as therapy for osteoporosis patients (Weber-Rajek et al., 2015) Whole-body vibration for 3 months has been shown to reduce arterial stiffness for middle-aged to older adults (Lai, 2015). It has been suggested as an alternative for exercise in reducing cardiovascular disease. Alternatively, too high of a vibration load induces injury. Vibrating environments can also be a deterrent for fine motor control -affecting individuals' ability to select controls and buttons, and it can also cause vision degradation and therefore needs to be appropriately controlled to ensure visual capability is maintained during spaceflight (NASA, 2011).

4.2.1.3 Humidity Level

Humidity is the amount of water vapor in the air. Lower humidity environments can cause drying of mucous membranes and skin causing irritation while high humidity environments can impact heat transfer in which evaporative cooling becomes less effective. The current method for regulating humidity on the Space Station is via condensers in the atmosphere revitalization system, where cabin air is flowed over a cold plate

Cardiovascular System: High humidity or low humidity environments affects the amount of evaporation that occurs on the skin allowing for temperature regulation. Elevated humidity increases the heat dissipation rate and causes the cardiovascular system to work harder to remove heat. (NASA, 2011; NASA, 2014d)

Happiness: Humid environments impact comfort levels of the crew -where either high or low humidity could create uncomfortable working and living spaces (NASA, 2014).

4.2.1.4 CO2 Level

High carbon dioxide (CO2) levels are lethal to humans and must be removed from the cabin environment. But the removal rate and the total composition in the atmosphere can be regulated as deemed by the designer. There are certain trade-offs that are important to consider with CO2 which involves the effects elevated CO2 have on humans alternatively, systems that scrub CO2 quickly and efficiently are often costlier and require more mass, volume, and power. This particular factor has a time constraint tied to it as well.

Bone Strength: DOCUMENTED There is evidence linking elevated carbon dioxide levels to respiratory acidosis which directly impacts the amount of Calcium stored in the bone and blood resulting in more bone resorption and decreases in bone formation (Holy et al., 2011; Drummer et al, 1998; Rice, 2004)

Cardiovascular System: Elevated CO2 levels cause increase in respiratory rates in an effort to remove CO2 which lead to elevated heart rates.

Cognitive Impacts: ***Abstract Reasoning, Abstraction, Risk Decision Making: Scanning & Visual Tracking, Sensory-Motor Speed, Spatial Learning & Memory, Spatial Orientation,***

Vigilant Attention, Working Memory: *Documented.* Impacts to cognition due to carbon dioxide has been documented in various studies. With elevated levels of CO_2, cognition slows causing delayed reactions, poor decision-making, and memory loss.

Motivation: High CO_2 levels have been shown to reduce initiative (Satish et al., 2012). Additionally, on ISS Expedition 6, there were reported cases of "lethargy, malaise, listlessness, and fatigue when $ppCO_2$ rose above 4 mmHg," and the symptoms subsided within minutes of reducing the $ppCO_2$ to 2 mmHg (Law et al., 2010).

4.2.1.10 Air Flow

Physiological Impacts: *Cardiovascular System, VO2 Max:* *Probable.* Air flow rate is required at a certain amount to move CO_2 from building up.

Psychological Impacts: *Mood/Emotion:* *Documented.* Evidence shows that individuals are sensitive to airflow where high airflow causes discomfort amongst the participants (Toftum, 2002).

4.2.2 Vehicle Architecture

4.2.2.1 Arrangement of Functional Areas

The vehicle's functional areas can be arranged in a variety of configurations. Three configuration possibilities were defined as:

1) Easy flow of motion and dynamically reconfigurable
2) Moderately reconfigurable
3) Fixed, with large obstructions

Psychological Impacts: *Attitude, Mood/Emotion:* *Informal*. Due to the lack of data, the only impacts that are captured here are specific to the crewmember attitude and mood/emotion. Based on the rationale for impacts on office personnel when encountered with similar functional set-up the informal impact of crewmembers psychological well-being is easily relatable. Without thorough study, the impact values are arbitrarily set as -0.001 for the moderately configurable set-up and -0.002 for the fixed set-up.

4.2.2.2 Presence of Location Aids

Three design choices for location aid placement in the spacecraft include:

1) Available and appropriately located
2) Limited location aids
3) None

Cognitive Impacts: ***Spatial Learning and Memory, Spatial Orientation****: Probable*. Location aids have been noted by astronauts to help with their orientation and spatial location. These are anecdotal stories of astronauts using visual clues to recognize directionality of the particular module of the ISS.

Psychological Impacts: ***Behavior, Attitude, Mood/Emotion:*** *Informal.* While not formally documented, the aspect of having none to a few location aids throughout the spacecraft would be an annoyance for astronauts and could be considered a future hazard. Not knowing the orientation of a particular module could cause disorientation and lead to lack of spatial awareness. But also the constant re-framing of location and directionality using other visual cues from the structure of the habitat may cause confusion as well as additional visual burden. These little annoyances can add up to impact the crewmember's psychological well-being and therefore documented here as providing a level of degradation.

4.2.2.3 Availability of Hatches

Three design choices for the number of hatches available in a spacecraft have been identified here as:

1) Available in all emergency situations
2) Available for highest probability emergencies
3) Available for ingress/egress

Psychological Impacts: ***Attitude:*** *Informal.* The availability of hatches does not immediately impact the day-to-day activities of the crewmember and therefore does not have the direct impacts to performance. What it does change is the crewmember's attitude regarding the quality design of the spacecraft and their feeling of safety. Informal rationalization infers that crewmembers who know that there are few emergency exits may exhibit a more cautious attitude. This informal impact assumes an arbitrary attitude degradation over time of -0.001.

4.2.2.4 Anthropometric Accommodations

Anthropometric measures have been taken for a large range of participants since the early 1940's when the US military began using the measures to design better airplanes. In a spacecraft, the anthropometrics can change due to the 0-g environment and often make measurements much more difficult. Regardless, the ability to design for anthropometric bounds of the crewmember is important for overall crew health and performance. The design choices specific to anthropometric accommodations describe how well the spacecraft has been designed to meet the crew's body size and biomechanics. The choices are as follows:

1) Appropriately accommodated
2) Minimally accommodated
3) Not accommodated

Physiological Impacts: *Bone Strength, Cardiovascular System, Fine Motor Control, Muscle Strength, Proprioceptive Posture:* *Documented*. The Risk Analysis Report for Incompatible Vehicle Design documents cases where poor anthropometric accommodations have resulted in numerous injuries from minor to more serious (Whitmore, 2013). These are well-documented incidents, but the impact is harder to capture for this framework. Therefore, the impact values have been set at the arbitrary -0.001 for the minimal accommodation selection and -0.002 for no accommodation.

Cognitive Impacts: *Risk Decision Making, Sensory-Motor Speed:* *Probable.* With limited accommodation to anthropometrics, it causes cognitive impact in the form of reduced sensory-motor speed and can affect general risk decision making of the crewmember if they know that certain activities could increase injuries.

Psychological Impacts: *Behavior, Attitude, Mood/Emotion:* *Probable.* Also documented in NASA's Evidence Risk reports is the increased crew frustration due to poorly accommodating spacecraft and especially one that does not mitigate for crew injuries. Crewmember behaviour, attitude, and mood would be impacted because of the poor spacecraft design, but because the data has not been recorded as direct measures, the impact is set at the arbitrary value of -0.001.

4.2.2.5 Access to Work Items

Having easier access to work items allows for much smoother task activities and operations, and in cases of emergencies or contingencies can result in a much more efficient dealing of the situation. Three design choices are listed as:

1) Easy access and appropriate location of work items
2) Mostly accessible work items
3) Obstructed access to work items

Psychological Impacts: *Behavior, Attitude, Mood/Emotion:* *Informal*. The lack of access to work items can be both frustrating and in certain cases dangerous. While the lack of access does not immediately degrade physiological or cognitive resources, it does present a psychological impact. The rationalization of the impact is in the frustration and annoyance that it causes therefore the arbitrary impact values are set.

4.2.2.6 Support of Traffic Flow, Translation Paths

Having efficient traffic flow and translation paths for the astronauts are important for both work efficiency, but also in the case of emergency where astronauts need to get around the spacecraft with agility and speed. Items that support traffic flow include handrails or flat surfaces that astronauts can use to push themselves along corridors. Additionally, the general layout of the spacecraft is part of this consideration where the paths between modules are not blocked. The three design choices are listed as:

1) Acceptable support for traffic flow
2) Minimal support for traffic flow
3) No support for traffic flow

Psychological Impact: *Behavior, Attitude, Mood/Emotion*. *Informal*. As with the arrangement of the functional areas, the rationalization for crew psychological impacts is guided by understanding of the office space. Specific configurations could reduce frustrations and annoyance for poorly located handrails.

4.2.2.7 Availability of Windows

Windows provide visual access to the surrounding environment. They can be a useful tool for improving situational awareness, or as an area of enjoyment where astronauts can gaze out into the darkness of space and watch the rotation of the earth, stars, and sun. The four choices available for window selection include:

1) Several available
2) Moderate number of windows
3) Minimal, small windows
4) None

Psychological Impacts: *Behavior, Attitude, Mood/Emotion.* *Probable.* While there are no directly measured physiological or cognitive impacts due to the lack of windows, the crew psychological well-being is impacted. With the installation of the ISS's Cupola, several astronauts of have anecdotally mentioned how much they enjoyed staring out the window and watching the earth pass below. Though no direct measurement of changes in mood have been recorded, it can be assumed some degradation in psychological well-being occurs when windows are limited.

4.2.2.8 Safety Accommodations

Various designs can be considered to provide safety accommodation. In this case, the general accommodation is considered aspects within the spacecraft pressurized volume such as fire extinguishers, emergency lighting, soft covers for sharp corners or bump hazards. The four choices available include:

1) Several safety provisions (for hazards >25% probability)
2) Moderate number of safety provisions (for hazards >75% probability)
3) Minimal number of safety provisions (for hazards >90% probability)
4) None

Psychological Impacts: *Behavior, Attitude:* *Informal.* While no physiological or cognitive impairments would be impacted by the lack of safety equipment unless during an emergency situation, the psychological impact can be large. Knowing that no safety equipment exists can cause crew members to be much more cautious with their work and also behave in more reserved manner in case an incident occurs.

4.2.3 Habitability

4.2.3.1 Microorganism Virulence

The choices for microorganism virulence include:

1) Acceptable level
2) Sometimes exceeds acceptable level
3) Lethal

Physiological Impacts: *Digestion, Immune System:* *Documented.* As with an ailing patient on earth, the impacts of an illness directly affect the person's digestion as well as their immune system. This is no different in a space environment, and in some cases, could potentially be much worse.

Psychological Impacts: *Behavior, Mood/Emotion:* *Probable.* When a crewmember is sick due to microorganisms like bacteria or virus, it can cause a direct impact on their psychological outlook. Often when sick as is apparent to patients on earth, behavior and mood/emotion is affected.

4.2.3.2 Inventory Management Capability

Having a well-organized and easily understandable storage capability allows for improved workflow, safety, and overall comfort in the space. Knowing where things are stored in a clear manner ensures the ability to access the item and having a clear knowledge of what is onboard the spacecraft. The three design choices are:

1) Clear, intuitive, well-marked, standard inventory management

2) Some inventory management available (not for all items)

3) None

Psychological Impacts: ***Behavior, Attitude, Mood/Emotion:*** *Informal.* Without good inventory management, finding work items and storage become a nightmare. Not knowing where particular hardware is located can cause frustration, annoyance, and in emergency cases could cause potential fatality if for instance the defibrillator was needed but not located due to poor storage and tracking of equipment.

4.2.3.3 Habitable Volume

Choices for habitable volume include:

1) Ample space

2) Suitable space

3) Minimal space

4) Too small (human cannot fit)

Physiological Impacts: ***Bone Strength, Cardiovascular System, Muscle Strength, Proprioceptive Posture, Vision:*** *Documented*. The issue with limited habitable volume is the ability to bring onboard good exercise equipment much less to have space to use it. The limited exercise is what is tracked as the degradation due to limited space availability.

Psychological Impacts: ***Behavior, Attitude, Mood/Emotion:*** *Probable.* With limited habitable volume psychological well-being is degraded. While the amount of impact to behaviour, attitude, or mood is not well quantified, it has been anecdotally mentioned as a cause for crew frustration and annoyance.

4.2.3.4 Confinement

The space environment is extremely hazardous and therefore astronauts are often confined to the spacecraft as the only habitable area. To help with confinement issues, the idea is to allow astronauts more exploration via the use of their extravehicular mobility unit (EMU) or in future scenarios the use of rovers. Therefore, the choices for confinement selection include:

1) Can do as many EVA's for enjoyment not just work
2) Can do some EVA's for enjoyment not just work
3) Minimum EVA, only as needed
4) Total confinement (no leaving spacecraft)

Psychological Impact: *Behavior, Attitude, Mood/Emotion:* *Informal*. While anecdotally there are diaries of polar explorers who have been confined into their tents or cabins during particularly stormy days and they describe boredom, lacklustre behaviour, and general depression. The same can be expected with confined crewmembers aboard the spacecraft. It must be noted though that intuitively, there is an understanding that this is also highly dependent on the habitable volume. If there is ample space for astronauts to wander or explore there may not be an impact at all to the crew's psychological well-being.

4.2.3.5 Level of Sensory Stimulation

Sensory stimulation is important for maintaining crewmember well-being, and can come in forms of varied noises, scents, imagery, or even textures and touch. These are generally harder to supply onboard a spacecraft but can be a benefit to crews in space for long periods of time. The design choices include:

1) High sensory stimulation
2) Medium sensory stimulation

3) Low sensory stimulation

4) None

Psychological Impact: *Behavior, Attitude, Mood/Emotion:* *Informal.* As mentioned above, the psychological well-being is greatly impacted by not having sensory stimulus. But this is also more important for long duration flights and not as evident for a short duration tourism type.

The complete mapping between the listed spacecraft design values and each crewmember resource element is listed in Appendix Appendix A3. Spacecraft Design Choices to Crew Performance Impact Mapping.

4.3 Mapping Activities to Crew Performance Resource Elements

The next consideration is to understand the mapping between the activities and how each one impacts the various crewmember resource elements. The value in each cell represents the influence of the particular activity on the crewmember's performance resource element. The values are ranked as whole numbers, where the larger the absolute value is the more impact that activity has on that particular resource element. Negative values represent the reduction or use of that particular resource element for that activity. Positive values represent the restoration of that resource element as a result of the activity.

Table 18. Mapping between activites and crewmember performance resource elements.

Activity to Crew Performance Impact Mapping	Physiological													Cognitive										Psychological		
	PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Breathing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drinking	1	1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Eating	1	1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Exercise	-2	-2	0	0	0	0	0	-2	-1	-1	0	0	-2	0	0	0	0	0	0	0	0	0	0	1	1	1
Hygiene Activities	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Leisure Activities	0	0	0	-1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Sleeping	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Contingency Operations	0	-1	0	-1	-1	0	0	0	-1	-1	0	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	-1	0	-1
Emergency Operations	0	-2	0	-2	-2	0	0	0	-2	-1	0	-2	-2	-2	-2	0	-2	-2	-2	-2	-2	-2	-2	-1	0	-1
Flight Control	0	0	0	-2	-2	0	0	0	-2	-1	-2	-2	0	-1	-1	0	-1	-2	-2	-2	-2	-2	-2	1	1	1
Mission Planning & Scheduling	0	0	0	0	0	0	0	0	-2	0	0	-1	0	-2	-2	-2	-2	-1	0	-1	-1	-1	-2	-1	-1	-1
Robotic/Habitat Operations	0	0	0	-2	-2	0	0	0	-2	-1	0	-2	0	-1	-1	0	-1	-2	-2	-2	-2	-2	-2	1	1	1
Systems Monitoring	0	0	0	0	0	0	0	0	-2	0	0	-2	0	0	-2	-1	0	-2	0	0	0	-2	-2	-1	0	-1
Spacecraft Navigation	0	0	0	-2	-1	0	0	0	-2	0	0	-2	0	-2	-2	0	-2	-2	-1	-2	-2	-2	-2	-1	-1	-1
Execute Experiments	0	0	0	-2	0	0	0	0	-2	-1	0	-2	0	-2	-2	0	0	-1	-1	-2	-2	-2	-2	1	1	1
Manage Science Experiments	0	0	0	0	0	0	0	0	-2	0	0	-1	0	-2	-2	-1	-2	-1	0	-1	-1	-1	-2	-1	-1	-1
Cleaning Spacecraft	0	0	0	-1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1
Maintain Operational Hardware	0	0	0	-2	0	0	0	0	0	-1	0	-1	0	0	0	0	0	-1	0	-2	-1	0	-1	-1	0	-1
Maintain Science Hardware	0	0	0	-2	0	0	0	0	0	-1	0	-1	0	0	0	0	0	-1	0	-2	-1	0	-1	-1	0	-1
Repair Operational Hardware	0	0	0	-2	0	0	0	0	-1	-1	0	-1	0	-2	-2	0	-1	-2	0	-2	-2	-1	-2	-1	-1	-1
Repair Science Hardware	0	0	0	-2	0	0	0	0	-1	-1	0	-1	0	-2	-2	0	-1	-2	0	-2	-2	-1	-2	-1	-1	-1

This table mapping activity to crew performance impact is used in conjunction with the level of difficulty of the task due to the vehicle design to describe a weighted impact that each activity has on the crewmember. To find the level of difficulty of the task as induced by the vehicle design, another mapping table is used called the "Spacecraft Design Choice Affecting Activity Difficulty". Due to the nature of its size, the table is listed in Appendix A3. The difficulty rating due to the vehicle design choice can be a value of 1, 2, 3, or 4300, where 1 means the design does not change the activity difficulty, 2, and 3 increase the difficulty by 2 or 3-fold respectively. The values are summed up and then divided by the number of design parameters (in this case 43 vehicle specific parameters) to provide an overall difficulty increase of the particular design selection. In the case of 4300, even if it shows up once in a specific design parameter, that means the difficulty value increases at least 100x, which is captured as reducing that particular resource element by 100 units which can be translated as the design causing an inability to do that task (or fatality in some cases). The difficulty ratings are summed from each spacecraft design selection and then divided by the number of choices. In this case there are only 43 design choices because this only includes vehicle design choices and does not include vehicle environment impacts as those are captured as part of the vehicle environment induced impact. This difficulty rating is then multiplied element-wise onto each of the activity impact mappings listed in Table 18. For an optimal vehicle design the difficulty weighting factor is 1, therefore the activity impact mappings do not change. The design impacts on the activity is a complex interaction that can be modelled in a non-linear fashion, but because of the lack of data regarding these impacts, this linear relationship is sufficient to capture some level of interaction between these two components, and the addition of non-linear relationships is left for future work.

4.4 Mathematical Modelling Theory

With the qualitative mapping discussed, the mathematics can be laid out. This is accomplished by developing the theory through rate equations. Mathematically speaking, the model has two main components that affect crew performance, the design selection impact to the crew, and the task impact. These two components comprise individual crewmember performances and in terms of rates, their impacts can be written in a mathematical expression as follows:

$$\frac{d\boldsymbol{P_i}}{d\boldsymbol{t}} = \boldsymbol{D_i}(\boldsymbol{s},\boldsymbol{t}) + \boldsymbol{T_i}(\boldsymbol{s},\boldsymbol{t}) \quad \textbf{Equation 4}$$

Where P_i are the specific crewmember performance resource elements as indicated by the subscript i (e.g. bone strength, cardiovascular system, digestion, etc.), D_i is the design selection impact to the crewmember on that specific resource element, i, and T_i is the impact to that resource element due to the activities that the crewmember must perform. In this form both D and T are functions of the specific design selection, s, and time, t. To start with a basic mathematical model for the framework, the design selection impact, *D*, and the task-related impact, *T*, are assumed to be linearly independent and therefore summed together for a simple implementation.

For practical purposes, the design choices are limited to a finite number of choices, N. Assuming linearity in the vector 's' which represents some random design selection, the equation can be re-written in the following form:

$$\frac{dP_i}{dt} = \sum_{j=1}^{N}(D_i(s_j,t) + T_i(s_j,t)) \quad \textbf{Equation 5}$$

To find total performance impact an integration over time can be performed:

$$P_i(t) = \int_{t_0}^{t}\sum_{j=1}^{N}(D_i(s_j,t) + T_i(s_j,t))\mathrm{d}(t) \quad \textbf{Equation 6}$$

Or the equation can be written in discrete form as:

$$P_i(t) = \sum_{t_0}^{t}\sum_{j=1}^{N}(D_i(s_j,t) + T_i(s_j,t)) \quad \textbf{Equation 7}$$

The Design Selection Impact to the crewmembers can be split into two corresponding factors – those caused by the vehicle environment and those specific to functional architecture that the crewmember directly interacts with, which can be written as the following:

$$D(s_j,t) = \overline{D}(s_j) + g(t) \quad \textbf{Equation 8}$$

The $\overline{D}(s_j,t)$ represents the average expected decay rate for the given design selection and correspond to the "Design to Crewmember Performance Mapping" discussed later. The $g(t)$ function describes the crewmember performance resource decay rate due to the vehicle environment. These $g(t)$ functions are known for a few select cases and are captured in the "Vehicle Environment Time Vector" discussed later on. In instances where they are not known, a simple baseline decay rate can be assumed, i.e. a certain percentage decay per month.

To simplify the task impacts on crewmember performance, the task mapping can be split between two components as follows:

$$\boldsymbol{T}(\boldsymbol{s_j}, \boldsymbol{t}) = \boldsymbol{f}(\boldsymbol{t})\overline{\boldsymbol{T}}(\boldsymbol{s_j})$$ **Equation 9**

The $\overline{T}(s_j)$ represents the average expected decay rate for the given task activity list as dictated by the design selection (the "Activity to Crewmember Performance Mapping") and the f(t) function describes whether the task is active or not and is given by a pulse input function.

These pulses are characterized by a high value of 1 or greater, representing the task being actively conducted in which the particular resource elements specific to that activity are depleted or gained. The value from this pulse function, f(t), is multiplied by the impact of the activity to resource elements (fine motor control, abstract reasoning, etc.), therefore, a positive pulse reflects the direct impact of the activity to the resource element. The resource elements depleted (represented by a negative amount) or gained (represented by a positive amount) are documented in the "Activity-to-Crew Performance Mapping" shown in Table 18. When an activity is occurring, the pulse function causes a moment of depletion or gain of resources. But after the activity is completed, a rebound occurs to reset the level of resources depleted or gained. To reflect the reality of the situation, the rebound does not fully recover the resources in this case the rebound provides 99.9% recovery. An intuitive example is to imagine a scenario of exercise, where the athlete does not fully recover from the exercise after the activity, but rather through sleep and eating a nutrient-rich meal. As an initial assumption, this rebound value is chosen to match the same magnitude of impact caused by the design (about 0.001 units of resource element change) and it represents the total residual decay (or regeneration) of astronaut post task completion. The assumption is that the impact of the design on the crewmember's performance is about the same magnitude as the impact of the activities that they must perform.

4.5 PRACTICAL IMPLEMENTATION OF MATHEMATICAL MODEL

The crewmember performance resource element values (P_i) are expressed in a mathematical model which nominally takes the form of baseline plus time degradation plus tasking as shown in the equation below.

$$\boldsymbol{P_i(t) = 100 + \sum_{t_0}^{t} \sum_{j=1}^{N} (\overline{D_\iota}(s_j) + g(t) + f(t)\overline{T}_\iota(s_j))} \qquad \textbf{Equation 10}$$

The integrated time impact is a summation of the task function induced time impact and the environmental time decay. This approximate form assumes that the design choices are linear with respect to the performance factors such that their impact can be individually added to get a total crew performance loss per design and per task function. The environment induced impact is assumed to be independent of design choice and only reliant upon the environmental gravity selections. To convert this in a more practical and implementable arrangement, the following matrix layout is defined:

$$\begin{bmatrix} \textbf{\textit{Crew Performance}} \\ \textbf{\textit{Metrics}}, \boldsymbol{P(t)} \\ \\ (\mathbf{26}\ \boldsymbol{x}\ \mathbf{1}) \end{bmatrix} = \begin{pmatrix} \textbf{\textit{Initial Crewmember}} \\ \textbf{\textit{Performance Resource Element}} \\ \textbf{\textit{Baseline}}\ (\mathbf{100\%}) \\ \\ (\mathbf{26}\boldsymbol{x}\mathbf{1}) \end{pmatrix} -$$

$$\left(\begin{bmatrix} \textbf{\textit{Design Selection}} \\ (\mathbf{1}\ \boldsymbol{x}\ \mathbf{172}) \end{bmatrix} \begin{bmatrix} \textbf{\textit{Design to Crewmember}} \\ \textbf{\textit{Performance Mapping}} \\ \\ (\mathbf{172}\ \boldsymbol{x}\ \mathbf{26}) \\ \\ \end{bmatrix} \right)^{\boldsymbol{T}} + \left(\sum_{t_0}^{t_f} \begin{bmatrix} \textbf{\textit{Vehicle Environment}} \\ \textbf{\textit{Time Vector}}, \boldsymbol{g(t)} \\ (\mathbf{1}\ \boldsymbol{x}\ \boldsymbol{N}) \end{bmatrix} \right)^{\boldsymbol{T}} +$$

$$\left(\sum_{t_0}^{t_f} \begin{bmatrix} \textbf{\textit{Task Time}} \\ \textbf{\textit{Vector}}, \boldsymbol{f(t)} \\ (\mathbf{1}\ \boldsymbol{x}\ \boldsymbol{N}) \end{bmatrix} \begin{bmatrix} \textbf{\textit{Activity to Crewmemeber}} \\ \textbf{\textit{Performance Mapping}} \\ \\ (\boldsymbol{N}\ \boldsymbol{x}\ \mathbf{26}) \\ \\ \end{bmatrix} \right)^{\boldsymbol{T}}$$

Equation 11

The matrix sizes are based on pre-defined mappings between the design choice selections or activities and their impacts on the specific crew performance resource elements. The pre-defined mappings can be found in Appendix B. A visual representation of the flow of information is shown in Figure 23.

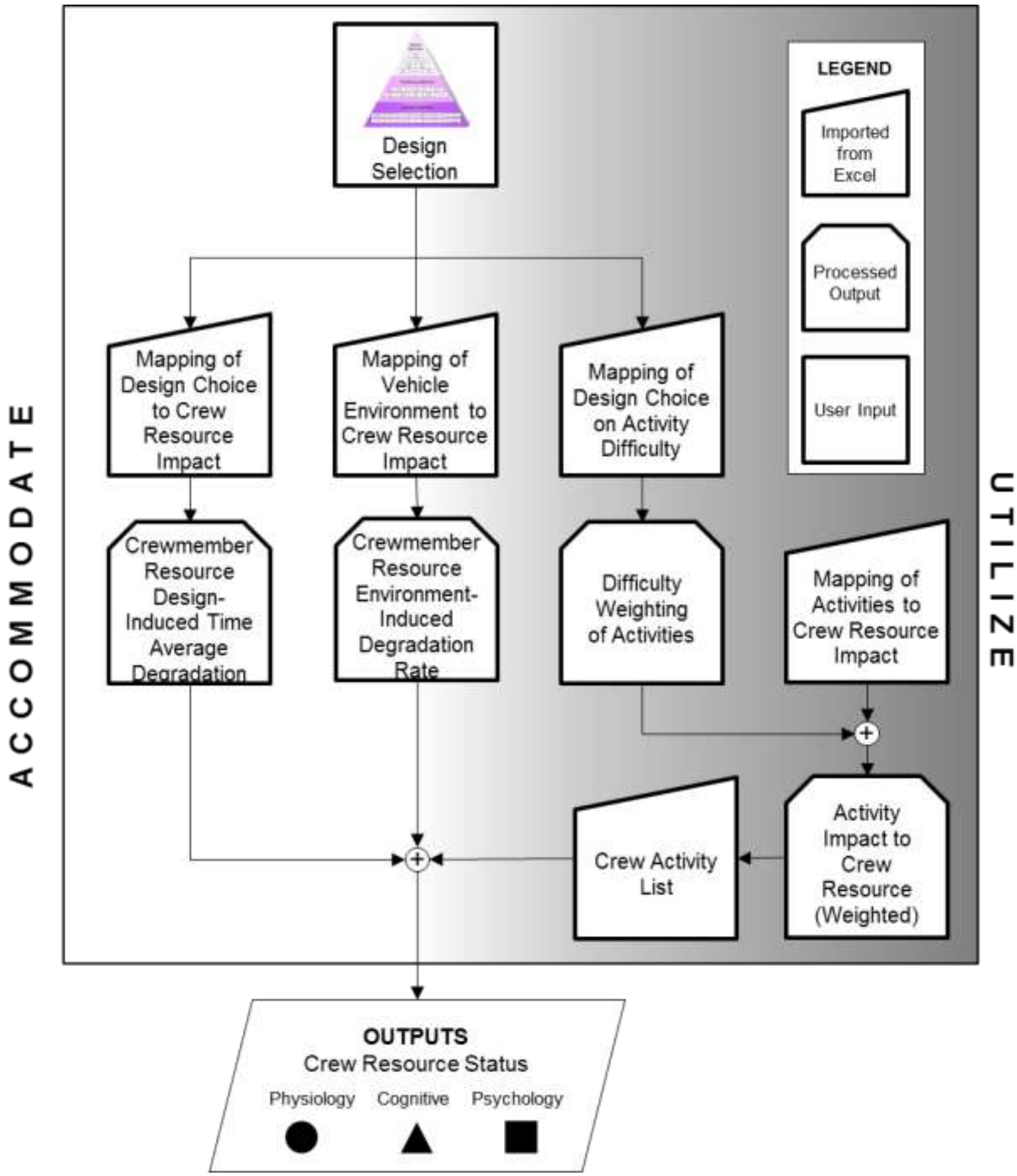


Figure 23. Visual representation of mathematical information flow.

4.5.1 ENVIRONMENT-INDUCED IMPACTS

An environment induced impact is included in this model. While these impacts are design selection specific, a limited amount of data is available for specific cases. In cases where no data is present, the impact is assumed to be either a linear decay or a zero decay.

When humans are exposed to the zero gravity environment in space, a change over time occurs. This time dependent impact rate has been studied and empirical trends presented in NASA's Human Integration Degradation Handbook (NASA, 2014) summarizing the time dependence. These environment-induced impacts are summarized in Figure 24 shown below.

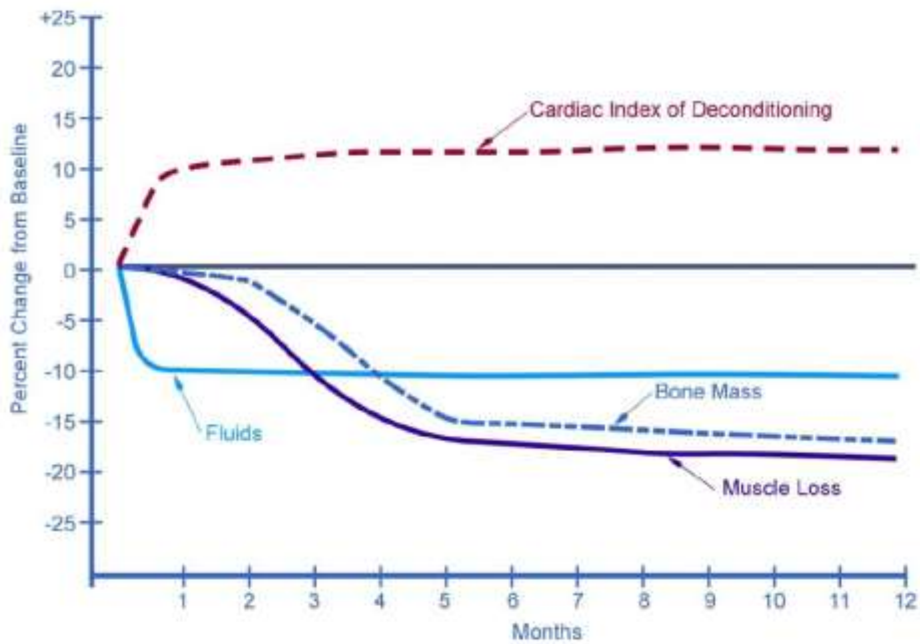


Figure 24. Percent change from baseline of key physiological metrics.

From the relation presented, an empirical function can be fit to determine the time dependant values for utilization in the model. This is accomplished by extracting the data from the graph using the JAVA program Data Thief (B. Tummers, DataThief III. 2006 http://datathief.org/). From the plot it is apparent that these trend lines are sigmoidal in shape. The curves are assumed to fit a common sigmoidal function, the error function. To allow for greater degree of freedom in fitting, the following equation form is assumed and the coefficients determined through a least squares minimization.

$$\boldsymbol{P_n = b_{1,n} + b_{2,n} erf((t - b_{3,n})/b_{4,n}) + b_{5,n} erf((t - b_{6,n})/b_{7,n})} \qquad \textbf{Equation 12}$$

Using this approach, the following relations are determined for the environment induced impacts of the cardiac function, bone mass, and muscle performance factors in the zero gravity in equations 10 through 12 respectively (note the variable *x* used in the Matlab regression equation is replaced with a *t* to denote the time factor):

$$\boldsymbol{3.666537 + 5.665088 * erf((t - 0.164422)/0.268212) + 2.469145 * erf((t - 0.348657)/3.991582)}$$

Equation 13

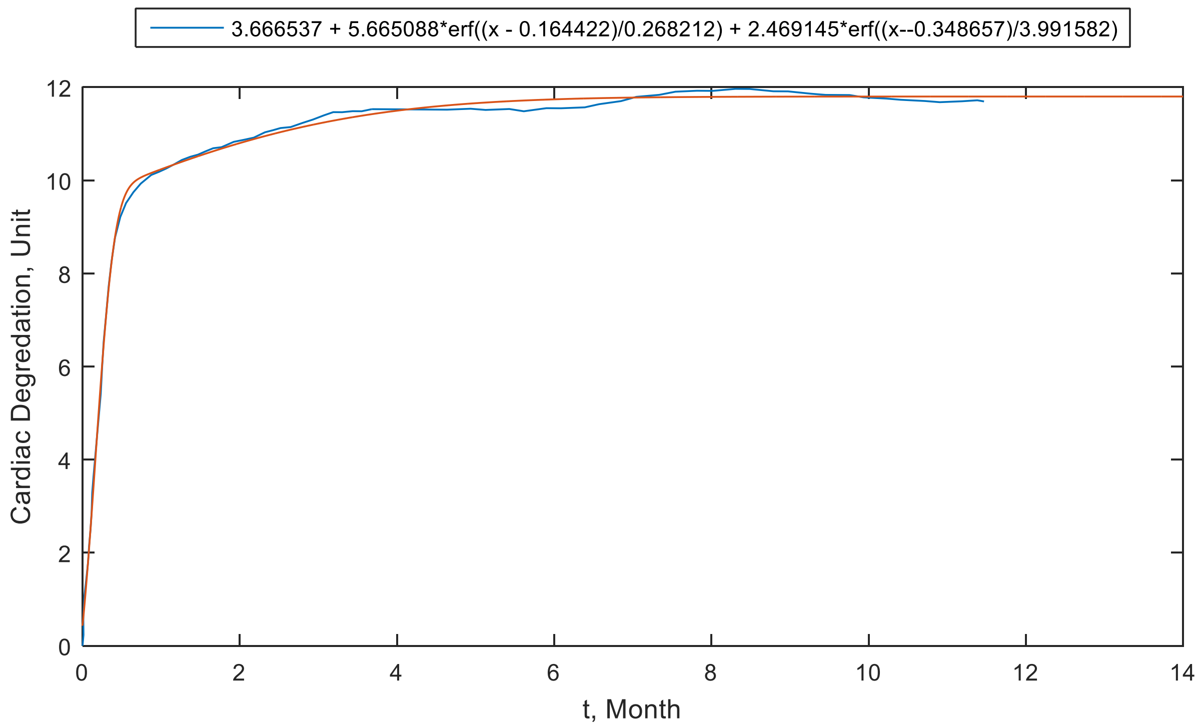
$$\boldsymbol{-8.848303 - 7.824956 * erf((t - 3.695185)/1.473982) - 0.889235 * erf((t - 9.548112)/2.805284)}$$

Equation 14

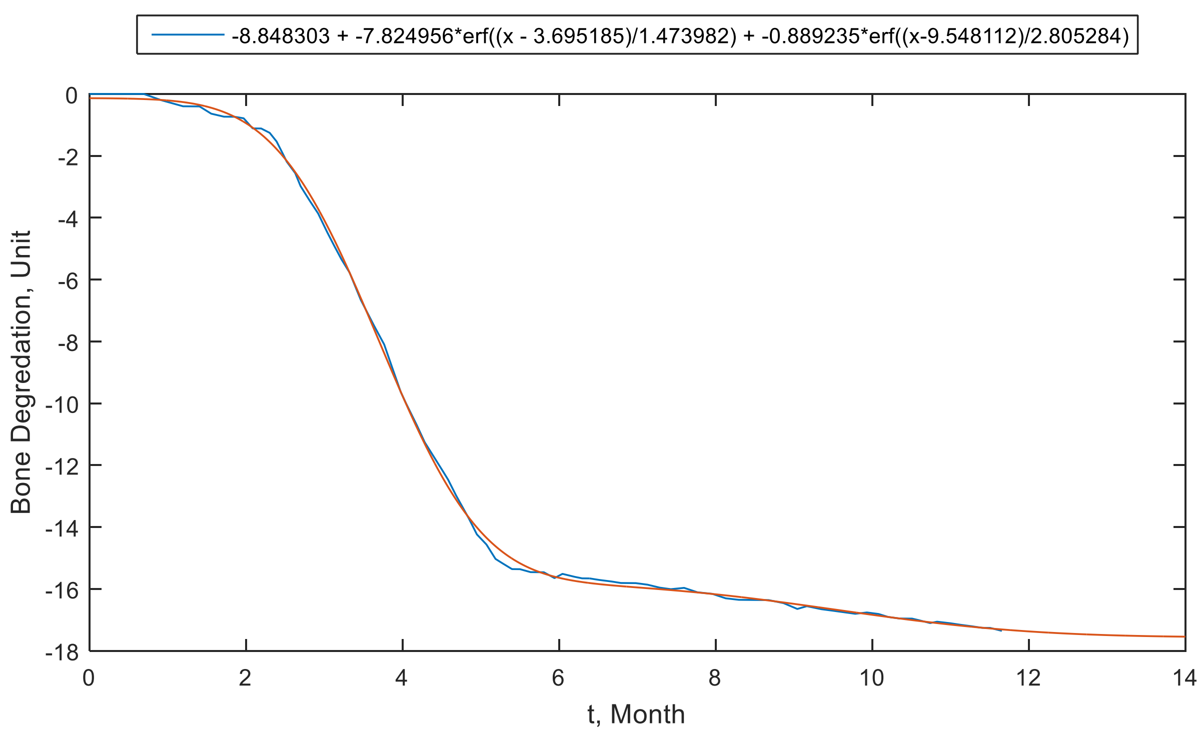
$$\boldsymbol{-9.323626 - 8.414837 * erf((t - 2.898860)/1.584169) - 1.365004 * erf((t - 6.670830)/4.679852)}$$

Equation 15

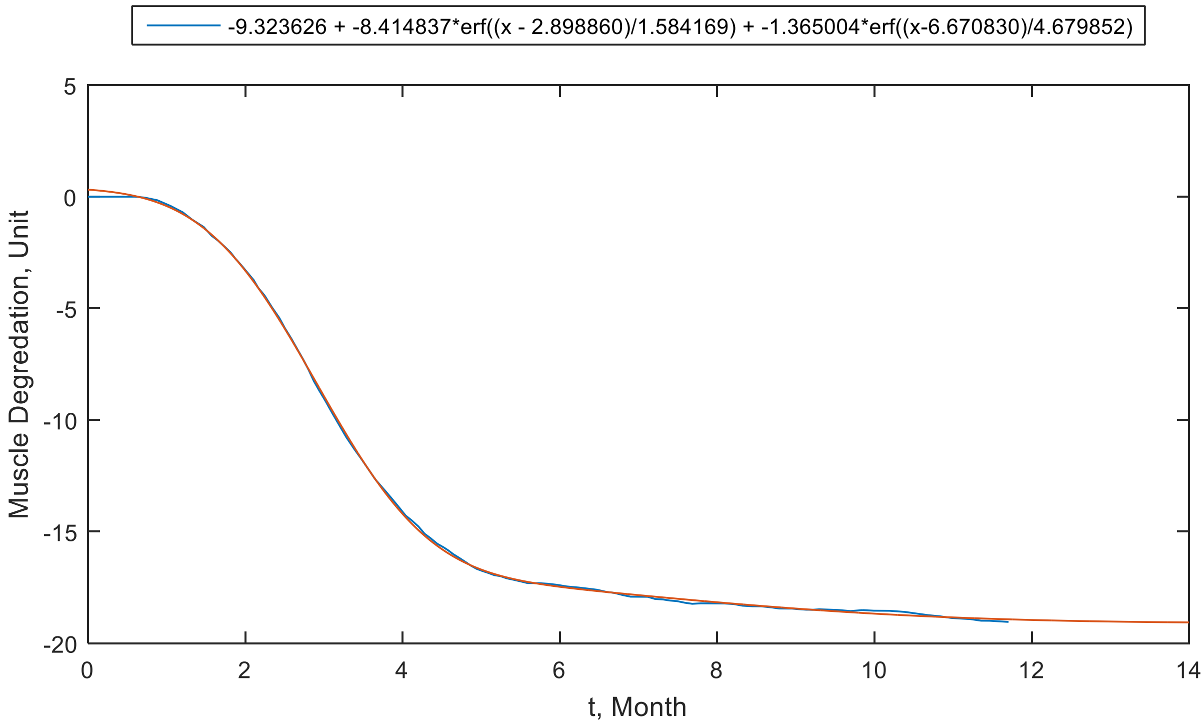
These equations are overlaid on the empirical data from NASA to demonstrate the fit in the figures below.



3.666537 + 5.665088*erf((x - 0.164422)/0.268212) + 2.469145*erf((x--0.348657)/3.991582)
Cardiac Degredation, Unit
t, Month



-8.848303 + -7.824956*erf((x - 3.695185)/1.473982) + -0.889235*erf((x-9.548112)/2.805284)
Bone Degredation, Unit
t, Month



These equations are then implemented in the mathematical model as a degradation rate induced by the vehicle environment parameters.

For unknown environment time impacts, a baseline 2% per month decay rate is assumed for the remaining physiological variables representing digestion, fine motor control, hearing, hormones, immune system, nervous system, proprioceptive posture, vestibular system, vision and VO2 max, and a 4% linear decay is implemented for the cognitive performance variables. It is noted here that not all environmental factors may degrade crewmember performance elements. For example, moving heavy objects in microgravity requires much less force than in 1-g environment. But for this early version of the model implementation, these linear assumptions are used as a blanket value for the unknown or untested cases.

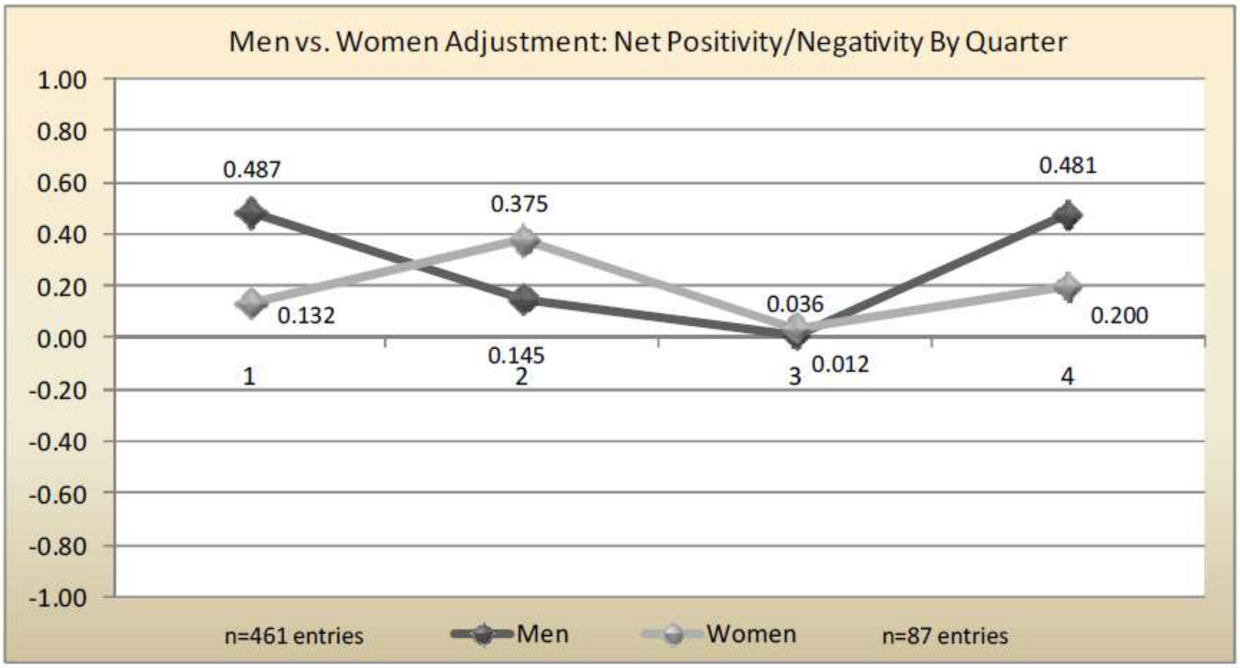
Another positive impact appears in psychology, where many astronauts experience excitement and joy at being in space. In a journal review of astronaut diaries, one astronaut is quoted writing: “All is going very well. Morale is high, tasks are going well and we only have 30 days to go. Spirits are high on board. Everybody is having a great time. Another great day in space!" (Stuster, 2010) But characterizing the environment induced impact on crewmember psychological well-being is a complicated topic as there are numerous factors that can shape an individual's behaviour, attitude, and emotions.

Luckily there has been some research in this field in tracking and analyzing the contents of astronaut diaries. The area of study is called "Content Analysis" and focuses on analyzing the frequency of 'positive' and 'negative' words as an inference on the individual's state of mind. In spaceflight and analogous polar expedition studies, content analysis has revealed an interesting decline in mood and emotions in the 3rd quarter of the mission. This experience simply known as the "3rd quarter" phenomenon reveal crewmembers in long-duration isolated, confined, extreme (ICE) environments encounter an all-time low during the third quarter only to raise again in the fourth and final quarter of their mission. While there is some on-going debate as to whether a 3rd quarter phenomenon exists in spaceflight (Kanas, 2016), there has been some data collected that can be used here as a baseline for mapping the psychological changes that occur for some crewmembers. Because the data values are specific to net positivity to negativity ratio of words in an astronaut diary assessment, the values are not significant in this context, but rather it is the profile of the graph is of interest. A regression mapping is used with a sinusoidal plot to find a representative equation. The resulting curve fit equation is described as:

$$\mathbf{10 * cos\left(2 * pi * t * \frac{3}{4\left(\# \ of \ mission\frac{days}{30}\right)}\right) + 5 - 4 * t} \qquad \textbf{Equation 16}$$

Where, t, is noted here as measured in a timescale of months. Often this psychological trend is measured by quarters of the mission timeline so the equation is purposefully scalable depending on the mission length.

Figure 25. Net positivity/negativity by quarter comparisons for adjustment only entries (Stuster, 2010).



CHAPTER 5: TEST SCENARIOS

To provide qualitative validation of the model, several test scenarios are conducted. While it is not possible to directly compare the model outputs to documented experimental data, there does exist several qualitative descriptions of astronaut performance changes due to certain conditions in spaceflight.

Since some data is available for the vehicle induced 0-g spaceflight environment, this variable will be kept fixed. The following case studies therefore examine the vehicle design and tasking induced impacts as follows:

Case Study 1: 0g-ISS-like, Optimal Design, No Tasking

Case Study 2: 0g-ISS-like, Optimal Design, Some Tasks

Case Study 3: 0g-ISS-like, Optimal Design, High Workload

Case Study 4: 0g-ISS-like, Non-Ideal and Mixed Design, No Tasking

Case Study 5: 0g-ISS-like, Non-Ideal and Mixed Design, High Workload

Additionally, cumulative overlays of different case studies are provided to more clearly demonstrate which parameters have a stronger influence on crew performance. In these test cases single crew-member performance is analyzed as it has better corollary with available empirical and qualitative data.

Another assumption with this model is that the astronauts will perform all their tasks to the best of their ability as constrained by the spacecraft design. The implementation of this model assumes the self-sustenance activities are performed the same, but the quality of the activity is reflected in the vehicle design choices. Specifically, the astronauts will only die from dehydration and starvation or sleep deprivation if the vehicle design does not provide for their survival.

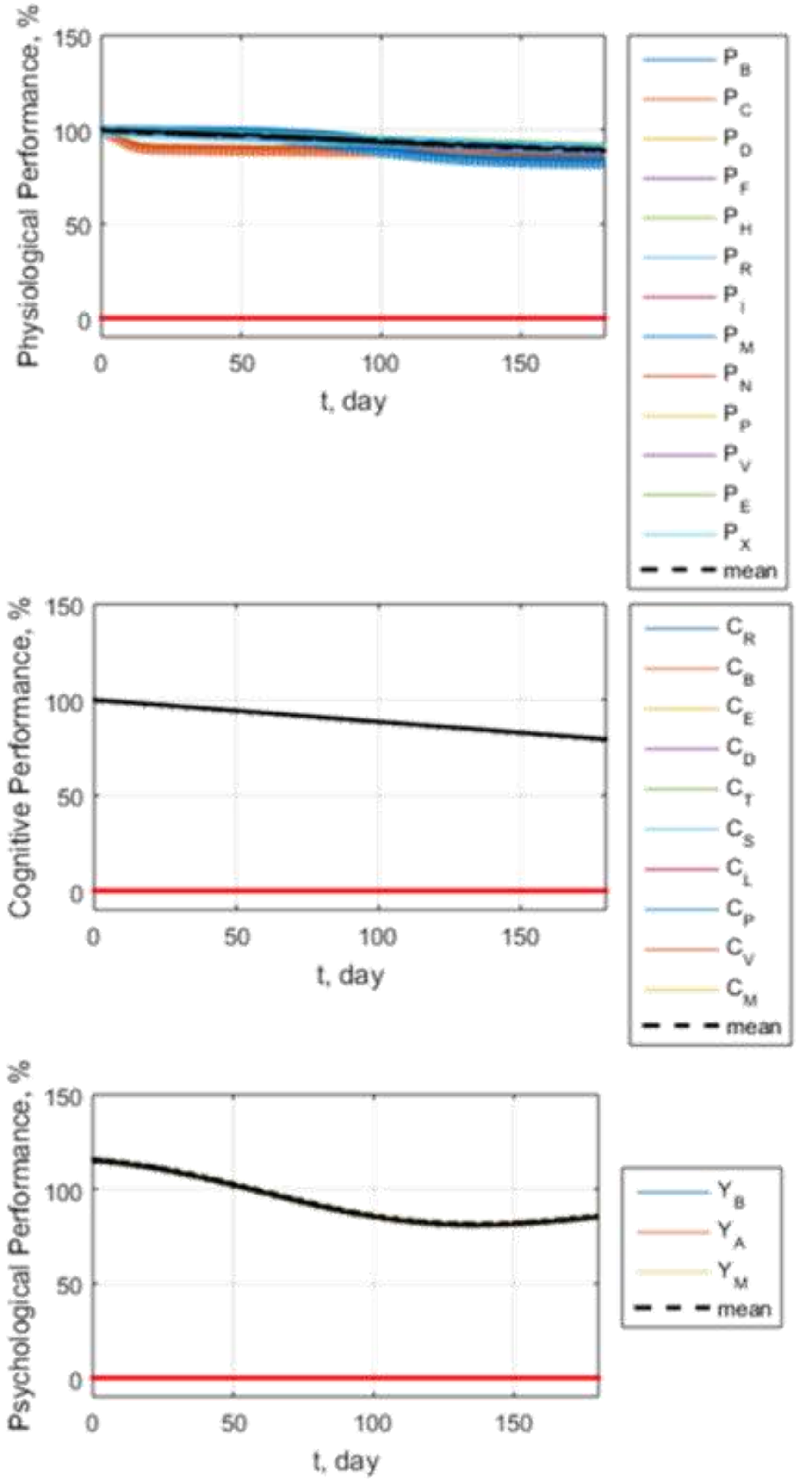
5.1 Case Study 1: Baseline Design Selection

The first case study is meant to show the model can compile and provide results matching data currently available about spaceflight in the 0-g environment. In this scenario, the astronaut performs no tasking other than those tasks required for sustenance. Therefore, it is expected that the crewmembers will experience an approximate ten percent loss in bone mass, muscle mass, and cardiovascular function after a 180-day mission. Additionally, it is expected their cognitive and psychological well-being will degrade due to boredom and lack of mental engagement. Finally, it is expected that the third quarter phenomenon will appear in the psychological measurements.

Mission Parameters:

# of Crewmembers: 3
Duration: 180 days

Vehicle Environment: 0-g, ISS-like
Vehicle Design: Optimal Selection
Tasking: Accommodate & No Tasks



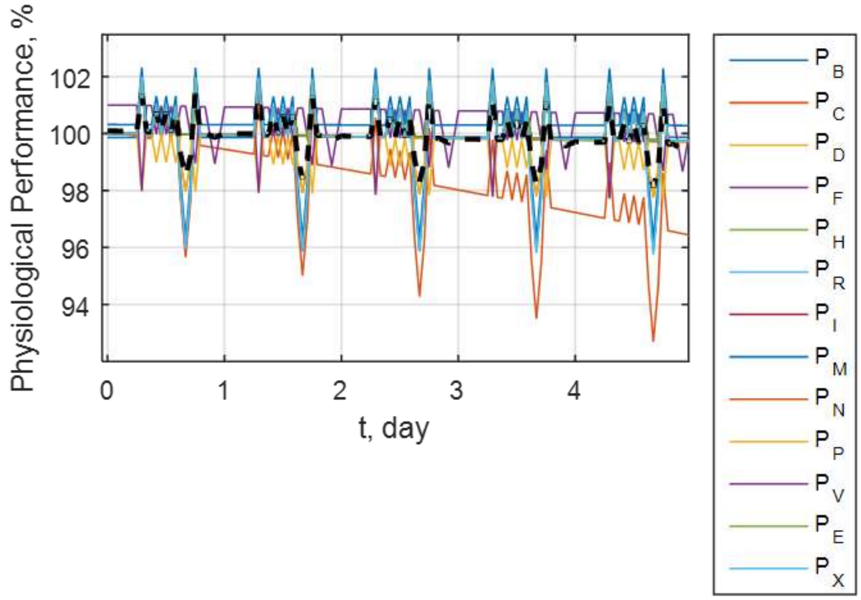
As is seen in the output figures the crewmember's performance resource elements (physiology, cognition, and psychology) all react as expected with the 180-day mission. The interpretation of this baseline result indicates that while the crewmembers are performing the self-sustenance activities of eating, drinking, sleeping etc., they are not well-fulfilled with no tasks to perform and therefore results in a decline in their cognitive and psychological well-being. Many of the individual resource elements are obscured in this plot as they overlay on top of one another in addition the dotted black line indicating the average value.

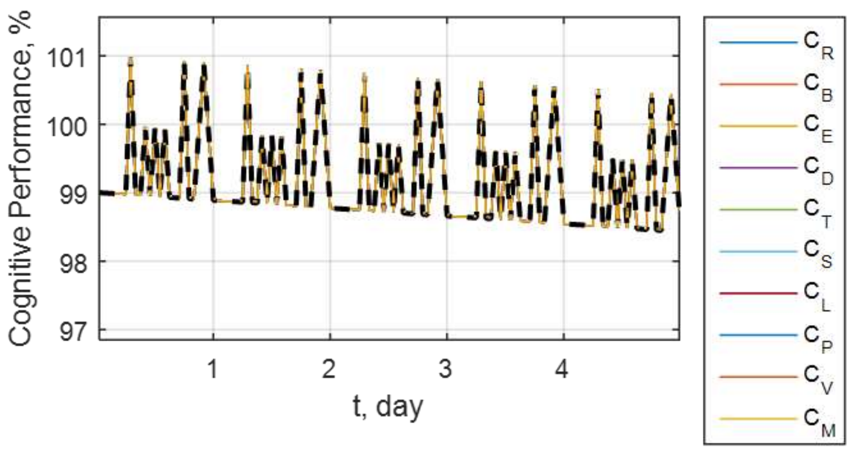
Along this time scale of 180-day mission it is difficult to see the day-to-day variations that are captured in the model. A zoomed in plot capturing the first five days on-orbit is provided to show the impact of daily activities (in this case self-sustenance only).

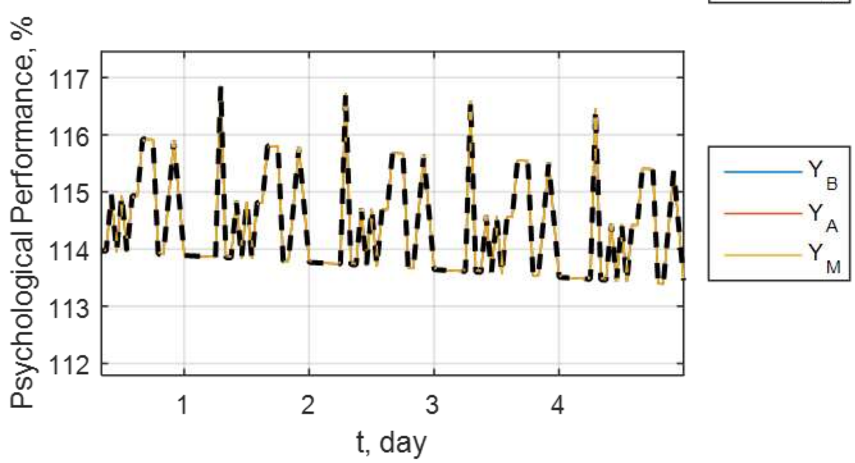
Mission Parameters:

# of Crewmembers: 3
Duration: 180 days
(zoom in on first 5 days)

Vehicle Environment: 0-g, ISS-like
Vehicle Design: Optimal Selection
Tasking: Accommodate & No Tasks







In these plots, each data spike represents the initiation and subsequent completion of a particular activity, eating drinking or sleeping in this case study. While conducting the task, the astronaut receives a boost to their psychological well-being. This effect is short lived however as completion of the task returns the astronaut's mind back to their approximate state before performing the task. The dotted black line represents the mean value of all the element resources, and it is seen more clearly in these close-up plots that the values are aligned on top of one another. These results are a good indicator of the model functionality. It also demonstrates that the outputs are qualitatively representative of the limited spaceflight data and expected outcomes.

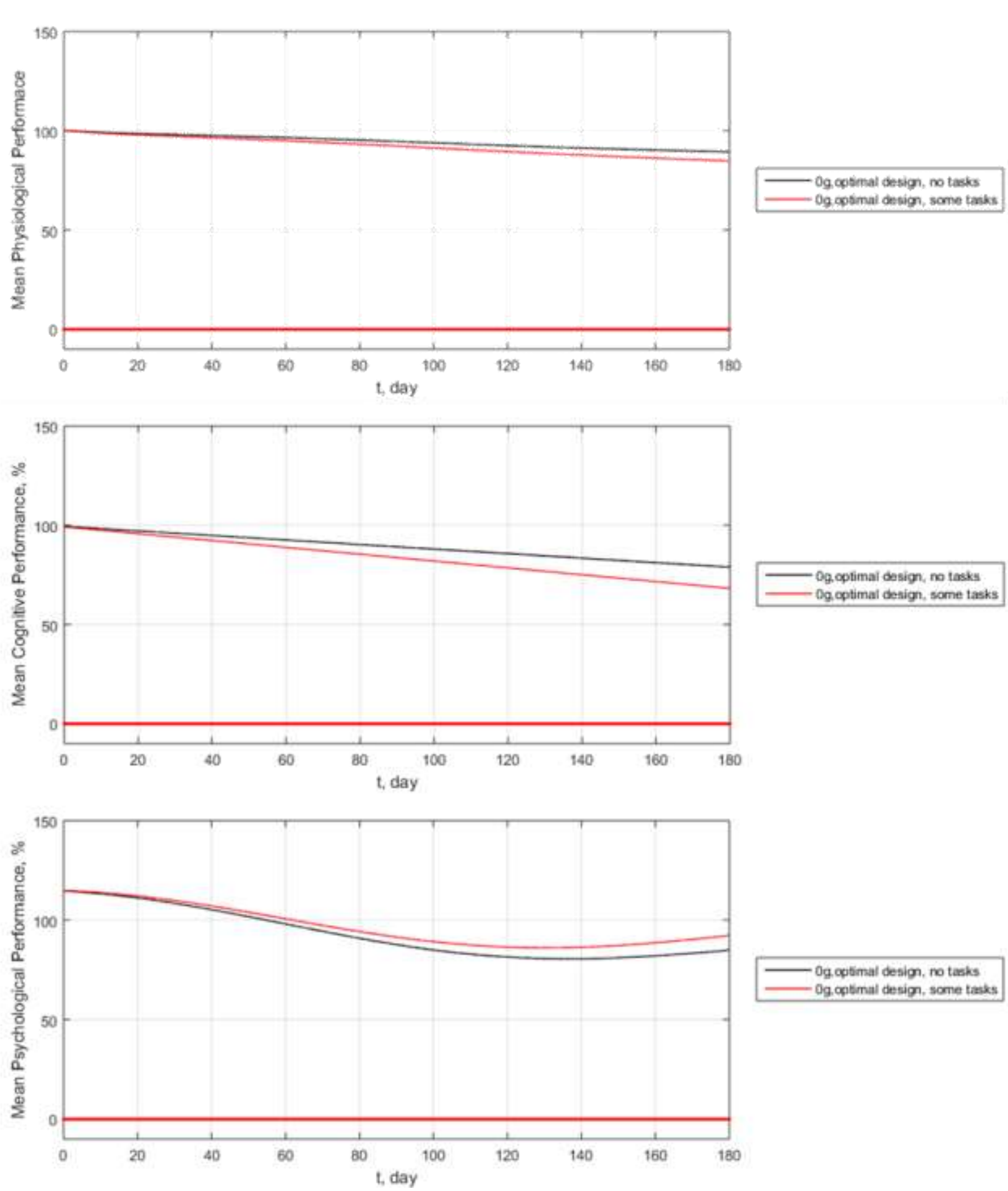
5.2 Case Study 2: Baseline with Activities

Again with this second case study the environment is preserved as that of a 0-g ISS-like spacecraft environment with an optimal spacecraft design, but instead of no tasks, this crew had a more representative workload with a handful of arbitrarily selected activities. The model was run to compare the baseline (0-g ISS-like, optimal design, no tasks) with only a change in tasking. The objective of this case study was to see how the addition of a few tasks can improve the crewmember's performance status.

Mission Parameters:

# of Crewmembers: 3
Duration: 180 days

Vehicle Environment: 0-g, ISS-like
Vehicle Design: Optimal Selection
Tasking: Compare No Tasks vs Some Tasks



The three plots show the crewmembers with some tasking (black line) compared to the crewmembers with some tasking (red line). It can be seen that the crewmembers with some tasking, have reduced physiological and cognitive resources, but they are slightly 'happier' as indicated by the boost in psychological resources. The physiological performance percentage on day 180 is 89.25% (black line) for crewmembers without tasks as compared to 84.93% (red) with tasks. The cognitive performance percentage on day 180 is 79.76% (black line) for crewmembers without tasks as compared to 68.51% (red line) with tasks. And the psychological performance day 180 is 92.67% (red line) for crewmembers with tasks as compared to 84.93% (black) with no tasks.

The interpretation is that with an optimal vehicle design in a 0-g ISS-like environment the lack of activites does causes a baseline decay in performance after 180 days, and by adding activities, the crewmembers' performance are degraded slightly in the physiological and cognitive resources, which indciates that those particular resources are used more throughout the mission due to the increased activity. But because of the crewmembers are active they receive a psychological boost which can be seen be the lower degradation amount in the psychological resources at the end of the 180 day mission.

An important aspect of the design is also note here in that the accomodation activities have a "return to baseline" rate of 0.001 while the utilization activities have a "return to baseline" rate 10 times larger of 0.01. The rationale is that the accommodation activities are a low-level sustainment activity that maintains the crewmember's resources while utilization activities cause greater variability in resource usage every time an activity is done.

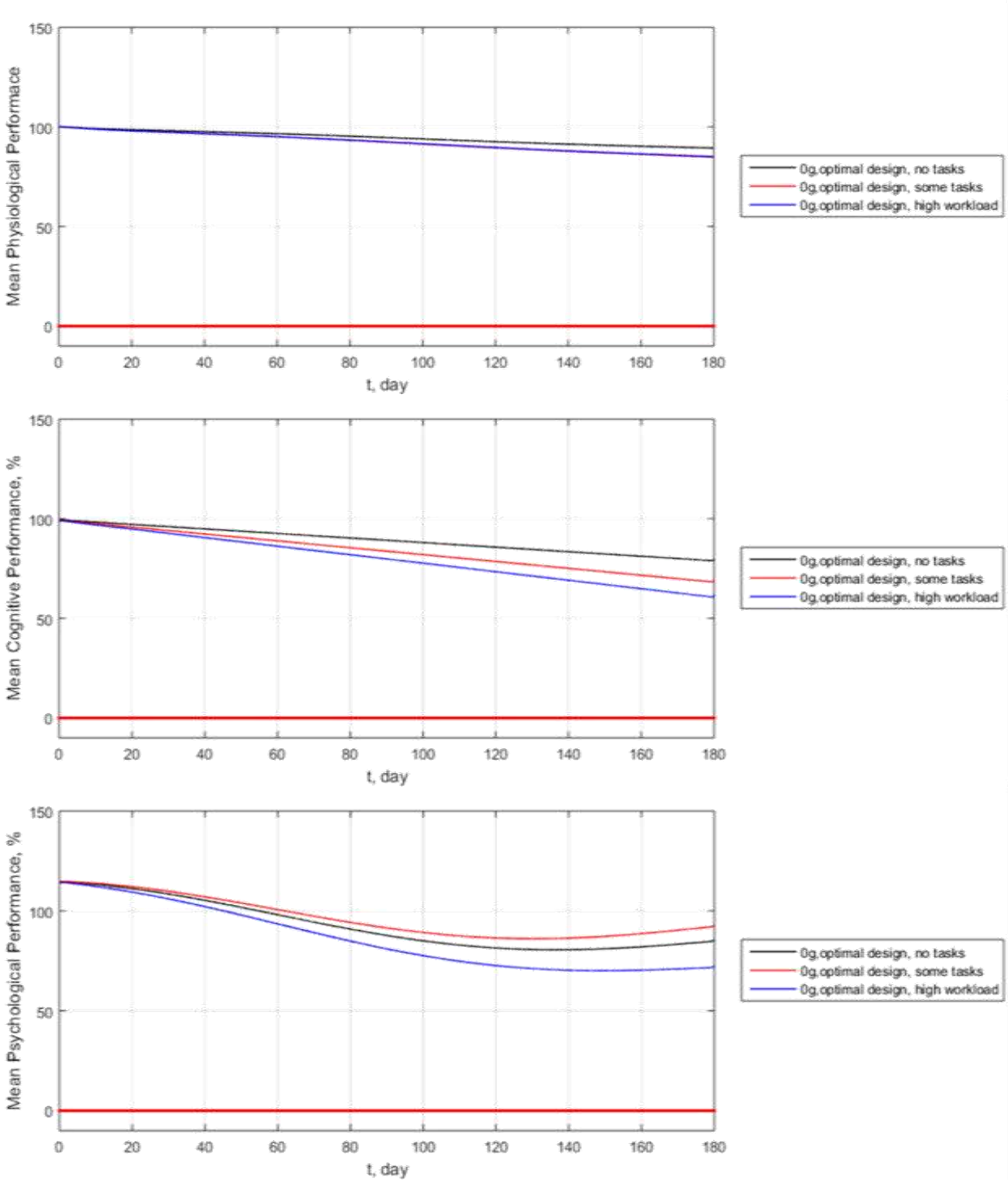
5.3 Case Study 3: Optimal Design, High Workload

Another case study was done to compare the model outputs with a high workload task list. The expectation is that with high workload, the crew's performance would be significantly impacted even with an optimally design vehicle. The high workload task list included the replacement of one hour of sleep (normally 8 hours of sleep) with a high demanding activity. The activities were specifically chosen as ones that had the biggest negative impact on the crew to test the limits of the model. Two particular demanding activities were nearly equivalent as the most negative impact activity which was either mission planning & scheduling or repair of operational spacecraft/science hardware. The crewmember was tasked with these specific activities throughout the day with no break in-between the activity unless it was for eating, sleeping, exercise, or leisure activities.

Mission Parameters:

# of Crewmembers: 3
Duration: 180 days

Vehicle Environment: 0-g, ISS-like
Vehicle Design: Optimal Selection
Tasking: No Tasks vs Some Tasks vs High Workload



In this case with the high workload (blue line) it is clear that there is a large impact on the crewmember's performance. Unlike, the case with "some tasks", this high workload case can be interpreted as causing an overload in work for the crewmember causing a downward trend in cognitive and psychological well-being. This is a well-known theory in the human factors field, called the Yerkes-Dodson Law that describes physiological arousal as an inverted-U, where both low and high arousal states inhibit performance. This theory has been extended into measures of cognition as well (Hancock, 1987) indicating that with too low or too high workload, cognitive performance is lowered.

The results of this plot indicate that it has the sensitivity to capture this variability that occurs due to changes in workload as represented by number of activities done by the crewmember.

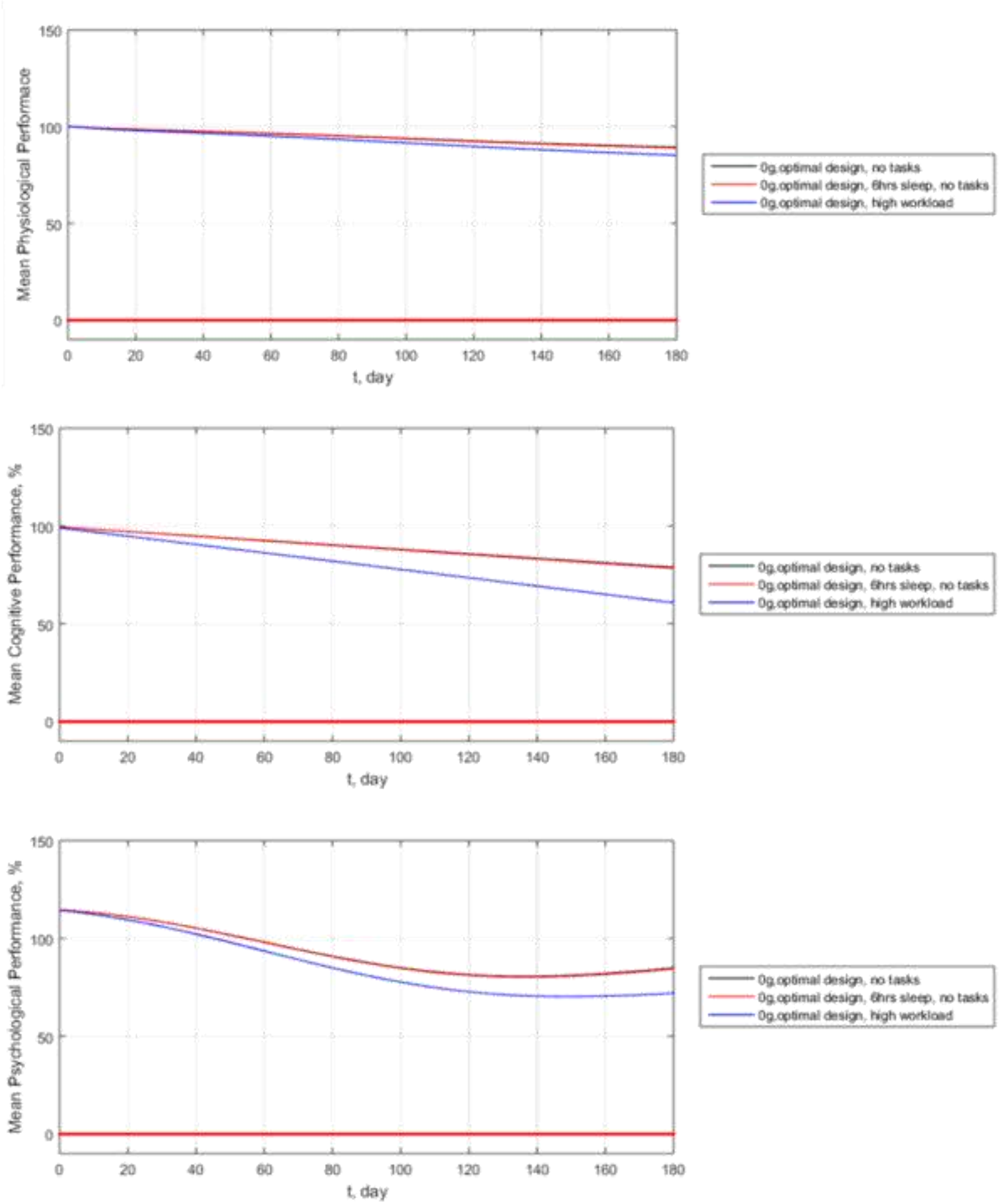
The final percentage value of the resource elements after 180 days for the high workload case was: 85.1% physiological resources remaining, 61.6% cognitive resources remaining, and 72.3% psychological resources remaining. The absolute values of the resource remainder is not to be taken as an exact prediction of the crewmember's status, rather the values are used for comparison between each design.

To understand the different in the high workload case, another scenario was examined to compare how much sleep might play a role in impacting the crewmember's performance. In this model, the normal amount of sleep is considered 8 hours. To test the changes due to reduced sleep compared to that caused by high workload, a scenario where the crewmember sleeps only 6 hours a night is tested.

Mission Parameters: **# of Crewmembers:** 3 **Vehicle Environment:** 0-g, ISS-like

Duration: 180 days **Vehicle Design:** Optimal Selection

Tasking: No Tasks vs 6hrs Sleep & No Tasks vs High Workload

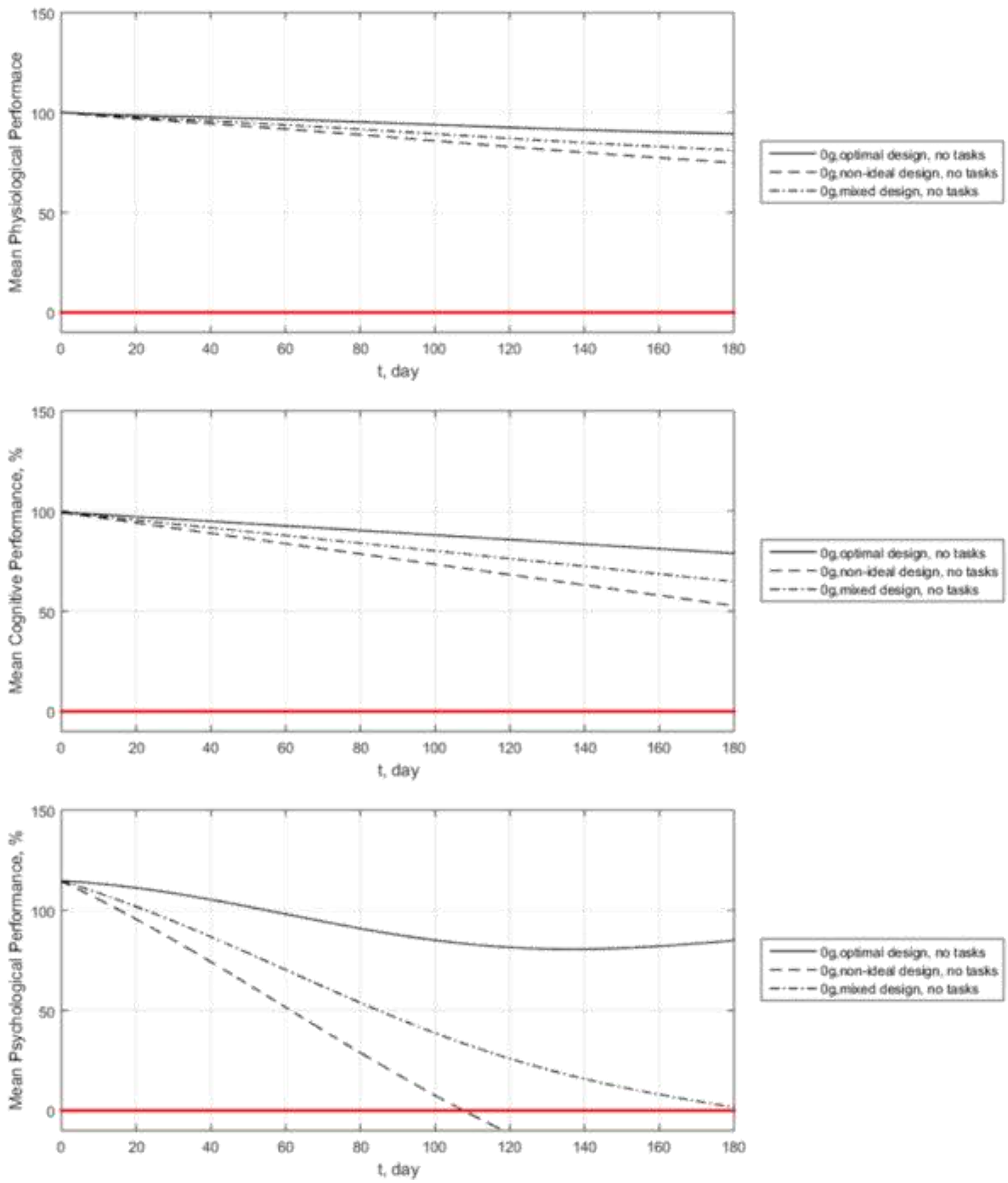


The plots show that the lack of sleep is not as much of a factor as the high workload. While this may not be representative of a real scenario in that oftentimes a high workload schedule often means that the crewmembers also do not sleep, but what it does tease out of this model is the distinction between accomodation activties (like sleep) versus utilization activities. In essensce this model simulates a specific amount of recovery from each activity. Accomodation activities have a recovery amount of 99.9% for each accommodation activity that is performed. Utilization activities have a recovery amount of 99%, which is nearly 1% less recovery than an accommodation activity. The rationale is that the accommodation activities are a low-level sustainment activity that maintains the crewmember's resources while utilization activities cause greater variability in resource usage every time an activity is done. This is an important artifact of the design of the model, and is discussed further in Chapter 6 regarding limitations and considerations of the model implementation.

5.4 Case Study 4: Non-Ideal and Mixed Design with No Tasks

This case study investigates the impact of a vehicle design selections on the crewmember's performance. This scenario compares both a non-ideal design and one that has a mix of both ideal and non-ideal design selections. The algorithm randomly selects a few design choices that can range from the optimal (no impact) design to non-ideal (biggest impact before fatality). Because it is a random selection, the values captured in this scenario may vary between model runs. These vehicle design selections are plotted alongside the baseline scenario (0g, optimal design, no tasks) as a comparison.

Mission Parameters: **# of Crewmembers:** 3 **Duration:** 180 days **Vehicle Environment:** 0-g, ISS-like **Vehicle Design:** Optimal vs Non-Ideal vs Mixed **Tasking:** No Tasks



The vehicle design here shows a strong impact on the crew's performance. The solid black line is the baseline 0-g ISS-like environment with optimal vehicle design selection, while the dashed black line represents the non-ideal selection design choices, which is essentially the worst case design before it is fatal, and the dash-dot line represents a "mixed" optimal and non-ideal design. These design selections influence the crew by imposing a linear impact rate as dictated by the Design-to-Crew Performance Mapping. The less ideal the design selection the larger the impact rate.

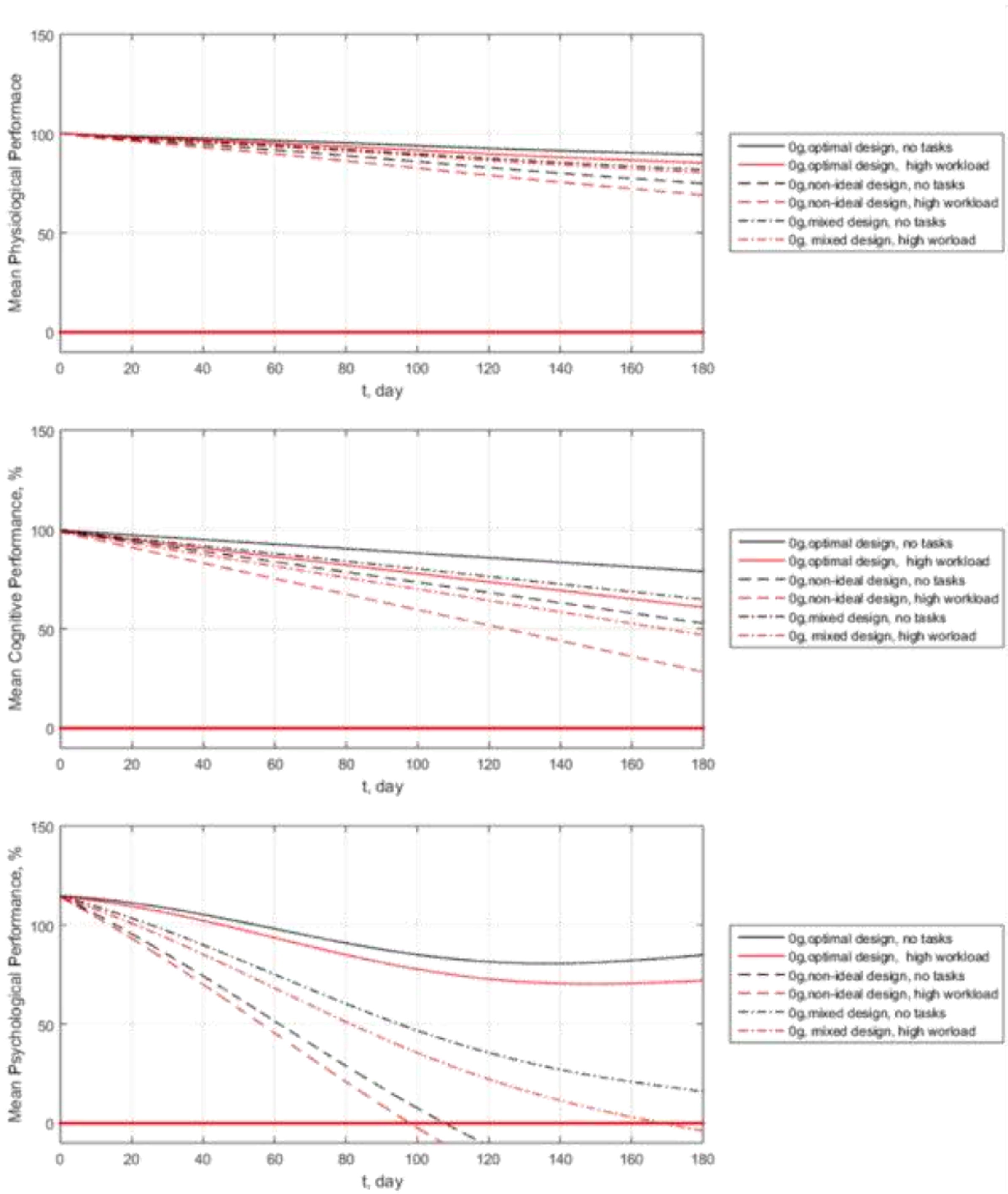
From a qualitative assessment, these plots are generally accurate describing the worst case design as the most degraded crew performance, and as expected with the mixed design, the crew do not perform as well as the optimal design, but not as poorly as the non-ideal design.

5.5 Case Study 5: Non-Ideal and Mixed Design with High Workload

This final case study examines the combination of design and workload influences on crewmember performance. This case study examines more closely the impacts caused by the vehicle design influences and compares it with that of the tasking level. For this case study the task list consists of the high workload as dictated in Case Study 3 where one hour of sleep is removed and replaced with a demanding and unpleasant task.

Intuitively, the increased workload and the less than optimal vehicle design should diminish the crew performance resources even further. To compare the effects, both tasking comparisons (no tasks vs high workload) must be run on the same plot.

Mission Parameters: **# of Crewmembers:** 3 **Duration**: 180 days **Vehicle Environment:** 0-g, ISS-like **Vehicle Design:** Optimal vs Non-Ideal vs Mixed **Tasking:** No Tasks vs High Workload

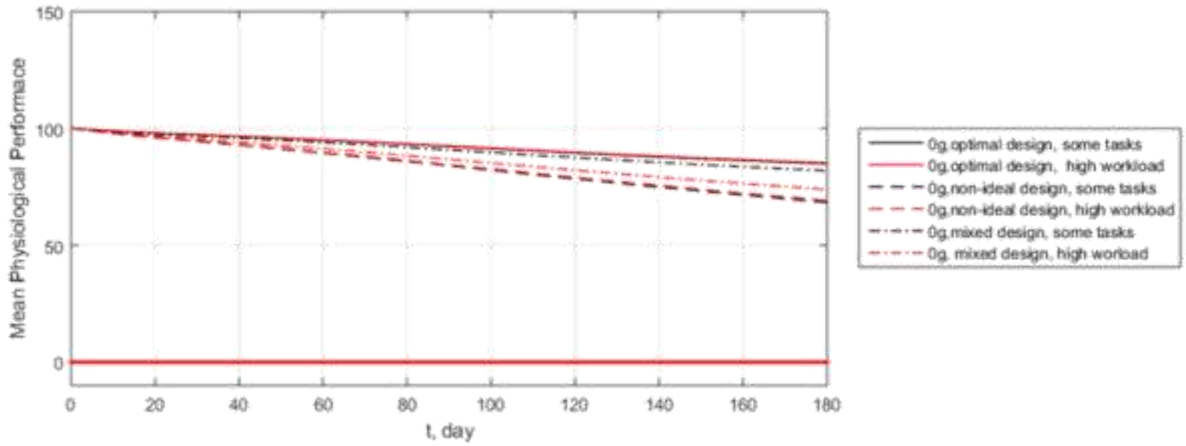


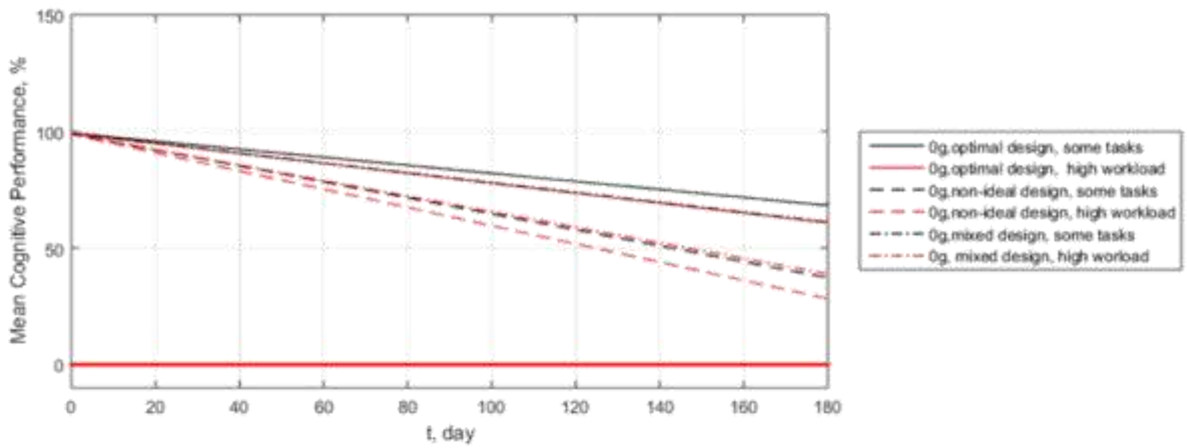
With the baseline optimal vehicle design, it is clear that an increased workload (solid red line) has a lower percentage resource availability after day 180 of the mission for all three resources. Looking at the non-ideal vehicle design, it is also clear that with increased workload (dashed red line) the performance resources are lower than the crew that do no tasks. And lastly with a mixed design (dash-dot line), the same trend is apparent. In general, these results are qualitatively coherent, in that increasing workload does indeed worsen the crewmember's performance.

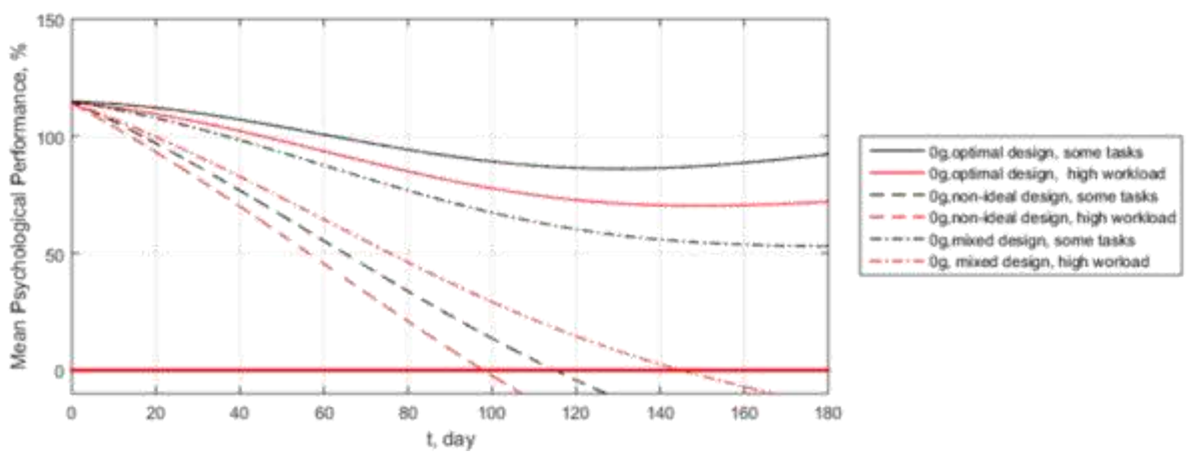
Another interesting insight seen from these overlaying plots is the influence of the vehicle design which appears to have a much stronger impact on crew performance than the type of tasking. The indication is that in all three design cases, the addition of high workload never pushes the performance resource amounts lower than the next vehicle design case. For example, the solid red line indicates the high workload case for an optimal design, the value of which remains greater than the mixed vehicle design with no tasks. But this prompts another interesting question as to whether the tasking could improve the outcome even if the design is non-optimal. From Case Study 2, it was shown that the "Some Tasks" scenario actually fares better for the astronaut's psychology, therefore, the expectation is that using "Some Tasks" could possibly improve the design outcomes instead of using "No Tasks".

Mission Parameters: **# of Crewmembers:** 3
Duration: 180 days

Vehicle Environment: 0-g, ISS-like
Vehicle Design: Optimal vs Non-Ideal vs Mixed
Tasking: Some Tasks vs High Workload







These plots indicate that the “Some Task” case can help improve the degraded performance caused by non-optimal design selections in both the physiological and cognitive resource status, but is not able to overcome the differences for the crewmember’s psychological resources.

In general, these case studies provide a wide swath of representative cases that demonstrate the model outputs. Case Study 1 demonstrated the ability to generate expected qualitative trends that reflect existing spaceflight data. Case Study 2 gave insight on how this baseline changes with variable activity levels. Case Study 3 showed how too many activities can start tipping the scale and reduce performance in the crewmembers. Case Study 4 demonstrated how the model can capture different vehicle designs and their impacts on the crewmember. Case Study 5 demonstrated the combined effects of vehicle design selection and various activity levels.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

6.1 DISCUSSION

This work has laid the foundation for bridging the gap between spacecraft design and human performance. The outcome of this work can be described as two major milestones: 1) framework of how to quantify crewmember performance using an elemental resource breakdown and 2) a simplistic mathematical model to show how it might be implemented. While many assumptions are needed to define relationships between components of the model, the general framework provides an initial starting point for future development. This model provides a building block on which to generate thoughtful, objective, and formal discussions. Additionally, a set of publications and conference presentations have been written and presented for the different segments of the work.

A design model based on constantly changing and improving technology is never complete, new information always needs to be included in order to make the model more accurate and comprehensive. When enough new data is generated, or when data leads to a new or unexpected conclusion the model needs to be reworked to fit the new conclusion. Previously, several crew performance measures had been studied and collected, but there have been few documented efforts at aggregated and integrating this work into a predictive model. With this preliminary framework presented here, data can be collected from future experimental tests to improve the model. Additionally, the framework now outlines a novel way to start integrating these disparate areas of human performance research that have often been isolated from each other.

This work brings structure for design engineers and human factor researchers to better include human performance as a quantitative measure that can be compared against the traditional design measures of mass, volume, power, or cost. The systematic process and use of currently existing metrics was specifically targeted to ensure easy adoption of these values into future practices for spacecraft designers and managers alike. While not claiming to be a comprehensive framework, it lays a foundation that can be used as more human spaceflight data is collected.

6.1.1 Model Limitations

Like all preliminary framework and model development work, there are several limitations for its current capability. This work represents an attempt at building a comprehensive crew performance model, as such, there are several areas that could benefit from additional research and analysis. There are three major limitations that have been identified for this model: 1) lack of empirical data 2) lack of factor dependencies and 3) limited validation.

6.1.1.1 Lack of Empirical Data

As noted throughout this work, the limited amount of human spaceflight data makes it difficult to create an accurate model of each level of impact. The specific type of data that is needed includes the low-level impact caused by each design or activity factor and which performance element it impacts and to what degree. Other data that is missing is the vehicle environment impact on the crew over time. While this model has implemented real data from four specific resource element impacts caused by a 0g ISS-like environment (cardiac degradation, bone mass, muscle mass, and overall psychological well-being) there are still 22 other resource elements that do not have empirical data. The more data that is available, the more accurate the outputs of the model. Additionally, more data will also help to inform the relationships that might exist between the elements.

Metrics used here are based on the assumption that the metrics are validated and already used, but while there are varying opinions on the used metrics and they can be changed to ones that are more relevant or as it evolves; the framework has the flexibility to use whatever metric that is most useful for the application.

6.1.1.2 Lack of Factor Dependencies

This current implementation of the model assumes factor independence where changes in one factor does not impact other factors. While this assumption keeps the modeling simple, it does not represent reality. There are several dependencies between the factors (design choices), activities, and the performance elements. For example, preliminary research has shown that there may be a causal relationship between high CO2 level in the environment and reduced food intake.

Another complexity that is not readily captured in this work is the effect of time over the various activities that must occur. For example, maintenance of the CO2 scrubber may be an interesting and possibly enjoyable activity for an engineer, but after the system breaks down again for the tenth time on Day 300 of the mission, the activity may no longer be enjoyable. The resources required to do that same activity on Day 1 is no longer the same on Day 300 and this change over time for activity resource requirements is not currently captured. Along this same vein, the crewmembers themselves may lose skills over time due to lack of training, aka "use-it or lose it" and this change of skill set is not adequately captured in the current framework.

Additionally, it is known that specific PSFs are not all independent, and in some cases cause a positive feedback. For example, muscle strength is correlated to bone strength through connective tissues that attach to bone. The loss of muscle strength also contributes to bone loss in addition to the microgravity environment. These co-dependencies generally tend towards the use of network models, but would have to be carefully considered in regards to the purpose of the model. Network models, while useful for identifying interconnected variables, can become too complex for designers to adequately identify any insights regarding design impacts on performance and therefore fail to make appropriate design decisions.

6.1.1.3 Limited Validation

Another limitation of the model is in the limited validation. The limited validation is a consequence of the lack of data, but also not having had a comprehensive set of data to begin the measurements. Because this work focused solely on development of the model, there was little effort in designing experiments to validate the model performance. Instead, the work focused on providing a demonstration of how the model could be tested and the types of scenarios that could lead to validation of the model outputs. A full validation effort would require a complete set-up of re-configurable design parameter and consistent measures and monitoring of crew with the given list of standard measures in a simulate space mission set-up. Such a validation effort is beyond the scope of this work, but can be considered in the future for refinement of the model.

While the demonstrated mathematical model's predictive capability is limited to the identified designs and tasks, the framework and methodology leading to the model's development can be reapplied to new designs and tasks, increasing the predictive capability of the resulting model. Therefore, while the presented linear model is not predictive outside, the prescribed designs discussed previously, the framework is highly adaptable to new information.

6.1.2 Contributions to the Field

This work provides a new perspective for human systems integration methodology for spaceflight systems. Human-centered design is a growing field and highly relevant for the space community due to the increased number of spacecraft in development. It has had many challenges in breaching the engineering fields as human behavior and performance are often viewed as non-quantitative or a 'soft science'. In this regard, the framework developed here builds a bridge between the engineering and human factors domain with the intention of establishing a language and a mechanism for which the two disciplines can better coordinate and understand these complex human systems.

This work was not focused on re-inventing the wheel, rather it aggregated several existing techniques, approaches, metrics into one understandable and usable framework. By building off of metrics and measures that already exist resolves many of the issues with future validation efforts. This work set out to accomplish several objectives, the main goal which was to create a framework that can be adopted early in the concept design phase for spacecraft design to help quantitatively evaluate how well spacecraft accommodate and utilize the crew. The goal was achieved and a framework was adequately developed for the intended use. Additionally, there were three objectives associated with the main goal that were each completed. The first was the framework development, the second was testing it out with a computational model, and third was analyzing and demonstrating the capabilities of the model. Each of these objectives were accomplished and documented throughout this thesis.

6.2 Conclusions

The results generated from this model may need further analysis to establish how well the model truly represents the design. From a high-level perspective, this model could be a useful tool for future spacecraft designers to obtain a quantitative evaluation of how well a spacecraft has been designed to accommodate and utilize the crew.

With the limitations of the mathematical model identified it is important to recognize that the primary deliverable of this work is the framework which is widely applicable. The mathematical model presented in this work represents one possible extension of the framework into a predictive model. This particular extension is non-ideal however as this is largely due to the lack of experimental data to inform model development beyond heuristic levels. With better information, the framework can be extended into a better weighted linear model or eventually a non-linear model.

With that said, working through the linear model development led to several insights regarding how individual crew performance metrics would be mathematically related to design choices and task requirements. The linear model demonstrated that the spacecraft design affected the crew in terms of both a baseline effect induced by the environment and an increase or decrease due to task difficulty. This can be considered as continual and instantaneous degradations respectively. The linear model also helped demonstrate that astronauts must perform tasks to be happy and mentally healthy but that task overload leads to reduced performance. This highlighted the idea that there is a tasking sweet spot where the astronauts are properly utilized, but not overworked.

To build a better mathematical model within this framework, future missions could focus on rating how astronauts respond to different system configurations. One example of a test that could capture this type of information in the ambient noise category could revolve around tasking astronauts to complete cognitive, physiological, or psychological tests while wearing headphones that produce different levels of ambient noise while measuring their physiological response. Such a test could help to isolate the Noise Level design selection and see how it could be reflected in various activities that can be accomplished.

Ultimately, what has been demonstrated with this work is the ability to use the overarching framework of crew performance measures as a method for quantifying and relating human performance to spacecraft design choices.

6.3 Future Research

Defining a human spacecraft design evaluation model can prove to be an aid in human spacecraft design. It bridges the human element with the engineering design trades and provides a basis for analyzing designs for its ability to accommodate and utilize the crew. The development of a comprehensive and dynamic model addresses the challenge of evaluating human spacecraft design by providing a quantitative measure for comparing candidate design options. The model output can be used as an additional parameter for spacecraft designers to objectively address crew performance trade-offs across different designs. Future work could capitalize on various parameter selections as well as increasing the fidelity of the model.

More recently, NASA has released a draft solicitation (2016) for the Small Business Grant Initiative (SBIR/STTR) with a specific subtopic area focused on Modelling and Estimation of Integrated Human-Vehicle Design Influences. The full text of the draft solicitation reads:

> "The development of human space exploration vehicles and habitats requires an understanding of the relationships and interactions among the technical and human crew aspects of the system. Methods are sought to systematically model and estimate impacts to the behavioral, physiological and clinical outcomes on crewmembers relative to vehicle design options, incorporating how the vehicle and humans will evolve and interact over the course of a mission. It is anticipated these methods will reveal attributes, or groups of attributes, of a system design as influential that would not otherwise be detected in the design phases of mission development."

The work being solicited by NASA in this draft STTR solicitation indicates the need and development potential of this particular research area. It outlines the current lack of such tools for modeling crew performance in the context of mission design.

While this work implies that to some extent human behavior can be predicted by their design of their environment, it borders a more contentious issue regarding predicting human behavior and in part controlling it. The moral and ethical standard on controlling behavior with the environment is another topic of discussion best left to philosophical discussion.

Ultimately, for these models to work well, more empirical data is needed to validate the logic of the relationships between the mapping, and also the find the appropriate crew performance impact coefficients. Because of the flexibility and the comprehensive nature of this established framework, several components of the model can be validated first on the ground with analog missions.

6.4 Publications, Presentations, and Posters

6.4.1 Journal and Conference Papers

Fanchiang, C., Marquez, J. J., and Klaus, D. M. (2016) Assessing Human Spacecraft Design Effectiveness as a Function of Crew Accommodation and Utilization. *IEEE Transactions on Human-Machine Systems.* [in review]

Fanchiang, C., Marquez, J.J., Gore, B.F. and Klaus, D. (2015) Survey and Assessment of Crew Performance Evaluation Methods Applicable to Human Spacecraft Design. *IEEE Aerospace Proceedings.* Paper number: 2077 (8.0505)

Klaus, D.M., Ocampo, R.P. and Fanchiang, C. (2014) Spacecraft Human-Rating: Historical Overview and Implementation Considerations. *IEEE Aerospace Proceedings* (978-1-4799-1622-1/14, no. 2272)

Fanchiang, C., Huang, R., Threet, E. (2014) Mars Approach Vehicle and Earth Return for Interplanetary Crew (MAVERIC): An Innovative, Robust, and Simple Architecture for a Mars Flyby Mission. Mars Society Convention.

Anthony, J. Christensen, C., Darnell, A., Fanchiang, C., Milanese, M. Nie, C., Niederwieser, T., Russel, E. (2014) Enabling the space frontier by implementation of a low mass cis-lunar outpost. NASA Revolutionary Aerospace Systems Concepts Academic Linkage Conference. Cocoa Beach, Florida, U.S.A. May 31, 2014.

Fanchiang, C., Hava, H., Holquist, J., Hale, G., Havens, K., Carton, M. (2013) Bioregenerative Life Support System (BLSS) for Long Duration Human Space Missions. NASA Revolutionary Aerospace Systems Concepts Academic Linkage Conference. Cocoa Beach, Florida, U.S.A. June 18-20, 2013

Fanchiang, C. Zinner, N., Bidner, F., Grunder, Z., Imobersteg, J., Jasper, L., Tozer, S. (2012) Extraterrestrial Outpost (ExO): Design and Implementation of Long-Term Sustainable Lunar Habitat. *AIAA 2012-5299*.

Fanchiang, C., Johnson, M. (2012) *Evaluation of Commercial Human Space Flight Laws and Regulations in the United States.* 63rd International Astronautical Congress, Naples, Italy, Oct 2012.

Fanchiang, C. (2012) Characterization and Evaluation of Manned Spacecraft Operability Factors. 63rd International Astronautical Congress, Naples, Italy, Oct 2012.

Klaus, D.M., Fanchiang, C. and Ocampo, R.P. (2012) Perspectives on Spacecraft Human-Rating. *AIAA-2012-3419.*

6.4.2 Technical Presentations and Posters

Fanchiang, C. (2016) Using a Concept-Level Crew Performance Model to Assess Human Spacecraft Designs (*abstract and poster IAC-16,A1,IP,17,x32089*) 67th International Astronautical Congress (IAC), A1. IAA/IAF Space Life Sciences Symposium, Guadalajara, Mexico, September 2016

Fanchiang, C., Klaus, D.M. and Marquez, J. J. (2015) A Framework for Quantifying Human Performance to Support Conceptual Spacecraft Design Evaluation (*abstract and poster #0177)* NASA Human Research Program (HRP) Investigator's Workshop, Session B: Space Human Factors Engineering, Galveston, TX, January 2015

Fanchiang, C. and Klaus, D.M. (2013) Spacecraft Human-Rating (poster) FAA COE CST 3rd Annual Technical Meeting, Washington DC, Oct 2013 (2nd place student poster competition)

Fanchiang, C. Klaus, D. (2013) Defining a Crew Utilization Figure of Merit to Characterize Human Performance Influence on Spacecraft Design (*poster*) 43rd International Conference for Environmental Systems. Vail, CO. 14-18 July 2013.

Fanchiang, C., Johnson, M. (2012) *Evaluation of Commercial Human Space Flight Laws and Regulations in the United States.* 63rd International Astronautical Congress, Naples, Italy, Oct 2012.

Fanchiang, C., Klaus, D. M., Gore, B. F., Marquez, J. J. (2015) *Survey and Assessment of Crew Performance Evaluation Methods Applicable to Human Spacecraft Design.* IEEE Aerospace Conference 2015. Big Sky, Montana. 1-8 Mar 2015.

Fanchiang, C., Klaus, D., and Marquez, J. (2015) *A Framework for Quantifying Human Performance to Support Conceptual Spacecraft Design Evaluation*. NASA Human Research Program (HRP) Investigators Workshop 2015. Galveston, Texas. Jan 2015.

Fanchiang, C., Klaus, D. (2012) *Defining an Operability Index for Human Spacecraft Design*. 42nd International Conference for Environmental Systems. San Diego, CA. 15-19 July 2012. (3rd place student poster competition)

Fanchiang, C., Hava, H., Holquist, J., Hale, G., Havens, K., Carton, M. (2013) Bioregenerative Life Support System (BLSS) for Long Duration Human Space Missions. NASA Revolutionary Aerospace Systems Concepts Academic Linkage Conference. Cocoa Beach, Florida, U.S.A. June 18-20, 2013

Fanchiang, C. and Klaus, D.M. (2012) FAA Human-rating Terminology and Definition (*poster*) FAA COE for CST, Second Annual Technical Meeting, Socorro, NM, Oct/Nov 2012

Fanchiang, C. Zinner, N., Bidner, F., Grunder, Z., Imobersteg, J., Jasper, L., Tozer, S. (2012) Extraterrestrial Outpost (ExO): Design and Implementation of Long-Term Sustainable Lunar Habitat, AIAA Space 2012 Conference & Exposition, Pasadena, CA, Sept 2012

Fanchiang, C., Klaus, D. (2011) Definition of an Operability Index for Human Spacecraft Design (*poster*) 62nd International Astronautical Congress, Cape Town, South Africa, Oct 2011.

Fanchiang, C., McCoy, J., Griswold, C., Healy, C., Huhn, S., Donaldson, T., Kemper, B. (2010) Aerospace Graduate Project Lab: Dream Chaser Internal Systems Layout Tool (*poster*) Capstone Project Conference, Boulder, Colorado, May 2010

FUNDING SOURCES

1. Harriet G. Jenkins Graduate Fellowship (2013- 2016)
2. Zonta Amelia Earhart Graduate Fellowship (starts Fall 2014)
3. P.E.O International Scholar Award (starts Fall 2014)
4. Achievement Rewards for College Scientists (ARCS) (2012-present)
5. Society of Women Engineers Rocky Mountain Section (2012)
6. FAA Center of Excellence for Commercial Space Transportation (FAA COE CST) (2011-2013)
7. BioServe Space Technologies (2010-2011)

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APPENDIX

APPENDIX A1. HUMAN PERFORMANCE MODELS

#	FAA HF Tool Category	FAA HF Tool Subcategory	Specific Method/Tool	Description	Adaptable for Human Spaceflight?	Process/ Tool	Fields of Use (Aviation, Space, Nuclear..)	Outputs	Fidelity Level Req'd (H/M/L)	Outputs Quantitative/ Qualitative?	Who Created?	# of Resources Req'd (H/M/L)	Time Req'd to set-up? (H/M/L)	Computer Skills Required?	Still In Use?	Validated?	When Used in SE Design Process?
1	Human Computer Interaction Tools	Prototyping	Distributed Environment for Simulation & Rapid Engineering (DESIREE)	Sim platform for ATC; rapid prototyping for terminal and enroute ATC sims	No	Simulation	Aviation	Sim	H	QL	FAA RDHFL		H				Conceptual
2	Human Computer Interaction Tools	Prototyping	High-Fidelity Prototyping	Mimic look and feel of actual system (physical mock-ups/workstations)	Yes	Prototype	Any	Mockups	H	QL		L	H	Depends on Product	Yes		High-Level/ Prelim
3	Human Computer Interaction Tools	Prototyping	Low-Fidelity Prototyping	Prototype not look like actual; provide fast user feedback	Yes	Prototype	Any	Mockups	L	QL		L	M	Depends on Product	Yes		Conceptual
4	Human Computer Interaction Tools	Prototyping	Parallel Design	Multiple alternative designs to test	Yes	Design Groups	Any	Multiple Designs	M/L	QL	UsabilityNet ©	M	M	Depends on Product	Yes		Conceptual
5	Human Computer Interaction Tools	Prototyping	Prototype -Scale Model	Not full-scale model	Yes	Prototype	Any	Mockups	M	QL		L	M	Depends on Product	Yes		High-Level/ Prelim
6	Human Computer Interaction Tools	Prototyping	Prototype - Storyboarding	series of screen sketches; illustrate and organize ideas for feedback	Yes	Storyboard	Any	Storyboard	L	QL		L	L	Depends on Product	Yes		Conceptual
7	Human Computer Interaction Tools	Prototyping	Prototyping - Horizontal	Display wide range of features but w/o extensive functionality behind each function (appropriate for understanding relationships across a board system and for showing range of abilities of a system)	Yes	Prototype	Any	Mockups	L	QL		M	M	Depends on Product	Yes		High-Level/ Prelim
8	Human Computer Interaction Tools	Prototyping	Prototyping -Paper	Paper design; user makes selections and activates interfaces elements with mouse/finger	Yes	Prototype	Any	Drawings	L	QL		L	L	Depends on Product	Yes		Conceptual
9	Human Computer Interaction Tools	Prototyping	Prototyping -Vertical	Demos exact functionality of small subset of product	Yes	Prototype	Any	Mockups	H	QL		H	H	Depends on Product	Yes		Detailed
10	Human Computer Interaction Tools	Prototyping	Rapid Prototyping	create interface/product with software then get feedback from users and repeat until optimal solution reached	Yes	Simulation	Any	Sim	M	QL		M	H	Depends on Product	Yes		Conceptual
11	Human Computer Interaction Tools	Prototyping	Video Prototyping	Video-based sim of interface functionality using simple materials and equipment (users do not directly interact with sim, just view it)	Yes	Video	Any	Video	M	QL		M	M	Depends on Product	Yes		Detailed
12	Human Computer Interaction Tools	Prototyping	Wizard of OZ Technique	Variant of computer-based prototyping involves a user interacting w/ a computer system which is operated by a hidden developer (or 'wizard'); wizard processes the input and simulates system output; suited for exploring design possibilities that are demanding to implement	Yes	Prototype	Software	Sim	M	QL		M	H	Some	Yes		Detailed
13	Human Computer Interaction Tools	Usability	Cello Method	derived from expert-based heuristic method; collaborative eval. from multiple experts guided by a defined list of design criteria; criteria from psychology and ergonomics theory, experimental results, practical experience and organizational or personal belief.	Yes	Written Review	Any	Written Report	L	QL		H	M	No	Yes		Detailed
14	Human Computer Interaction Tools	Usability	Co Discovery	usability testing similar to think aloud protocol, except 2 participants attempt to perform tasks together while being observed in a realistic work environment; participants perform the task using the product and talk through the activity	Yes	Written Review	Any	Written Report	M	QL		M	H	No	Yes		High-Level/ Prelim
15	Human Computer Interaction Tools	Usability	Cognitive Walkthrough	use prototype, concept design, or final product, a group of evaluators step through tasks, evaluating at each step to ID and operate system element; take into consideration user's thought process and decision making	Yes	Written Review	Any	Written Report	L	QL		M	H	No	Yes		Detailed
16	Human Computer Interaction Tools	Usability	Diagnostic Evaluation	diagnostic evaluation using representative sample of subject matter experts running thru variety of scenarios	Yes	Written Review	Any	Written Report	M	QL		H	H	No	Yes		Software/ Hardware Development
17	Human Computer Interaction Tools	Usability	Feature Inspection	assess product feature set in context of task to be performed; emphasis on sequence of tasks, accessibility, potential for confusion, and documentation	Yes	Written Review	Any	Written Report	M	QL		H	H	No	Yes		High-Level/ Prelim

#	FAA HF Tool Category	FAA HF Tool Subcategory	Specific Method/Tool	Description	Adaptable for Human Spaceflight?	Process/ Tool	Fields of Use (Aviation, Space, Nuclear..)	Outputs	Fidelity Level Req'd (H/M/L)	Outputs Quantitative/ Qualitative?	Who Created?	# of Resources Req'd (H/M/L)	Time Req'd to set-up? (H/M/L)	Computer Skills Required?	Still In Use?	Validated?	When Used in SE Design Process?
18	Human Computer Interaction Tools	Usability	Focus Groups	brings together stakeholders/experts to refine requirements of a system or to evaluate it; views elicited by facilitator	Yes	Interview	Any	Written Report	M	QL		M	M	No	Yes		Ops/ Maintenance
19	Human Computer Interaction Tools	Usability	Formal Usability Inspection	teams of stakeholders/experts evaluate different aspects of system; meeting convened to submit assessments	Yes	Written Review	Any	Written Report	M	QL		H	M	No	Yes		Unit Testing
20	Human Computer Interaction Tools	Usability	Heuristic Evaluation	Expert evaluation, done by 3 analysts using guidelines/principles, noting their observations and ranking by severity; experts in hF	Yes	Written Review	Any	Written Report	M	QL		H	M	No	Yes		Detailed
21	Human Computer Interaction Tools	Usability	Journal Sessions	User provided with disk/CD with prototype interface with tasks; software captures info related to user actions; has dialog boxes for user to comment	Yes (but just for computer)	Prototype and Data Collection	Software	Software/Written Review	M	QL		M	M	Minimum	No. CD's are archaic		Unit Testing
22	Human Computer Interaction Tools	Usability	Mockup	Large-scale proportioned model of the final equipment use for validation of layout, mockup types: 1) Class I -basic shape design equipment 2) Class II - demonstrator for customer evaluation 3) Class III -engineering/manufacturing/sim vehicle or facility and is used to plan the layout	Yes	Prototype	Any	Mockups	M	QL		H	H	No	Yes		High-Level/ Prelim
23	Human Computer Interaction Tools	Usability	Questionnaire for Interaction Satisfaction (QUIS)	assess users' subjective satisfaction with specific aspects of HCI; contains demographic questionnaire, a measure of overall system satisfaction along six scales and hierarchically organized measures of 11 specific interface factors; and 9-point scale, reconfigurable to each analysis by including only sections of interest to the user	Yes (but just computer part)	Questionnaire	Any	Written Report	M	QL	University of Maryland	M	M	Minimum	Yes		Detailed
24	Human Computer Interaction Tools	Usability	Scenario Building	usability test involves presenting representative end-users with scenarios, or specific tasks	Yes	Written Review	Any	Written Report	M	QL		L	L	No	Yes		High-Level/ Prelim
25	Human Computer Interaction Tools	Usability	Self-Reporting Logs	journaling session by user	Yes	Written Review	Any	Written Report	M	QL		L	L	No	Yes		Unit Testing
26	Human Computer Interaction Tools	Usability	Software Usability Measurement Inventory (SUMI)	Test user satisfaction: comprises a validated 50-item paper-based questionnaire in which respondents score each item on a three-point scale (i.e., agree, undecided, disagree). SUMI measures software quality from the end user's point of view. The questionnaire is designed to measure scales of: 1) Affect - the respondent's emotional feelings towards the software (e.g., warm, happy). 2) Efficiency - the sense of the degree to which the software enables the task to be completed in a timely, effective and economical fashion. 3) Learnability - the feeling that it is relatively straightforward to become familiar with the software. 4) Helpfulness - the perception that the software communicates in a helpful way to assist in the resolution of difficulties. 5) Control - the feeling that the software responds to user inputs in a consistent way and that its workings can easily be internalized. (Source: Porteous, Kirakowski and Corbett, 1993).	Yes	Questionnaire	Software	Written Report	M	QL	Human Factors Research Group (HFRG), University College, Cork	L	L	No	Yes		Software/ Hardware Development
27	Human Computer Interaction Tools	Usability	System Usability Scale (SUS)	10-item questionnaire that employs a Likert scale to obtain an overview of user satisfaction with software	Yes	Questionnaire	Any	Written Report	H	QL	John Brooke	L	L	No	Yes		Validation
28	Human Computer Interaction Tools	Usability	Usability Content Analysis	structured method for eliciting detailed information about a product and how it will be used, and for deriving a plan for a user based evaluation of a product. For this method stakeholders meet to detail the actual circumstances (or intended use) of a product. This is produced in a document called the Context Report Form, which is then examined by a usability consultant who decides who decides if each factor is indeed important for the usability of the product. Following this inspection, a summary list, called the Context of Evaluation, of these factors is produced. This list specifies important characteristics of the products' users, their tasks, their environment, and also lays the foundation for an observational evaluation.	Yes	Written Review	Any	Written Report	M	QL	Human Factors Research Group (HFRG), University College, Cork	L	L	No	Yes		Software/ Hardware Development
29	Human Computer Interaction Tools	Usability	Usability Problem Inspector (UPI)	inspection tool based on an organizing framework of usability concepts and issues. The UPI is intended to help inspectors conduct a highly	Yes	Written Review	Any	Written Report	H	QL		L	L	No	Yes		Unit Testing

#	FAA HF Tool Category	FAA HF Tool Subcategory	Specific Method/Tool	Description	Adaptable for Human Spaceflight?	Process/ Tool	Fields of Use (Aviation, Space, Nuclear..)	Outputs	Fidelity Level Req'd (H/M/L)	Outputs Quantitative/ Qualitative?	Who Created?	# of Resources Req'd (H/M/L)	Time Req'd to set-up? (H/M/L)	Computer Skills Required?	Still In Use?	Validated?	When Used in SE Design Process?
				focused inspection of a target application, resulting in a list of usability problems that users will potentially have with the application. The UPI brings together aspects of both the heuristic evaluation and the cognitive walkthrough. The UPI fits in between these two, capturing the ease of use of the heuristic evaluation, but also providing interaction-based structure from the cognitive walkthrough													
30	Human & System Performance Assessment Tools	Cognitive Testing	Armed Forces Qualification Test	This is a standardized test used by the military for screening basic enlisted members. It measures mechanical and mathematical aptitude. Scores are then used to place Army recruits into a military specialization	Yes	Standardized Test	Any	Test Score	H	QN	US Army	M	M	Minimum	Yes		Ops/ Maintenance
31	Human & System Performance Assessment Tools	Cognitive Testing	Boyett & Conn's White Collar Performance Measure	lists of performance measures to evaluate personnel in white collar organizations.	Yes	Written Review	Any	Written Report	H	QN	Boyett and Conn	L	L	No			Unit Testing
32	Human & System Performance Assessment Tools	Cognitive Testing	Complex Cognitive Assessment Battery	nine tests of higher cognitive functions. The tests include Tower Puzzle, Mark Numbers, Numbers and Words, Information Purchase, Route, Planning, and Missing Items. The PC-based software features the capability of customized test configurations, menu-driven software, repeated measures, variable levels of difficulty, and automated scoring and reporting. CCAB is written in the C programming language.	Yes	Software Tests	Any	Test Score	H	QN		M	M	Minimum, C	Yes	Yes	Ops/ Maintenance
33	Human & System Performance Assessment Tools	Function Allocation	Aviation Topics Speech Acts Taxonomy (ATSAT)	Baseline assessment of communications and assessment of communication errors: supports the encoding and hierarchical arrangement of operator and task performance. The encoded messages can be entered in a spreadsheet and be imported for statistical analysis. ATSAT uses the phraseology standard contained in FAA Order 7119.65 Handbook of Air Traffic Control.	Maybe	Assessment	Aviation	Statistical analysis	H	QN		M	M	Minimum			Conceptual
34	Human & System Performance Assessment Tools	Function Allocation	Cognitive Function Analysis	a methodology that enables a design team to understand better the right balance between cognitive functions that need to be allocated to human(s) and cognitive functions that can be transferred to machine(s). Cognitive functions are described by eliciting the following inputs: task requirements; users, background (skills and knowledge to cope with the complexity of the artifact to be controlled); users' own goals (intentional actions); and external events (reactive actions).	Yes	Written Report	Any	Written Report	L	QL		M	L	No	Yes		Conceptual
35	Human & System Performance Assessment Tools	Function Allocation	Decision Action Diagrams	These diagrams are similar to functional flows except that decision points are added. Each function is expressed as a "verb-noun" combination with occasional adjectives or other modifiers. Each decision point is placed in a diamond-shaped outline symbol and written in question form. The question must be binary, answerable by a "yes" or "no" response. Both functional action blocks and decision diamonds are labeled with reference numbers, similar to those used for functional flow diagrams. These are necessary to ensure traceability. It is used to show the flow of required system data, in terms of operations and decisions through a system. Like functional flow diagrams, decision/action diagrams may be developed and used at various levels of detail. Initial decision/action diagram charts are concerned with gross functions without regard to whether functions are performed by human, machine, software, or some combination of these. Decision/action diagrams prepared subsequent to tentative human-machine-software function allocations will reflect this allocation in the decisions, operations, and branching that are represented.	Yes	Written Report	Any	Written Report	L	QL		M	L	No	Yes		Conceptual
36	Human & System Performance Assessment Tools	Function Allocation	Decision Matrix for Allocation of Function	The chart below shows where the "goodness" in response to some performance demand is scaled from unsatisfactory (U) to excellent for both the human (h) and automation (a). Demands that fall	Yes	Written Report	Any	Written Report	L	QL		M	L	No	Yes		Conceptual

#	FAA HF Tool Category	FAA HF Tool Subcategory	Specific Method/Tool	Description	Adaptable for Human Spaceflight?	Process/ Tool	Fields of Use (Aviation, Space, Nuclear..)	Outputs	Fidelity Level Req'd (H/M/L)	Outputs Quantitative/ Qualitative?	Who Created?	# of Resources Req'd (H/M/L)	Time Req'd to set-up? (H/M/L)	Computer Skills Required?	Still In Use?	Validated?	When Used in SE Design Process?
				into the Uah region indicate the need for system redesign; those falling into the Uh or Ua regions are biased toward static allocation design perspectives favoring the machine or human, respectively; and demands in the Pa, Ph, and Pha (where both human and machine can perform the function reasonably well) regions will offer the most design options, including the potential for dynamic function allocation													
37	Human & System Performance Assessment Tools	Function Allocation	Fitts List	used to help determine the allocation of function between humans and machines. The technique involves comparing the capabilities of man and machine in terms of general task abilities, such as "data sensing," and "reacting to unexpected events." A list with comparative characteristics of man and machine was published by Fitts in 1951 and has subsequently been enhanced.	Yes	Reference	Any	Written Report	L	QL	Fitts	M	L	No	Yes (enhanced versions)		Conceptual
38	Human & System Performance Assessment Tools	Function Allocation	Functionality Matrix	displays the system functions that each user will require for the different tasks that they perform. Critical task functions are identified so that more time can be paid to them during usability testing later in the design process. This method is useful for systems where the number of possible functions is high and where the range of tasks that the user will perform is well specified. In these situations, the functionality matrix can be used to trade-off different functions, or to add and remove functions depending on their value for supporting specific tasks. It is also useful for multi-user systems to ensure that the tasks of each user type are supported. The steps in creating a functionality matrix are: 1) Identify user groups (or take from Form 3) and enter into matrix rows. 2) Identify tasks per user group and enter into matrix rows. 3) List potential functions and features and enter into matrix columns. 4) Identify functions which are critical to task. 5) Identify functions which are only occasionally used. 6) Add new functions or features as required to support gaps in tasks. 7) Remove functions that are not required. 8) Develop prototypes to help create more detailed user requirements specification.	Yes	Written Report	Any	Written Report	L	QL		M	L	No	Yes		Conceptual
39	Human & System Performance Assessment Tools	Function Allocation	Operational Sequence Diagrams (OSD)	graphic representation of operator tasks as they relate sequentially to both equipment and other operators. The OSD is essentially a flow process chart (FPC) expanded in terms of channels or workstations. By using symbology to indicate actions, inspections, data transmitted or received, data storage, or decisions, the OSD shows the flow of information through a system. The information flow is shown in relation to both time and space (workstations).	Yes	Diagramming	Any	Graphic	L	QL		M	M	Yes	Yes		Conceptual
40	Human & System Performance Assessment Tools	Function Allocation	Reliable Human Machine System Developer	a six-stage system engineering process, a cognitive model of the human, and operational sequence diagrams to assist the designer in developing human-machine interfaces subject to top-level reliability or yield requirements. Through its system engineering process, REHMS-D guides the designer through the understanding of customer requirements, the definition of the system, the allocation of human functions, the basic design of human functions, the assignment of job aids, and the design of tests to verify that the human functions meet the allocated reliability requirements. REHMS-D can be used for both the synthesis of new systems and the analysis of existing systems.	Yes	Written Report	Any	Written Report	L	QL		M	M	No			Conceptual
41	Human & System Performance Assessment Tools	Generic Performance Measurment	Air Crew Fatigue Avoidance Tool (FAST)	Software tool developed for the US Air Force to predict the joint effects of sleep schedule, sleep deprivation, and circadian variation on human performance.	Yes	Software	Aviation		M	QN		M	M	Yes			Software/ Hardware Development

#	FAA HF Tool Category	FAA HF Tool Subcategory	Specific Method/Tool	Description	Adaptable for Human Spaceflight?	Process/ Tool	Fields of Use (Aviation, Space, Nuclear..)	Outputs	Fidelity Level Req'd (H/M/L)	Outputs Quantitative/ Qualitative?	Who Created?	# of Resources Req'd (H/M/L)	Time Req'd to set-up? (H/M/L)	Computer Skills Required?	Still In Use?	Validated?	When Used in SE Design Process?
42	Human & System Performance Assessment Tools	Generic Performance Measurment	Behaviorally Based Performance Rating Scale	a research-oriented testing and assessment tool designed to measure the efficacy of new systems, system enhancements, and operational procedures in simulation research. The rating form can be applied to observable behaviors where subject matter experts rate the behavioral performance of operators. Intra-rater (within rater) reliability was for example assessed when supervisory air traffic control specialists SATCS used the technique (Vardaman & Stein, 1998). Raters were found to be stable over time in the ratings they assigned. Inter-rater (between rater) reliability of SATCS performance ratings were reported to be somewhat lower in that study. A relationship between SATCS performance ratings and personality traits from the Sixteen Personality Factor personality inventory was found.	Yes	Written Report	Any		M	QN		H	L	No			Software/ Hardware Development
43	Human & System Performance Assessment Tools	Generic Performance Measurment	Charlton's Measures of Human Performance in Space Control Systems	Attempts to measure human performance in space control operations using questionnaires.	Yes	Written Report	Space	Written Report	M	QN	Charlton	M	M	No	Yes		Software/ Hardware Development
44	Human & System Performance Assessment Tools	Generic Performance Measurment	Consistency Inspections	inspections are conducted to determine if multiple products from the same development effort are consistent in their design and operation.; involves a usability professional who analyzes the system to identify differences in design elements. Differences are then resolved through the use of design teams.	No. Not that relevant	Written Report	Any	Written Report	M	QL		H	L	No			Software/ Hardware Development
45	Human & System Performance Assessment Tools	Generic Performance Measurment	Distributed Cognition	An approach to studying all aspects of cognition. The most well known level of analysis is to account for complex socially distributed cognitive activities.	Not really	Written Report	Any		M	QL		H	L	No			Unit Testing
46	Human & System Performance Assessment Tools	Generic Performance Measurment	Eastman Kodak Company Measure for Handling Tasks	A series of 8 measures have been developed to assess human performance in repetitive assembly, packing, and handling.	No	Observation	Any	Written Report	M	QN	Eastman Kodak Company	M	M	No			Ops/ Maintenance
47	Human & System Performance Assessment Tools	Generic Performance Measurment	Environment Analysis	simply a description of the environment in which the activities or basic tasks will be performed. This information can be used to determine certain system characteristics that will be required to operate successfully. Wickens, Gordon, and Liu write, "If ATMs are to be placed indoors, environmental analysis would include a somewhat limited set of factors, such as type of access (e.g., will the locations be wheelchair accessible?), weather conditions (e.g., will it exist in a lobby type area with outdoor temperatures?), what type of clothing will people be wearing (i.e., will they be wearing gloves?)	Yes	Written Report	Any	Written Report	L	QL		L	L	No	Yes		Conceptual
48	Human & System Performance Assessment Tools	Generic Performance Measurment	FAA Behaviorally Based Rating Scale	a form consisting of 24 rating scales. These scales focus on observable actions that trained air traffic control specialists could use to make behaviorally based ratings of air traffic controller performance.	No	Questionnaire	Aviation	Test Score	H	QN	FAA	H	M	No	Yes		Ops/ Maintenance
49	Human & System Performance Assessment Tools	Generic Performance Measurment	Haworth-Newman Avionics Display Readability Scale	This scale is based on the Cooper Harper Scale, it is used to investigate displays.	Yes	Questionnaire	Aviation	Written Report	H	QN		M	M	No			Unit Testing
50	Human & System Performance Assessment Tools	Generic Performance Measurment	Mission Profile	Represents the events or situations that maintainers or operators could confront in a new system. Mission profiles are mostly applicable in the conceptual phase.	Yes	Written Report	Any	Written Report	L	QL	DoD	L	L	No			Conceptual

Note: This table only lists the first 50 of 405 methodologies. This keeps the documentation cleaner and easier to scan through for the committee to review. In the final dissertation, all 405 methodologies will be listed for completion.

Appendix A2. Accommodation versus utilization issues related to the spacecraft physical environment.

Spacecraft Physical Environment			
Spacecraft Design Choice	**Accommodate Issues**	**Utilize Issues**	**A or U**
Noise Level	Too noisy causes hearing loss (P_H)	Can't hear task feedback or critical alarms (C_D, C_S, C_V, Y_B, Y_A, Y_M)	A, U
Vibration Level	Too much vibration is uncomfortable, harmful, and deadly (P_F, P_D, P_P)	Can't see task procedures; can't press appropriate buttons/switches, can't execute task accurately (P_P, C_S, C_T)	A, U
Humidity Level	Too much humidity uncomfortable, and harmful cause overheating; too low humidity causes irritation from dryness; and encourages bacteria growth (P_I, P_D)	Can cause condensation and mold/bacteria growth on panels, causes sweating and can impact vision and require constant wiping (P_E,C_D,C_T)	A, U
CO_2 Level	Too much causes headache, nausea, and can be fatal (P_I, P_D)	Cause slow thinking, bad decision-making, and unconsciousness/death (C_S, C_P, C_M, C_E, C_F, C_A)	A, U
Atmospheric Particulates	Too much causes headache, respiration problems, coughing, sneezing, or itchy eyes; far too much can cause breathing problems and can be fatal, also encourages bacterial growth (P_I, P_D)	Reduce visibility, affect respiration, eye irritant (C_S)	A, U
Acceleration/Gravity Level	Too much causes loss of consciousness leading to death, 0g impacts physiological systems (P_C, P_X)	High acceleration reduces vision and motion and can cause unconsciousness; low acceleration causes physiological changes (C_S, C_E)	A, U
Toxic Substance Level	Too much will be fatal (P_D, P_H, P_R, P_I)	Too much causes headaches and poor performance (C_P, C_E, S_H)	A, U
Lighting (Ambient)	Too dark or too bright strains eyesight (P_E, Y_A Y_M)	Too dark can't see work (C_S, Y_A, Y_M)	A, U
Temperature	Too cold causes frostbite and hypothermia to death; too hot causes overheating, heat stroke to death (P_C, P_D, P_R, Y_M)	Too cold, work sluggishly, too hot, work sluggishly, also frustrating in heat (C_S, C_E, C_A, Y_A, Y_B)	A, U
Air Flow	No air flow causes CO2 pockets without O2 which is fatal (P_B, P_C, P_D, P_N, P_X, Y_M)	Can't take away heat and CO_2 from body causes discomfort and death (C_S, C_P, C_M, Y_A)	A, U
Oxygen Level	No O2 causes death; too much high risk for fire and oxygen toxicity (P_C, P_R)	Can't work without oxygen (C_S, C_P, C_M, C_E, Y_A)	A
Odor	Foul odors cause discomfort and possible nausea; no scents become boring and sterile (P_D, Y_M)	Too much highly distracting (C_S, Y_A)	A, U
Atmospheric Pressure Level	Too low, blood boils and no O_2 exchange with alveoli (P_C, P_X)	Too low can't function (C_D)	A, U
Radiation Exposure Level	Lowest is best; medium to high can cause DNA breakage and onset of cancer; too high will cause radiation poisoning or kill immediately (P_B, P_C, P_D, P_I, P_R, P_N)	Too high can cause nausea and death (C_S, Y_A)	A, U

Table A2. Accommodation versus utilization issues related to the spacecraft architecture.

Spacecraft Architecture			
Spacecraft Design Choice	**Accommodate Issues**	**Utilize Issues**	**A or U**
Arrangement of Functional Areas	Can be frustrating looking at mess or clutter (Y_M)	Inefficient arrangements reduce workflow, reduce productivity, cause potential injury or strain from non-ergonomic or task-related motions, or just bumping into objects that are poorly placed (Y_B, Y_A, Y_M)	A, U
Presence of Location Aids		No location aids cause inefficient workflow; poorly placed ones can cause confusion and increase task time and frustration of crew (Y_A, Y_B)	U
Availability of Hatches		Limited hatches can cause bottleneck of movement; most important is during emergency egress and having enough to allow for timely escape as needed; also needs to be easily removable so it doesn't trap	U

		the crew inside the vehicle or make it too strenuous to open and close (Y_B, Y_A)	
Anthropometric Accommodations	Must fit the crew members; poor fit causes ergonomic problems resulting in stresses and injury and potential disability to the crew (P_B, P_C, P_M, P_P)	Bad fit can cause injury or strain and inability to accomplish task (C_E, Y_B, Y_A)	A, U
Access to Work Items		Must be accessible and easily to access especially for safety critical items that need to be used in a timely fashion (Y_A, Y_B)	U
Support of Traffic Flow, Translation Paths	Bad flow of movement cause frustration or lack of access (Y_M)	Poor flow causes inefficiency (C_D, Y_A, Y_M)	U
Availability of Windows	Without windows reduced morale and satisfaction (Y_M)	May need them for achieving tasks (like docking, landing) (Y_S, Y_M)	U
Safety Accommodations		Needed to accomplish safety tasks (Y_B, Y_A)	A, U

Table A3. Accommodation versus utilization issues related to the spacecraft habitability.

Habitability			
Spacecraft Design Choice	**Accommodate Issues**	**Utilize Issues**	**A or U**
Microorganism Virulence	Too many microorganisms cause diseases (P_I, P_D)	Disease cause low morale, physical discomfort that can reduce performance of a task (C_T, Y_B)	A, U
Inventory Management Capability		Good IMC helps improve efficiency; bad IMC causes frustration and reduced performance (Y_B, Y_A)	U
Habitable Volume	Affects morale and entertainment of crew (Y_B, Y_A, Y_M)	Good HV increases happiness and improves moods and productivity, but bad HV can stifle happiness, productivity, and creativity; also too little HV can affect ability to do task (Y_M)	A, U
Confinement	Lower confinement improves psychological issues -this is evolutionarily motivated (Y_M, Y_B)	Has a latent impact due to psychology on motivation (Y_B, Y_M, Y_A)	A
Level of Sensory Stimulation	Lowers morale and happiness levels (P_R, Y_M)	Minimal sensory stimulation may cause slower recognition of stimulus when doing a task (C_S, C_P, C_E, C_A)	A, U
Availability of Personal Items	Personal items are important for psychological well-being (Y_M)		A
Availability of Medical Care		For critical emergencies, medical needs must be available (Y_A)	U
Cleanliness of Environment	Lack of cleanliness can impact overall psychological problems also increase bacterial and disease exposure to crew (P_C, Y_M)	Poor cleanliness can cause inoperability of workspace (i.e. sticky keyboards, dirty vents) (Y_A, Y_M)	A
Food System	No food provision will cause starvation for longer duration missions (>days) (P_D, P_B, P_C, Y_M)	Without food or even with lackluster food less motivation and ability to execute tasks (P_C, C_S, C_P, C_M, C_E, C_L, C_R, Y_A, Y_M)	A, U
Nutrition	Not enough nutrition will cause weakness, lower immune strength, malnutrition, and starvation (P_D, P_B, P_C, P_I, P_H, N_B, P_V)	Lower energy reduces performance capability (P_C, C_S, C_P, C_M, C_E, C_L, C_R, Y_M, Y_A, Y_M)	A
Availability of Private Space	Helps improve psychology (Y_B, Y_A, Y_M)		A
Availability of Recreation/Personal Activities	Helps improve psychology (Y_B, Y_A, Y_M)		A
Décor of Environment	Helps improve psychology (Y_B, Y_A, Y_M)		A
Hygiene Support	Impacts on health and enjoyment of space and crew members (Y_B, Y_A, Y_M)		A

Table A4. Accommodation versus utilization issues related to the spacecraft user interfaces.

User Interfaces			
Spacecraft Design Choice	**Accommodate Issues**	**Utilize Issues**	**A / U**
Mobility Aids & Restraints Availability & Quality		Improves physical performance and efficiency for getting around (C_P, Y_A)	U
Information Displays/Decision Aids		Good displays help make tasks more efficient, and bad displays can cause fatal errors (C_P, C_T, Y_B, Y_M, Y_A)	U

Control Panels/Input Devices		Good control systems help with task efficiency; bad controls can cause fatal errors (C_P, C_T, C_D, Y_B, Y_M, Y_A)	U
Situation-Specific Lighting	Dim or no lighting for sleep, need full light spectrum for health including Vitamin D (P_B, P_C)	Good lighting helps get the task accomplished; bad lighting can cause fatal errors and prevent completion of task (C_S, C_A)	U
Human/Vehicle Automation Integration		Good integration causes improved performance; bad integration causes accidents (C_T, C_L, C_A, Y_B, Y_M, Y_A)	U
Human/Robotics Integration		Good integration helps performance; bad integration causes accidents (C_T, C_L, C_A, Y_B, Y_M, Y_A)	U
Caution & Warning Functionality		Good caution and warning helps identify issues and allows crew to solve them properly; bad capability causes accidents (C_T, C_L, C_M, C_V, C_D, C_P, Y_A, Y_B)	U
Range of Motion Accommodations	Must design for all possible range of human body movement (or lack thereof) (P_P, P_B, P_C, P_M)	Must design for human body to execute tasks otherwise cause injury, disability or fatal accidents (C_D, C_E, Y_B, Y_M, Y_A)	A, U
Body Surface Area, Volume, & Mass Props Accommodations	Must design for human body sizes; otherwise can cause discomfort, pain, or injury (P_C, P_B, P_M)	Need this info for developing the appropriate operations/tasks (C_S, Y_A)	A, U
Suit Design	Poor suit design causes discomfort, pain, or injury (P_F, P_B, P_C, P_D)	Need good suit design for optimizing crew's capabilities (P_F, P_C, C_S, Y_A, Y_M)	A, U
Identifiability		Similar to info display must be done well to help improve task performance (C_P, Y_B)	U
Standardization		Easier for crew to identify and memorize various tasks and hardware types to improve efficiency and reduce errors (C_S, C_P, C_M, C_T, C_L, C_B, Y_B, Y_M, Y_A)	U
Hardware Tool Availability		Makes it easy to do task (Y_B, Y_M, Y_A)	U
Hardware Ease of Use		Makes it easy to do task (Y_B, Y_M, Y_A)	U
Software Ease of Use		Makes it easy to do task and make updates as needed (Y_B, Y_M, Y_A)	U
Information Management Support		Makes it easy to execute tasks (Y_B, Y_M, Y_A)	U
Orientation of User Interfaces		Makes it easy to accomplish tasks (if standardized) (C_S, C_P, Y_M, Y_A)	U
Reach Envelope Accommodations		Must be accounted for to allow human to execute tasks (P_P, P_B)	U
Strength Accommodations		Must be accounted for to allow human to execute tasks (P_P, P_B)	U

APPENDIX A3. SPACECRAFT DESIGN CHOICES TO CREW PERFORMANCE IMPACT MAPPING

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Acceleration/Gravity Level	1g (no differences)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Acceleration/Gravity Level	0g-5g exposure	-0.003	-0.001	-0.001	-0.001	0	0	0	-0.001	-0.001	-0.001	-0.001	-0.001	0	0	0	0	0	-0.001	-0.001	-0.001	-0.001	0	0	0	0	0
Acceleration/Gravity Level	>5g exposure	-0.003	-0.002	-0.002	-0.002	0	0	0	-0.002	0	-0.002	-0.002	-0.002	0	0	0	0	0	-0.002	-0.002	-0.002	-0.002	0	0	0	0	0
Acceleration/Gravity Level	Fatal	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Oxygen Level	Earth-like level (20.95%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oxygen Level	Hyperoxia (>21%) Oxygen Toxicity	0	-0.001	-0.001	0	0	0	0	0	-0.001	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oxygen Level	Hypoxic < ppO2 = 2.1psi	0	-0.001	-0.001	-0.001	0	-0.001	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Oxygen Level	Fatal <10-13%	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Atmospheric Pressure Level	Normal Atmospheric Level (14.7 psia)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atmospheric Pressure Level	5-10 psi	0	0	0	0	-0.001	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atmospheric Pressure Level	<5 psi	0	0	0	0	-0.002	0	0	0	0	0	0	-0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atmospheric Pressure Level	Lethal <.91 psi	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Habitable Volume	Ample Space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Habitable Volume	Suitable Space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Habitable Volume	Minimal Space	-0.001	-0.001	0	0	0	0	0	-0.001	0	-0.001	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Habitable Volume	Too small (human can't fit)	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Confinement	Can do as many EVA's for enjoyment not just work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Confinement	Can do some EVA's for enjoyment not just work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Confinement	Minimum EVA only as needed	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Confinement	Total Confinement (no leaving vehicle)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Level of Sensory Stimulation	High sensory stimulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Level of Sensory Stimulation	Medium sensory stimulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Level of Sensory Stimulation	Low sensory stimulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Level of Sensory Stimulation	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Availability of Medical Care	Level of Care 3-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Availability of Medical Care	Level of Care 1-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Availability of Medical Care	Level of Care 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Availability of Medical Care	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Food System	Fresh, large variety of food	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Food System	Packaged food	-0.001	-0.001	-0.001	0	0	-0.001	-0.001	-0.001	-0.001	0	0	-0.001	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Food System	Not enough food	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Food System	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Hygiene Support	Normal facilities for hygiene support	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hygiene Support	ISS style	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Hygiene Support	Apollo style	0	0	-0.001	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Hygiene Support	None	0	0	-100	0	0	0	-100	0	0	0	0	0	0	-0.900	-0.900	-0.900	-0.900	-0.900	-0.900	-0.900	-0.900	-0.900	-0.900	-0.900	-0.900	-0.900
Water System (CF added)	Good tasting water and easy to access	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water System (CF added)	Acceptable water quality and ease of access	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water System (CF added)	Minimal water quality hard to access	0	0	-0.001	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Water System (CF added)	None	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Countermeasure Hardware	Adequate & easy/fun/reliable to use	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Countermeasure Hardware	A few available	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Countermeasure Hardware	Minimal countermeasures to lessen degradation	-0.001	-0.001	0	0	0	0	-0.001	-0.001	-0.001	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Countermeasure Hardware	None	-0.002	-0.002	0	0	0	0	-0.002	-0.002	-0.002	0	0	0	-0.002	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
CO2 Level	Low (ppCO2 < 3.8 mmHg (0.5%))	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CO2 Level	Avg (ppCO2 <7.6 mmHg) (1%)	-0.001	-0.001	-0.001	0	0	-0.001	0	0	-0.001	0	0	0	-60	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
CO2 Level	High (>13000ppm/24 hr, >7000ppm/180 days) (>3%)	-0.002	-0.002	-0.002	-0.001	-8.000	-0.002	0	0	-0.002	0	-0.001	-0.001	-60	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.002	-0.002	-0.002
CO2 Level	Fatal (>40,000ppm) (>219mmHg) (>30%)	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Radiation Exposure Level	<10,000 mrem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Radiation Exposure Level	>5,000 mrem/yr	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0
Radiation Exposure Level	>50,000 mrem/yr, 100 rem single dose	-100	-100	-100	0	0	0	-100	0	-100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-100	-100	-100
Radiation Exposure Level	Fatal >/= 500 rem single dose	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Arrangement of Functional Areas	Easy movement & dynamically reconfigurable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Arrangement of Functional Areas	Moderately reconfigurable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Arrangement of Functional Areas	Fixed, with large obstructions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Arrangement of Functional Areas	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Availability of Hatches	Available in all emergency situations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Availability of Hatches	Available for highest probability emergencies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0
Availability of Hatches	Available for ingress/egress	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0
Availability of Hatches	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.003	-0.001
Availability of Windows	Several available	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Availability of Windows	Moderate # of windows	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Availability of Windows	Minimal Small Windows	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Availability of Windows	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Safety Accommodations	Several safety provisions (for hazards >25% chance)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Safety Accommodations	Moderate # of provisions (for hazards >75% chance)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	0

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Safety Accommodations	Minimal # of provisions (for hazards >90% chance)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	0
Safety Accommodations	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	0
Nutrition	Good nutrition	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nutrition	Mediocre nutrition	-0.001	0	-0.001	0	0	-0.001	-0.001	-0.001	-0.001	0	0	-0.001	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Nutrition	Minimal nutrition	-0.002	0	-0.002	0	0	-0.002	-0.002	-0.002	-0.002	0	0	-0.002	0	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
Nutrition	Fatal (missing important nutrients)	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Human/Vehicle Automation Integration	Dynamic and adaptable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Human/Vehicle Automation Integration	Assisted integration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Human/Vehicle Automation Integration	Minimal integration (Separate systems)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Human/Vehicle Automation Integration	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Human/Robotics Integration	Dynamic and adaptable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Human/Robotics Integration	Assisted integration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Human/Robotics Integration	Minimal integration (Separate systems)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Human/Robotics Integration	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Body Surface Area, Volume, & Mass Properties	Dynamically accommodated	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body Surface Area, Volume, & Mass Properties	Acceptable consideration	0	0	0	-0.001	0	0	0	-0.001	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Body Surface Area, Volume, & Mass Properties	Poorly considered	0	0	0	-0.002	0	0	0	-0.002	0	-0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Body Surface Area, Volume, & Mass Properties	Not considered	0	0	0	-0.003	0	0	0	-0.003	0	-0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Noise Level	Below NASA 3001 Noise Requirements	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Noise Level	Meets minimum NASA 3001 Noise Requirements	0	0	0	0	-0.001	0	0	0	0	0	-0.001	0	0	-0.001	-0.001	-0.001	0	0	0	0	0	-0.001	0	-0.001	-0.001	-0.001
Noise Level	Noise >200 Pa (160dBA)	0	0	0	0	-100	0	0	0	0	0	-0.002	0	0	-0.002	-0.002	-0.002	0	0	0	0	0	-100	0	-0.002	-0.002	-0.002
Noise Level	Fatal (>200dBA)	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Vibration Level	Minimal vibration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Vibration Level	Short period, short bursts (~3.9-5.2 m2/s RMS)	0	0	0	-0.001	0	0	0	0	0	0	0	-0.001	0	0	0	0	0	-0.001	0	0	0	-0.001	0	0	0	-0.001
Vibration Level	Excessive Vibration (>5.2 m2/s RMS)	-0.001	0	-0.001	-0.002	0	0	0	-0.001	-0.001	0	0	-0.001	0	0	0	0	0	-0.002	-0.001	0	0	-0.002	0	-0.001	0	-0.002
Vibration Level	Fatal	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Humidity Level	Ideal (20-75%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Humidity Level	Dry <20% Humidity	0	0	0	0	0	-0.001	-0.001	0	0	0	0	-0.001	-0.001	0	0	0	0	-0.001	0	0	0	0	0	-0.001	0	-0.001
Humidity Level	High (>75% Humidity)	0	-0.001	0	0	0	-0.001	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	-0.001	0	-0.001
Humidity Level	Unregulated	0	-0.002	-0.001	0	0	-0.002	0	0	0	0	0	0	-0.002	-0.001	-0.001	-0.001	-0.001	0	0	0	0	-0.001	0	-0.900	-0.900	-0.900
Atmospheric Particulates	Low to None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atmospheric Particulates	Acceptable Level of Particulates	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atmospheric Particulates	Sometimes Exceeds Acceptable Levels of Particulates	0	0	-0.001	0	-0.001	0	-0.001	0	0	0	0	-0.001	-0.001	0	0	0	0	-0.001	0	0	-0.001	-0.001	0	-0.001	-0.001	-0.001
Atmospheric Particulates	Very High Level of Particulates	0	0	-0.002	0	-0.002	0	-0.002	0	0	0	0	-0.002	-0.002	0	0	0	0	-0.002	0	0	-0.002	-0.002	0	-0.002	-0.002	-0.002
Toxic Substance Level	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Toxic Substance Level	Acceptable Toxic Substance Level	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Toxic Substance Level	High Toxic Substance Level	0	-0.001	-0.001	-0.001	0	-0.001	-0.001	0	-0.001	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	0	0	-0.001
Toxic Substance Level	Fatal	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Lighting (Ambient)	Dynamically matching lighting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lighting (Ambient)	Acceptable lighting levels	0	0	0	0	0	-0.001	0	0	0	0	0	-0.001	0	0	0	0	0	-0.001	0	0	0	-0.001	0	-0.001	0	-0.001
Lighting (Ambient)	Too little light for operations or comfort	-0.001	0	0	0	0	-0.002	0	0	0	0	0	-0.002	0	0	0	0	0	-0.002	0	0	0	-0.002	0	-0.002	0	-0.002
Lighting (Ambient)	None	-0.002	0	0	0	0	-0.003	0	0	0	0	0	-0.900	0	0	0	0	-0.001	-0.900	0	0	0	-0.003	0	-0.003	-0.001	-0.003
Temperature	Room Temp (57-75*F)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature	Below Room Temp (32*F<57*F)	0	-0.001	0	-0.001	0	-0.001	-0.001	0	-0.001	0	0	0	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Temperature	Greater than Room Temp (75*F)	0	-0.001	-0.001	-0.001	0	-0.001	0	0	-0.001	0	0	0	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Temperature	Fatal (>212*F, <-100*F for long periods of time)	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Air Flow	Optimal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Air Flow	Low Ventilation	0	-0.001	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Air Flow	High Ventilation	0	0	0	0	0	0	-0.001	0	0	0	0	-0.001	-0.001	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Air Flow	None (Fatal due to CO2)	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Odor	Minimal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Odor	Somewhat	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Odor	Overwhelming	0	0	-0.900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.900	-0.900	-0.900
Odor	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Presence of Location Aids	Available and appropriately located	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Presence of Location Aids	Limited location aids	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	0	0	-0.001	-0.001	-0.001
Presence of Location Aids	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	0	0	-0.002	-0.002	-0.002
Presence of Location Aids	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Anthropometric Accommodations	Appropriately accommodated	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Anthropometric Accommodations	Minimally Accommodated	-0.001	-0.001	0	-0.001	0	0	0	-0.001	0	-0.001	0	0	0	0	0	0	-0.001	0	-0.001	0	0	0	0	-0.001	-0.001	-0.001
Anthropometric Accommodations	Not Accommodated	-0.002	-0.002	0	-0.002	0	0	0	-0.002	0	-0.002	0	0	0	0	0	0	-0.002	0	-0.002	0	0	0	0	-0.002	-0.002	-0.002
Anthropometric Accommodations	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Access to Work Items	Easy access and appropriate location of work items	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Access to Work Items	Mostly accessible work items	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Access to Work Items	Obstructed access to work items	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Access to Work Items	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Support of Traffic Flow, Translation Paths	Acceptable support for traffic flow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Support of Traffic Flow, Translation Paths	Minimal support for traffic flow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Support of Traffic Flow, Translation Paths	No support for traffic flow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Support of Traffic Flow, Translation Paths	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Microorganism Virulence	Acceptable level	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microorganism Virulence	Sometimes exceeds acceptable levels	0	0	-0.001	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001
Microorganism Virulence	Lethal	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Microorganism Virulence	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Inventory Management Capability	Clear, intuitive, well-marked, standardized	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inventory Management Capability	Partly available (not for all items)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Inventory Management Capability	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Inventory Management Capability	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Availability of Personal Items	As many momentos as can be brought (~10kg)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Availability of Personal Items	Limited to weight of 5 kg/crew	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Availability of Personal Items	Limited to weight of 1 kg/crew	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Availability of Personal Items	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Cleanliness of Environment	Clean	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cleanliness of Environment	Workable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cleanliness of Environment	Dirty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Cleanliness of Environment	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Availability of Private Space	Ample	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Availability of Private Space	Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Availability of Private Space	Minimal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Availability of Private Space	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Availability of Recreation/Personal Activities	Ample recreational/personal activities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Availability of Recreation/Personal Activities	Handful recreational/personal activities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Availability of Recreation/Personal Activities	Limited recreational/personal activities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Availability of Recreation/Personal Activities	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Décor of Environment	Good positive décor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Décor of Environment	Medium décor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Décor of Environment	Minimal décor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Décor of Environment	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Mobility Aids & Restraints Availability & Quality	Appropriately placed and easy to use	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mobility Aids & Restraints Availability & Quality	Mostly available and somewhat easy to use	-0.001	0	0	0	0	0	0	-0.001	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Mobility Aids & Restraints Availability & Quality	Minimally available and okay to use	-0.002	0	0	0	0	0	0	-0.002	0	-0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Mobility Aids & Restraints Availability & Quality	None	-0.003	0	0	0	0	0	0	-0.003	0	-0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Information Displays/Decision Aids	Helpful and Intuitive Displays	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Information Displays/Decision Aids	Somewhat helpful and usable displays	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0
Information Displays/Decision Aids	Minimally helpful displays	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Information Displays/Decision Aids	None	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
Control Panels/Input Devices	Helpful and Intuitive Devices	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Control Panels/Input Devices	Somewhat helpful and usable devices	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Control Panels/Input Devices	None	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
Control Panels/Input Devices	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Situation-Specific Lighting	Appropriate lighting for specific situations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Situation-Specific Lighting	Minimal lighting for specific situations	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0	0	-0.001	0	-0.001	0	-0.001	-0.001	0	0	-0.001	-0.001	-0.001
Situation-Specific Lighting	None	0	0	0	0	0	0	0	0	0	0	0	-100	0	0	0	-100	0	-100	0	-100	-100	0	0	-0.900	-0.900	-0.900
Situation-Specific Lighting	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Caution & Warning Functionality	Clear, intuitive, standardized	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Caution & Warning Functionality	Helpful & appropriate for most systems	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Caution & Warning Functionality	Difficult to understand, non-standard, limited	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	-0.001	-0.001	-0.001
Caution & Warning Functionality	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0	0	0	-0.001	0	-0.002	-0.002	-0.002
Range of Motion Accommodations	Dynamically accommodated	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Range of Motion Accommodations	Acceptably accommodated	0	0	0	-0.001	0	0	0	-0.001	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	-0.001	-0.001
Range of Motion Accommodations	Poorly accommodated	0	0	0	-0.002	0	0	0	-0.002	0	-0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	-0.002	-0.002
Range of Motion Accommodations	Not considered	0	0	0	-0.003	0	0	0	-0.003	0	-0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	-0.003	-0.003
Suit Design	Easy don-doff; prevents injury; flexible	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Suit Design	Moderate don-doff & flexibility; prevents some injury	-0.001	-0.001	0	-0.001	-0.001	0	0	-0.001	0	-0.001	0	-0.001	-0.001	0	0	0	-0.001	-0.001	-0.001	0	-0.001	0	0	-0.001	-0.001	-0.001
Suit Design	Hard to don-doff; high injury rate	-0.002	-0.002	0	-0.002	-0.002	0	0	-0.002	0	-0.002	0	-0.002	-0.002	0	0	0	-0.002	-0.002	-0.002	0	-0.002	0	0	-0.002	-0.002	-0.002
Suit Design	None	-0.003	-0.003	0	-0.003	-0.003	0	0	-0.003	0	-0.003	0	-0.003	-0.003	0	0	0	-0.003	-0.003	-0.003	0	-0.003	0	0	-0.003	-0.003	-0.003
Identifiability	Easily identifiable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Identifiability	Moderately identifiable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0	-0.001	-0.001	-0.001	0	-0.001	-0.001	0	0	0
Identifiability	Hard to identify	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0	-0.002	-0.002	-0.002	0	-0.002	-0.002	0	0	0
Identifiability	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Standardization	All systems standardized	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Standardization	Most systems standardized	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	-0.001	-0.001	-0.001	-0.001	0	0	0	-0.001	-0.001	-0.001
Standardization	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	-0.002	-0.002	-0.002	-0.001	0	0	0	-0.002	-0.002	-0.002
Standardization	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Hardware Tool Availability	Easily available hardware	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hardware Tool Availability	Mostly available hardware	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	-0.001	-0.001	-0.001
Hardware Tool Availability	Hard to find	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0	0	0	0	0	-0.002	-0.002	-0.002
Hardware Tool Availability	None Available	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.003	0	0	0	0	0	0	-0.003	-0.003	-0.003

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Hardware Ease of Use	Easy, Intuitive	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hardware Ease of Use	Acceptable Quality	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	-0.001	-0.001	-0.001
Hardware Ease of Use	Difficult to use, non-intuitive	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0	0	0	0	0	-0.002	-0.002	-0.002
Hardware Ease of Use	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Software Ease of Use	Easy, Intuitive	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Software Ease of Use	Acceptable quality	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	-0.001	-0.001	-0.001
Software Ease of Use	High-learning curve, non-intuitive, not commented	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0	0	0	0	0	-0.002	-0.002	-0.002
Software Ease of Use	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Information Management Support	Clear intuitive information conveyed	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Information Management Support	Exists	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	-0.001	-0.001	-0.001
Information Management Support	None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0	0	0	0	0	-0.002	-0.002	-0.002
Information Management Support	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Orientation of User Interfaces	Clear, intuitive, standard orientation of interfaces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Orientation of User Interfaces	Non-standard interfaces	0	0	0	0	0	0	0	0	0	0	-0.001	0	0	0	-0.001	0	0	-0.001	0	-0.001	-0.001	0	0	-0.001	0	-0.001
Orientation of User Interfaces	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Orientation of User Interfaces	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Reach Envelope Accommodations	Dynamically matches crew reach envelope	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reach Envelope Accommodations	Mostly matches crew reach envelope	0	0	0	0	0	0	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0
Reach Envelope Accommodations	Not designed for crew reach envelope	0	0	0	0	0	0	0	0	0	-0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0
Reach Envelope Accommodations	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Strength Accommodations	Dynamically matches crew strength	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Strength Accommodations	Mostly matches crew strength	0	0	0	-0.001	0	0	0	-0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.001	0	0
Strength Accommodations	Not matched to crew strength	0	0	0	-0.002	0	0	0	-0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.002	0	0

Spacecraft Design Choices to Crew Performance Impact Mapping		Physiological													Cognitive										Psychological		
		PB(t) = Bone Strength	PC(t) = Cardiovascular System	PD(t) = Digestion	PF(t) = Fine Motor Control	PH(t) = Hearing	PR(t) = Hormones	PI(t) = Immune System	PM(t) = Muscle Strength	PN(t) = Nervous System	PP(t) = Proprioceptive Posture	PV(t) = Vestibular System	PE(t) = Vision	PX(t) = VO2 Max	CR(t) = Abstract Reasoning	CB(t) = Abstraction	CE(t) = Emotion Identification	CD(t) = Risk Decision Making	CT(t) = Scanning & Visual Tracking	CS(t) = Sensory-Motor Speed	CL(t) = Spatial Learning & Memory	CP(t) = Spatial Orientation	CV(t) = Vigilant Attention	CM(t) = Working Memory	YB(t) = Behavior	YA(t) = Attitude	YM(t) = Mood/Emotion
Strength Accommodations	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

APPENDIX A4. SPACECRAFT DESIGN CHOICE AFFECTING ACTIVITY DIFFICULTY.

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance					Operations					Payload					Housekeeping					
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Acceleration/Gravity Level	1g (no differences)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Acceleration/Gravity Level	0g-5g exposure	2	2	2	2	2	2	2	2	2	2	1	2	2	2	2	1	2	2	2	2	2
Acceleration/Gravity Level	>5g exposure	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	2	3	3	3	3	3
Acceleration/Gravity Level	Fatal	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Oxygen Level	Earth-like level (20.95%)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oxygen Level	Hyperoxia (>21%) Oxygen Toxicity	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
Oxygen Level	Hypoxic < ppO2 = 2.1psi	2	1	2	2	1	1	2	1	1	2	2	2	2	2	3	2	2	2	2	2	2
Oxygen Level	Fatal <10-13%	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Atmospheric Pressure Level	Normal Atmospheric Level (14.7 psia)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Atmospheric Pressure Level	5-10 psi	2	1	2	2	1	1	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Atmospheric Pressure Level	<5 psi	3	1	3	3	1	1	3	1	1	3	3	3	3	3	3	3	3	3	3	3	3
Atmospheric Pressure Level	Lethal <.91 psi	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Habitable Volume	Ample Space	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Habitable Volume	Suitable Space	1	1	1	2	2	2	1	1	1	1	1	1	1	1	2	1	2	2	2	2	2
Habitable Volume	Minimal Space	1	1	1	3	3	3	1	2	2	2	1	2	1	1	3	1	3	3	3	3	3
Habitable Volume	Too small (human can't fit)	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Confinement	Can do as many EVA's for enjoyment not just work	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Confinement	Can do some EVA's for enjoyment not just work	1	1	1	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Confinement	Minimum EVA only as needed	1	1	1	3	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Confinement	Total Confinement (no leaving vehicle)	1	1	1	-3	1	5700	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Level of Sensory Stimulation	High sensory stimulation	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Level of Sensory Stimulation	Medium sensory stimulation	1	1	2	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Level of Sensory Stimulation	Low sensory stimulation	1	1	3	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Level of Sensory Stimulation	None	1	1	-3	1	1	-3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance					Operations					Payload						Housekeeping				
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Availability of Medical Care	Level of Care 3-5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Medical Care	Level of Care 1-2	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Medical Care	Level of Care 0	1	1	1	1	1	1	1	3	5700	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Medical Care	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Food System	Fresh, large variety of food	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Food System	Packaged food	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Food System	Not enough food	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Food System	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Hygiene Support	Normal facilities for hygiene support	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hygiene Support	ISS style	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1
Hygiene Support	Apollo style	1	1	2	2	3	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1
Hygiene Support	None	1	1	3	3	5700	1	1	1	1	1	1	1	1	1	1	1	5700	1	1	1	1
Water System (CF added)	Good tasting water and easy to access	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Water System (CF added)	Acceptable water quality and ease of access	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Water System (CF added)	Minimal water quality hard to access	1	2	2	1	2	1	1	2	2	1	1	1	1	1	1	1	2	2	2	1	1
Water System (CF added)	None	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Countermeasure Hardware (exercise, Penguin suit) (CF added)	Adequate countermeasures and easy/fun/reliable to use	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Countermeasure Hardware (exercise, Penguin suit) (CF added)	A few countermeasures to maintain baseline threshold	1	1	1	2	1	2	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Countermeasure Hardware (exercise, Penguin suit) (CF added)	Minimal countermeasures to lessen degradation	1	1	1	3	1	3	1	3	3	2	1	1	1	1	1	1	1	1	1	1	1
Countermeasure Hardware (exercise, Penguin suit) (CF added)	None	1	1	2	5700	1	5700	1	-3	-3	3	1	1	1	1	1	1	1	1	1	1	1
CO2 Level	Low (ppCO2 < 3.8 mmHg (0.5%))	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CO2 Level	Avg (ppCO2 <7.6 mmHg) (1%)	2	1	2	2	1	1	2	2	2	2	2	2	2	2	2	2	1	2	2	2	2

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance					Operations						Payload					Housekeeping				
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
CO2 Level	High (>13000ppm/24 hr, >7000ppm/180 days) (>3%)	2	1	3	3	2	2	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3
CO2 Level	Fatal (>40,000ppm) (>219mmHg) (>30%)	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Radiation Exposure Level	<10,000 mrem	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Radiation Exposure Level	>5,000 mrem/yr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Radiation Exposure Level	>50,000 mrem/yr, 100 rem single dose (Acute Radiation Syndrome)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Radiation Exposure Level	Fatal >/= 500 rem single dose	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Arrangement of Functional Areas	Easy flow of motion and dynamically reconfigurable	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Arrangement of Functional Areas	Moderately reconfigurable	1	1	1	1	1	1	1	2	2	1	1	2	1	1	2	1	2	2	2	2	2
Arrangement of Functional Areas	Fixed, with large obstructions	1	1	1	1	1	1	1	3	3	1	1	3	1	1	3	1	3	3	3	3	3
Arrangement of Functional Areas	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Availability of Hatches	Available in all emergency situations	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Hatches	Available for highest probability emergencies	1	1	1	1	1	1	1	2	2	1	1	2	1	1	1	1	1	2	2	2	2
Availability of Hatches	Available for ingress/egress	1	1	1	1	1	1	1	3	3	1	1	3	1	1	1	1	1	3	3	3	3
Availability of Hatches	None	1	1	1	1	1	1	1	5700	5700	1	1	-3	1	1	1	1	1	-3	-3	-3	-3
Availability of Windows	Several available	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Windows	Moderate # of windows	1	1	1	1	1	2	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1
Availability of Windows	Minimal Small Windows	1	1	1	1	1	3	1	2	2	2	1	2	3	1	1	1	1	1	1	1	1
Availability of Windows	None	1	1	1	1	1	-3	1	3	3	3	1	3	-3	1	1	1	1	1	1	1	1
Safety Accommodations	Several safety provisions (for hazards >25% probability)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Safety Accommodations	Moderate # of safety provisions (for hazards >75% probability)	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Safety Accommodations	Minimal # of safety provisions (for hazards >90% probability)	1	1	1	1	1	1	1	3	3	1	1	1	1	1	1	1	1	1	1	1	1
Safety Accommodations	None	1	1	1	1	1	1	1	5700	5700	1	1	1	1	1	1	1	1	1	1	1	1
Nutrition	Good nutrition	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance					Operations					Payload						Housekeeping				
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Nutrition	Mediocre nutrition	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nutrition	Minimal nutrition	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nutrition	Fatal (missing important nutrients in diet)	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Human/Vehicle Automation Integration	Dynamic Integration (monitors and adapts to changing roles)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Human/Vehicle Automation Integration	Assisted Integration (Human and vehicle work together as initially designed)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Human/Vehicle Automation Integration	Minimal Integration (Separate systems)	1	1	1	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1	1	1	1
Human/Vehicle Automation Integration	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Human/Robotics Integration	Dynamic Integration (monitors and adapts to changing roles)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Human/Robotics Integration	Assisted Integration (Human and vehicle work together as initially designed)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Human/Robotics Integration	Minimal Integration (Separate systems)	1	1	1	1	1	1	1	2	2	2	1	2	1	2	1	1	1	1	1	1	1
Human/Robotics Integration	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Body Surface Area, Volume, & Mass Properties	Dynamically accommodated	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Body Surface Area, Volume, & Mass Properties	Acceptable consideration	1	1	1	1	1	1	2	2	2	1	1	2	1	1	2	1	1	1	1	1	1
Body Surface Area, Volume, & Mass Properties	Poorly considered	1	1	1	1	1	1	3	3	3	1	1	3	1	1	3	1	1	1	1	1	1
Body Surface Area, Volume, & Mass Properties	Not considered	1	1	1	1	1	1	-3	-3	-3	1	1	-3	1	1	-3	1	1	1	1	1	1
Noise Level	Below NASA 3001 Noise Requirements	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Noise Level	Meets minimum NASA 3001 Noise Requirements	1	1	1	1	1	2	2	2	2	2	1	2	2	1	1	1	1	1	1	1	1
Noise Level	Noise >200 Pa (160dBA)	1	2	2	2	2	3	3	3	3	3	2	3	3	2	2	2	2	2	2	2	2
Noise Level	Fatal (>200dBA)	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Vibration Level	Minimal vibration	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Vibration Level	Short period, short bursts (~3.9-5.2 m2/s RMS)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
Vibration Level	Excessive Vibration (>5.2 m2/s RMS)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance					Operations					Payload					Housekeeping					
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Vibration Level	Fatal	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	3
Humidity Level	Dry <20% Humidity	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Humidity Level	Ideal (20-75%)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Humidity Level	High (>75% Humidity)	2	2	2	2	2	2	2	2	2	2	1	2	1	1	2	1	2	2	2	2	2
Humidity Level	Unregulated	3	3	3	3	3	3	3	3	3	3	1	3	1	1	3	1	3	3	3	3	3
Atmospheric Particulates	Low to None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Atmospheric Particulates	Acceptable Level of Particulates	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Atmospheric Particulates	Sometimes Exceeds Acceptable Levels of Particulates	2	2	2	2	1	2	2	2	2	2	1	2	1	2	2	1	2	1	1	1	1
Atmospheric Particulates	Very High Level of Particulates	3	3	3	3	2	3	3	3	3	3	2	3	2	3	3	2	3	2	2	2	2
Toxic Substance Level	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Toxic Substance Level	Acceptable Toxic Substance Level	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Toxic Substance Level	High Toxic Substance Level	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Toxic Substance Level	Fatal	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Lighting (Ambient)	Dynamically matching lighting	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Lighting (Ambient)	Acceptable lighting levels	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Lighting (Ambient)	Too little light for operations or comfort	1	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Lighting (Ambient)	None	1	3	3	3	3	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Temperature	Room Temp (57-75*F)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Temperature	Below Room Temp (32*F<57*F)	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Temperature	Greater than Room Temp (75*F)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Temperature	Fatal (>212*F, <-100*F for long periods of time)	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Air Flow	Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Air Flow	Low Ventilation	2	1	1	2	2	2	2	1	1	1	1	1	1	1	2	1	2	1	1	2	2
Air Flow	High Ventilation	2	1	1	1	1	2	2	1	1	1	1	1	1	1	2	1	2	1	1	1	1
Air Flow	None (Fatal due to CO2)	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Odor	Minimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance							Operations					Payload					Housekeeping				
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Odor	Somewhat	2	2	2	2	1	2	2	2	2	2	1	2	2	1	2	1	2	1	1	1	1
Odor	Overwhelming	3	3	3	3	1	3	3	3	3	3	1	3	3	1	3	1	3	1	1	1	1
Odor	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Presence of Location Aids	Available and appropriately located	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Presence of Location Aids	Limited location aids	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Presence of Location Aids	None	1	1	1	1	1	1	1	3	3	1	1	1	1	1	1	1	1	1	1	1	1
Presence of Location Aids	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Anthropometric Accommodations	Appropriately accommodated	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Anthropometric Accommodations	Minimally Accommodated	1	1	1	2	1	2	2	2	2	2	1	2	1	1	2	1	2	2	2	2	2
Anthropometric Accommodations	Not Accommodated	1	1	1	3	1	3	3	3	3	3	1	3	1	1	3	1	3	3	3	3	3
Anthropometric Accommodations	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Access to Work Items	Easy access and appropriate location of work items	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Access to Work Items	Mostly accessible work items	1	1	1	1	1	1	1	2	2	1	1	2	1	1	2	1	2	2	2	2	2
Access to Work Items	Obstructed access to work items	1	1	1	1	1	1	1	3	3	1	1	3	1	1	3	1	3	3	3	3	3
Access to Work Items	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Support of Traffic Flow, Translation Paths	Acceptable support for traffic flow	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Support of Traffic Flow, Translation Paths	Minimal support for traffic flow	1	1	1	1	1	1	1	2	2	1	1	2	1	1	1	1	1	1	1	1	1
Support of Traffic Flow, Translation Paths	No support for traffic flow	1	1	1	1	1	1	1	3	3	1	1	3	1	1	1	1	1	1	1	1	1
Support of Traffic Flow, Translation Paths	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Microorganism Virulence	Acceptable level	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Microorganism Virulence	Sometimes exceeds acceptable levels	2	2	2	2	2	1	2	1	1	1	2	1	2	1	2	1	2	2	2	2	2
Microorganism Virulence	Lethal	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700	5700
Microorganism Virulence	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance							Operations					Payload					Housekeeping				
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Inventory Management Capability	Clear, intuitive, well-marked, standard inventory management	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Inventory Management Capability	Some inventory management available (not for all items)	1	1	1	1	1	1	1	2	2	2	2	1	2	1	1	2	1	2	2	2	2
Inventory Management Capability	None	1	1	1	1	1	1	1	3	3	3	3	1	3	1	1	3	1	3	3	3	3
Inventory Management Capability	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Availability of Personal Items	As many momentos as can be brought (~10kg)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-3	1	1	1	1
Availability of Personal Items	Limited to weight of 5 kg/crew	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1
Availability of Personal Items	Limited to weight of 1 kg/crew	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1
Availability of Personal Items	None	1	1	1	1	1	-3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Cleanliness of Environment	Clean	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Cleanliness of Environment	Workable	1	1	1	1	2	2	1	2	2	2	1	2	2	1	2	1	2	2	2	2	2
Cleanliness of Environment	Dirty	1	1	2	1	3	3	1	3	3	3	1	3	3	1	3	1	3	3	3	3	3
Cleanliness of Environment	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Availability of Private Space	Ample	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Private Space	Average	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Private Space	Minimal	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Private Space	None	1	1	1	1	1	3	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Recreation/Personal Activities	Ample recreactional/personal activities	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Recreation/Personal Activities	Handful recreational/personal activities	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Recreation/Personal Activities	Limited recreational/personal activities	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Availability of Recreation/Personal Activities	None	1	1	1	1	1	5700	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Décor of Environment	Good positive décor	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Décor of Environment	Medium décor	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Décor of Environment	Minimal décor	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Décor of Environment	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance					Operations					Payload					Housekeeping					
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Mobility Aids & Restraints Availability & Quality	Appropriately placed and easy to use	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mobility Aids & Restraints Availability & Quality	Mostly available and somewhat easy to use	1	1	1	2	2	2	2	2	2	2	1	2	2	1	2	1	2	2	2	2	2
Mobility Aids & Restraints Availability & Quality	Minimally available and okay to use	1	1	1	3	3	3	3	3	3	3	1	3	3	1	3	1	3	3	3	3	3
Mobility Aids & Restraints Availability & Quality	None	1	1	1	-3	-3	-3	-3	-3	-3	-3	1	-3	-3	1	-3	1	-3	-3	-3	-3	-3
Information Displays/Decision Aids	Helpful and Intuitive Displays	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Information Displays/Decision Aids	Somewhat helpful and usable displays	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	1	2	2	2	2
Information Displays/Decision Aids	Minimumlly helpful displays	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	1	3	3	3	3
Information Displays/Decision Aids	None	1	1	1	1	1	1	1	-3	-3	-3	-3	-3	-3	-3	-3	-3	1	-3	-3	-3	-3
Control Panels/Input Devices	Helpful and Intuitive Devices	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Control Panels/Input Devices	Somewhat helpful and usable devices	1	1	1	1	1	1	1	2	2	2	1	2	1	2	1	1	1	1	1	1	1
Control Panels/Input Devices	None	1	1	1	1	1	1	1	3	3	3	1	3	1	3	1	1	1	1	1	1	1
Control Panels/Input Devices	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Situation-Specific Lighting	Appropriate lighting for specific situations	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Situation-Specific Lighting	Minimal lighting for specific situations	1	2	2	1	2	1	1	2	2	2	1	2	2	2	2	1	2	2	2	2	2
Situation-Specific Lighting	None	1	3	3	2	3	2	1	3	3	3	1	3	3	3	3	1	3	3	3	3	3
Situation-Specific Lighting	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Caution & Warning Functionality	Clear, intuitive, standard caution and warning for all relevant systems	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Caution & Warning Functionality	Helpful and appropriate caution and warnings for most relevant systems	1	1	1	1	1	1	1	1	1	1	2	1	2	2	1	1	1	2	2	2	2
Caution & Warning Functionality	Difficult to understand, non-standard, and limited caution and warnings	1	1	1	1	1	1	1	2	2	2	3	2	3	3	2	1	1	3	3	3	3
Caution & Warning Functionality	None	1	1	1	1	1	1	1	3	3	3	-3	3	-3	-3	3	1	1	-3	-3	-3	-3
Range of Motion Accommodations	Dynamically accommodated	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Range of Motion Accommodations	Acceptably accommodated	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance							Operations					Payload				Housekeeping				
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habit at Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Range of Motion Accommodations	Poorly accommodated	1	1	1	2	2	1	1	2	2	2	1	2	1	1	2	1	2	2	2	2	2
Range of Motion Accommodations	Not considered	1	1	1	3	3	1	1	3	3	3	1	3	1	1	3	1	3	3	3	3	3
Suit Design	Easy don-doff; prevents injury; easy manuever and flexibility	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Suit Design	Moderate don-doff; prevents some injury; can be manuevered and somewhat flexible	1	1	1	1	1	1	1	2	2	1	1	2	1	1	2	1	1	2	2	2	2
Suit Design	Hard to don-doff; high injury rate	1	1	1	1	1	1	1	3	3	1	1	3	1	1	3	1	1	3	3	3	3
Suit Design	None	1	1	1	1	1	1	1	-3	-3	1	1	-3	1	1	-3	1	1	-3	-3	-3	-3
Identifiability	Easily identifiable	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Identifiability	Moderately identifiable	1	1	1	1	1	1	1	2	2	1	1	2	2	1	2	1	2	2	2	2	2
Identifiability	Hard to identify	1	1	1	1	1	1	1	3	3	1	1	3	3	1	3	1	3	3	3	3	3
Identifiability	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Standardization	All systems standardized	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Standardization	Most systems standardized	1	1	1	1	1	1	1	2	2	1	1	2	2	1	2	1	2	2	2	2	2
Standardization	None	1	1	1	1	1	1	1	3	3	1	1	3	3	1	3	1	3	3	3	3	3
Standardization	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Hardware Tool Availability	Easily available hardware	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hardware Tool Availability	Mostly available hardware	1	1	1	1	1	1	1	2	2	1	1	2	1	1	2	1	2	2	2	2	2
Hardware Tool Availability	Hard to find	1	1	1	1	1	1	1	3	3	1	1	3	1	1	3	1	3	3	3	3	3
Hardware Tool Availability	None Available	1	1	1	1	1	1	1	-3	-3	1	1	-3	1	1	-3	1	-3	-3	-3	5700	5700
Hardware Ease of Use	Easy, Intuitive	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hardware Ease of Use	Acceptable Quality	1	1	1	1	1	1	1	2	2	2	1	2	1	2	2	1	1	2	2	2	2
Hardware Ease of Use	Difficult to use, non-intuitive	1	1	1	1	1	1	1	3	3	3	1	3	1	3	3	1	1	3	3	3	3
Hardware Ease of Use	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Software Ease of Use	Easy, Intuitive	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Software Ease of Use	Acceptable quality	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	1	1	2	2	2	2
Software Ease of Use	High-learning curve, non-intuitive, not commented	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	1	1	3	3	3	3

Spacecraft Design Choice Affecting Activity Difficulty		Self-Sustenance							Operations					Payload					Housekeeping				
		Breathing	Drinking	Eating	Exercise	Hygiene Activities	Leisure Activities	Sleeping	Contingency Operations	Emergency Operations	Flight Control	Mission Planning &	Robotic/Habitat Operations	Systems Monitoring	Spacecraft Navigation	Execute Experiments	Manage Science	Cleaning Spacecraft	Maintain Operational	Maintain Science	Repair Operational	Repair Science Hardware
Software Ease of Use	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Information Management Support	Clear intuitive information conveyed	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Information Management Support	Exists	1	1	1	1	1	1	1	2	2	1	2	1	2	1	1	2	1	2	2	2	2
Information Management Support	None	1	1	1	1	1	1	1	3	3	1	3	1	3	1	1	3	1	3	3	3	3
Information Management Support	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Orientation of User Interfaces	Clear, intuitive, standard orientation of interfaces	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Orientation of User Interfaces	Non-standard interfaces	1	1	1	1	1	1	1	2	2	2	1	2	1	2	2	1	1	2	2	2	2
Orientation of User Interfaces	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Orientation of User Interfaces	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Reach Envelope Accommodations	Dynamically matches crew reach envelope	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Reach Envelope Accommodations	Mostly matches crew reach envelope	1	1	1	1	1	1	1	2	2	2	1	2	1	1	2	1	2	2	2	2	2
Reach Envelope Accommodations	Not designed for crew reach envelope	1	1	1	2	2	1	1	3	3	3	1	3	1	1	3	1	3	3	3	3	3
Reach Envelope Accommodations	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Strength Accommodations	Dynamically matches crew strength	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Strength Accommodations	Mostly matches crew strength	1	2	2	2	2	2	1	2	2	2	1	2	1	1	2	1	2	2	2	2	2
Strength Accommodations	Not matched to crew strength	1	3	3	3	3	3	1	3	3	3	1	3	1	1	3	1	3	3	3	3	3
Strength Accommodations	N/A	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

APPENDIX A5. MATLAB SCRIPT FOR CREW PERFORMANCE MODEL

```
% Solve the system of equations to find performance metrics v. time as
%   described by Fanchiang --> Run Monte Carlo Simulation to Optimize Design
clear all
close all
%% Import the matrices defined in excel

num_of_crew = 1; % define number of crewmembers
num_performance_elements = 26; % define number of crewmember performance resource elements
num_crew_activity_type = 21; % define number of activity types for the crewmembers
num_design_choices = 1; %define number of design spacecraft design choices to compare
num_design_parameters =43;
num_mission_days = 180; %number of mission days
design_input_length = 172;
vehicle_environment = 2; % choose vehicle environment (1 = 1 gravity, 2 = 0 gravity, 3 = hypergravity)

% Set the time units by changing these two variables (make sure they match)
time_unit =24; % Set this time unit as the scaling for the time axis (24*30=by months, 24=by days, 1 = by
hours)
x_label ='t, day'; % t, hr, day, month
total_mission_time = 24*num_mission_days/time_unit; % Specify total mission length by 24hrs x # of mission days

% load the design to crew mapping matrix
Design2CrewImpact_Mapping = xlsread('Design2CrewPerformance_Mapping.xlsx',1,'A1:Z228');
% Design2CrewImpact_Mapping =10*Design2CrewImpact_Mapping;
Design2CrewImpact_Mapping(design_input_length,:) = NaN*ones(1,num_performance_elements);

% load the design to task mapping matrix
Design2Task_Mapping = xlsread('Design2Task_Mapping.xlsx');
Design2Task_Mapping(design_input_length,:) = NaN*ones(1,num_crew_activity_type);

% load the task to crew mapping matrix
Task2Crew_Mapping = xlsread('Task2CrewPerformance.xlsx');% Uncomment this!
% Task2Crew_Mapping = 10*Task2Crew_Mapping;
% Task2Crew_Mapping(228,:) = NaN*ones(1,26); % Uncomment this!
% Task2Crew_Mapping = zeros(21,26); % Specify Task Mapping % Comment this out!

% Generate task time histories
Crew_Task_Function1day = xlsread('TaskFunction.xlsx','NoTasks'); % Imports TaskFunction list for 1 CM
Crew_Task_Function = repmat(Crew_Task_Function1day,num_mission_days,1);


% Generate Crew Time Degredation due to vehicle environment

if vehicle_environment == 1;
    Crew_Time_Degredation_Array =
{@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(
t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0};
    Crew_Time_Degredation = @(t)cellfun(@(f)f(t),Crew_Time_Degredation_Array);

elseif vehicle_environment == 2;
    Crew_Time_Degredation_Array = {@(t)-8.848303-7.824956*erf((t-3.695185)/1.473982)-0.889235*erf((t-
9.548112)/2.805284),@(t)-(3.666537+5.665088*erf((t-0.164422)/0.268212)+2.469145*erf((t-
0.348657)/3.991582)),@(t)-2*t,@(t)-2*t,@(t)-2*t,@(t)-2*t,@(t)-2*t,@(t)-9.323626-8.414837*erf((t-
2.898860)/1.584169)-1.365004*erf((t-6.670830)/4.679852),@(t)-2*t,@(t)-2*t,@(t)-2*t,@(t)-2*t,@(t)-2*t,@(t)-
4*t,@(t)-4*t,@(t)-4*t,@(t)-4*t,@(t)-4*t,@(t)-4*t,@(t)-4*t,@(t)-4*t,@(t)-4*t,@(t)-
4*t,@(t)10*cos(2*pi*t*3/(4*(num_mission_days/30)))+5-4*t,@(t)10*cos(2*pi*t*3/(4*(num_mission_days/30)))+5-
4*t,@(t)10*cos(2*pi*t*3/(4*(num_mission_days/30)))+5-4*t};
    Crew_Time_Degredation = @(t)cellfun(@(f)f(t),Crew_Time_Degredation_Array);

elseif vehicle_environemtn == 3;
    Crew_Time_Degredation_Array =
{@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(
t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0,@(t)0};
    Crew_Time_Degredation = @(t)cellfun(@(f)f(t),Crew_Time_Degredation_Array);
end

% Crew_Time_Degradation_Array = xlsread('Time_Degradation.xlsx');% Import time degradation, assume linear:
                      % Metrics = Degredation*t


% Remove Nan Values
a = [isnan(Design2CrewImpact_Mapping(:,1)),[1:design_input_length]'];
```

```
a(a(:,1) == 0,:) = [];
Design_Mapping_Nan_Removed = Design2CrewImpact_Mapping;
Design_Mapping_Nan_Removed(a(:,2),:) = [];

Design2Task_Mapping(a(:,2),:) = [];

%% Specify time vectors and input

N = num_crew_activity_type; % Number of tasks
time_vec = linspace(0,24*num_mission_days,24*num_mission_days); % Specify time range (assume 1 day of 24 hrs to
start)
time_step = time_vec(2) - time_vec(1); % Initialize time step



%% Random Design Generator
% Randomly pick input vectors and solve system to optimize baseline
for n = 1:num_design_choices;%1e5 % Setup Monte Carlo for the number of design choices

    for j=1:num_of_crew;
%     Time_Degradation = Crew_Time_Degradation(:,j);

    Task_Function = (Crew_Task_Function(:,1+num_crew_activity_type*(j-1):num_crew_activity_type*j))';

        for i = 1:num_design_parameters % Number of input design parameters
            Input = zeros(1,4); %Initialize input matrix
            %Generate two vectors
            if n == 1
                Index = 1;%randi(4);
            elseif n == 2
                Index = 2;
            else
                Index = randi(2); % Generate random
            end

                % If NaN value is present indicating no choice, re-select
                if isnan(Design2CrewImpact_Mapping(4*i-3+(Index-1),1))
                    while isnan(Design2CrewImpact_Mapping(4*i-3+(Index-1),1))
                        Index = randi(4);
                    end
                end

            Input(Index) = 1; % Set value from index to 1, leave rest zero
            Sample_Vector(4*i-3:4*i) = Input; % Note that this sample vector could be specified (this is the
design)

        end

        % Remove the NaN rows %%%%
            Sample_Vector(a(:,2)) = [];
        %%%%%%%%


    %%%%%%%%%%%%%%%%%%% Run this Portion if you specify Design Vector and Comment out n for loop and random
design generator (ctrl-r/ctrl-t) %%%%%%%%
    % Solve System
    % Computes Baseline Decay due to Vehicle Design Selection
    Design_Vector(:,n) = Sample_Vector';
    Baseline_Metrics = Sample_Vector*Design_Mapping_Nan_Removed;
    Initial_Baseline_Metrics(:,n,j) = 100 + Baseline_Metrics';

    % Determine the design to task weighting coefficients
    Design_Task_Weights =
(Sample_Vector*Design2Task_Mapping)'*ones(1,num_performance_elements)/num_design_parameters; % Divide by 57 to
make degradation amount set to 1 if design induces no change
    Task2Crew_Mapping_Weighted = Task2Crew_Mapping.*Design_Task_Weights; % Re-Scale Task Mapping Matrix by
Design to Task weighting coefficients

    Task_Decay = zeros(1,num_performance_elements); % Initialize Task Function
    Baseline_Decay = zeros(1,num_performance_elements); % Initialize Baseline Decay

    %Propogate forward in time
        for t = 1:length(time_vec);
             Baseline_Decay = Baseline_Decay + Baseline_Metrics*time_step;
             Task_Decay = Task_Decay + (Task_Function(:,t)')*Task2Crew_Mapping_Weighted*time_step; %Find Task
Function effect running sum over time expired
```

```
            temp = Baseline_Decay' + Task_Decay' + Crew_Time_Degredation(time_vec(t)/(24*30))';
            %temp(temp+100>100)=0;

            Time_Metrics(:,t,n,j) =  temp; % Find time dependent metrics (divide time vec by hours/month)

        end

    Performance(:,n,j) = 100 + squeeze(Time_Metrics(:,end,n,j)); %Capture end of mission performance

    end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end

%% Plot Results

% % Examine final mission performance factor
% figure('position',[50 50 1000 300])
%
% color_vec = {'ok','xk','ob','xb','or','xr'};
% for j = 1:num_of_crew
%     for i = 1:n
%         plot(1:num_performance_elements,squeeze(Performance(:,i,j)),char(color_vec(j*2-1))); %Plot end of
mission performance
%         set(gca,'XTick',[1:num_performance_elements]);
%         hold on
%
%         plot(1:num_performance_elements,squeeze(Initial_Baseline_Metrics(:,i,j)),char(color_vec(j*2)));
%     end
% end
%
set(gca,'XTickLabel',{'P_B','P_C','P_D','P_F','P_H','P_R','P_I','P_M','P_N','P_P','P_V','P_E','P_X','C_R','C_B'
,'C_E','C_D','C_T','C_S','C_L','C_P','C_V','C_M','Y_B','Y_A','Y_M'}');
% axis([0 num_performance_elements+1 -10 150])
% ylabel('Baseline, %')
% grid on
%
% plot([0,num_performance_elements+1],[0,0],'r','linewidth',2)
% hold off
%
% p=legend('Crew1_F','Crew1_0', 'Crew2_F', 'Crew2_0', 'Crew3_F', 'Crew3_0');
% set(p,'location','eastoutside')


% Examine time history of single mission performance factor
% Plots physiology performance factors for all crewmembers
for i = 1:n
    figure('name','Physiolgical Performance','position',[0 0 500 1000])
    for k = 1:num_of_crew
        for j = 1:13
                subplot(3,1,k);plot(time_vec/time_unit,100 + squeeze(Time_Metrics(j,:,i,k)));
                hold on
        end

        axis([0 total_mission_time -10 150])
        xlabel(x_label)
        ylabel('Physiological Performance, %')
        grid on
        subplot(3,1,k);plot(time_vec/time_unit,100+mean(squeeze(Time_Metrics(1:13,:,i,k))),'--
k','linewidth',2);
        subplot(3,1,k);plot([0,total_mission_time],[0,0],'r','linewidth',2)

        h=legend('P_B','P_C','P_D','P_F','P_H','P_R','P_I','P_M','P_N','P_P','P_V','P_E','P_X','mean');
        set(h,'location','eastoutside')

        Phy_design_crew_mean(k,:,i) = 100+mean(squeeze(Time_Metrics(1:13,:,i,k)));
    end
end

% Plots cognitive performance metrics for all crewmembers
for i = 1:n
    figure('name','Cognitive Performance','position',[500 0 500 1000])
    for k = 1:num_of_crew
        for j = 14:23
                subplot(3,1,k);plot(time_vec/time_unit,100 + squeeze(Time_Metrics(j,:,i,k)));
                hold on
        end
            axis([0 total_mission_time -10 150])
```

```
            xlabel(x_label)
            ylabel('Cognitive Performance, %')
            grid on
            subplot(3,1,k);plot(time_vec/time_unit,100+mean(squeeze(Time_Metrics(14:23,:,i,k))),'--
k','linewidth',2);
            subplot(3,1,k);plot([0,total_mission_time],[0,0],'r','linewidth',2)

            h=legend('C_R','C_B','C_E','C_D','C_T','C_S','C_L','C_P','C_V','C_M','mean');
            set(h,'location','eastoutside')

            Cog_design_crew_mean(k,:,i) = 100+mean(squeeze(Time_Metrics(14:23,:,i,k)));
    end
end

% Plots psychological metrics for all crewmembers
for i = 1:n
    figure('name','Psychological Performance','position',[1000 0 500 1000])
    for k = 1:num_of_crew
        for j = 24:26
                subplot(3,1,k);plot(time_vec/time_unit,100 + squeeze(Time_Metrics(j,:,i,k)));
                hold on
        end
            axis([0 total_mission_time -10 150])
            xlabel(x_label)
            ylabel('Psychological Performance, %')
            grid on
            subplot(3,1,k);plot(time_vec/time_unit,100+mean(squeeze(Time_Metrics(24:26,:,i,k))),'--
k','linewidth',2);
            subplot(3,1,k);plot([0,total_mission_time],[0,0],'r','linewidth',2)

            h=legend('Y_B','Y_A','Y_M','mean');
            set(h,'location','eastoutside')

            Psy_design_crew_mean(k,:,i) = 100+mean(squeeze(Time_Metrics(24:26,:,i,k)));
    end
end
hold on;

%% Plot Means
% if num_of_crew ==2 && num_design_choices ==3;
%         color_vec = {'sk', '-sr','ok', 'or', 'xk', 'xr'};
%
% elseif num_of_crew ==1 && num_design_choices ==3;
%         color_vec = {'ok', 'or','ob'};
%
% else
%         color_vec = {'-sk','-sr','-sb','-ok','-or','-ob','-k','-xr','-xb'};
% end
color_vec = {'-k','-r','-b','--k','--r','--b','-.k','-.r','-.b'};

figure('name','Physiological Performance Means','position',[0 0 500 350])
for i = 1:n
    for k = 1:num_of_crew
        clean_phy_mean = smooth(Phy_design_crew_mean(k,:,i),72);
        plot(time_vec/time_unit,clean_phy_mean,char(color_vec(3*i-3+k)),'linewidth',1);
        hold on
    end
end
axis([0 total_mission_time -10 150]);
grid on
plot([0,total_mission_time],[0,0],'r','linewidth',2)
xlabel(x_label)
ylabel('Mean Physiological Performace')
h =
legend('Crew1_{n=1}','Crew2_{n=1}','Crew1_{n=2}','Crew2_{n=2}','Crew1_{n=3}','Crew2_{n=3}');%,'Crew1_{n=3}','Cr
ew2_{n=3}','Crew3_{n=3}');
set(h,'location','eastoutside')

figure('name','Cognitive Performance Means','position',[500 0 500 350])
for i = 1:n
    for k = 1:num_of_crew
        clean_cog_mean = smooth(Cog_design_crew_mean(k,:,i),72);
        plot(time_vec/time_unit,clean_cog_mean,char(color_vec(3*i-3+k)),'linewidth',1);
        hold on
    end
end
axis([0 total_mission_time -10 150]);
grid on
plot([0,total_mission_time],[0,0],'r','linewidth',2)
```

```
xlabel(x_label)
ylabel('Mean Cognitive Performance, %')
h =
legend('Crew1_{n=1}','Crew2_{n=1}','Crew1_{n=2}','Crew2_{n=2}','Crew1_{n=3}','Crew2_{n=3}');%,'Crew1_{n=3}','Cr
ew2_{n=3}','Crew3_{n=3}');
set(h,'location','eastoutside')

figure('name','Psychological Performance Means','position',[1000 0 500 350])
for i = 1:n
    for k = 1:num_of_crew
        clean_psy_mean = smooth(Psy_design_crew_mean(k,:,i),72);
        plot(time_vec/time_unit,clean_psy_mean,char(color_vec(3*i-3+k)),'linewidth',1);
        hold on
    end
end
axis([0 total_mission_time -10 150]);
grid on
plot([0,total_mission_time],[0,0],'r','linewidth',2)
xlabel(x_label)
ylabel('Mean Psychological Performance, %')
% h =
legend('Crew1_{n=1}','Crew2_{n=1}','Crew3_{n=1}','Crew1_{n=2}','Crew2_{n=2}','Crew3_{n=2}');%,'Crew1_{n=3}','Cr
ew2_{n=3}','Crew3_{n=3}');
h =
legend('Crew1_{n=1}','Crew2_{n=1}','Crew1_{n=2}','Crew2_{n=2}','Crew1_{n=3}','Crew2_{n=3}');%,'Crew1_{n=3}','Cr
ew2_{n=3}','Crew3_{n=3}');
set(h,'location','eastoutside')
```