EVALUATION AND AUTOMATION OF SPACE HABITAT INTERIOR LAYOUTS

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EVALUATION AND AUTOMATION OF HABITAT INTERIOR LAYOUTS

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NOMENCLATURE

Acronyms

ACO = Ant Colony Optimization

AHP = Analytic Hierarchy Process

ANP = Analytic Network Process

CAD = Computer Aided Design

ECLSS = Environmental Control and Life Support Systems

EVA = Extravehicular Activity

EXAMINE= Exploration Architecture Model for IN-space and Earth-to orbit (Parametric Sizing Tool)

GA = Genetic Algorithms

GN&C = Guidance Navigation and Control

ISA-GJK = Incremental Separating Axis – Gilbert, Johnson, and Keerthi

ISS = International Space Station

IVA = Intravehicular Activity

JSC = Johnson Space Center (NASA center)

LDW = Logical Decisions for Windows®

LEO = Low Earth Orbit

LER = Lunar Excursion Rover

LSS = Lunar Surface Systems

MAUT = Multi-Attribute Utility Theory

MCDM = Multi-Criteria Decision Making

ORU = Orbital Replacement Unit

PCM = Pressurized Crew Module (LSS)

PEM = Pressurized Excursion Module (LSS)

PLM = Pressurized Logistics Module (LSS)

PSO = Particle Swarm Optimization

SA = Simulated Annealing

SUF = Single-measure Utility Function, or Single-attribute Utility Function

SUW = Structural Unit Weight (kg/m^2)

TCS = Thermal Control System

WCS = Waste Collection System

VLSI = Very Large Scale Integration

Symbols

A = layout A

ΔC = change in objective function simulated annealing

D = Euclidean distance matrix

$D_{red,\ eval}$ = reduced Euclidean distance matrix for separation and collocation measure of an evaluation criterion

d_{ij} = Euclidean distance measure between item i and item j

i = an index for the evaluation criteria

L = evaluation criteria value or level

n = normal vector

ω = Constant augmenting PSO velocity update (inertia term)

$p1$ or $p2$ = points in space

P_{accept} = Probability to accept a new solution in simulated annealing

P_j = Penalty function enforcing constraint j

ϕ_{gbest} = Constant augmenting global component of PSO velocity update

ϕ_{pbest} = Constant augmenting personal component of PSO velocity update

R = relationships matrix

rand () = Random number between 0 and 1

r_{ij} = measure of relationship between item i and item j

T = temperature in simulated annealing

U_i = individual utility function of i-th evaluation criterion value

V = particle velocity

w_i = weightings the i-th subcriterion

w_{ij} = weightings of the weighted adjacency matrix of the pair of items i and j

X_i = *i-th evaluation criterion value*

X_{best} = best possible value of evaluation criterion value y

X_{worst} = worst possible value of evaluation criterion value y

Y = overall objective function value

SUMMARY

Designing habitats for crewed in-space or planetary surface missions is a complex, highly constrained task with many conflicting objectives. This process involves four iterative steps: selecting mission-appropriate interior equipment and accommodations, sizing the habitat geometry, arranging this equipment within the habitat geometry into habitat layouts, and evaluating the design. The third step of this process, which is often overlooked in the conceptual phase of habitat design, seeks to ensure that the interior equipment required for a crewed mission can be physically accommodated while providing the best compromise between engineering and crew performance metrics such as mass, volume, packaging efficiency, workflow efficiency, volume quality, and habitability. At the conceptual phase of design, developing layouts which balance these concerns is necessary to identify feasibility issues, safety concerns, or requirements violations before they result in expensive design changes, increased mass growth, or reduced functionality.

Current methods for evaluating the goodness of these layouts involve human-in-the-loop mockup tests, in-depth CAD (Computer Aided Design) evaluations, or unrepeatable, subjective design evaluation studies. However, these methods are not currently compatible with the conceptual phase of design or optimization because of the significant time required to generate and evaluate even one layout. They also lack a comprehensive set of evaluation metrics which capture all the listed concerns. In order to support the mass, cost and volume-constrained long duration human missions to asteroids, the Moon, and Mars, improvements to the currently available habitat layout evaluation methods which can lead to faster generation and evaluation of layouts are needed. Additionally, because the development of an overall habitat design optimization capability is strongly desired, a habitat interior layout automation capability must be developed.

The objective of this research is to develop a new evaluation methodology for habitat interior layouts which speeds and expands the current layout evaluation process and enables consideration of interior layout automation. After researching the underlying causes for the limitations of the current interior layout evaluation methods, two key contributions were identified which can enable the desired improvements. The first is a restructuring of the evaluation process using systems engineering methods to construct a comprehensive quickly calculable multi-objective function capturing designer preferences and critical constraints. The second contribution is the development of a new, comprehensive set of automatically calculable evaluation criteria which capture the full range of habitability, workflow, and volumetric efficiency considerations. The automatic calculation of these criteria values is enabled by the development of new analytical and numerical calculation methods utilizing separation/collocation matrices, collision detection algorithms, and numerical grid-based iterative calculation methods. By applying these features, this new habitat layout evaluation method can extend the state-of-the-art design capability by enabling:

- quick, real time comparison of alternate habitat interior layout concepts
- optimization of three-dimensional habitat interiors for multiple objectives
- automated generation of layouts according to user preferences
- increased understanding of how the interior arrangement affects overall habitat effectiveness

This new habitat layout evaluation method is structured as follows. First, inputs are defined including mission requirements (e.g., mission duration, number of crew, gravity magnitude, etc.). A functional decomposition process is then used to translate these requirements into functions which are used to specify the pressure vessel geometry and hardware geometries, locations, and characteristics (e.g., mass, function, power requirements, etc.) through a functional decomposition process. Then, the hardware are represented as polyhedral objects defined by vertices and faces to provide a mathematical means to construct layouts by translation and rotation of the objects. Using these layouts and hardware pieces as inputs, the evaluation process begins by capturing designer preferences needed to construct the objective function: 1) the relative importance of the evaluation criteria and 2) the perceived utility of measured evaluation criteria values which are used to normalize the evaluation criteria. By capturing these designer preferences before calculating evaluation criteria and constraints dependent upon the layout, the time-consuming subjective inputs can be captured once and applied consistently to a large number of layouts investigated using the objective step. This minimizes repetition in the evaluation process, greatly increasing the speed of the analysis.

The Analytic Hierarchy Process was chosen to rank the relative importance of each criterion by capturing pair-wise preferences of experts through a structured process. These preferences are then manipulated to create a set of normalized weightings ranking the evaluation criteria. Single-Attribute Utility Functions are used to map the values measured for each evaluation criterion to some normalized value from 0 to 1 based upon the user's perceived utility of that value compared to the range of possible values and requirements for that particular criterion. The 'Mid-Preference Level Splitting' method of defining the shape of these utility functions was selected for its simple and intuitive process. This method uses a structured set of expert elicitation questions to identify the value which is exactly mid-way in preference between the low and high end values of the evaluation criterion.

The next step of the layout evaluation method is the calculation of evaluation criteria values measuring the effectiveness of the layout design. A new, comprehensive list of criteria derived from literature review and expert consultation into human factors, behavioral health, spacecraft design, and terrestrial architecture is developed for this step to capture all of the conflicting objectives of conceptual level layout design. Qualitative criteria, which would have required subjective designer measurement, are mapped to equivalent quantitative proxies so that all criteria can be automatically calculable from the geometry, locations, functions, and characteristics of interior equipment. By using only quantifiable measures to define these evaluation criteria, the non-repeatable and timely user interaction required for the assignment of values can be separated from this assignment, allowing for significant acceleration of this portion of the process over the current methods.

Automatic criteria calculation methods are needed in order to measure the comprehensive set of habitat layout evaluation criteria. Several mechanisms are identified to create these methods including the use of collision detection algorithms, functional separation/collocation matrices, and the use of discrete grid-based iterative methods which use Boolean half-space tests to identify particular subsets of the volume. Collision detection algorithms, which mathematically test for the presence of overlapping geometries, are used to test for geometrically feasible equipment placement and to characterize subsets of the volumes according to evaluation criteria definitions. A multi-layered approach to collision detection is investigated to accelerate these tests by applying successively increasing degrees of fidelity and by implementing an industry standard method known as the Incremental Separating Axis-Gilbert, Johnson, and Keerthi algorithm for the final tests. Discrete grid-based numerical methods, which use a discrete number of test locations to numerically approximate various types of available volume, can be used to quickly quantify a criterion through a simple summation of points which pass criterion-specific tests. Most tests performed at these locations are Boolean collision tests which identify if the test point is in the interior or exterior of nearby equipment. Functional separation/collocation matrices are matrices which capture the desired spatial interrelationships between functions. These are used to operate upon distance matrices which contain the relative separation of these functions (as determined by the location of associated equipment) to produce scores for how effective the current placement of equipment is at addressing the desired functional separations or collocations. Together, these mechanisms allow for the development of quick and effective automatic quantification methods for each of the criteria, some of which would have previously required a subjective assessment.

The final step of the layout evaluation process is the assembly and calculation of a weighted, constrained multi-criteria objective function from the designer preferences, evaluation criteria values, and applicable constraints. The resulting values represent an aggregate measure of the overall performance or desirability of a layout for the specific set of designer preferences. This value can then be used to quantitatively compare multiple layouts or to modify a single layout to improve its overall acceptability. By implementing stochastic optimization methods such as Particle Swarm Optimization, the process of improving layouts can be automated to enable the generation of layout concepts performing well as measured by the defined objective function.

Both the evaluation and automation methods are demonstrated utilizing a cis-lunar habitat module design problem to improve a baseline habitat interior layout. The evaluation example compares two cis-lunar habitat layouts against their rationale and each other to demonstrate that each of the components of the aggregate objective function calculation is performing as expected. This example clearly demonstrates the success of the evaluation process to quickly evaluate a layout and compare it against another for a given set of designer preferences. The application of a Particle Swarm algorithm to iteratively improve the objective function value is somewhat successful. It was determined that the fine balance between penalty function calculations, evaluation criteria utilities, and particle swarm tuning parameters was required to ensure the optimizer converges to feasible layout concepts. The challenges of automation in practice are discussed, followed by descriptions of the alternate methods potentially capable of addressing these challenges. In short, it was determined that automation was feasible, and future work was identified to develop a more complete method rigorously demonstrating successful automation.

CONTRIBUTIONS OF RESEARCH

This dissertation leverages techniques from many different fields of study to achieve high quality, fast, conceptual design-compatible habitat layout evaluation and automated layout generation. Specific contributions of the author to the state-of-the-art are summarized below:

- Developed a comprehensive, measurable set of evaluation criteria which capture a full range of engineering (mass and volume) and habitability (quality of volume, functionality, safety, etc.) concerns <u>and</u> developed automatic methods to measure them; capability not apparent in current literature
- Created a structured, fast, and complete process for habitat interior evaluations useful for habitation design community and any other community designing highly constrained, highly integrated interiors
- Demonstrated viability of automation of layout interior designs, which brings forward the ability to conceptually size and design habitats with consideration of habitability, usability, and crew health desires dependent upon interior designs. In particular, this eliminates use of habitable volume as the sole measure determining habitat size
- Enables overall habitat conceptual design optimization when combined with equipment selection and mass sizing/cost analyses well documented in literature.

Additionally, there are several additional benefits of developing a comprehensive set of habitat layout evaluation criteria and enabling fast generation and evaluation of habitat interior designs. A comprehensive set of criteria:

- Provides a structured and quantifiable way to justify the selection of one layout over another for a given set of objective preferences, which will enable trades to be performed identifying the architectural elements which most directly affect the ‘goodness’ of a configuration.

- Increases available knowledge of the mechanisms of designing utility into interior designs
- Enables designers to trade the shapes of hardware and pressure vessels to suit the objectives dictated by the mission (never demonstrated in literature).

Fast generation and evaluation of interior designs:

- Facilitate designer capabilities to respond to requirements changes, investigate ‘what if’ scenarios, and ensure good integration with other elements of the system architecture as the concept is developed (lander, propulsive stages, and launch vehicles); all of which are characteristic of conceptual design process of exploration missions.
- Enable early representation of the layout dependent habitat design concerns affecting mission design or the design to project management or other element design teams during conceptual design.
- Provide more complete coverage and documentation of the configuration design space, leading to the discovery of better alternatives or the identification of important features which improve the design.
- Enable designers to provide justified ‘push-backs’ on limiting constraints or requirements for the first time in literature.
- Could reduce design time and resources to save in development costs both directly (less spent - more saved) and indirectly (better configurations require less expensive design changes later in the product lifecycle).
- Enable trade studies, including understanding the impact to the habitat configuration when trading various requirements, managerial preferences (weightings), choice of subsystems, and different component geometry shapes. Trades such as these can be used to expedite knowledge normally discovered in later design stages to the conceptual design phase.

CHAPTER ONE: INTRODUCTION

Over the past fifty years of human space exploration, the human race has proven its ability to live in Low Earth Orbit (LEO) for moderate durations and carry out short duration missions beyond LEO to the surface of the Moon. The next step for human space exploration is to send humans beyond Low Earth Orbit to pursue long duration human missions to distant destinations such as asteroids and the surface of Mars [Augustine et al., 2009; Craig, Hermann, & Troutman, 2015; Executive Office of the President - "National Space Policy…", 2010]. These future missions pose unique challenges to the design of spacecraft. The interplanetary trajectories necessary to reach the exploration destinations have durations on the order of a year or more and do not allow for quick, anytime abort back to Earth. Missions will be significantly demanding from a propulsion perspective, requiring highly efficient, mass constrained systems. In addition, long duration transits in space and lack of Earth abort opportunities will increase the physiological and psychological needs of the crew, which will require larger, more capable systems. In order to enable these missions, the development of systems which deliver increased capability with minimal mass and volume is critical, particularly for systems supporting human crews: habitats.

In the context of spacecraft design, <u>habitats</u> are the pressurized systems in which the crew live and work during human space exploration missions. Habitats must provide a living volume appropriate for the mission duration and house all of the functions and consumables required to support crew (e.g., a breathable atmosphere, clean water, food, a place to sleep, workstations to support crew tasks, etc.) [Kennedy, 2002a]. Designers must ensure all of these subsystems are included and properly integrated within a habitat while minimizing mass and cost. This is critical as habitats are often large, massive elements which must be pushed through most of a mission's propulsive maneuvers to support the crew. This large 'gear ratio' drives the design of launch vehicles and propulsion stages and often drives the overall cost and complexity of a mission. Therefore, the optimization of habitat designs is an important aspect of the development of any human space exploration mission.

The habitat design process involves the selection, sizing, and arrangement of the interior equipment and logistics required for a mission into an interior layout, which must fit within an appropriately sized pressure shell. The objective of habitat designers is to minimize mass, and thus habitat size, while providing adequate space and a functional layout for crew health and productivity [Howe & Sherwood, 2009; Kennedy, 2002a; and Simon & Wilhite, 2010]. The interior arrangement step of this process seeks to ensure that the interior equipment required for a crewed mission can be physically accommodated while providing the best compromise between performance metrics such as mass, volume, workflow efficiency, and habitability. Balancing interior layout performance is especially critical at the conceptual design so that feasibility issues, safety concerns, and requirements violations can be identified before they result in expensive design changes, increased mass growth, or reduced functionality as illustrated in Fabrycky & Blanchard, 1991 (high design freedom and low cost committed). However, ensuring that an interior layout is effectively balanced is non-trivial as there is currently <u>no comprehensive and timely method to measure the effectiveness of an interior layout and track the complex, conflicting habitat design objectives during conceptual design.</u> This missing evaluation capability increases the uncertainty surrounding conceptual habitat designs and prevents further efforts to optimize habitat designs for improved exploration mission performance. This leads to ignored consideration of interior designs during the conceptual design process which can result in unrealistic designs that have significant risk of mass growth and design changes in later design cycles. Excluding consideration of habitat interiors can also lead to sub-optimal habitat designs which can decrease the performance of missions, especially as mission duration increases.

This dissertation proposes a new, structured method to quickly measure the effectiveness of habitat interior designs, allowing for comparison of layouts at conceptual design and enabling the previously unavailable capability to automate the generation of habitat interiors. This will increase the understanding of habitat interior concerns at conceptual design and potentially result in cost and performance improvements enabling long duration missions. The following sections briefly discuss the current habitat interior layout design and evaluation process (Section 1.1), identify gaps preventing automated layout generation and evaluation (Section 1.2), and then describe a proposed solution for addressing these gaps and enabling automated layout generation and evaluation (Section 1.3). Then a set of research questions is used to frame the research discussed in this work.

1.1 Motivation

Lessons learned from the history of human spaceflight and decades of designs produced by "space architects" and other habitat design teams have shaped the current methods and processes for designing habitats interiors. The basic steps in the conceptual design process of habitat interior layouts have remained consistent across the design methods used in the last two decades [Hopson, Aaron, & Grant, 1990; Kennedy, 1994; Larson & Pranke, 1999; Messerschmid & Bertrand, 1999; Allen et al., 2003; Osburg, 2002; Tullis & Bied, 1988]. These basic steps are shown Figure 1 [Howe & Sherwood, 2009; NASA, 2010].

First, the designer defines the mission objectives, associated requirements, and physical constraints which influence habitat design. These include the mission destination, the number of crew, crewed and uncrewed durations, the number of Extravehicular Activities (EVAs), the anticipated concept of operations, launch vehicle mass and volume constraints, etc. These mission requirements (particularly destination and duration) are then used to identify the required hardware (e.g., Life Support, EVA, etc.), functions/crew tasks (e.g., sleeping, eating, etc.), and basic geometric features of the pressure vessel (e.g., the number and location of hatches, translation path requirements, the maximum habitat length and diameter dictated by the launch vehicle, etc.). These functions and tasks dictate the required complement of equipment (e.g., crew quarters, food preparation equipment, etc.) and necessary supplies (e.g., food, water, cleaning supplies, etc.) [Equipment Information: Larson & Pranke, 1999; Chambliss, 2007; Connors, Harrison, & Akins, 1985; Eckart, 1996; Lyle, Stabekis, & Stroud, 1973; Komar, Hoffman, Olds, & Seal, 2008; etc.]. The resulting <u>pressure vessel geometry</u> and <u>pieces of equipment</u> representing functions must then be arranged into habitat interior layouts according to some rationale.

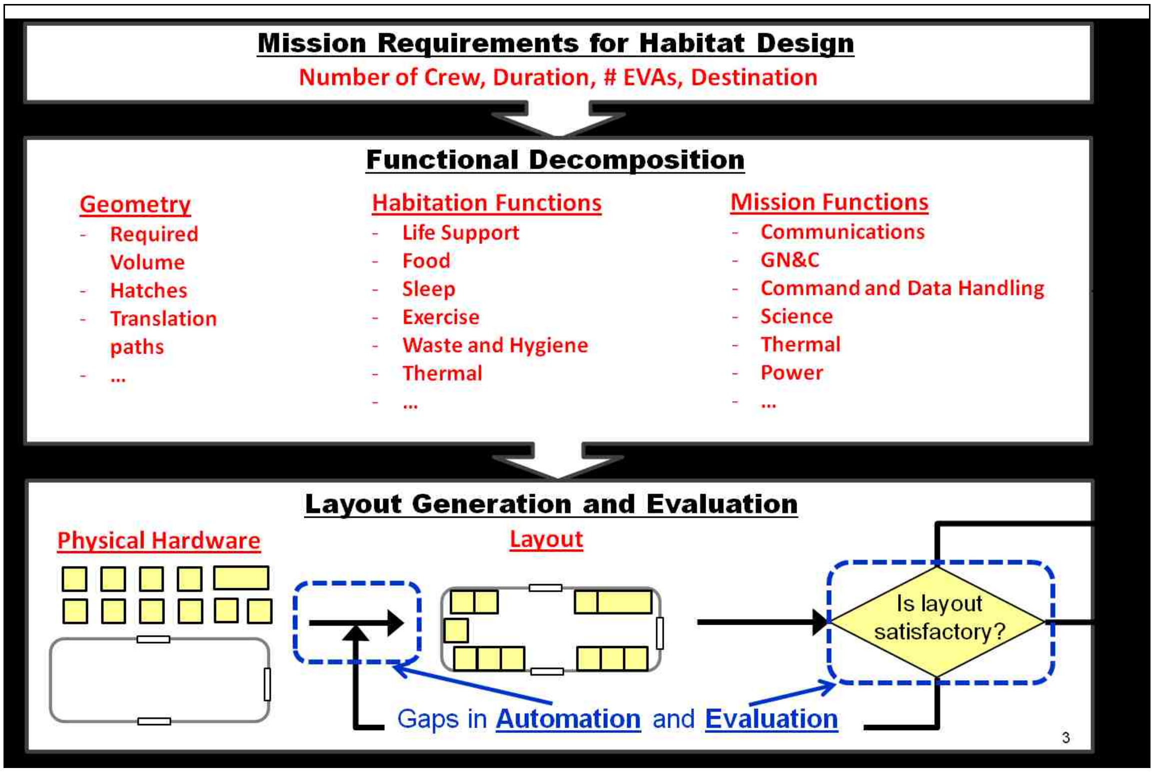


Figure 1: Habitat Interior Layout Design Process

A good layout should provide an efficient use of the available space, meet all of critical human requirements and standards (e.g., NASA, 1995; NASA, 1999; and NASA, 2010), and promote habitability, which is defined as a

> *"...measure of the degree to which an environment promotes the productivity, well-being, and situationally desirable behavior of its occupants."* [Wise, 1985]

Efficient use of space drives the habitat to smaller masses and volumes in order to reduce the required launch vehicle and in-space propulsion stage performances. However, this reduction of mass and volume can quickly compromise habitability objectives and dimensional constraints which ensure conformance to human standards [Howe & Sherwood, 2009; Kennedy, 2002a and 2002b]. These conflicting objectives and the highly constrained nature of space habitats make the layout generation process very challenging.

The current process for arranging habitat interior subsystems and supplies into layouts is similar to the terrestrial architectural design process. Design requirements, constraints, customer preferences, and an analysis of the relationships between required functions are qualitatively factored into manual sketches of the draft interior layout created using designer experience and training [Tullis & Bied, 1988; Nixon, 1986; Kennedy, 2002a; Howe & Sherwood, 2009; NASA, 2010]. This draft may take the form of a two-dimensional layout drawing [Osburg, 2002; Imhof, 2007; Kennedy, Toups, & Rudisill, 2009] or a detailed three-dimensional model [Fitts, 2002; Szabo, Kallay, Twyford, & Maida, 2007] and is iteratively improved as time allows. The key point is that the best practice for initial arrangement of interior layouts is currently a manual process because the slowness of the current evaluation process prevents consideration of many interior designs. This requires time and expertise which are rarely available at conceptual design phases, so there is a desire to speed this process. Some efforts have been made in the terrestrial architecture and industrial engineering fields to automate this arrangement process by using stochastic optimization methods and rule based, logical procedures to dictate placement of interior objects [Kalay, 2004; Lobos & Donath, 2010; Homayouni, 2006; and Dyckoff 1990]. However, the results are still lacking in applicability to the space habitat layout problem which requires a comprehensive set of objectives suited to the spaceflight physical/operational environment and consideration of three dimensions to account for the unique utilization of space in microgravity. Table 1 summarizes the available layout generation methods and their limitations which are described in more detail in Chapter 2.

Table 1: Historical Layout Generation/Optimization Methods

Alternative Approach	Description	Limitations
Space Layout Planning Methods [e.g., Kalay, 2004; Lobos & Donath, 2010; Homayouni, 2006]	• Area of terrestrial architecture focusing on automation and optimization of (mostly) 2-dimensional layouts of building interiors.	• Limited number/scope of objectives considered in optimization • Mostly 2D rectangular problems • Deal with less constrained, less integrated requirements than space habitats • Heavily relies on historical statistics and architectural design rules for room placement rationale • Not used in terrestrial architectural practice [Lobos & Donath, 2010]
Facility Layout / Packing Problems [e.g., Dyckhoff, 1990; Cagan, Shimada, & Yin, 2000; Szykman & Cagan, 1997; Tutenel, Bidarra, Smelik, & de Kraker, 2009]	• Set of geometric problems with 1-2 objectives used to optimize the placement of objects into shipping containers and warehouses	• Normally 1-2 objectives only • Mostly pure geometry problems focusing on packaging efficiency and lacking the complexity of integrated living spaces • Proof of optimality difficult (np-hard) leads to stochastic and numerical solutions [Dyckhoff, 1990]
Constraint-based / Rule-based Methods [e.g., Akazawa et al. 2005; Sanchez, Le Roux, Luga, & Gaildrat, 2003; Xu, Stewart, & Fiume, 2002]	• Interior design/generation methods using preprogrammed constraints and rules to dictate the placement of interior items • Ex. Place bookshelf along wall; group chair with table	• Hardcoded rules and constraints limit the possible design space available in space habitat designs (i.e. no novel solutions) • Often provides constraint compliant, but non-optimized designs • Limited set of objectives

The final step of the habitat interior design process is the evaluation of the acceptability of the draft layout as a basis for determining if further iteration is required. Table 2 shows the current methods used for space habitat layout evaluation. In these currently available methods, designs are either qualitatively evaluated against a collected set of customer desires and hard constraints [Nixon, 1986; Nixon, Miller, & Fauquet, 1989; SICSA, 2008; SICSA, 2009] or quantitatively compared using one or two criteria with a detailed engineering analysis [Szabo et al., 2007; Tullis & Bied, 1988; Wise, 1985]. In either case, this process can be time intensive and more difficult than the traditional terrestrial design process, which is much less constrained and is more able to leverage heritage designs for comparison. Also, a more extensive set of evaluation criteria is desired to capture the complex, integrated nature of spacecraft interiors while adequately addressing habitability concerns.

Table 3 compares the performances and characteristics of the existing evaluation methods (as presented in the identified references) and identifies a desired performance for the method proposed in this research based upon the needs of habitat designers at conceptual design phases. The following section assesses gaps in the current process to achieve this desired evaluation performance.

Table 2: Currently Available Approaches for Evaluation of Spacecraft Interior Layouts

Alternative Approach	Description	
Human-in-the-loop Mockup/Analog Tests **[Fitts & Howard, 2009; Hertz, 2003; Howe & Sherwood, 2009; Litaker et al., 2013; Nixon, 1986; Nixon et al., 1989]**	- Use wood and foam-core models or research analogs to test crew activities with astronauts using qualitative rating scales to capture crew preferences/comfort	 Howe 2009
Subjective Design Evaluation Studies **[Adams & McCurdy, 1999; Adams & McCurdy, 2000; Di Capua, Mirvis, Medina, & Akin, 2009; NASA, 2010; SICSA, 2008; SICSA, 2009]**	- Qualitatively compare the perceived performance of interior design alternatives with relative subjective ratings	
Semi-Quantitative Evaluation Studies **[Celentano, Amorelli, & Freeman, 1963; Cohen, 2004; Tullis & Bied, 1988; Wise, 1985]**	- Establish quantitative criteria to assess layout goodness	
In-depth CAD Evaluations **[Fitts, 2002; Szabo et al., 2007]**	- Use detailed CAD models to manually measure desired criteria and perform virtual mockup tests	 Fitts 2002
Architectural Programming (and other a priori methods) **[Duerk, 1993; Osburg, 2002; NASA, 2010]**	- Use an interview process with the user to create a design catered to an individual preferences; features one layout activity	

Table 3: Comparison of Performance of Existing Evaluation Methods

	Human-in-the-loop Mockup Tests [Fitts & Howard, 2009; Hertz, 2003; Howe & Sherwood, 2009; Nixon, 1986; Nixon et al., 1989]	**Subjective Design Evaluation Studies [Di Capua et al., 2009; SICSA, 2009]**	**In-Depth CAD Evaluations [Fitts & Howard, 2009; Szabo et al., 2007]**	***Architectural Programming and other A Priori* Design Methods [Duerk, 1993; NASA, 2010; Osburg, 2002]**	**Desired Capability**
Model Setup Time	Weeks	Hours - Weeks	Days - Weeks	Days - Weeks	**1-2 Days**
Time for a Single Evaluation	Days	Minutes - Hours	Hours	Days – Months	**Minutes**
Additional Time for Alternate Configurations	Small changes: Hours–Days Large changes: Weeks	Minutes - Hours	Hours	Days - Weeks	**Seconds**
Completeness of Criteria Set	Incomplete, focusing on usability and feasibility only	Somewhat complete	Incomplete, focusing on few criteria at a time	Somewhat complete	**Complete**
Measurement Method	Cooper-Harper and other rating systems, manual measurement	Qualitative relative ratings	Detailed quantitative CAD measurements	Qualitative feel based upon experience	**Quantitative, automatic**
Automatically Calculable	No	No	Possibly	No	**Yes**

1.2 Gap Analysis of Current Interior Evaluation Process

In practice, layout generation and evaluation are rarely carried out during early conceptual design because they are time consuming, and the design is often in flux as the mission requirements change. However, as the durations of human exploration missions increase, larger habitat masses have a more driving impact on the mission design while the human habitability concerns pushing towards larger, more functional interior spaces become increasingly important [Baggerman, Rando, & Duvall 2004; Jones, 1973; Franklin, 1978; Whitmore, McQuilkin, & Woolford, 1997; Osburg, 2002; Adams, 1998; Adams & McCurdy, 2000; Kitmacher, 2002; and Robinson, Sterenborg, Häuplik, & Aguzzi, 2008]. There is a desire to consider layout information early in the design process to improve designs, mitigate potential mass growth, and prevent expensive design changes in later design cycles. In order to address the layout concerns early in the design process, advances are necessary to speed up the interior layout evaluation process, increase its completeness, and tie this process into the automated generation of layout alternatives. The NASA Systems Engineering Trade Study Process [NASA, 2007] was used to frame gaps in the current interior layout design process in order to determine what actionable improvements could be made to enable automatic evaluation and layout generation. This mapping shown in Figure 2 identifies these gaps in the current process, shown in red, which prevent automatic evaluation and layout generation. Actionable steps to fill these gaps are presented in the following paragraphs (each step summarized in italics).

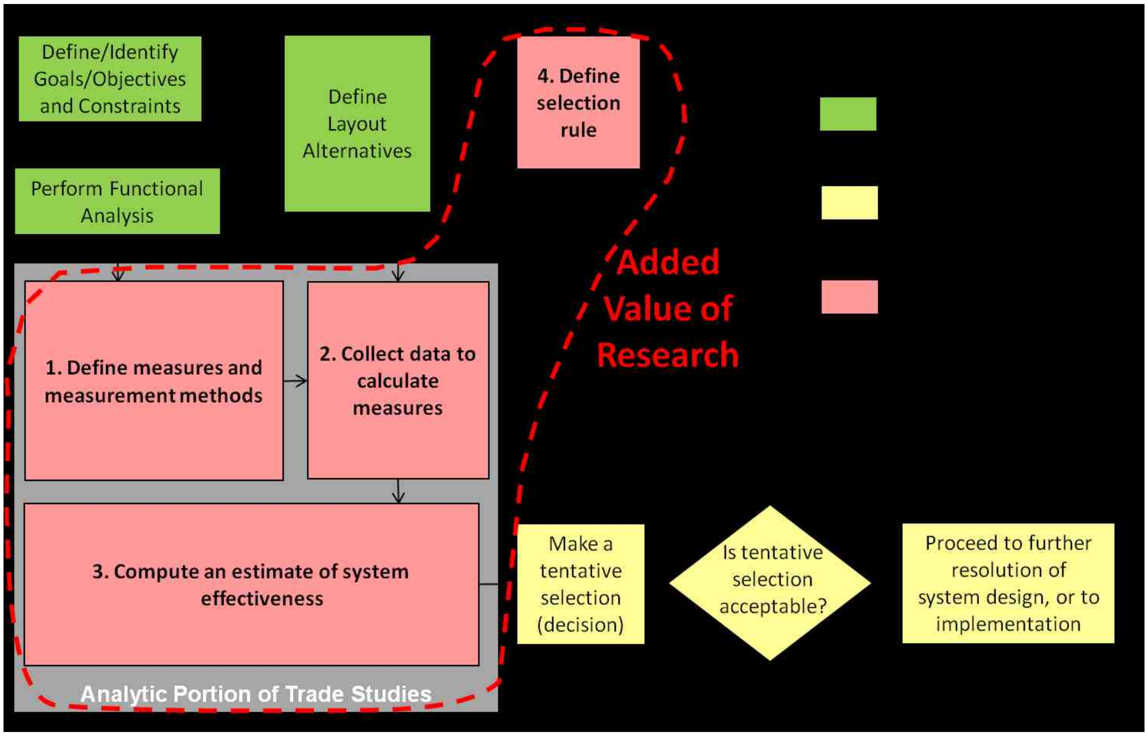


Figure 2: NASA Systems Engineering Trade Study Process (Modified) [NASA, 2007]

Gap 1: The Define Measures and Measurement Methods Gap identifies the non-comprehensive and qualitative nature of existing evaluation criteria sets used in previous layout evaluation studies. These previous studies use an incomplete set of interior layout evaluation criteria, often missing human habitability design considerations [Aguzzi, Häuplik, Laan, Robinson & Sterenborg, 2006; Cohen, 2004; Howe & Sherwood, 2009; and Osburg, 2002]. Additionally, historical studies lack fast, quantitative measurement methods, instead relying on qualitative human judgment or time-consuming manual measurement methods from detailed CAD models to compare layout alternatives [SICSA, 2009; Szabo et al., 2007; and Simon &

Wilhite, 2010]. *There is a desire for the development of a comprehensive set of quantifiable interior layout evaluation criteria and automated measurement methods for each criterion which are consistent with available layout data* [Dudley-Rowley & Bishop, 2002].

Gap 2: The Collect Data to Calculate Measures Gap identifies that in order to enable automated methods to measure criteria to be utilized, layout data including hardware geometry and the relationships between functions must be put into a mathematically accessible form consistent with identified measurement methods. While detailed CAD models can achieve this, they are time consuming to create and lack the flexibility desired. *Geometry data and the relationships between the hardware are available [Tullis & Bied, 1988; NASA, 2010], but must be input into a computer framework consistent with the evaluation criteria calculation methods.* Additionally, this data must be compatible with the definition of layout alternatives and be simple enough to prevent difficulties performing the calculation methods.

Gap 3: The Compute an Estimate of System Effectiveness Gap results from a lack of measurable criteria to gage layout performance. A method is also needed to combine all evaluation criteria values and user preferences into a single measure of the overall layout effectiveness which enforcing the necessary constraints on the design [NASA, 2010]. *A multi-criteria objective function created using systems engineering techniques should be created to provide this overall measure of effectiveness, enabling defendable, repeatable comparison between alternatives.*

Gap 4: Finally, the Define Selection Rule Gap identifies that design of any system for human use is subject to qualitative preferences which change the evaluation results based upon the designer's attitude towards the design problem. *A structured process to capture user preference separate from the quantification of evaluation criteria values is desired to ensure repeatability and provide insight into the effect of the user's preference on the resulting preferred design.* These user preferences are also necessary to identify acceptable layouts based upon the objective function and determine whether further iteration is necessary.

The proposed research presented in the rest of this paper seeks to develop the implementation details associated with each of these identified necessary improvements, to enable faster, more complete habitat interior layout evaluation, and establish the foundations for automating the generation of acceptable layouts for use at conceptual design.

1.3 Research Questions and Objectives

The previous section identified several actionable improvements which must be addressed to enable accelerated layout evaluation and automated layout generation. In the following section, a set of questions is presented to frame the proposed research to implement these improvements and create an integrated layout evaluation and generation capability.

1.3.1 Primary Research Question

Research Question 1: *How can the current interior layout evaluation process for habitat interiors be improved to enable automation and create better designs at conceptual design?*

Hypothesis 1: *A systems engineering-based process can be used to develop a comprehensive habitat layout evaluation objective function which:*

- *Balances increased habitability and reduced habitat size and*
- *Captures and enforces constraints on the placement of interior objects.*

Furthermore, by building this objective function with a comprehensive set of automatically quantifiable evaluation criteria, the evaluation process can be performed fast enough to enable design automation at conceptual design.

Systems engineering-based multi-criteria decision making techniques have frequently been applied to complex multi-criteria design problems to increase understanding of the design space and enable optimization through the use of a multi-criteria objective function. In order to develop a fast, comprehensive, and transparent evaluation process, these methods can be applied so long as quantifiable evaluation criteria and constraints can be defined and automatically measured from geometry. Research into prior evaluation frameworks suggests that such a set of criteria and constraints can be defined. Therefore, it is hypothesized that by addressing each of the 4 gaps, this capability can be developed. Each of the following secondary research questions are used to address these gaps.

1.3.2 Secondary Research Questions

The following secondary research questions are used to frame the research addressed in Chapter 3 with proposed solutions for each research area.

Research Question 2: *How can the performance of an interior layout be measured quantitatively while capturing both engineering and habitability concerns?*

Hypothesis 2: *A literature derived, expert-approved list of quantifiable evaluation criteria applicable to all gravity orientations, durations, and sizes can be created leveraging existing literature. By using quantitative, measurable proxies for qualitative criteria, the objective function can be initially quantified for conceptual design.*

Gaps Addressed: *Gap 1: Evaluation Criteria Set Gap*

Research Question 3: *How can the values for these quantifiable evaluation criteria be calculated quickly for a layout without manual calculation by the designer?*

Hypothesis 3: *Automatic quantification methods can be developed for criteria by using several mechanisms featured in literature for similar problem including:*

- *collision detection algorithms,*
- *discrete grid-based iterative methods which use Boolean half-space tests to identify particular subsets of the volume.*
- *functional separation/collocation matrices,*

Gaps Addressed: *Gap 1 (Evaluation Criteria Set), Gap 2 (Layout Geometry and Data Representation)*

Research Question 4: *How can the various criteria values and designer preferences be combined into an overall value function which measures the relative 'goodness' of alternative habitat layouts?*

Hypothesis 4: *Single-attribute Utility Functions (SUFs) can be used to normalize evaluation criteria values against the designer desired values. Analytic Hierarchy Process can be used to obtain weightings capturing the relative importance of each criterion. Penalty functions can be used to enforce constraints. Then the SUFs can be combined with the evaluation criteria calculated values, relative weightings, and constraint penalty functions in a constrained 'weighted sum' multi-criteria objective function to measure overall performance.*

Gaps Addressed: *Gap 3 (Measure of Overall Performance), Gap 4 (Method to Capture Preferences)*

Research Question 5: *What optimization method can be used to automate the improvement of layout?*

Hypothesis 5: *Stochastic optimization methods can be used to change the location matrix of all of the objects to create new layouts. Particle Swarm Optimization (PSO) is anticipated to provide the best performance with its additional tracked history over Simulated Annealing and Genetic Algorithms. It is also anticipated that a hybrid PSO methods using more traditional optimization methods for local tests around optima may improve performance (if necessary).*

1.4 Dissertation Overview

Chapter 1 introduced the need for a structured, comprehensive, and timely habitat interior layout evaluation methodology capable of ensuring good habitat designs are available during the conceptual formulation of human space exploration missions. This chapter highlighted the necessary improvements to the current interior layout design and evaluation processes which frame the research described in this thesis.

Chapter 2 presents a review of the literature which is useful in the development of the interior layout evaluation methodology and tool. This review includes a detailed description of current habitat interior design/evaluation methods and metrics. It then describes the requirements, constraints, and subsystem functions/interactions which must be addressed for acceptable and desirable layout designs. Next the mechanisms mentioned in Research Question 3 that enable the automated calculation of evaluation criteria are described including geometry modeling methods, collision detection tests, and numerical grid based methods. Finally, stochastic optimization methods which are necessary to implement the automated generation of acceptable layouts are described.

Chapter 3 presents the proposed interior layout evaluation methodologies introduced in Chapter 1. First an overview of the systems engineering-derived layout evaluation process is given. This is followed by a description of the development of a comprehensive set of evaluation criteria and automated methods to quantitatively measure them. This chapter will also describe the constraints and designer preferences which are combined with the measured evaluation criteria values to quantify an objective function providing an integrated measure of overall layout effectiveness. Finally, the use the chosen stochastic optimization method utilized iteratively improve values of this multi-criteria objective function and enable the automated generation of favorable layout alternatives is described, followed by a high level description of the software implementation used to test these evaluation and generation methods.

Chapter 4 demonstrates the effectiveness of the layout evaluation process by analyzing manually created sample layouts of a notional habitat intended for a mission to cis-lunar space. It describes the mathematical modeling of the design problem (requirements, outfitting, preferences, etc.) in the software designed to implement the methodology. Then, alternative layouts are compared using this software to verify the measurement of the evaluation criteria and demonstrate the ability of the method to differentiate desirable and undesirable layouts.

Chapter 5 provides the foundations for automating the optimization of interiors and attempts to apply the evaluation framework developed in Chapter 4 to enable an automated habitat interior layout improvement capability utilizing the same cis-lunar example treated in Chapter 4. Specifically, the chapter describes the customized stochastic optimization implementation and comments on its ability to identify feasible and favorable candidate layouts for evaluation. It also discuss challenges to objective function convergence, full automation, and potential solutions to identified issues. Finally, it describes the value of the current tool and the potential benefit of a fully automated iterative layout improvement capability.

Finally, Chapter 6 briefly provides conclusions about the layout evaluation and automated generation process presented in this research and its implications for the design and sizing of habitat systems to support future human exploration missions. This chapter also discusses the recommendations on future work in this area to investigate the impact of uncertainty in designer preferences, provide increased fidelity and speed of the results, and expand the habitat layout design space to non-conventional habitat designs.

Finally, it should be mentioned that this dissertation pulls heavily from conference papers and a peer-reviewed journal article published by the author for descriptions of relevant background information and descriptions of the proposed methodology. References to these works are included where those sections are utilized.

CHAPTER TWO: BACKGROUND

This chapter contains a review of literature which establishes the current state of the art in habitat interior layout design and layout evaluation methodologies. It also describes the necessary background information for the development of an improved habitat interior layout evaluation method. A detailed description of space habitat and habitat interior design considerations is provided, including a description of habitat design requirements, subsystems, potential evaluation criteria, and constraints. This chapter then describes geometry modeling and collision detection methods necessary to perform layout feasibility checks and to measure geometry-based evaluation criteria. Finally, it describes previous attempts in literature of automating layout design, provides examples of methods and tools used to optimizing similar geometry-based layout problems, and describes the pros and cons of some of the stochastic optimization methods which have been successfully applied.

2.1 Habitat Layout Design

The purpose of this section is 1) to provide a summary of existing methods to evaluate habitat interior layout designs and 2) to provide a summary of habitat interior design requirements, subsystems, accommodations, integration concerns, and all other information necessary to assess habitat interior configurations. This information is used in the description of the proposed layout generation and evaluation methodology presented in Chapter 3. The information in this section is a compilation of spacecraft design texts, design studies, NASA requirements documentation, conversations with habitat design experts, and papers describing the habitat design process as a whole.

2.1.1 Habitat Layout Design Process

Space habitats are described by many phrases in literature: “inhabited space systems” [Osburg, 2002], “human-rated spacecraft” [Allen et al., 2003], or any type of pressurized element in which crew presence is implied such as a lander, base, station module, crew transfer/entry/ascent/descent vehicle. Fundamentally, the primary purpose of a space habitat is to provide a "pressurized environment for ... humans to live and work" [Kennedy, 2002a]. These habitats must provide adequate volume to accommodate all of the equipment and consumables required to support crew and perform all of the tasks crew are required to perform throughout the mission. These tasks include typical living tasks (e.g., eating, sleeping, exercise, etc.) and work tasks (e.g., monitoring, maintaining, and operating the spacecraft; performing mission specific science; carrying out exploration objectives; etc.) [Larson & Pranke, 1999]. Additionally, habitats must also be designed and outfitted to keep crew healthy and happy by fulfilling all of the physiological, psychological, and social needs of crew [NASA, 2010; Simon, Whitmire, Otto, & Neubek, 2011]. This implies logically designed and arranged equipment, and improved consideration of the crew's physical and cultural preferences [Simon et al., 2011].

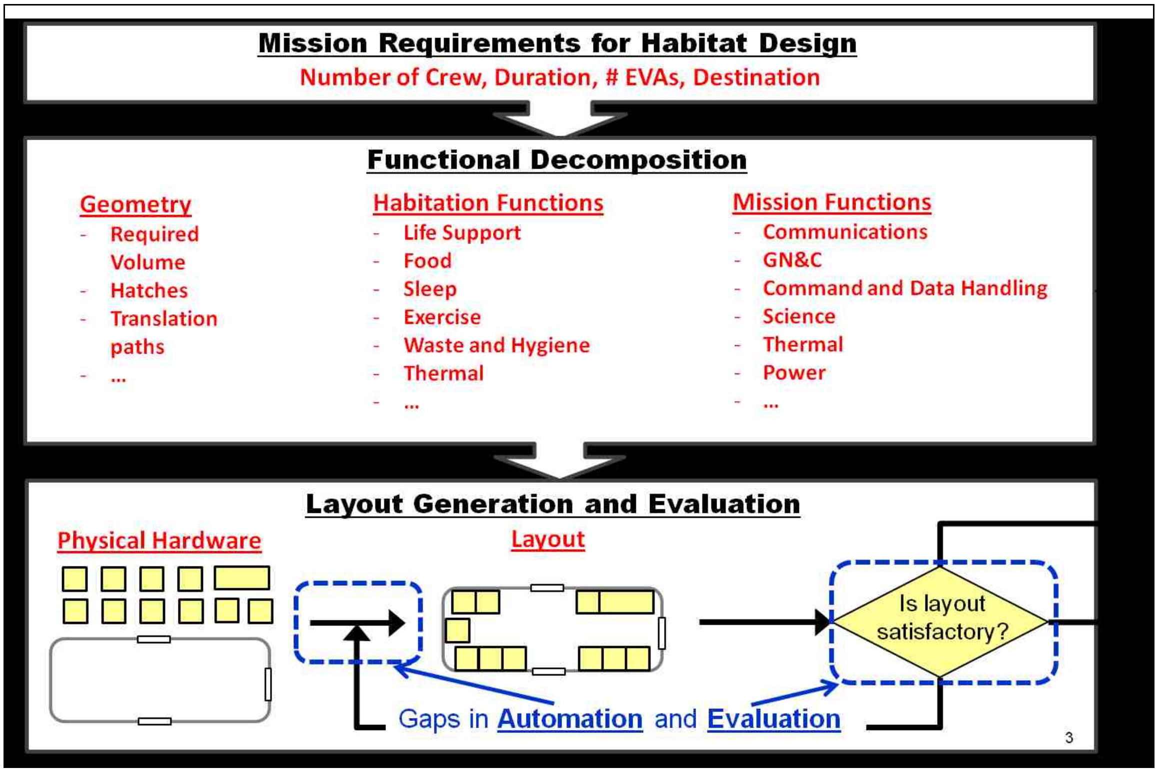


Figure 3: Habitat Interior Layout Design Process (Figure 1 reproduced from Ch.1)

As shown in Figure 3, designing habitats involves analyzing mission requirements (e.g., duration, number of crew, etc.) to identify crew tasks and spacecraft functions, selecting the systems and accommodations necessary to perform those tasks/functions, sizing the habitat to contain these items, and integrating them together into configurations which are both efficient and comfortable [Howe & Sherwood, 2009]. The mapping of mission requirements to the required habitat subsystems and crew accommodations is fairly well documented and driven mostly by mission duration, the types of activities which would be performed during the mission, and the selection of technologies dictated by the designer and program budget [Larson & Pranke, 1999]. For example, choosing a long duration mission normally dictates the need for a partially closed-loop, high-reliability life support system to reduce habitat mass, unless the application of other advanced technologies such as high-efficiency propulsion system negates the need for additional habitat mass reductions.

The integration of these systems and accommodations into a habitat interior layout has been historically carried out using a process very similar to the traditional terrestrial architecture design process [Duerk, 1993; Duerk, 2004; Osburg, 2002]. In this process, the architect utilizes years of experience designing similar facilities and some artistic license to sketch layouts which meet all quantitative requirements while qualitatively evaluating the complex, interacting desires of the customer. These layouts are repeatedly refined as mission concepts and the required crew operations are further defined. As space habitats become more complex, a structured, question-based data collection process referred to as "architectural programming" from terrestrial architecture can be implemented to identify required layout features and track all of the conflicting design considerations [American Institute of Architects, 2008]. Architectural programming is standard practice for the design of space habitat interiors due to the multiple conflicting habitat design objectives and constraints [Howe & Sherwood, 2009].

After initial layouts are created, they are iteratively improved by qualitatively evaluating the inter-object relationships and habitat mass and volume constraints to identify an 'acceptable' layouts. As mentioned in Chapter 1, in order to enable consideration of interior layout designs at conceptual design phases and to enable end-to-end habitat design optimization there is a desire to 1) develop an extensive set of automatically quantifiable layout evaluation criteria which include both engineering and habitability objectives and 2) develop a tool for the automated evaluation and generation of interior layout concepts. The next section outlines the previous methods used to evaluate spacecraft interior layouts.

2.1.2 Previous Work in Space Habitat Interior Layout Evaluation Methods

There are several characteristics of space habitats which make their evaluation unique from terrestrial interiors. The most substantial change is that space habitats must be designed for microgravity, partial gravity, or some combination of the two over the course of a mission [Cohen, 1996; Howe & Sherwood, 2009; Kennedy, 2002a]. Microgravity allows all surfaces within a habitat, including ceilings and floors, to be accessible and useful for crew tasks and associated hardware. Microgravity and partial gravity also require revised anthropometrics and biomechanics relationships as the human body resting positions and movement are vastly differently than in normal Earth gravity [Akin, 2012; NASA, 2010]. This causes reach envelopes, translation geometries, and equipment placement which make up functional areas to be substantially different from terrestrial architecture [NASA, 2010]. Another major difference between terrestrial and space architecture is that all of the functions required to support crew for long duration, pressure-sealed confinement must be integrated within a single habitation system made up of one or multiple pressure vessels [Kennedy, 2002a]. This poses a unique accessibility challenge with unique human factors and scheduling constraints [Fitts, 2002; Tullis & Bied, 1988]. Additionally, the unique hardware for spaceflight functions (e.g., closed loop life support, thermal hardware, science hardware, etc.) imposes additional spaceflight-unique relationship constraints not found in most terrestrial applications. Finally, the unique stresses of long-duration isolation and confinement in a dangerous, high-risk environment requires that space habitats must be designed with unique psychological and habitability considerations in mind [Adams & McCurdy, 1999; Fraser, 1968; Imhof, 2007; NASA, 2010; Simon et al., 2011; Stuster, 2010; Wise, 1985]. In summary, there are enough unique considerations to distinguish the space habitat evaluation method from the terrestrial architecture design methods, and this has led to the creation of many specialized methods for spacecraft design evaluation within space architecture practice.

Table 4 list some of the more influential and relevant space habitat design evaluation references which present various methodologies and criteria sets for assessing habitat interiors. These papers fall into five layout evaluation categories (Human-in-the-loop Mockup/Analog Tests, Subjective Design Evaluation Studies, Quantitative Evaluation Studies, In-Depth CAD Evaluations, and Architectural Programming) shown in Table 5 and the typical performance of evaluations within each category are compared in Table 6.

Table 4: Representative Space Habitat Evaluation Studies

Alternative Approach	Description	Limitations
Celentano et al., 1963 – "Establishing a Habitability Index"	• Early reference on habitability needs for long duration missions which established a somewhat quantifiable habitability index for comparing habitats	• Interior design ("Living Space") criteria focus on volume and only comment on other measures
Wise, 1985 – "The Quantitative Modeling of Human Spatial Habitability"	• Details numerical methods for capturing spatial perception from visual, kinesthetic, and social logic perspectives including a detailed description of an isovist model for visual spaciousness	• Focuses on spatial issues • Does not weight or combine measures as it argues factors are too interdependent to merit combination • Relies on expert designer in the loop
Tullis & Bied, 1988 - "Space Station Functional Relationships Analysis	• Evaluation of interiors based upon separation and colocation of systems	• Incomplete, focuses on schedule, traffic, privacy, and noise
Nixon, 1986; Nixon et al., 1989 – Space Station Habitability Studies	• Describes a subjective Likert-scale evaluation of multiple hardware mockups utilizing a detailed set of evaluation criteria	• Many interesting evaluation criteria, but only subjective scoring of subjects experience in a mockup with little definition of criteria is used
Adams & McCurdy, 1999; 2000 – "Habitability in Advanced Space Mission Design": Parts 1 and 2	• Adams & McCurdy, 1999 describes several criteria for assessing habitat concepts, including some requirements. Adams & McCurdy, 2000 assesses several habitat types on their potential performance on these criteria	• Though some criteria are measurable, all are assessed qualitatively on a Likert scale. Specific layouts are not addressed
Fitts, 2002 – "International Space Station (ISS) Internal Volume Configuration (IVC)	• Assesses ISS modules using CAD analysis against approved set of pass/fail criteria	• Utilizes manual, quantitative measures with definitive constraints, but criteria set is incomplete • Focuses on constraint satisfaction
Cohen, 2004 – "Habitat Multivariate Design Model Pilot Study"	• Addresses how to determine shape and size of habitats based upon several spatial variables	• Numerical, but incomplete • Focuses on pressure vessel geometry, not interiors
Di Capua et al., 2009– "Minimal Functional Habitat"	• Design study for surface habitat design • Qualitative preference analysis to identify design features to implement	• Relatively complete, but all measure of effectiveness are qualitatively ranked • Mitigations are design feature focused as opposed to layout focused
SICSA, 2008; 2009;	• Design studies of habitat architectural concepts including ranking of configurations	• Good selection of criteria, but limited to qualitative ratings between few concepts
NASA, 2010 - NASA Human Integration Design Handbook	• NASA handbook on designing human spaces describing criteria and requirements	• Most comprehensive list of criteria, but lacks definition of measurement methods for individual criteria and an overall performance measure

Table 5: Currently Available Approaches for Evaluation of Spacecraft Interior Layouts (Replicated from Table 2)

Alternative Approach	Description	
Human-in-the-loop Mockup/Analog Tests **[Fitts & Howard, 2009; Howe & Sherwood, 2009; Litaker et al., 2013; Nixon, 1986; Nixon et al., 1989; Hertz, 2003]**	• Use wood and foam-core models or research analogs to test crew activities with astronauts using qualitative rating scales to capture crew preferences/comfort	 Howe 2009
Subjective Design Evaluation Studies **[Adams & McCurdy, 1999; Adams & McCurdy, 2000; Di Capua et al., 2009; NASA, 2010; SICSA, 2008; SICSA, 2009]**	• Qualitatively compare the perceived performance of interior design alternatives with relative subjective ratings	
Semi-Quantitative Evaluation Studies **[Celentano et al., 1963; Cohen, 2004, Tullis & Bied, 1988; Wise, 1985]**	• Establish quantitative criteria to assess layout goodness	
In-depth CAD Evaluations **[Fitts, 2002; Szabo et al., 2007]**	• Use detailed CAD models to manually measure desired criteria and perform virtual mockup tests	 Fitts 2002
Architectural Programming (and other a priori methods) **[Duerk, 1993; Osburg, 2002; NASA, 2010]**	• Use an interview process with the user to create a design catered to an individual preferences; features one layout activity	

Table 6: Comparison of Existing Evaluation Method Performances (Replicated from Table 3)

	Human-in-the-loop Mockup Tests	Subjective Design Evaluation Studies	Semi-Quantitative Evaluation Studies	In-Depth CAD Evaluations	Architectural Programming and other *A Priori* Design Methods	Desired Capability
Model Setup Time	Weeks	Hours - Weeks	Hours - Weeks	Days - Weeks	Days - Weeks	**1-2 Days**
Time for a Single Evaluation	Days	Minutes - Hours	Hours - days	Hours	Days – Months	**Minutes**
Additional Time for Alternate Configurations	Small changes: Hours–Days Large changes: Weeks	Minutes - Hours	Minutes - Days	Hours	Days - Weeks	**Seconds**
Completeness of Criteria Set	Incomplete, focusing on usability and feasibility only	Somewhat complete	Somewhat complete	Incomplete, focusing on a couple of criteria at a time	Somewhat complete	**Complete**
Measurement Method	Cooper-Harper and other rating systems, manual measurement	Qualitative relative ratings	Manual quantitative measurements or calculations	Detailed quantitative CAD measurements	Qualitative feel based upon experience	**Quantitative, automatic**
Automatically Calculable	No	No	Possibly	Possibly	No	**Yes**

Human in the Loop Mockup/Analog Tests

As the name suggests, human-in-the-loop mockup/analog evaluations utilize human evaluators who perform tasks or inhabit an enclosed environment for a period of time to demonstrate the performance of the interior design or refine design features through observation of potential improvements. For example, Nixon's work on wardroom design [Nixon, 1986; Nixon et al.,1989] used wood and foam-core mockups while Litaker et al. [Litaker et al., 2013] used the Habitat Demonstration Unit: a spacecraft analog designed to simulate the operations on the lunar surface. Evaluators use structured rating scales such as Cooper-Harper, Likert, or the NASA Task Load Index (TLX) [Hart & Staveland, 1988; Hart, 2006] to rate tasks or overall layout impressions against well-defined qualitative measures. A strength of this approach is that it provides a real, hands-on evaluation which facilitates the identification of less tangible design issues which would be overlooked in the other methods, such as usability, feasibility, and human factors concerns. The primary challenge with this type of evaluation is that it takes a substantial amount of time and resources to construct the physical simulation environment and perform each evaluation, which are both very limited in early conceptual design phases. Attempts have been made to reconcile this by utilizing virtual layouts and immersive virtual reality hardware to perform virtual evaluations, but the limitations of virtual reality technologies (lack of realistic touch and other sensory perceptions) currently limit their application to the refinement of design features and quantification of only a few criteria. Hands-on evaluations are still highly desirable in later design phases, but are not compatible with conceptual design and the desired performance of automated design methods described in Table 6.

Subjective Design Evaluation Studies

Subjective design evaluation studies establish a set of qualitatively assessable evaluation criteria to perform relative comparisons of two-dimensional or three-dimensional layouts. These studies typically use similar rating scales as the human-in-the-loop evaluations to rate designs against a set of relatively complete figures of merit. For example, the SICSA study on evaluating and selecting lunar habitat module concepts [SICSA, 2008] develops a list of evaluation criteria which feed into the selection between multiple layout concepts for a lunar habitat. Alternatives were scored qualitatively to establish designer preferences. The strength of these studies is that they can quickly compare multiple layouts against multiple criteria, which makes them well suited to the conceptual habitat design problem. The major limitation of these methods is that the total time to evaluate multiple layouts increases linearly with each additional layout. Additionally, it becomes difficult to distinguish the differences between multiple layouts, and scores can have unintentional biases based upon the evaluator's perception, preferences, and cultural background [Simon et al., 2011]. Many of these studies have developed criteria sets which are somewhat quantitative, but quantitative measurement is often bypassed because the uncertainty surrounding the exact mission parameters and habitat dimensions is high at the conceptual design phase. Without automated evaluation criteria measurement methods, it is more time consuming to perform the measurements and calculations required to quantify the criteria for each new layout than it is to simply rerate the effectiveness of the layout qualitatively.

Semi-Quantitative Layout Evaluation

Semi-quantitative layout evaluation studies seek to capture the usability and habitability of a layout using a semi-complete set of quantitative measures. Most of these measures are measurements of physical parameters which have been observed in human-in-the-loop testing or in terrestrial architecture to produce more habitable, usable layouts. Semi-quantitative evaluation methods are the most applicable to the automation of interior layout design and evaluation because they offer repeatable, automatable methods to measure layout performance. The most relevant of these papers is "The Quantitative Modeling of Human Spatial Habitability" by J. A. Wise [Wise, 1985], which describes a method for measuring spatial perception from visual, kinesthetic, and social logic perspectives using isovist analysis. Isovist analysis utilizes measurements called isovist radials which are measurements from a reference point representing an observer to each of the points visible to that observer within an interior. Wise et al. use isovist analysis [Benedikt, 1979] parameters derived from layout geometries to quantify intangible aspects of habitability like spaciousness, proportion, body envelopes, and social logic parameters affected by layouts like privacy and social power. By providing quantitative methods, Wise makes layout evaluation structured and repeatable. However, there are a few limitations to the Wise et al. work which prevents its direct application to the automated, conceptual habitat evaluation and generation problems. Wise et al. examines a broad range of mostly spatial criteria for the interior design of spacecraft and maintains that tradeoffs between these criteria are not likely needed as design choices can be made to creatively achieve all desired characteristics of a layout. This method relies on an expert designer in the loop to apply creative ways of achieving the desired metrics, whereas the goal of the proposed method is to automate interior layout generation steps utilizing the most salient, driving criteria. Additionally, the mass constraints and other systems-level considerations involved in the integration of the interplanetary habitat design into mission architectures increases the importance of performing these tradeoffs during the conceptual design phase when design flexibility remains, but a detailed designer look may be impractical.

In-depth CAD Evaluations

In-depth CAD evaluations are often used in detailed design to refine design features and tightly integrate pieces of hardware. These methods are currently used extensively to monitor the layout of the International Space Station for interferences [Fitts, 2002]. The strength of these evaluations is that the results are mostly quantitative measurements derived from precise measurements of medium to high-fidelity CAD models. The weakness of these approaches are the amount of effort and time necessary to create each three-dimensional layout model if multiple layouts are to be considered. Additionally, the evaluation criteria measurement methods used in these evaluations are often very manual in nature, which limits the applicability of these methods directly to automation without some modification. In fact, the proposed method [Simon, Bobskill, & Wilhite, 2012] utilizes similar methods for measuring habitable volume as the CAD assessments [Szabo et al., 2007], but automates and accelerates the calculation through the use of numerical algorithms approximating the measurements. In addition to CAD evaluation methods, Building Information Management (BIM) systems have been frequently integrated with CAD models to embed relevant design information and requirements directly into CAD models [Polit-Casillas & Howe, 2013]. This design evaluation is well suited to detailed design phases in which the layout is mostly fixed.

Architectural Programming

Architectural programming is a standard information management technique used frequently in terrestrial architecture practice where a structured set of questions is utilized to establish the preferences of the customer while ensuring that the resultant design meets all requirements [Duerk, 1993]. This can be thought of as a method which procedurally allows designers to evaluate the interior design *a priori* and generate feasible designs which can then be further iterated to improve the look and feel of the space. While architectural programming is an effective way of generating layout alternatives, it has two weaknesses which reduce its effectiveness for use in the automated design of long duration space habitats. First, the highly constrained nature of the long duration space habitat design problem described in previous sections requires a more optimized solution than the one typically generated through the architectural programming process, which benefits from more margin on mass/volume. Second, the time it takes to compare many layout alternatives with architectural programming scales somewhat linearly with the number of alternatives, which makes it ill-suited for automation.

As shown in Table 6, comparison of these various spacecraft interior layout evaluation methods reveals the desired performance of the proposed evaluation method. A method is desired which can quickly investigate large numbers of possible configurations with an absolute scale of measurement to allow for direct comparison between alternatives. The method described in Chapter 3 will describe how reduced fidelity geometry and increased automation could be leveraged to enable these improvements. The following section describes the habitat design requirements, heuristics, evaluation criteria and constraints described in literature which must be considered in a complete evaluation process.

2.1.2 Space Habitat Interior Design Requirements and Heuristics

Space habitat design requirements and interior layout heuristics which capture major layout considerations drive the selection of evaluation criteria and constraints required to perform quantitative interior layout evaluations that lead to realistic layouts. Spacecraft requirements ensure that the required functionality and performance of habitat interior are provided to “ensure safety and reliability of human-rated exploration vehicles” and the crew they support [Allen et al., 2003]. Table 7 lists requirements which specifically impact interior layouts which are derived from NASA standards [NASA, 1995], OSHA (Occupational Safety and Health Administration) requirements, and spacecraft design texts [Allen et al., 2003; NASA, 1999; Salvendy, 1997; Larson & Pranke, 1999; Connors et al. 1985,]. This list is not exhaustive, but provides a feel for the types of requirements that influence the size and placement of interior items. These requirements are defined at a high-level during conceptual design until mission/destination operations are more clearly defined. Increased definition of the specific mission objectives set more numerical thresholds for each of the key requirements and reduce the number of applicable implementations capable of fulfilling these requirements. For example, mission duration and destination define acceptable radiation protection thresholds and meeting those radiation protection thresholds can be accomplished by a ‘safe haven’, water walls, or by shielding [Larson & Pranke, 1999]. Selecting the appropriate option requires analyzing the mission objectives and making a decision based upon multiple criteria including cost, mass, volume, and risk.

Table 7: Space Habitat Architecture Requirements

Habitat Design Requirements	References
Comply with appropriate military, NASA, or equivalent human-rated systems requirements	[Larson & Pranke, 1999; Allen et al., 2003; NASA, 1995; NASA, 1999; Salvendy, 1997;]
Provide an environment for the crew which is safe to live and work in for the specified mission duration and destination	[NASA, 1995; Kennedy, 2002a; Larson & Pranke, 1999]
Provide the necessary systems and accommodations for the sustainment of human life	[Larson & Pranke, 1999]
Environmental Control and Life Support Systems (ECLSS)	[Allen et al., 2003; Larson & Pranke, 1999; Eckhart, 1996; Chambliss, 2007; Anderson, Ewert, Keener, Wagner, 2015]
Associated consumables, distribution, and storage	
Crew accommodations and associated storage	[Allen et al., 2003; NASA, 1995; Larson & Pranke, 1999]
Thermal Control System (TCS)	[NASA, 1995; Larson & Pranke, 1999; Lyle, Stabekis, & Stroud, 1973]
Provide maintenance access for these and all other critical systems	
Provide sufficient redundant units or capability for critical systems	[Larson & Pranke, 1999 (p31)]
Provide either an internal power source or an interface to an external system sufficient to support critical systems through the day/night cycle. Also provide a power management and distribution system to support powered systems.	[Larson & Pranke, 1999 (p 39)]
Provide a reliable structure with adequate safety margins to maintain pressure	[NASA, 1995; NASA, 1999]
Providing volume sufficient for physiologically, psychologically, and psychosocial health and an efficient work environment when all systems and cargo are stored and packaged	[NASA, 1995 8.6, Larson & Pranke, 1999 (Ch. 7), Connors et al. 1985]
Provide crew station volume accommodating the necessary tasks to be performed in the habitat without interfering with other tasks	[NASA, 1995 (sec. 8.2.3). Salvendy, 1997; Larson & Pranke, 1999 (p 30)]
Arrange equipment to provide separation of certain types of systems to increase safety of crew, efficiency of work environment, etc.	[NASA, 1995 (section 8.2 and 8.3), Allen et al., 2003; Larson & Pranke, 1999]
Compatibility with surrounding activities and facilities	
Hygiene separation for biological containment and crew safety	
Dust separation from crew activity and living quarters for health and equipment operation	
Noise separation for crew health and workstation efficiency	
Provide protection from space or surface environment	[Allen et al., 2003]
Radiation protection	
Micro Meteoroid and Orbital Debris (MMOD) protection	
Plasma and electrostatic environment	
Vacuum	
Dust protection	
Thermal extremes protection	
Provide areas and equipment for sleep and rest, eating, exercise, hygiene and personal time sufficient for the defined mission	[Allen et al., 2003; Larson & Pranke, 1999]
Provide method and path for emergency egress routes	[NASA, 1995; sec. 8.7.3.4]
Provide adequate translation paths outside of the crew working envelopes	[NASA, 1995 sec 8.8]

Table 7 (continued)

Hatches and doors should be placed away from hazards and allow for full path of motion	[NASA, 1995 , sec8.10]
Provide the tools necessary to perform the required diagnostics/repairs and increase the efficiency of the work	
Provide workstations for control of systems and performance of research	[Allen et al., 2003; NASA, 1995; Salvendy, 1997]
Provide equipment for communication with mission command either independently or by utilization of an existing communication infrastructure	[Larson & Pranke, 1999 (Ch. 26)]
Provide the pressurized interfaces and sufficient translation path for goods/person transport	[NASA, 1995]
Provide equipment and consumables for extra vehicular activity required from the mission description and a designated area to maintain EVA equipment	[Larson & Pranke, 1999 (p 134)

Requirements typically fall into three categories which are not mutually exclusive: required capabilities, required arrangements, and required performance thresholds. Required capabilities specify the types of hardware which must be provided to support crew work and rest. These are easily identified from major design standards documents like NASA's Standard 3000 and the Human Integration Handbook [NASA, 1995; NASA, 2010]. Required arrangements apply constraints to the relative positions and orientations of conflicting or synergistic functional areas as well as constraining their location relative to habitat structural features like hatches and windows [NASA, 1995; NASA, 2010]. Requirements thresholds identify required levels of performance for spacecraft interior and systems. These can often be nebulous to quantify due to the multiple varying opinions on many parameters values specific to spacecraft interiors. One frequent example of this is habitable volume, which has been discussed at length within NASA to establish recommendations for future missions [Simon et al., 2012 and Simon et al., 2011]. The NASA Standard 3000 indicates that 20 m^3 per person is appropriate for long duration missions [NASA, 1995; section 8.6.2.1], but several NASA references report different required values citing special circumstances or different functionality which must be adequately packaged [Allen et al., 2003; Simon et al., 2012].

Simply addressing the requirements listed in Table 7 does not imply an acceptable/desirable design, as additional considerations and crew preferences are required to ensure that the form of the interior layout is consistent with crew expectations of a livable space. To ensure the proposed evaluation method leads to acceptable designs, the most significant rules and design considerations which are used in current habitat interior design methods are collected here as a table of habitat interior design heuristics. Heuristics are “rules of thumb” which are often used to guide layout design towards favorable alternatives. Table 8 lists some of the habitat interior design heuristics used in practice [Osburg, 2002; Eckart, 1996; 1999; Salvendy, 1997; Larson & Pranke, 1999; Allen et al., 2003; Connors et al. 1985; Howe & Sherwood, 2009; and Kennedy, 2002a; etc.].

These requirements and heuristics serve two purposes: defining measurable ‘evaluation criteria’ which can be used to evaluate alternative configurations and defining ‘constraints’ on the placements and orientations of components. Evaluation criteria allowing for comparison of the acceptability of a layout include metrics like habitable volume, mass, translation path width, and separation for hygiene. Constraints on the placement of objects which must be satisfied include translation path and door clearances, heights of workstation consoles, and allowance for maintenance access. Chapter 3 will describe in detail how these requirements and heuristics are translated into these evaluation criteria and quantitative methods to measure them.

Table 8: Habitat Interior Configuration Design Heuristics and Considerations

Design Area	Heuristic	References
Dimensions and Volume	Launch vehicle geometric constraints drive outer mode line dimensions	Osburg, 2002; Adams & McCurdy, 2000
	Quantify spatial habitability issues (line-of-sight, volumetric, other metrics) for objective ranking of alternatives	Osburg, 2002; Wise, 1985; SICSA, 2008
	Spaciousness increases with neatness/degree of organization and skillful distribution of furnishings	Osburg, 2002
	Volume must be reserved for line runs of power, water, air, etc.	
	Areas in cylindrical habitats without full standing height are useful for sleeping, seated workstations, storage	SICSA, 2008
Mass	Provide the maximum usable volume and floor area for the associated structural mass	Eckart, 1999; SICSA, 2008
	Line lengths for power, air, water, etc. should be minimized using adjacency matrices and proper placement of resource sources	
	Center of gravity of components should roughly approximate center of volume	SICSA, 2008
Translation Paths	Paths should be wide enough for two crew members to pass each other with EVA suit donned (1.4 m), in case of depressurization or other emergency egress situation	Eckart, 1999;
	Dual egress capability at each location for redundancy and emergency sealing off of habitat segments	Eckart, 1999;
	Stairs or floor translation mechanism must be designed with bounding gait and mobility in the mission gravity	Eckart, 1999;
Shapes of Spaces	Ceiling height for partial gravity orientations should be set for psychological well-being and bounding gait (e.g., 3 m in case of lunar surface)	Eckart, 1999;
Maintainability and Access	Provide access to external walls, cable standoffs, behind subsystems, stowage	Osburg, 2002; SICSA, 2008
	Attempt to provide enough space that equipment in regular use (exercise, dinner table, etc.) can remain deployed.	Osburg, 2002
Workstations	Workstations should be of standardized, uncomplicated design and should be grouped for task completion	Eckart, 1999;
	Avoid sharp corners and edges for safety	Eckart, 1999;
Anthropometrics	Provide appropriately sized and placed work surfaces for partial gravity posture	Eckart, 1999; Salvendy, 1997
	Operational volume around workstations and systems with which crew interact must be reserved for that interaction	Salvendy, 1997
Biomechanics	Locate and organize stowage to facilitate retrieval of objects subject to biomechanical limits such as lifting posture, load carrying from posture, etc.	Salvendy, 1997

Table 8 (continued)

Design Area	Heuristic	References
General Habitability	Habitability requirements increase as mission duration, risk, isolation, and confinement increase	Connors et al. 1985,
	Adhere to local vertical	Connors et al. 1985,, Adams & McCurdy, 1999
	Increase horizontal line of sight distances and visible volume	Adams & McCurdy, 1999, Wise, 1985
Privacy and Social Interaction	Individual, private crew quarters for sleeping, reading, writing	Eckart, 1999;
	"Quarters should be large enough to enable occupant to dress and undress with a reasonable amount of volume for movement"	Bernasconi, Versteeg & Zenger, 2008
	An area must be included to accommodate all-crew member meetings	Eckart, 1999;
	Separation of living and working environment for enhanced privacy	Bernasconi et al., 2008
Noise	Minimize sources of noise, particularly in private spaces	Eckart, 1999;
	Noise levels for labs and work areas < 55dB	Eckart, 1999;
	Noise levels for sleeping areas < 35 dB	Eckart, 1999;
Vibration	Control vibration throughout the habitat	Eckart, 1999;
Hygiene	Provide separation of hygiene facilities from sleeping and galley areas	Allen et al., 2003
	In partial gravity or microgravity conditions, collection of water and debris may require vacuum lines or hand-held vacuums to be placed near hygiene stations	Allen et al., 2003
	If dust control methods are not developed for long-duration surface missions, whole body cleansing in the form of a rigid water-tight shower like on Mir or Earth analogs	Allen et al., 2003
	Exercise requirements necessitate full body cleansing facilities	Connors et al. 1985,
Lighting	Provide task specific lighting	Allen et al., 2003
	Provide emergency lighting	Eckart, 1999;
Window	Provide at least one window for Earth/Space/Surface viewing	Osburg, 2002; Adams & McCurdy, 2000
	Preferred location: conference/ dining area, exercise area, quiet area	Osburg, 2002; Adams & McCurdy, 2000
	Placement of windows and lighting devices should take into consideration light sensitive activities, such as sleeping, use of displays, or tasks requiring dark adaptation	Allen et al., 2003
Hatches and Doors	Hatch and door size should accommodate the largest crewmember and any equipment to be transported	Allen et al., 2003
	Translation paths for suited crewmembers may be required in some cases	Allen et al., 2003
	Doors and hatches should be placed to avoid potential traffic congestion with crew systems. The reverse is also true.	Allen et al., 2003
Seating and other Furniture	Should accommodate posture in mission gravity	Eckart, 1999;
Microgravity Considerations	IVA mobility aids should be made available in microgravity or low gravity situations	Allen et al., 2003

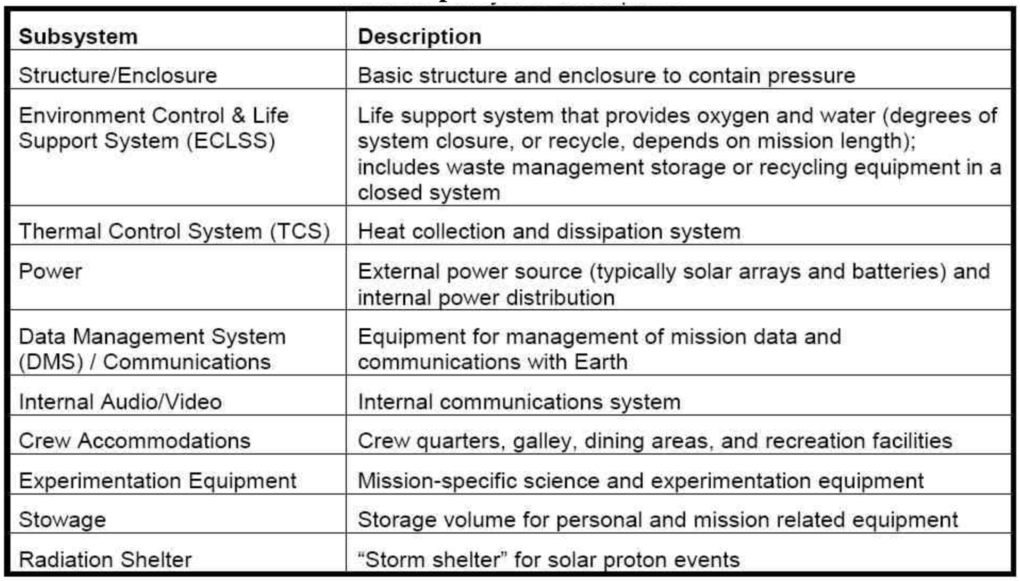
2.1.4 Subsystem Information

Habitat interior layouts are arrangements of subsystems, accommodations, and logistics packaged within a pressure vessel geometry [Larson & Pranke, 1999]. Kennedy describes designing habitats as:

> "… *providing volume for all crew living functions, including galley/wardroom, sleep and hygiene accommodations, radiation protection, and stowage. The habitat will also serve as the location for a number of crew work functions, such as science laboratories, crew medical care & exercise, mission operations, communications with Earth, maintenance, and Extravehicular Activity (EVA), including airlocks. Adequate volume is required for each of these functions in addition to that devoted to housing the habitat systems, such as Environmental Control & Life Support, Avionics, and Power Management and Distribution*" [Kennedy, 2002a]

Subsystems include the systems which operate to support the habitat which nominally operate with little crew interaction such as life support, thermal control, power, communications, etc. [Larson & Pranke, 1999; Eckart, 1996]. Accommodations are systems which the crew interact with on a regular basis to support crew life and include crew quarters, galley, refrigerators, tables, exercise equipment, etc. [Larson & Pranke, 1999]. Finally, logistics include spares, resupply items, and consumables such as food and medicine which would nominally be resupplied between missions. Some information on these packaged components like the mass, volume, interfaces, and functionality are necessary inputs to the evaluation criteria quantification methods described in Chapter 3. Table 9 describes the habitat subsystems and accommodations required to support a crewed habitat and Figure 4 indicates which are packaged inside the habitat volume (and thus are relevant to an interior layout design). In depth descriptions of each of these subsystems are provided in the references listed in Table 10 and the specifics of subsystem information used to prove out the method described in Chapter 3, 4, and 5 are provided in Appendix C.

Table 9: Habitat Subsystem Descriptions [reproduced from Kennedy, 2002a with permission]



Subsystem	Description
Structure/Enclosure	Basic structure and enclosure to contain pressure
Environment Control & Life Support System (ECLSS)	Life support system that provides oxygen and water (degrees of system closure, or recycle, depends on mission length); includes waste management storage or recycling equipment in a closed system
Thermal Control System (TCS)	Heat collection and dissipation system
Power	External power source (typically solar arrays and batteries) and internal power distribution
Data Management System (DMS) / Communications	Equipment for management of mission data and communications with Earth
Internal Audio/Video	Internal communications system
Crew Accommodations	Crew quarters, galley, dining areas, and recreation facilities
Experimentation Equipment	Mission-specific science and experimentation equipment
Stowage	Storage volume for personal and mission related equipment
Radiation Shelter	“Storm shelter” for solar proton events

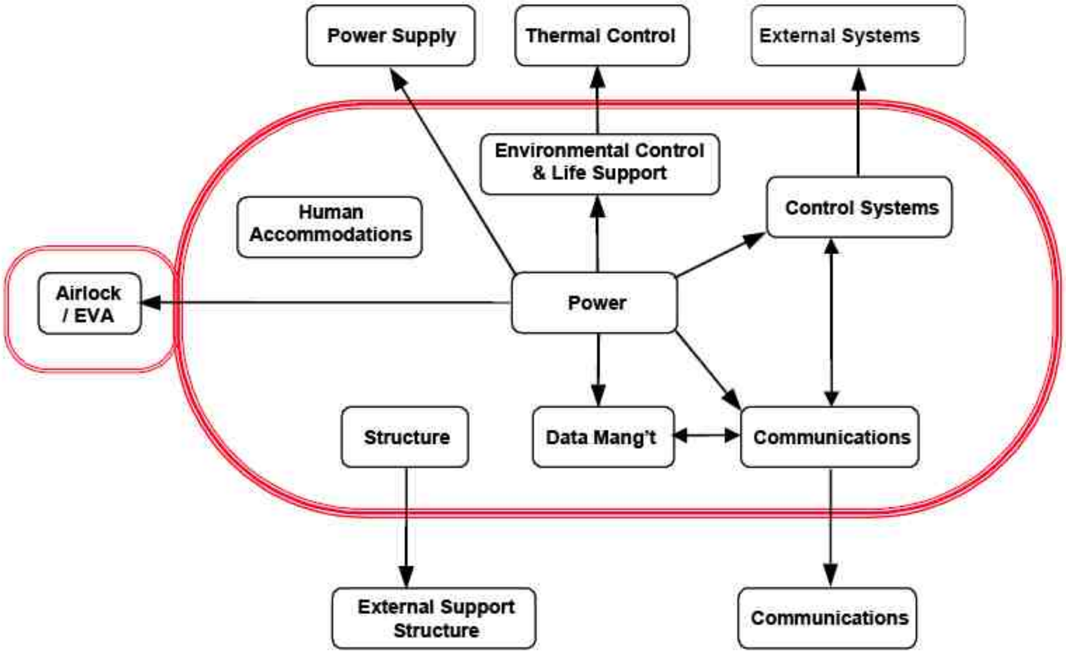


Figure 4: Habitat Elements and Interfaces [reproduced from Kennedy, 2002a with permission]

Table 10: Subsystem References

Subsystem	References
Environmental Control and Life Support Systems / Thermal Control Systems	Eckart, 1996; Eckart, 1999; Hanford, 2004; Larson & Pranke, 1999
Human or Crew Accommodations	Larson & Pranke, 1999; Allen et al., 2003;
Power Management and Distribution System	Eckart, 1999; Larson & Pranke, 1999;
Science Equipment	Budden, 1994
Extravehicular Activity (EVA) Equipment	Larson & Pranke, 1999
Workstation Design (Communications, Data Management, etc.)	Larson & Pranke, 1999; NASA, 1995; Salvendy, 1997

2.2 Geometry Modeling and Collision Detection

In order to enable quantifiable evaluation of habitat interior layouts using computer software, mathematical representation of the hardware to be packaged must be defined in a manner allowing distance measurement between objects and enabling collision detection to eliminate infeasible overlap of hardware. This section presents information about simple geometric modeling and collision detection which will be applied in the evaluation criteria and constraint measurement methods described in Chapter 3.

2.2.1 Geometry Modeling

A mathematical representation of hardware geometry is necessary to define the layout geometries which feed quantitative evaluation measurement methods. Historically, the habitat interior design process uses detailed CAD models or drafted drawings to represent the space taken up by the hardware in the layouts [Fitts, 2002; Howe & Sherwood, 2009]. These models can be powerful tools at the detail design phase, but long creation times and model detail complexity are often incompatible with the fast layout evaluation goal defined in Section 2.1. A simple polyhedral representation of the hardware geometry derived from computer animation and video game programming is well-structured for use in layout creation and has been used extensively in the majority of three-dimensional layout design references [Bénabès, Bennis, Poirson, & Ravaut, 2010]. By representing geometries as simple polyhedral objects specified by matrices of vertices and face-normal vectors as shown in Figure 5, the overlap of geometries can be detected with standard collision detection algorithms to prevent the creation of unrealizable layouts [Ericson, 2004]. Additionally, this polyhedral object representation allows for generation of layouts by simply manipulating the location and orientation of each subsystem through definition of translation and rotation matrices. What results is a fast, simple, mathematically operable method of constructing layout alternatives with relatively simple sets of data.

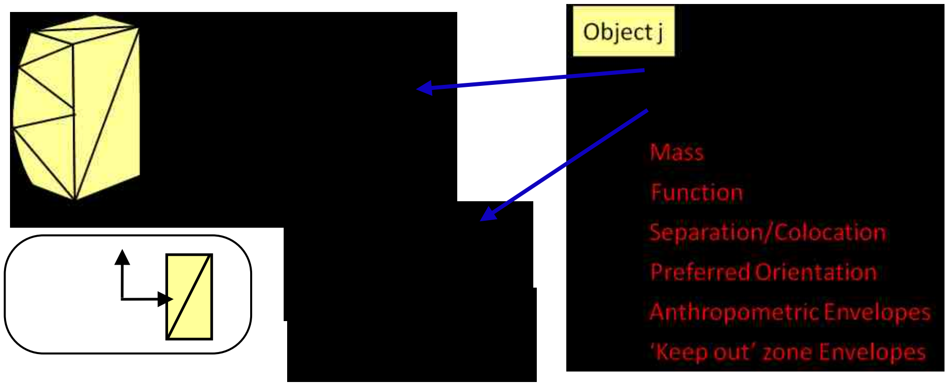


Figure 5: Mathematical Representation of Object Geometry Collocated with Detailed Information

In addition to representing the geometry effectively, the polyhedral representation of geometry is easily defined in object-oriented programming languages. This is fortunate as using object-oriented programming simplifies the embedding of detailed function and interface information together with the geometry data in arrays or matrices within an indexed object. The types of object information required include: the mass of an object, the function it belongs to, any separation or collocation relationships associated with the provided function, geometry and location of anthropometric envelopes reserved for human interaction with the object, and keep out zones for moving parts. Collocated storage of this information with geometry data facilitates straightforward calculation of evaluation criteria which track these characteristics in combination with geometry. The importance of this layout and data representation method will be discussed more in Chapter 3.

2.2.2 Collision Detection

Collision detection (also known as interference detection or contact determination) is the detection of contact, overlap, or intersection of geometries [Ericson, 2004]. It is used extensively in video games [Eberly, 2006], virtual prototyping, robotics [Lin, 1993], animation [Lin, 1993], and engineering simulations [Hahn, 1988]. In the evaluation of habitat layout alternatives it serves two purposes. First, interferences between pieces of hardware and between hardware and pressure vessel structure must be detected to ensure that only physically realizable layouts are acceptable. Second, collision detection can be used to measure several of the volume evaluation criteria which measure volume or task performance criteria counting potential interferences between different types of objects.

In order to develop tests for physical realizability and quantification methods for the evaluation criteria mentioned in Chapter 3 and Appendix B, three types of required collision tests are summarized in Figure 6. Determining if a point is located inside an object allows for the calculation of sizes of open spaces when combined with other information in a numerical volume estimation algorithm [Simon et al., 2012]. Determining the intersection point between a line and an object can be used to determine line of sight distances or isovist radials necessary for determining lengths of open space [Wise, 1985]. Testing for overlap between any two three-dimensional geometries enables the detection of interferences between hardware and between working envelopes. This collision detection test is also necessary for testing the realizability constraint which requires that packaged geometries not overlap.

Figure 6: Types of Collision Detection Needed in Automatic Evaluation Criteria Quantification Methods

There are several methods available to perform these collision tests documented in dedicated texts [Ericson, 2004; van den Bergen, 2003]. Three qualitative figures of merit are used in the comparison of collision detection methods: performance (i.e., run time), accuracy in detecting collisions, and ease of implementation. Based upon the complexity of the geometry and number of objects anticipated in a realistic layout problem, different options are available for each of types of tests. The following options presented in Table 11 are proposed for each test:

Table 11: Applicable Methods/Algorithms for Required Collision Detection Tests

Collision Detection Test	Method 1	Method 2 (preferred)
Test if point is in interior of an object	• Half space tests with spatial partitioning to reduce objects compared [Ericson, 2004] • May generalize to Chung-Wang Separating-Vector Algorithm [Chung & Wang, 1996; Ericson, 2004]	• Incremental Separation Axis – Gilbert, Johnson, and Keerthi (ISA-GJK) Algorithm [van den Bergen, 2003; Gilbert, Johnson, & Keerthi, 1988]
Intersection point between a line and an object	• Intersection of line against a triangle algorithm [Ericson, 2004] • Closest point to line algorithm [Ericson, 2004] can be used to reduce necessary tests	• Incremental Separation Axis – Gilbert, Johnson, and Keerthi (ISA-GJK) Algorithm [van den Bergen, 2003; Gilbert et al., 1988]
Collision detection between three-dimensional geometries	• Chung-Wang Separating-Vector Algorithm [Chung & Wang, 1996; Ericson, 2004]	• Incremental Separation Axis – Gilbert, Johnson, and Keerthi (ISA-GJK) Algorithm [van den Bergen, 2003; Gilbert et al., 1988]

Simple Collision Detection Tests

Half-space tests are a fundamental building block of collision detection methods. Half-space tests determine the signs of the dot products between the face normal vector, n, of the polyhedron face and the vector p#, between a vertex on the face and the point being investigated, as shown in [van den Bergen, 2003]. If the sign of the dot product between the two vectors is positive for any of the polyhedron faces, then the point is outside the object. If the sign is negative for all faces, then the point lies within the object and is said to collide with that object. In the example shown in Figure 7, p1·n is positive, indicating that p1 lies outside of the face and p2 ·n is negative indicating that p2 lies within the face. If the dot product is zero, then the point lies on the surface.

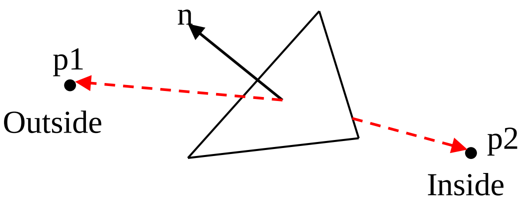


Figure 7: Illustration of Half-space Tests

If the geometry of the polyhedral objects is restricted to triangles, this becomes a simple test of determining the intersection point between a line and some triangle, which is solved similarly to half- space tests. The point of intersection between the line and the plane of the triangle is calculated. This point is then tested to determine if it lies within the triangle by determining if the signs of particular cross and/or dot products of intermediate products are positive or negative. Several methods exist and are described in Ericson, 2004 with discussion on reducing the required number of calculations and speeding the tests.

The Chung-Wang Separating Vector Algorithm

The Chung-Wang Separating Vector Algorithm [Chung & Wang, 1996] is one of the advanced industry standard collision detection algorithms. It works by finding the extreme vertices between of two objects and using them to iteratively find a separating axis. This separating axis can be defined by the separating-axis test described in Eberly:

> "Two convex polyhedra do not intersect if there exists a line with direction M such that the projections of the polyhedra onto the line do not intersect. In this case there must exist a plane with normal vector M that separates the two polyhedra." [Eberly, 2008a; Eberly, 2008b]

Rather than testing full factorial of many different vector cross products to find if this axis exists, the Chung Wang algorithm uses sophisticated methods to converge to the axis much faster. The steps of the algorithm are described in Ericson, 2004 and open-source code is available.

Incremental Separating Axis – Gilbert-Johnson-Keerthi Algorithm

Finally, the Incremental Separating Axis – Gilbert-Johnson-Keerthi (ISA-GJK) algorithm [van den Bergen, 2003; Gilbert et al., 1988] can be used consistently for each of the types of collision detection listed in Figure 6. This algorithm provides fast and consistent collision detection between any two convex geometries. When a collision test between a point and hardware geometry is required, the point can be modeled as a small sphere enabling one type of collision test for all applications. This algorithm is described in detail in Ericson, 2004 and code is provided in van de Bergen 2005. In this body of work, Method 2: the ISA-GJK algorithm was implemented because of its speed, accuracy, ease of implementation, and applicability to all three collision detection tests.

One caveat to the application of these collision detection methods worth mentioning is that most tend to be substantially simplified with convex objects (defined such that a line can be drawn from one point within the object to any other point in the object without passing outside of the object). This adds the additional complexity that object geometries in the habitat interiors must be modeled as the combination of multiple convex objects to avoid the use of much more complicated collision detection tests. For more information on non-convex tests, the reader is referred to Ericson, 2004 and Ikonen, Biles, Kumar, Wissel, & Ragade, 1997.

Finally, because of the criticality of fast collision detection tests for video game and computer animation applications, many methods to speed up collision detection tests have been created. Even moderately-sized problems can require extremely large numbers of collision tests. The primary way of ensuring real-time performance of collision detection methods is to use lower fidelity tests to remove pairs of objects which cannot be colliding from consideration. This can be achieved by the utilization of one or more of the following four concepts: bounding volumes, bounding volume hierarchies, spatial partitioning, and coherence which each reduce the number of objects to be tested significantly.

- **Bounding Volumes:** The more polygons an object is made up of, the more complicated and time consuming collision detection tests can be. A ‘bounding volume’, illustrated in Figure 8, is a simple approximated geometry often used to represent more complicated geometries in collision detection tests. There are many types of bounding volumes which trade the speed of collision detection tests for more accurate representation of geometries. Utilization of less precise bounding volumes as a first cut analysis to rule out collision can reduce the overall testing time over more accurate complicated geometries. References for more information on bounding volumes and their construction are included [Ericson, 2004; Bartz, Klosowski, and Staneker, 2005; Konečný & Zikan, 1997; Konečný, 1998; Klosowski, Held, Mitchell, Sowizral, & Zikan, 1998; Kavan, Kolingerova, & Zara, 2006; Barber 1996; O’Rourke, 1998].

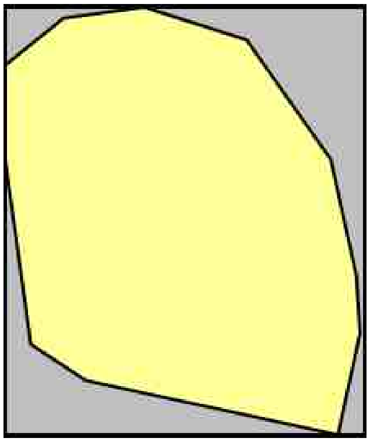


Figure 8: Bounding Volume of Complex Geometry

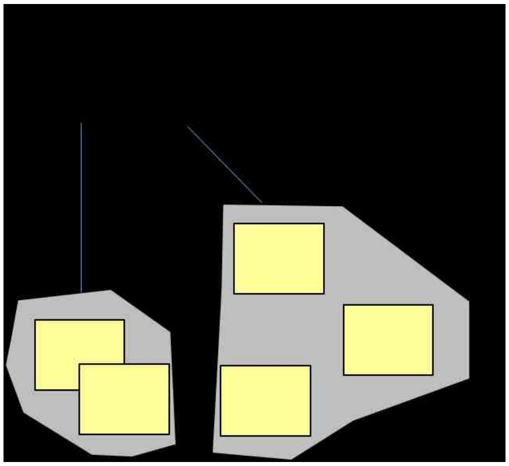


Figure 9: Boundary Volume Hierarchies

- **Bounding Volume Hierarchies:** Rather than comparing each bounding volume against each other bounding volume, bounding volumes can be arranged into tree hierarchies, reducing the number of tests by *model partitioning* [van den Bergen, 2003]. Within a hierarchy, children do not have to be investigated if parents do not intersect. Figure 9 illustrates this. Since bounding volumes 1 and 2 don't overlap, any collision detection tests between those boxes in bounding volume 1 and those in bounding volume 2 need not be compared. The hierarchies are not disjoint and can be used to speed tests for complex objects [Klosowski et al., 1998]. Desired characteristics of boundary volume hierarchies are found in Kay & Kajiya, 1986 and Hubbard, 1995 and summarized in Ericson, 2004. Ericson, 2004 provides methods for generating the trees. There are several other references which use bounding volume hierarchies [Gottschalk, Lin, & Manocha, 1996; Klosowski et al., 1998].

- **Spatial Partitioning:** Spatial partitioning, which is shown in Figure 10 is similar to bounding volume hierarchy, but instead of grouping bounding volumes into trees, bounding volumes are grouped by physical location to reduce the pairs of objects to be tested to those in the same region of space [Ericson, 2004]. Selecting the appropriate cell size and arrangement is important. If cells are too large with respect to object sizes, then the number of calculations could remain unchanged. If cells are too small, the necessary additional information required would take extra time and memory [Ericson, 2004; Cohen, 1995]. Spatial partitioning can be performed using uniform grids or various types of trees including octrees and k-d trees [Jiménez, Thomas, & Torras, 2001]. Octrees are axis aligned hierarchal partitioning where each parent can have 8 children (split evenly into a two by two cube). Subdividing continues until no more than a maximum number of items are contained in each cell. k-d trees split the space at an arbitrary position one dimension at a time in a cyclic manner (first x, then y, then z, then x, and so on). This simplifies the code necessary to construct the tree because only intersection along one plane needs to be checked [Bentley, 1975; Friedman, Bentley, & Finkel 1977].

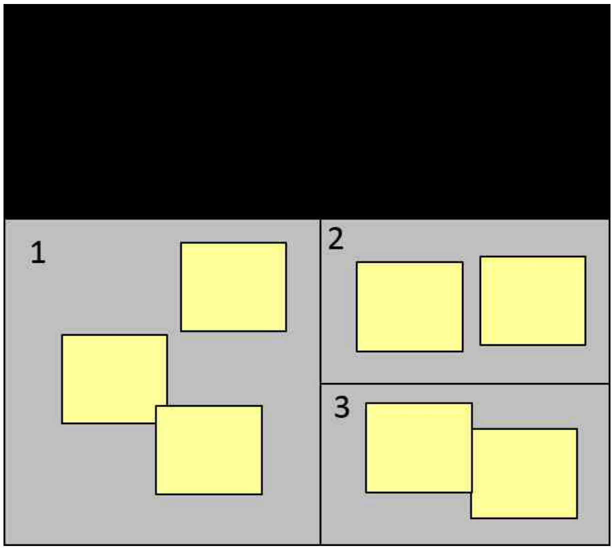


Figure 10: Spatial Partitioning

- **Coherence:** Coherence simply refers to leveraging the key variables determined in previous steps to speed convergence. The separating axis or closest-point from a previous step can be used as a starting point for the next test. Use of coherence is extremely valuable when dealing with small time steps associated with many real time applications [Ericson, 2004].

These four concepts may be implemented in any combination as deemed necessary by the desired timescale of the evaluation procedure.

2.3 Automated Layout Generation

The previous sections in this chapter have described the available methods used to evaluate space habitat interior layouts and presented the necessary background information to develop timely methods to perform these evaluations to inform concept design. In order to enable the iterative improvement of the evaluated layouts leading to an automated layout generation capability which can produce desirable layouts, a layout generation literature is surveyed to develop an automated habitat interior layout generation method. Literature has clearly characterized the need for the production of "superior layout alternatives for further consideration and treatment by decision makers" [Ahmad, 2005, Tompkins, White, Bozer, & Tanchoco, 2010]. Automation of layout design is a large field of study spread across many disciplines with many proposed solution approaches, each focused on a specific application [Ahmad, 2005; Lobos & Donath, 2010; Homayouni, 2006]. The focus of this section is to briefly describe the large automated layout design problem as a whole, then identify the desired characteristics of effective automation algorithms applicable to the space habitat interior layout design problem. Finally, this section will identify those methods utilized in literature which are best suited to implement in the proposed process addressed in this thesis.

2.3.1 Automated Layout Design Problem

The layout design problem seeks a "superior outcome in the spatial arrangement of modules in a given space, satisfying given preferences and constraints, and optimizing some fitness metrics" [Ahmad, 2005]. This problem is investigated under many names in many fields of study including *space layout planning* [Homayouni, 2006], the *facility layout problem* [Cagan, Shimada, & Yin, 2000; Lobos & Donath, 2010; Tompkins et al., 2010], *layout optimization* [Cohoon, Hegde, Martin, & Richards, 1991], and some similar problems with similar characteristics and solution methodologies including circuit board design [Mazumder & Rudnick, 1999; Schnecke & Vornberger, 1997] and bin packing [Ahmad, 2005; Dyckhoff, 1990]. As a result, there is a substantial amount of literature in the various work domains which is covered in several survey references [Ahmad, 2005; Cagan et al., 2000; Cohoon et al., 1991, Dyckhoff, 1990; Homayouni, 2006; Liggett, 2000; Lobos & Donath, 2010; Kalay, 2004; Tompkins et al., 2010; Wäscher, Haußner, & Schumann, 2007; etc.].

In layout design problem solutions, 'modules' (whatever is being arranged, e.g., rooms, objects, furniture, equipment, goods, buildings, etc.) are arranged using a placement algorithm which may be guided by historically applied heuristics and/or fitness function values to satisfy geometric constraints while accommodating the desired design features and relationships between module types. This complex problem is generally broken into two steps: 1) develop feasible alternatives layouts and 2) evaluate those alternatives against a single or weighted sum of multiple criteria to guide selection of additional layouts [Tompkins et al., 2010]. In the development of feasible layout alternatives step, the goal is to develop layouts which satisfy constraints on object placement such as the non-overlap constraint (modules can't be physical be packaged with overlapping geometries) and adjacency constraints (certain pairs of modules must or must not be adjacent). Approaches in the facility layout community group layout alternatives generation approaches into two major types: construction and improvement approaches [Liggett, 2000; Francis, McGinnis Jr., & White, 1992; Tompkins et al., 2010]. Construction approaches develop new layouts from scratch, often by rule-based, ordered placement which leads to less expensive, but poorer solutions [Liggett, 2000]. Improvement approaches improve upon a starting layout. They usually converge on local optima dependent upon their starting layout [Liggett, 2000]. By linking these two approaches, the strength of construction approaches to quickly develop initial layouts can speed convergence of improvement approaches [Liggett, 2000].

Typically, the layout generation problem is structured as an optimization problem, which is implemented in computer software due to the complexity of the mathematical formulations of the problem [Cagan et al., 2000]. The NP-hard and subjective nature of layout design problems make it difficult to prove optimum solutions with analytical methods [Ahmad, 2005]. This has led to the development of many heuristics and stochastic optimization algorithms to solve these problems while avoiding local optimum [Ahmad, 2005; Bénabès et al., 2010; Cagan et al., 2000; Dyckhoff, 1990; Homayouni, 2006; Lobos & Donath, 2010; Tompkins et al., 2010]. In particular simulated annealing and genetic algorithms have been extensively applied. In the next section, characteristics of the space habitat layout design problem are used to focus the literature review to the most applicable approaches addressing the specific needs of the proposed method.

2.3.2 Previous Work in Interior Layout Automated Generation

There is a very large set of references on the topic of improved layout generation; significantly more than can or should be covered exhaustively in this thesis. Characteristics of the habitat design problem which differentiate it from the general layout design problem are used to focus on a subset of applicable literature. There are three major differences between the terrestrial layout design problem and the space habitat layout design problem which limit the application of terrestrial layout design methods/tools to space habitat design. First, modern terrestrial layout design tools benefits from hundreds of years of design. Occupant preferences and the resulting design rationale have been codified into a standard set of validated layout measurements based upon the purpose of a facility (standard aisle widths, room sizes, etc.), and a the relationships between various functions have been formalized into design standards (e.g., "kitchen work triangle [University of Illinois Building Research Council, 1993], standard standoff distances, building codes, extensive architectural standards documentation [American Institute of Architects, 2000]). These standards and established functional relationships can simplify the generation of desirable interior layouts by enabling the application of constructive ordered placement algorithms which inherently meet these standards a priori [Akazawa, Okada, & Niijima, 2005; Liggett, 2000; Lobos & Donath, 2010; Xu et al., 2002]. Unfortunately, space habitats have few historical precedents to draw from, and it can be argued that there are few agreed upon standard or unnegotiable specifications for habitat layout design [e.g., NASA, 1995]. Additionally, pure constructive algorithms which develop acceptable, but poorly evaluated layouts are of little use in the design of long duration habitats which requires some degree of improvement to alleviate tight mass/power/volume mission architecture constraints. Finally, the sometimes complex geometries in habitat design do not work well with the existing constructive algorithms which leverage the simple geometries in the traditional layout design problems to reduce algorithm complexity, particularly in 2-D applications. Therefore, facility layout problem approaches which rely upon constructive procedures for object placement that exclusively leverage terrestrial precedents and standards are of some use, but may be of limited to no use in space habitat design.

The second major difference is that the space habitat layout problem is a highly integrated, multi-criteria problem with confined, tightly constrained interiors and non-uniform geometries. The characteristics of this problem require a slightly different approach than many of the less constrained, single-objective layout design approaches treated in literature (with the exception of select references dealing with specialized facilities such as naval vessels and small space residences) [Kennedy, 2002a; Ölçer, 2008; Simon & Toups, 2014]. Additionally, the highly constrained space habitat design problem has a relatively sparse feasible layout design space because the high packing density of internal accommodations, subsystems, and logistics makes satisfaction of the non-overlap constraint difficult. For this reason, references which address sparse design spaces due to this non-overlap constraint or references which address satisfaction of the non-overlap constraint directly are more analogous, and thus applicable, to the habitat layout design problem.

The third difference is that a space habitat is designed for multiple gravity environments such as microgravity, which utilizes surfaces such as ceiling and floors more extensively than terrestrial applications [Simon et al., 2012]. Additionally, because space habitats are sealed systems which provide all of the resources necessary to support crew, constraints like ventilation, access to water and waste, and emergency egress paths are critical. Assessments of how layouts affect their efficacy must be investigated in three dimensions to avoid oversights [Akin, 2012; Fitts, 2002]. For this reason, the simplification found in many habitat design references to two-dimensional layout problems would neglect many of the interactions which can only be represented in a three-dimensional layout. This additionally complicates the use of most constructive techniques which leverage two-dimensional geometry simplifications to allow for easy fulfillment of the non-overlap constraint. These two considerations increase the applicability of three-dimensional layout studies over the two-dimensional studies prevalent in most facility layout problem documentation. However, it should be understood that the solution algorithms may be similar between the two problems, and should be investigated for completeness.

Based upon these comments regarding the applicability of the existing literature to the space habitat layout design problem, Table 12 describes a small subset of applicable literature for automating habitat interior layout design based upon multiple criteria and constraints. This non-exhaustive subset was chosen for discussion based upon each study's ability to illustrate specific challenges of the multi-criteria, three-dimensional, highly constrained habitat layout generation problem. References in this table are mostly incremental improvement approaches bolstered by a stochastic metaheuristics, which are often simulated annealing or genetic algorithm variants.

Table 12: Applicable Interior Layout Automated Design Approaches

Alternative Approach	Description	Limitations
Simulated Annealing		
Szykman & Cagan, 1997	• A simulated annealing approach to three dimensional component layout which allows geometry constraints to be violated during the optimization process • Uses penalty functions on the objective function to drive the production of valid designs	• Limited to blocks and cylinders with 90 degree orientations • Simplified objective function
Smith, Hills, & Cleland, 1996	• A hybrid approach featuring simulated annealing method which hands off results to a knowledge-based system to address often negotiated requirements including usage of space, routing, and adjacencies • Applied to fuselage of military aircraft	• Block representation limits to orthogonal orientations • Packing density limitations
Genetic Algorithms		
Ahmad, 2005	• An expert system genetic algorithm approach to solve the 2D- bin packing problem which leverages deterministic placement heuristics for local placement	• 2-dimensional, simple geometries, few criteria • Use of placement heuristics to avoid collisions
Bénabès et al., 2010	• A genetic algorithm approach which uses designer interaction selectively to ensure overlap constraints are minimized in the initial population	• Designer interaction required during first iterations • Separation algorithm to avoid overlap of geometries is difficult to calculate in
Lau et al., 2014; based upon Cuco, De Sousa, and Neto, 2014	• A multi-criteria optimization approach for spacecraft exterior design utilizing evolutionary algorithm to determine a Pareto front on 5 objectives • Geometric constraints implemented as exterior penalty functions on the objective functions and by parameterizing the design variable	• Relies on user to make decisions between variables from Pareto front • Ignores some subjective quantities
Sanchez et al., 2003	• Constraint-based algorithm for 3D object layout utilizing genetic algorithm to optimize over topological, distance, and orientation constraints	• Like most constraint satisfaction problems, focus is on developing feasible layouts, not desirable ones • No criteria captured relevant to quality of human interaction

Habitat Automated Layout Decisions based upon Literature

There are three major habitat interior layout generation decisions identified by these references:

The first habitat layout generation decision is determining the appropriate method to ensure resultant layout alternatives respect the non-overlap constraint. Two approaches exist in literature:

1. Prevention using placement algorithms which avoid overlaps [Ahmad, 2005, Tompkins et al., 2010], leveraging discretized grid of possible module locations which avoids collisions (most 2D early approaches; described in Tomkins et al. 2002), and/or by performing a sub-optimization to minimize overlap [Bénabès et al., 2010]. In these studies, only "valid" (or feasible layouts satisfying the non-overlap constraint) are evaluated to facilitate convergence which could be hindered by the multi-modal, discontinuous objective function values caused by non-overlap penalties.
2. Accept overlapping solutions in early iterations and use penalty functions on the objective function to drive later iterations to valid solutions [Szykman & Cagan, 1997]. This approach has been demonstrated, but requires more care in optimization tuning for good convergence behavior.

Prevention methods are easier to converge, but may prevent a more thorough exploration of the design space. For the proposed method, the Accept method is applied, though prevention methods maybe implemented for initial layouts to speed convergence. Similarly block layouts utilizing discrete positions and orientations are avoided when possible, or made sufficiently high-resolution to approximate to continuous space and fully capture the available design space.

The second decision is the selection of a stochastic optimization method to drive the selection of subsequent layouts. This can be difficult as the multi-modal, sometimes discontinuous nature of the objective function can make it difficult to avoid converging to local optima. Options include:

- **Gradient-Based Methods:** Though gradient-based methods can be applied to multi-objective, multiple constraint problems, the "highly discontinuous and multi-modal" nature of layout problems complicates application of gradient based methods. This is because methods necessary to calculate gradients on the design space may have misleading effects" on search directions. Additionally, these methods would have difficulty identifying global optima [Cagan et al., 2000].

- **Genetic Algorithms:** Genetic Algorithms (GAs) are used extensively in layout generation problems [Ahmad, 2005; Bénabès et al., 2010; Borfeldt & Gehring, 2001; Corcoran & Wainwright, 1992; Lau et al., 2014; Sanchez et al., 2003]. They can be defined as follows:

  > "Genetic Algorithms are evolutionary optimization approaches which simulate a natural evolution process based on Darwinian Theory, in which the fittest species survive and propagate while the less successful ones tend to disappear. They are most appropriate for complex non-linear models where the location of the global optimum is a difficult task. (Genetic Algorithms) also differ from many optimization methods in the sense that they only use the objective function, not derivatives, to identify possible solutions." [Ölçer, 2008]

  These "fittest species" are locations and orientations which optimize the objective function and are passed down like genes to the next generation. Benefits of GAs are the ability to explore a large, non-linear, discontinuous design space efficiently and better handling of constraints [Deb, 2001]. They have also been proven effective in optimization of interconnections between components in Very Large Scale Integration (VLSI) and factory layout problems [Cohoon et al., 1991, Schnecke & Vornberger, 1997]. The problems with GA methods are the necessity of discretizing the design space, the large number of objective function evaluations required for convergence, and the lack of actual proof of optimality [Cagan et al., 2000].

- **Simulated Annealing:** Besides GAs, Simulated Annealing (SA) algorithms are the most widely applied methods for the multi-objective optimization problem. Simulated annealing is a stochastic technique based upon the analogy between heating and controlled cooling of metals to direct crystal formation to reduce defects [Kirkpatrick, Gelatt, & Vecchi, 1983; Smith, 2006]. In each step of the algorithm, the solutions are perturbed to alternate solutions, which are evaluated with the objective function. A parameter called 'temperature' is used to calculate a probability that a worse solution than that of the previous iteration will be accepted as shown:

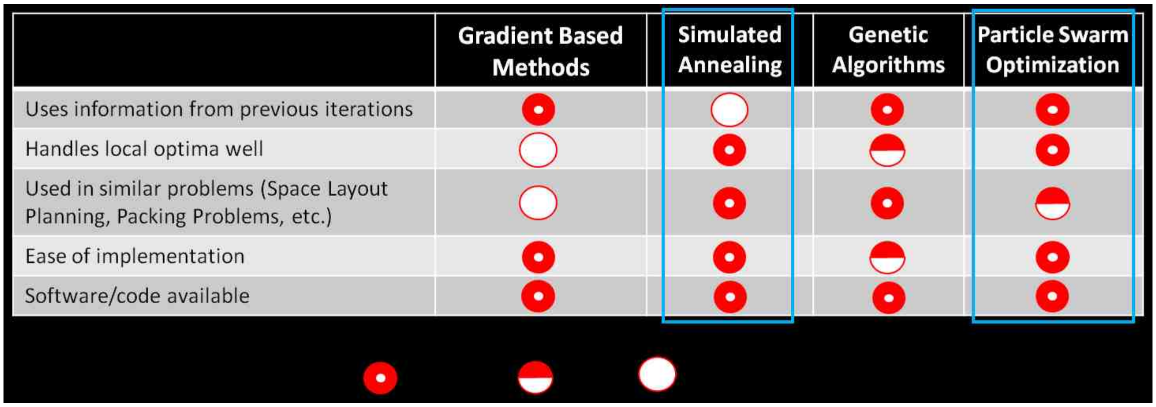
$$P_{accept} = e^{-\left(\frac{\Delta C}{T}\right)} \quad \textbf{(2)}$$

where ΔC is the change in objective function due to the move and T is the current temperature [Szykman & Cagan, 1995]. This permissible selection of worse solutions prevents the algorithm from getting caught in local minima [Cagan et al., 2000]. The algorithm is iterated while changing the temperature according to a cooling schedule to settle the solutions into the global optima. There are many other benefits to implementing a SA approach. First, like GAs, SA algorithms are zero-order methods which don't require the calculation of derivatives. SA algorithms have also been applied extensively and successfully to the three-dimensional facility layout problem, which is very similar to the habitat interior layout problem [Jajodia, Minis, Harhalakis, & Proth, 1992; Smith et al., 1996; Szykman & Cagan, 1995; Szykman & Cagan, 1997; Szykman, Cagan, & Weisser, 1998] and the Quadratic Assignment Problem (QAP) [Sharpe & Marksjo, 1985].

- **Ant Colony Optimization:** Ant Colony Optimization (ACO) is a stochastic method which is based off the foraging patterns of ants. As ants go out to find food, they leave behind pheromone trails which are progressively strengthened as other ants progress down these trails to the identified food source. Discovery of optima produce stronger pheromone patterns leading to the selection of design variables corresponding to the most travelled path. Pure ACO algorithms fail to compete with other options, but hybridized versions of the algorithm perform moderately well [Levine & Ducatelle, 2004]. The transition from a discrete optimization problem to a continuous design space represents a massive increase in complexity beyond other methods for dealing with continuous design spaces [Blum, 2005; Dorigo, Birattari, & Stutzle, 2006].

- **Particle Swarm Optimization:** Another "swarm intelligence" algorithm like ACO, Particle Swarm Optimization (PSO) generates a random sampling of design concepts, evaluates the objective functions of the concepts, making this information known to neighboring solutions, and uses combinations of local and global knowledge to converge to an optimum. Unlike ACO, this method is a zero-order method suited for continuous and discrete variables (with modification). Methods derived from particle swarm optimization are promising, but may have convergence issues with generated velocities when coupled with collision detection algorithms. Additionally, hybrid versions of PSO are often used to speed convergence in local minima.

These methods are compared against the desired characteristics of a habitat layout optimization method in Figure 11. From this information and investigation of how these methods have been applied to facility layout problems, packing problems, and other multi-objective, multiple constraint problems; particle swarm and simulated annealing are anticipated to be the prevailing approaches. Ultimately, it is clear from literature that either simulated annealing, genetic algorithms, or particle swarm optimization approaches can be implemented effectively in layout design problems, provided they are tuned effectively. The purpose of this thesis is to provide methods to measure layout performance and prove that an incremental improvement algorithm can be successfully applied, which proves that identification of local optima are possible. The scope of this dissertation will leave hybrid methods and the exact tuning of optimization methods as forward work.



	Gradient Based Methods	Simulated Annealing	Genetic Algorithms	Particle Swarm Optimization
Uses information from previous iterations	●	○	●	●
Handles local optima well	○	●	◓	●
Used in similar problems (Space Layout Planning, Packing Problems, etc.)	○	●	●	◓
Ease of implementation	●	●	◓	●
Software/code available	●	●	●	●

● ◓ ○

Figure 11: Comparison of Available Optimization Methods to Guide Automation of Layout Designs

Finally, the third decision to apply existing methods is the method of bringing designer and user preferences into the decision process. Ahmad, 2005 and Smith et al 1996 use knowledge-based systems which formalize designer knowledge into an autonomous decision making entity. Bénabès et al., 2010 and Lau et al., 2014 require designer intervention during the layout generation and/or evaluation to make critical decisions. The proposed approach described in Chapter 3 will use a combination of system engineering multi-attribute decision making methods that are infrequently used in layout design to develop a definitive set of user preferences which minimize user time while maintaining the ability to be easily adjusted to perform trades and maintain flexibility in design which is often lacking in layout design efforts.

In summary, the lessons learned from literature addressing the automated layout design problem have been captured to inform the development of a hybrid approach combining an iterative improvement, metaheuristic algorithm to generate layout alternatives and a multi-attribute decision making evaluation method to guide future iterations of the improvement algorithm. The main challenges facing this development are the handling of the non-overlap geometric constraint to produce feasible layouts without hindering the thorough exploration of the available design space or algorithm convergence performance, and the development of realistic layouts which can be used by conceptual mission and system designers. The limited scope of this thesis will demonstrate that such an automation approach can be developed for the habitat interior design problem, but will leave the refinement of the optimization algorithm for computationally efficient performance as future work. Chapter 5 will describe this proposed method, commenting on the specific implementation of each subpart.

CHAPTER THREE: METHODOLOGY

This chapter presents a methodology that will address the habitat interior layout design gaps and research questions identified in Chapter 1. First, the background information provided in Chapter 2 is synthesized with systems engineering methods to develop a novel approach for evaluating habitat interior layouts. This approach centers on the development of a habitat layout objective function to assess and compare the overall desirability of multiple possible layouts, which is structured to enable the automated generation and evaluation of desirable layout alternatives at the conceptual design phase. This chapter describes each part of this structured habitat layout objective function in detail, beginning with an overview of the evaluation criteria themselves and the automated methods used to quantify them. Then, geometrical constraints are discussed, followed by an overview of the systems engineering methods used to capture user preferences through utility functions and evaluation criteria weightings. It should be noted that this chapter draws heavily in text and content from Simon, Bobskill, & Wilhite 2012 and Simon & Wilhite, 2013; which were published based upon the content of this work.

3.1 Systems Engineering-Derived Layout Evaluation Process [Simon & Wilhite, 2013]

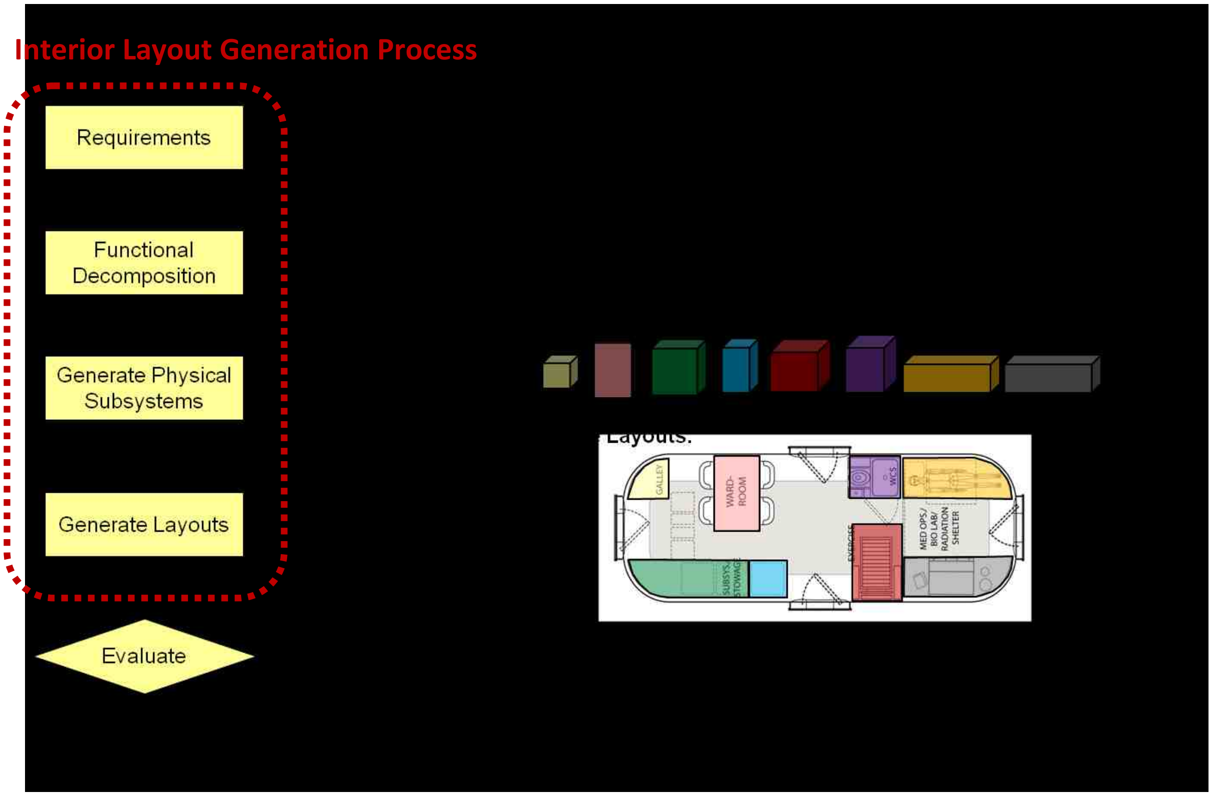
As mentioned in Chapter 1 and 2, the major improvements which are required to enable fast habitat interior layout evaluation are:

- A comprehensive, automatically quantifiable set of evaluation criteria
- A mathematical, computer representation of layout geometry and subsystem characteristics
- A structured method to capture designer preferences
- A multi-criteria objective function providing an aggregate measure of overall layout effectiveness including treatment of interior design constraints

In order to evaluate multiple layout alternatives quickly and reliably, these improvements are integrated into a structured, systems engineering-derived process which is designed to quantify a multi-criteria objective function measuring overall layout effectiveness from input geometry.

Prior to beginning this process, it is important that a description of the fundamental layout design problem and any study constraints guiding the design of the layout are defined. Examples of design problem descriptions with constraints are: “redesign the interior of an existing station module keeping pressure vessel geometry constant” or “design a minimum mass lunar surface habitat”. This description does not change the fundamental process, but it is necessary to specify unique aspects of the process such as identification of the applicable constraints and the context from which user preferences should be collected. For example, the “redesign of the interior of an existing station module keeping pressure vessel geometry constant” example increases the importance of constraints protecting translation path and may decrease the importance of mass-based evaluation criteria, which are not anticipated to vary much in in the available design space.

After the initial problem description is defined, the process is divided into two major steps: Initial Layout Generation and Layout Evaluation. First, a structured Initial Layout Generation method translates mission requirements into the required functions and associated hardware which will be packaged within the pressure vessel. These geometric ‘building blocks’ are then used to construct mathematical representations of layout alternatives compatible with the evaluation process. Then each of the layout evaluation improvements discussed in Table 3 can be integrated into a systems engineering-derived Layout Evaluation process, which calculates an objective function value measuring the overall desirability of each layout. Figure 12 and Figure 13 present the proposed combined process for layout generation and evaluation based upon the previously described basic systems engineering trade study process from Figure 2, but customized for habitat design and the implementation of the desired improvements. The following subsections provide more detailed information on how these steps are performed.



Interior Layout Generation Process

Requirements

Functional Decomposition

Generate Physical Subsystems

Generate Layouts

Evaluate

Figure 12: Systems Engineering Basic Habitat Interior Layout Process with Example [Kennedy, Toups, & Rudisill 2009]

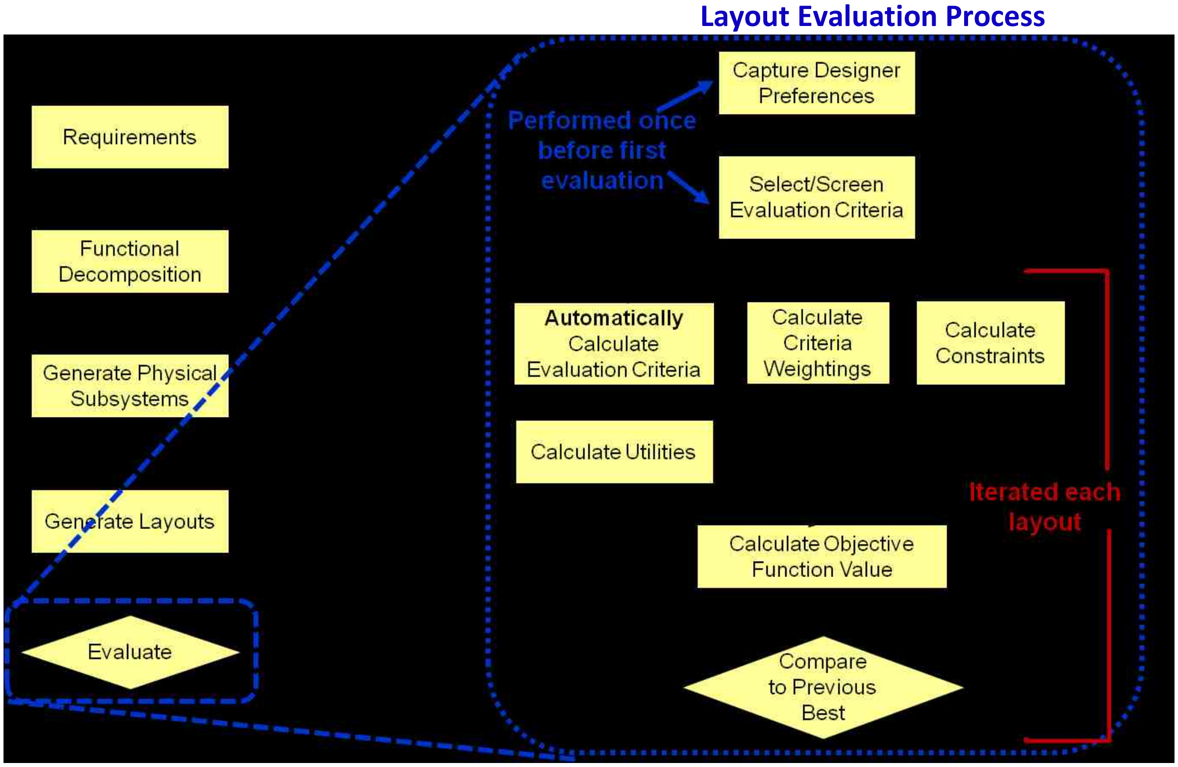


Figure 13: Proposed Systems Engineering Interior Layout Evaluation Process

To aid in the explanation of these proposed processes in this dissertation, two example layouts are utilized. For Chapter 3, the NASA Scenario 12.0 Pressurized Core Module (PCM) from the Constellation Lunar Surface Scenario (LSS) study [Kennedy, Toups, & Rudisill, 2009] shown in Figure 12 is used to demonstrate each step. This habitat was designed as part of a three module lunar surface habitat to support four crewmembers for durations up to 180 days. This particular module was chosen for the methodology explanation in Chapter 3 because of the considerable amount of information available on the motivation, design process, and assumptions. The PCM in particular was also chosen because of the diverse mix of functions represented in the design, which will aid in the demonstration of the chosen evaluation criteria and measurement methods. Additionally, the intuitiveness of the layout will facilitate discussions of functional locations, which would be more difficult with the topological layout utilized for the verification examples in Chapters 4 and 5. This PCM is used throughout the remaining sections of this Chapter 3 as a consistent basis for explaining many of the important features of the method.

In Chapters 4 and 5, an alternate layout for a Cislunar Habitat is used to verify and test the evaluation and automated layout generation methods. This layout was chosen over the Scenario 12.0 PCM for several reasons. First and foremost, the PCM was a two-dimensional layout, whereas the cislunar habitat layout is three-dimensional. Additionally, there was considerably more data available for the cislunar habitat interior hardware geometry, functions, and interfaces as the hardware is anticipated to be similar to existing International Space Station hardware. Because the cislunar habitat will be deployed in a microgravity environment, it is also a better example for proving out the microgravity-specific criteria. Finally, as the direction of NASA studies has shifted away from the moon towards more near term testing for Mars, the cislunar habitat evaluation allows the dissertation to be responsive to recent events and upcoming designs. The PCM will be referenced again briefly in Chapter 4 and 5 as a historical point of comparison of evaluation times between the currently available evaluation processes and the evaluation process described here and demonstrated in subsequent chapters with the cislunar habitat.

3.1.1 Initial Layout Generation Process [Simon & Wilhite, 2013]

Figure 12 shows the Initial Layout Generation process which translates high-level mission requirements into an initial geometric layout(s) of hardware ready for evaluation through the following four steps: Requirements, Functional Decomposition, Generate Physical Subsystems, and Generate Layouts.

Requirements

The first step is to define requirements including mission/system design objectives (destination, number of crew, crewed and uncrewed durations, research or exploration objectives), desired crew activities (number and frequency of EVAs, types of research to be performed), vehicle integration requirements (including: launch vehicle, in-space transportation, and lander/entry constraints; number of hatches, etc.), and any additional physical constraints on the design. These requirements (particularly destination and duration) are necessary to identify the required functions (e.g., Life Support, EVA, etc.), crew tasks (e.g., sleeping, eating, etc.), and basic geometric features of the pressure vessel (e.g., the number and location of hatches, the maximum habitat length and diameter dictated by the launch vehicle, etc.). In the case of the Scenario 12.0 PCM (or Cislunar Habitat) example, the design problem statement and requirements are to "redesign the interior of one module of a habitation system supporting four crewmembers for 180 days of exploration of the lunar surface (or support of research in cislunar space) while maintaining the current pressure vessel geometry and complement of subsystems" (and thus meeting the same launch vehicle constraints).

Functional Decomposition

After the requirements are successfully defined, the functions necessary to achieve the mission can be readily identified through a functional decomposition process [NASA, 2007]. This process which maps mission requirements to functions and hardware is well understood and documented in Larson & Pranke, 1999 and NASA, 2010. Most long duration habitats fundamentally provide the same basic set of functions to support exploration missions including the habitat support functions (Power, Thermal, Stack Control, Navigation, Vehicle Health Monitoring, etc.), crew work (EVA, Science, Maintenance, Repair, Communications, etc.), and living activities (Eating, Sleeping, Socializing, Breathing, etc.) [Kennedy, 2002a; Larson & Pranke, 1999]. Hardware implementations of these functions typically vary with mission duration. Major variations include the number of redundant hardware units necessary to reduce mission risk and various technologies to achieve increased hardware performance or mass reduction. Mass trades have been performed in literature to identify certain mission parameter values or breakpoints (certain mission durations, crew abort availabilities, etc.) which drive the selection of the specific hardware necessary for each mission. Comparison of the mission requirements to these breakpoint values allows direct selection of the hardware; typically that which minimizes mass or risk [Hardware and breakeven point information: Larson & Pranke, 1999; Chambliss, 2007; Connors et al. 1985; Eckart, 1996; Lyle, Stabekis, & Stroud, 1973; Komar et al., 2008; Swickrath, Anderson, & Bagdigian, 2011]. To illustrate, a carbon dioxide removal hardware selection breakpoint is the duration at which the mass of a system implemented using open loop lithium oxide canisters equals the mass of a partially closed bed molecular sieve system, which reduces consumables at expense of moderately heavier equipment mass [Eckart, 1996]. In both the Scenario 12.0 habitat concept and the cislunar habitat concept, the 180 day duration at a destination (which indicates little to no abort capability capable of returning crew under several days) dictated the selection of appropriate functions and subsystem hardware. Hardware items allocated to the PCM are focused on group and work activities and include: Galley, Wardroom, Life Support (partially closed), Stowage, Waste and Hygiene, Medical, and Biology/Life Science Research Station. As mentioned in Chapter 1, the identification of the equipment and logistics, their masses, dimensions, integration requirements (types of line runs), etc. are typically available at conceptual design and will be considered an input to the Generate Layouts step of the process.

Generate Physical Subsystems

The ‘generate physical subsystems’ step involves the creation of a mathematical representation of hardware geometry and other characteristics of the equipment that influence its layout placement (e.g., tasks performed at hardware, mass, etc.). The historical habitat interior design process uses detailed CAD models or drafted drawings to represent the space taken up by the hardware in the layouts. These models can be powerful tools at the detail design phase, but their long creation times and complexity is often incompatible with fast layout evaluation. The proposed process uses a simple polyhedral representation of the hardware geometry derived from computer animation and video game programming which is well structured for use in layout creation and evaluation criteria calculation methods. By representing geometries as simple polyhedral objects specified by matrices of vertices and faces as shown in Figure 14, the overlap of geometries can be detected with standard collision detection algorithms outlined in Chapter 2 to prevent the creation of unrealizable layouts [Ericson, 2004; van den Bergen 2005]. Additionally, this polyhedral object representation allows for generation of layouts by simply manipulating the location and orientation of each subsystem through definition of translation and rotation matrices. What results is a fast, simple, mathematically operable method of constructing layout alternatives with relatively simple sets of data.

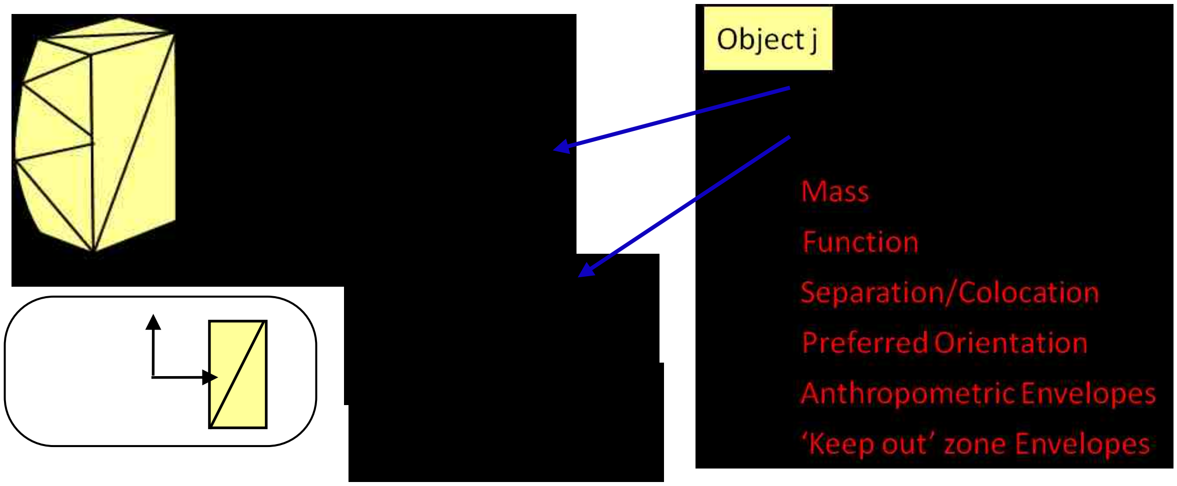


Figure 14: Mathematical Representation of Object Geometry Collocated with Detailed Information

An additional benefit of this simplified geometry representation is its compatibility with object-oriented programming, which allows for the embedding of detailed function and interface information together with the geometry data in arrays or matrices within an indexed object. The types of object information required include: the mass of an object, the function it belongs to, any separation or collocation relationships associated with the provided function, geometry and location of anthropometric envelopes for human interaction with the object, and envelopes / keep out zones for moving parts. Collocated storage of this information facilitates straightforward calculation of evaluation criteria. The importance of this layout and data representation method will be discussed more in Section 3.3.

Generate Layouts

The 'generate layouts' step simply involves assigning positions and orientations to each polyhedral object. This is achieved by generating a location and orientation matrix which represents a layout concept. These locations should be selected such that the extreme points of each polyhedral object are within the habitat pressure vessel defined by the designer to avoid the container constraint discussed later in this chapter. Additionally, the volume of hardware should not inherently exceed the volume of this pressure vessel, as such layouts are inherently unrealizable. Finally, the locations of hatches and windows can either be an input or dynamically traded as additional pieces of hardware with constraints to be on the pressure shell. Figure 12 provides an illustration of the location of the hardware within the Scenario 12.0 PCM. Similarly, the layout of the initial cislunar habitat will be discussed in Chapter 4.

3.1.2 Layout Evaluation Process [Simon & Wilhite, 2013]

This section provides a high-level overview of the layout evaluation process, leaving specifics of implementation and rationale to the remaining sections of this chapter. Figure 13 shows the proposed Layout Evaluation process, which combines quantitative evaluation criteria measurements, design problem constraints, and subjective designer preferences into a single aggregate measure of the overall performance of a layout. This process and its component steps are carefully structured to reduce the evaluation time of each layout.

3.1.2.1 Designer Preferences

Before any layouts are evaluated, the three types of preference information are collected from the designer: 1) the relative importance of the evaluation criteria to establish criteria weightings, 2) desired values and acceptable ranges for each of the criteria to establish utility functions, and 3) any constraints the designer wishes to place on the design problem. By collecting this information before layout evaluation, it is possible to consistently apply the same preferences and constraints to all investigated layout concepts and integrate the designer preferences during the evaluation process.

Criteria Weightings

The relative importance of evaluation criteria gives the designer an opportunity to customize the objective function to his/her preferences and the appropriate context of the design problem. For example, a human factors-focused designer tasked with improving the habitability of a space may care little for mass variations, judging them to be insignificant in comparison to functional adjacency considerations. As a result, this designer's preference should be reflected in the relative contributions of mass and adjacency evaluation criteria. This relative preference can be captured through the expert elicitation method of Analytic Hierarchy Process, which utilizes semi-qualitative, pair-wise comparisons between criteria to assign 'criteria weightings' reflecting their importance and contribution to the objective function [Saaty, 1980; Smith, 2007]. These weightings can also be used to screen out or eliminate evaluation criteria which are deemed non-important from the objective function formulation and allow layout designers to focus on those criteria with the most effect on the objective function. More information on evaluation criteria weightings and their generation are provided in Section 3.4.2

Utility Functions

In order to ensure each of the evaluation criteria values are combined in the objective function using common units (preventing criteria with high numerical values from dominating the solution), a function is used to normalize each calculated criteria value to a number between 0 and 1 (where 0 is lowest permissible performance and 1 is peak performance). This normalized score represents the designer's perceived 'utility' of a criteria value over the possible range of values. The method selected for collecting and applying this designer preference is Mid-Preference Level Splitting [Smith, 2007] which uses a structured set of questions to shape the 'utility function' used to map evaluation criteria values to utilities. This method was chosen for its ease of implementation and suitability for continuous evaluation criteria values [Smith, 2007]. More information about utility functions and the mid-preference level splitting method of utility function construction are provided in Section3.4.1

Design Problem Constraints

Design problem constraints are constraints enforced on the design problem itself, not the constraints which must be met to fulfill human and spaceflight standards. Examples of these constraints include hardcoded placement of certain pieces of hardware, how stringently to enforce constraints preventing the overlap of geometries in acceptable solutions, or decisions to bypass certain human standard constraints. As the software necessary to carry out this method develops, unique accommodations of these designer desires will be added to the input fields to allow for some degree of design problem customization. These constraints will then be added to the constraints based upon human and spaceflight standards which are discussed in Section 3.5. For the Scenario 12.0 PCM example, the interfaces such as hatch location and the functions located in adjacent modules are pre-specified as shown in Figure 15, with the distance of those functions from the associated hatches characterized as near, medium, or far.

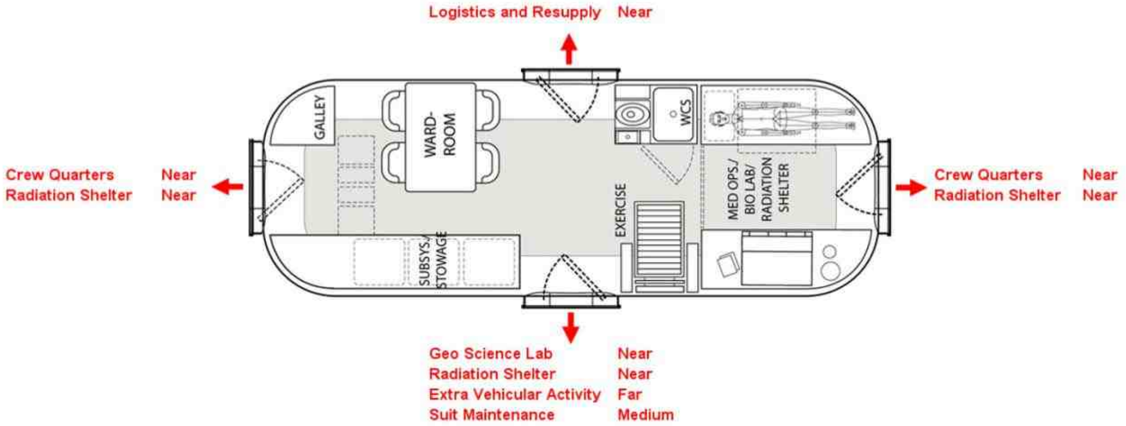


Figure 15: Adjacent Functions to the Scenario 12.0 PCM [Kennedy, Toups, & Rudisill, 2009]

3.1.2.2 Other Objective Function Components

After obtaining designer preferences, there are two remaining evaluation process components shown in Figure 13 which must be addressed to quantify the objective function: 1) automatically quantifiable evaluation criteria values capturing the desirability of a layout and 2) the constraints based on human and spaceflight standards. This section provides a high level overview of these components which is expounded upon in later sections.

Automatically Quantifiable Evaluation Criteria

Evaluation criteria measure the degree of desirability of one layout alternative over another and expand a constraint satisfaction problem which might create feasible layouts into a multi-criteria evaluation/optimization problem capable of producing more optimal solutions. Investigation of previous evaluation methods including those in Table 4 and Table 5 revealed that no comprehensive, expert-approved list of quantifiable space habitat evaluation criteria capturing both engineering and human habitability concerns exists [SICSA, 2009; NASA, 2010; Celentano et al., 1963; Cohen, 2004; Allen et al., 2003; Wise 1995]. In particular, the desire to improve consideration of habitability issues into the layout evaluation is well documented [Rysavy & Council, 1971; Jones, 1973; Cohen, 1990; Whitmore et al., 1997; Adams, 1998; Adams & McCurdy, 2000; Osburg, 2002; Allen et al., 2003; Rudisill, Howard, Griffin, Green, Toups, & Kennedy, 2008]. Additionally, examination of previous methods shows that manual intervention by a designer to quantitatively or qualitatively measure evaluation criteria values for individual layouts is a time consuming step which limits the number of layouts which can be investigated. The development of a comprehensive set of automatically quantifiable evaluation criteria calculable directly from layout geometry and hardware functional characteristics is critical to ensuring high-quality habitat designs and speeding up the evaluation process.

The evaluation criteria set developed in this thesis leverages existing quantitative and qualitative habitat/terrestrial architecture evaluation methods and human integration handbooks [Celentano et al., 1963; Tullis & Bied, 1988; Nixon, 1986; Cohen, 1990; Osburg, 2002; Fitts, 2002; Howe & Sherwood, 2009; NASA, 2010]. In order to ensure a comprehensive set of criteria was chosen, a structured screening process was used to reduce a large list of criteria (qualitative and quantitative) to a set of quantitative criteria and proxies capturing the breadth of driving layout concerns identified in literature (described further in Section 3.3). The resulting criteria list includes quantitative measures for mass, psychological acceptability, functionality, safety, human factors considerations, and other factors. Automatic algorithms for quantifying this filtered list of criteria were then developed (described completely in Section 3.4). The evaluation criteria set and the automatic methods used to quantify them implemented in the Layout Evaluation Process are described in Sections 3.3 and 3.4, respectively.

Constraints

The final component to quantify the objective function is the implementation of constraints bounding the feasible design space. For the habitat interior layout problem, constraints are limits imposed upon the physical location of interior equipment or the values of the evaluation criteria measurements [Simon & Wilhite, 2013]. These generally fall into two categories: geometric constraints and human spaceflight standards/safety constraints. Geometric constraints include:

- the ‘non-overlap’ constraint – addressing overlap between two pieces of hardware
- the ‘container’ constraint – addressing hardware protrusions beyond the bounds of the habitat pressure vessel

If either of these constraints is violated, the resulting layout cannot be manufactured, and is thus infeasible. Additional constraints from spaceflight and human factors standards include limitations like minimum translation path widths for safe emergency egress, minimum volume limits which would impair crew performance, and clearance to access emergency systems. Both of these types of constraints are independently checked or measured using methods similar to those quantifying evaluation criteria. Methods of implementing constraints in an evaluation vary in practice and are described briefly in Section 2.3.2. In this thesis, constraints are enforced through the addition of penalty functions to the unconstrained weighted objective function which yield undesirable objective function values. The full description of constraints and rationale for the chose implementation is provided in Section 3.4.

3.1.2.3 Objective Function

As shown in Figure 13, all of the components described in Section 3.1 are combined into a multi-criteria objective function which measures the overall desirability of habitat interior layouts. This weighted-sum multi-criteria objective function is provided in Equation 1.

$$Y(A) = 1 - \sum_i w_i U_i(X_i(A)) \quad + \quad \sum_j P_j(A) \tag{1}$$

where

Y(A) = the aggregate value of layout A

A = layout alternative described by location and orientation matrices

X_i(A) = the measured/calculated values of each criterion, i, corresponding to the layout A

U_i(X_i(**A**)) = the utility function for each criterion, i, calculated from the measured value X_i(A)

w_i = the relative importance weighting of each criterion, i

Pj(A) = penalty function values to enforce constraint j for layout A

where Pj(A) =

$$\begin{cases} \dfrac{0 \; if \;\; constra\text{int} \; is \; met}{\alpha * g_j(x) \; if \;\; the \;\; jth \; constra\text{int} \; is \; violated} \end{cases}$$

$$\begin{cases} 0 \; if \; constraint \; is \; met \\ \alpha * g_j(x) \; if \; the \; jth \; constraint \; is \; violated \end{cases}$$

where g_j(x) is the amount the constraint, j, is violated and α is some constant indicating how hard the constraint is to be applied

This evaluation objective function is constructed as shown in Figure 13. First, the evaluation criteria measurement methods utilize layout geometry and hardware specifications defined in the Initial Layout Generation step as inputs and automatically calculate values for each evaluation criterion. These evaluation criteria values are then normalized using the designer-defined utility functions and brought into the objective function. They are weighted by the designer-defined criteria weightings and summed to determine an unconstrained value of the input layout. This value varies from a worst rating of zero to a best rating of one. The final step to defining the objective function is then to calculate and check the human spaceflight standards and safety constraints. These constraints are implemented with exterior penalty functions to allow some small violations, but greatly penalize intermediate to large violations [Vanderplaats, 1984]. With the addition of these constraints, a constrained weight-sum objective function value can be determined. It should be noted that in order to prevent the objective function from returning negative numbers (which can complicate optimization algorithms), the unconstrained value of a layout represented by the sum of w*U(X(A)) terms (0 to 1, worst to best) is subtracted from 1, and the penalty functions values (which are positive) are added to the objective function. Thus feasible values violating no constraints are between zero and one, with minimal values preferred.

The objective function value for a layout can then be compared to the values of other layouts to progressively improve layout performance in subsequent iterations. In order to automate the creation of desirable layouts, this objective function can be minimized utilizing an optimization algorithm. Because of the multi-modal, discontinuous nature of the interior layout design space, stochastic optimization methods should be used to update the layout defined by translation and rotation matrices. More information on the layout iteration step will be described Section 5.1.

3.1.2.4 Evaluation Process Inputs

As mentioned in Sections 2 2.1, 2.2, and 3.1, several inputs are required to address a variety of layout evaluation problems. These inputs include mission specifications, assumed pressure vessel and hardware geometry, functional information about the hardware, and any interfaces which might dictate positions of interior hardware. A full list of inputs which may be requested is shown in Table 13. Though this may seem like a significant amount of information, most of these quantities are known at the mission conceptual design phase or can be assumed or estimated based upon similar problems. Additionally, selection of these input values will be facilitated in the future by the development of a library of evaluation problems and hardware information. In the subsequent sections, the use of these inputs for the calculation of evaluation criteria and constraints will be described in detail.

Table 13: Full List of Inputs Provided to the Evaluation Process

Mission Specifications	**Pressure Vessel Geometry and Specifications**	**Component Geometry and Specifications**
Destination (LEO, L1, Moon, Mars, etc.)	Basic dimensions	Dimensions
Duration of stay	Shape	Vertices coordinates
Number of crew	Orientation	Location (XYZ coordinates)
Crew composition (scheduling)	Mass (input option available)	Orientation
EVA requirements	Floor height or floor area	Face data (which vertices in what face, normal vectors)
Landing required of habitat?	Ceiling height	Specification of front face(s)
Gravity orientation / magnitude	Number of hatches	Component Mass
Surface dust present?	Hatch locations	Reserved volumes type vertices/lines/faces
External Interfaces	Hatch dimensions	Reserved volume geometries
Location of hatch closest to EVA area	Hatch type (EVA, inter-element, etc.)	Function / task supported
Distance of functions from hatch in external element (actual or estimate)	Diameter of endcap flattening for hatch placement	Line runs required
Orientation		Zoning requirements (privacy, noise, clean/dirty)
Water inlet location		Criticality of component
Power inlet location		Frequency/duration of use

This section has described the basic steps of performing layout evaluations. Each of the subsequent sections will describe these steps in detail, including the specific measurements, more specific quantification methods, and considerations feeding the evaluation process development.

3.2 Evaluation Criteria [Simon & Wilhite, 2013]

A habitat interior design evaluation criterion is a measure of the effectiveness of an interior layout to keep astronauts healthy, safe, and productive for the duration of the mission. Selecting a comprehensive set of these criteria is challenging as many criteria fundamentally measure the same characteristic and there are various levels of detail which can be considered. Some of these criteria are obvious and straightforward in definition and measurement, such as the total usable volume or "habitable volume" or the size of private space provided for the crew. Others seek to capture a vague principle observed from analog testing or spaceflight and are much more subjective in the assessment of value. In order to ensure a comprehensive set of criteria was chosen, a structured screening process was used to assess whether a criterion was essential to the assessment of interior layouts.

First, a comprehensive list of all possible habitat interior layout evaluation criteria (qualitative and quantitative) was created from an extensive literature review of space habitat design [Eckart, 1999; Howe & Sherwood, 2009; Larson & Pranke, 1999; NASA, 1995; Osburg, 2002], habitat habitability [Celentano et al., 1963; Fitts, 2002; NASA, 2010; Nixon, 1986; Tullis & Bied, 1988; etc.], industrial engineering, terrestrial architecture references (particularly from Architectural Programming) [Duerk, 1993] and a field of study focusing on automation in architecture, Space Layout Planning [Kalay, 2004; Lobos & Donath, 2010; Homayouni, 2006; etc.]). Additionally, several of the more complete evaluation criteria sets used in existing habitat design literature were included (summarized in Table 14). The fully comprehensive list of possible criteria was then screened based upon the following list of desired characteristics. Criteria should be:

- As independent as possible from other criteria to prevent an over-emphasis on any particular measure [Smith, 2007]
- Explicitly dependent upon layout or pressure vessel geometry and functionality (inputs described in Table 13), which allows for the exclusion of many aesthetic criteria such as

color or textures which can be changed with little to no impact after optimizing interior layouts

- Intuitive and easy to justify [Smith, 2007; section 9-4]
- Consistent with existing requirements [NASA, 1995; NASA, 1999]

Finally, as the habitat design experts are the target users of the proposed research, criteria should be expert recognized and approved. This final step was achieved by vetting the resulting list of criteria with the NASA Johnson Space Center habitation and layout evaluation experts.

Table 14: Historical Habitat Design Evaluation Criteria Sets

Alternative Approach	Description	Limitations
Celentano et al., 1963 – "Establishing a Habitability Index"	• Describes a top level index for habitability of a habitat based upon heuristics	• Somewhat generic, utilities are assumptive, only layout consideration is volume
Cohen, 2004 – "Habitat Multivariate Design Model Pilot Study"	• Addresses how to determine shape and size of habitats based upon several spatial variables	• Numerical, but incomplete • Focuses on pressure vessel geometry, not interiors
Di Capua et al., 2009– "Minimal Functional Habitat"	• Design study for surface habitat design • Qualitative preference analysis to identify design features to implement	• Relatively complete, but all measure of effectiveness are qualitatively ranked • Mitigations are design feature focused as opposed to layout focused
SICSA, 2008; 2009	• Design studies of designs including ranking of configurations	• Good selection of criteria, but limited to qualitative ratings between few concepts
Tullis & Bied, 1988 - "Space Station Functional Relationships Analysis	• Evaluation of interiors based upon separation and colocation of systems	• Incomplete, focuses on schedule, traffic, privacy, and noise
Wise, 1985 – "The Quantitative Modeling of Human Spatial Habitability"	• Details numerical methods for capturing spatial perception from visual, kinesthetic, and social logic perspectives	• Limits itself to spatial issues associated with confined spaces, thorough but incomplete • Does not weight or combine measures
NASA, 2010 - NASA Human Integration Design Handbook	• NASA handbook on designing human spaces	• Most comprehensive list of criteria, but lacks definition of measurement methods and overall performance measure

The resulting comprehensive evaluation criteria set is shown in Figure 16 grouped into the following four categories: Mass, Volume, Task Performance, and Crew Health, Well-Being, and Safety. Mass criteria track the effect that the interior layout has on the overall mass of the habitat, normally through increased structure or utility runs. Volume criteria measure the efficiency in the utilization of the interior volume and general psychological acceptability of the space. In general, larger, more open habitable spaces are preferred to tight confined spaces [NASA 2012]. Task Performance criteria measure the impact of the layout to the productivity of crew through the impact of schedule based factors and the placement of tasks within the habitat. Finally Crew Health, Well-Being, and Safety criteria track several factors which directly impact the physiological or psychological health of the crew or pertain to contingency operations, namely egress. Each of these criteria is summarized in Table 15 and described in detail (including quantification methods) in Appendix B as shown in Figure 17 and Figure 18 for habitable volume and separation for privacy.

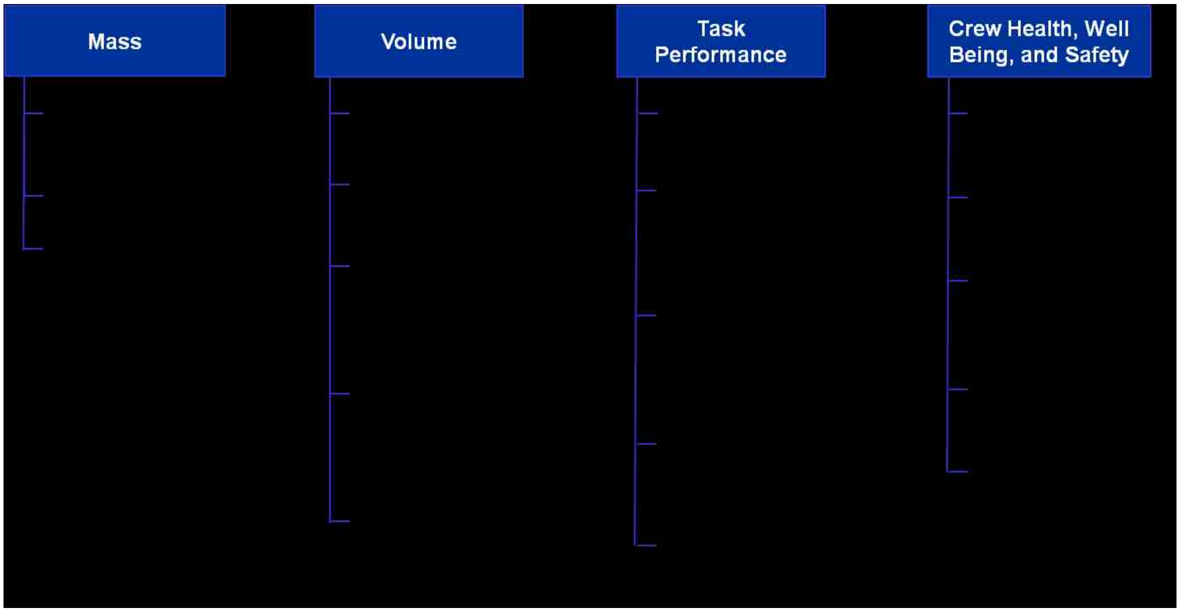
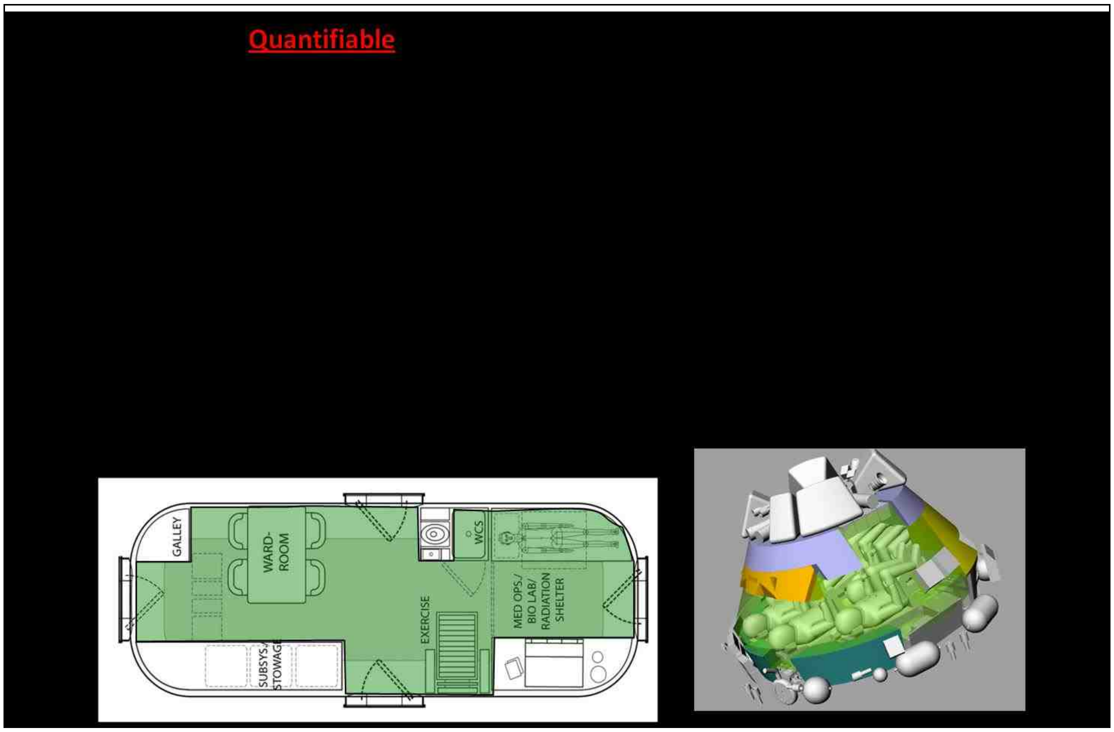


Figure 16: Comprehensive Habitat Interior Layout Evaluation Criteria Set

Table 15: Evaluation Criteria Descriptions (See Appendix B for more details)

	Description
Mass	
Structure Mass	The mass of primary and secondary structures which vary dependent on the configuration. This includes the pressure vessel, launch integration structure, hatches, windows, walls, floors, ceilings, and support mass for equipment.
Equipment Mass	The mass of the Life Support, Thermal, Power Distribution, Stowage, Crew Accommodations, Logistics, Avionics, etc. equipment. Does not include power and consumable distribution lines.
Plumbing/Electric Line Run Masses	The mass of power distribution, atmosphere distribution, vacuum, and various water/waste distribution lines based upon the placement of interior objects.
Volume	
Habitable Volume	The free, pressurized volume, excluding the space required for subsystems, structural elements, stowage, outfitting, accommodations, and structural Inefficiencies (nooks and crannies). It is literally the space livable, accessible, and functionally usable to crew. (also referred to as Net Habitable Volume)
Unusable Volume	The inaccessible volume and structural inefficiencies caused by the particular packing strategy. Also not usable for stowage)
Available Non-Dedicated Stowage Volume	The available space for the storage of goods within the free volume outside of translation paths and anthropometric envelopes.
Habitable Floor Area and Other Usable Horizontal Surface Area	The floor area available for crew movement (often indicating anthropometrically accessible floor area by a standing astronaut (excludes skinny spaces, space behind racks, under beds, under desks, etc.)) and the area of horizontal surfaces occupied by crew including desks, tables, work counters, shelves, beds, and chairs. Frequently replaces habitable volume for planetary surface designs with partial gravity.
Largest Spatial Vista	The maximum volume swept by the eye of a crew member. A measure of spaciousness and psychological/physiological acceptability of the environment. Analogous to maximum contiguous line of sight and contiguous field of view.
Task Performance	
Colocation of Sequential Tasks	The degree of colocation of tasks which are sequential (according to analogous crew schedules). A measure of the overall minimized required crew translation distances throughout an interior.
Anthropometry of High Duration Tasks Interferences	The number of long duration tasks whose anthropometric volumes interfere with either the anthropometric volumes of other high duration tasks, translation paths, or hatch clearance areas.
Colocation of Equipment by Function	The degree of grouping of equipment and components based upon the function or task they belong to. Facilitates more efficient operations.
Placement for Function/Ergonomics	A measure of the displacement of equipment from the location required by its function or ergonomic operation (e.g. a desk in a gravity environment should be ~36 in from the floor). Significant deltas are penalized.
Placement for High Frequency/Duration Use	A measure of the displacement of 'high frequency/duration of use' equipment from the 'prime real estate' locations for human interaction (waist to eye level)
Crew Health, Well Being, and Safety	
Size of Private Spaces	The size of space designated as private (e.g., crew quarters, waste and hygiene).
Separation for Privacy	The degree of separation between public and private areas, such as the crew quarters and the wardroom
Separation of Clean and Dirty Zones	The degree of separation between clean and dirty areas, such as crew quarters and hygiene area
Separation for Noise	The degree of separation between noisy and quiet areas, such as crew quarters and the wardroom area
Minimum Translation Path Width	The minimum width along the path which allows access to each hatch and subsystems



Quantifiable

Figure 17: Example of Evaluation Criteria Information Captured in Appendix B: Habitable Volume

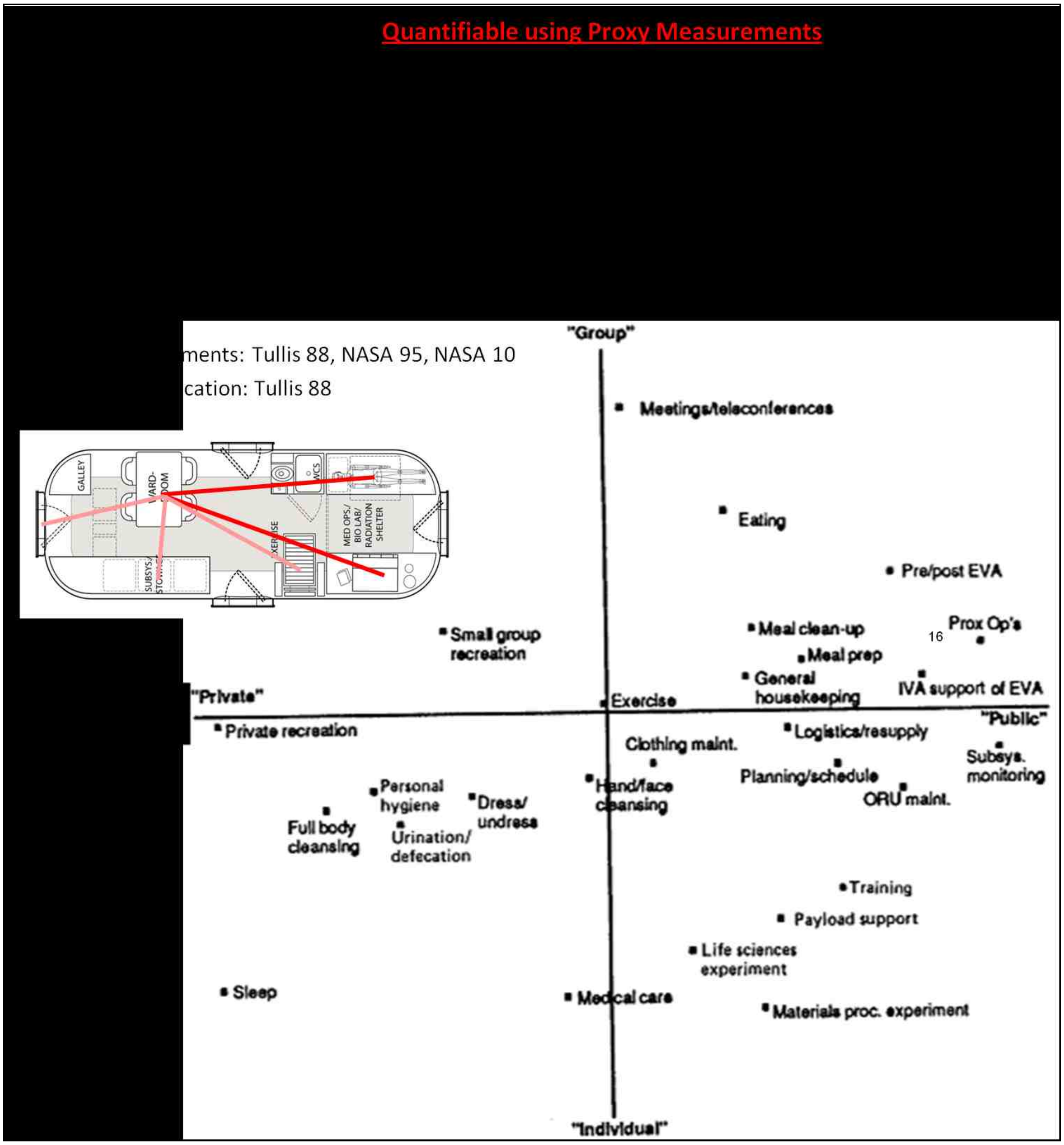


Figure 18: Example of Evaluation Criteria Information Captured in Appendix B: Separation for Privacy

As mentioned before, the bulk of habitat design references use criteria which are either incomplete in addressing all engineering and habitability concerns or qualitatively assessed, lacking quantitative measurement methods. No criteria set found in literature has captured a comprehensive, numerically measurable set of criteria. The major reason for this is that some interior criteria are seen as qualitative measures which must be subjectively assessed by a designer and are incompatible with quantitative measurement. While this is generally true, review of previous evaluation methods has also shown that designer measurement of evaluation criteria must be reduced to ensure consistent evaluations and accelerate the evaluation process. In the creation of a fully quantitative set of evaluation criteria, analysis and reformulation of qualitative measures is needed to allow for quantitative measurement. Figure 19 outlines the process taken to reformulate the criteria with a practical example. ‘Spaciousness’ is a broad measure of the psychological acceptability of the size and shape of an interior layout. It can be expressed through the combination of a wide range of criteria which can loosely be split into two categories: *quantitative* and *qualitative*. The quantitative measures are easily measurable and straightforward in definition. The qualitative measures are more difficult to measure, as they deal more with perception than physical measurement. Qualitative measures can be divided into three basic categories. Semi-layout independent measures like color or a “clean look’ tend to be modifiable with little to no impact on the design, layout, or size and can be removed from consideration. Designer preferences like the relative importance of each of these measures or the acceptable values of each criterion have already been discussed as weightings and utilities and have been purposefully separated from evaluation criteria measurement to ensure consistent application across all layout concepts. This separation of user interaction and evaluation criteria measurement is critical to the automation/acceleration of the evaluation process.

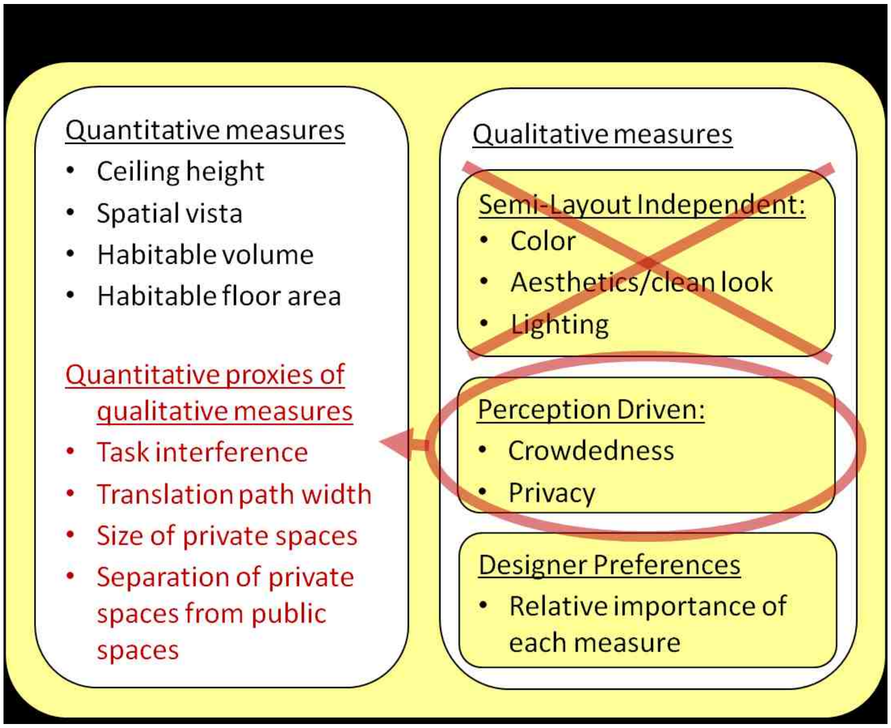


Figure 19: Mapping of Qualitative Evaluation Criteria to Quantitative Proxies

The remaining measures are perception-driven measures which are dependent upon layout, but cannot traditionally be determined without user assessment of the layout in an analogous test situation. However, measurable proxy variables can be used to approximate these qualitative perception-based criteria. In the example illustrated in Figure 19, crowdedness measures the degree to which crewmembers will feel crowded or that their tasks are impeded by the presence of other crew members. Crowdedness is strongly correlated with the privacy measure which measures the extent to which crew feel that their privacy needs are met. The combination of several quantitative measures like the number of overlaps of high-frequency and high duration tasks (which use schedules and task locations to measure how often crew locations might overlap) and the width of the translation paths (which measures the ability of crew to pass by one another without intersecting) can approximate the potential for crowding. Similarly the size and distribution of private and public spaces can also approximate aspects of crowdedness and privacy. By mapping all qualitative perception-based measures to quantitative proxies which approximately measure the same factors, a fully quantitative criteria set can be created. Every criterion in Figure 16 can be measured directly or by some quantitative proxy. Ensuring that these criteria can be automatically quantified is the focus of the next section.

3.3 Quantitative Evaluation Criteria Measurement Methods [Simon & Wilhite, 2013]

Though each of the evaluation criteria shown in Figure 16 is quantifiable, that does not imply that a method exists to automatically calculate its value without user interaction. For example, habitable volume is a quantifiably measurable quantity, but the current method for measuring it from an interior layout is manual measurement using a CAD model [Szabo et al., 2007]. There are also several other desired characteristics of the measurement methods:

- Calculable from layout and available data, with no user interaction
- Require minimal computational time to solution
- Scalable to various design precisions
- Traceable to definitions of measures provided in references (particularly NASA, 2010)
- Easy to setup

Several mechanisms enabling the automatic calculation of evaluation criteria values were identified through extensive investigation of related fields of study including packing/container loading problems [Dyckhoff, 1990; Wäscher et al., 2007], space layout planning [Ahmad, 2005; Bénabès et al., 2010; Kalay, 2004; Lobos & Donath, 2010; Homayouni, 2006; Szykman & Cagan, 1997], and spacecraft design [Lau et al., 2014; Cuco et al. 2014]. In particular, three mechanisms were identified which, when concurrently implemented, will enable the development of measurement methods meeting all desired characteristics: 1) collision detection, 2) grid-based numerical methods, and 3) separation/collocation matrices.

3.3.1 Collision Detection [Simon & Wilhite, 2013]

As mentioned in Section 2.2.2, automated evaluation criteria quantification methods require the three types of collision tests summarized in Figure 20, which is similar to Figure 6 with the additional listing of the evaluation criteria which the tests enable. Testing if a point is inside an object allows for the numerical determination of the size of open spaces and volumes of various types (specifically habitable volume, unusable volume, stowage volume, minimum translation path width and size of dedicated private spaces) when combined with some logic characterizing the various types of volume. This numerical volume estimation is described more in the next section. The second type of collision test to determine the intersection points between a line and an object can be used to determine line of sight distances necessary for line of sight and isovist radial based criteria such as spatial vista and minimum translation path width. The third test identifying overlap between three-dimensional geometries enables the detection of interferences between 1) two pieces of hardware for the non-overlap constraint, 2) hardware and keep out/anthropometric reserved volumes for task clearance checks, and 3) two anthropometric volumes representing task volumes to quantify the criterion addressing interference of high duration task volumes with other task volumes. As mentioned in Section 2.2.2, the preferred collision detection method implemented in this thesis is the Incremental Separating Axis – Gilbert-Johnson-Keerthi (ISA-GJK) algorithm [van den Bergen, 2003; Gilbert et al., 1988], which performs all of three tests with some modification (point-hardware collision is enabled by modeling the point as a small sphere). This method was selected due to its speed, accuracy, ease of implementation, and readily available open source code. Furthermore, to speed collision tests even further bounding volumes and spatial partitioning (specifically an octrees) are both utilized. Collision tests are a particularly powerful for the quantification of habitat interior evaluation criteria, especially when used in combination with numerical estimation techniques described in the next section.

Figure 20: Types of Collision Detection Needed in Automatic Evaluation Criteria Quantification Methods

3.3.2 Grid-based Iterative Methods [Simon, Bobskill, & Wilhite 2012]

To eliminate manual CAD-based measurement of volumes, an automated method of measuring and characterizing different types of volume is required. A numerical integration approach using an orthogonal Cartesian grid of discrete test points spanning the pressurized volume of the habitat is shown in Figure 21. This method first tests each point in the grid to determine if it is occupied by hardware or ‘free’. It then applies several Boolean collision detection tests based upon the definitions of volume-based criteria to determine if the point should count towards a particular type of volume. This testing continues for each point in the pressurized volume utilizing a grid-based iterative method or “Marching Grid Method” in which points are investigated in cross sections along the habitat length as shown in Figure 21. The total amount of a particular type of volume can then be determined by summing the points conforming to the criteria definition and using this sum with the point spacing of the grid to make a numerical approximation to the volume represented by the points. The major benefits of this marching grid approach are the reduced data storage requirements resulting from tracking a single number of points passing each test and the facilitation of spatial partitioning enabled by the marching grid method.

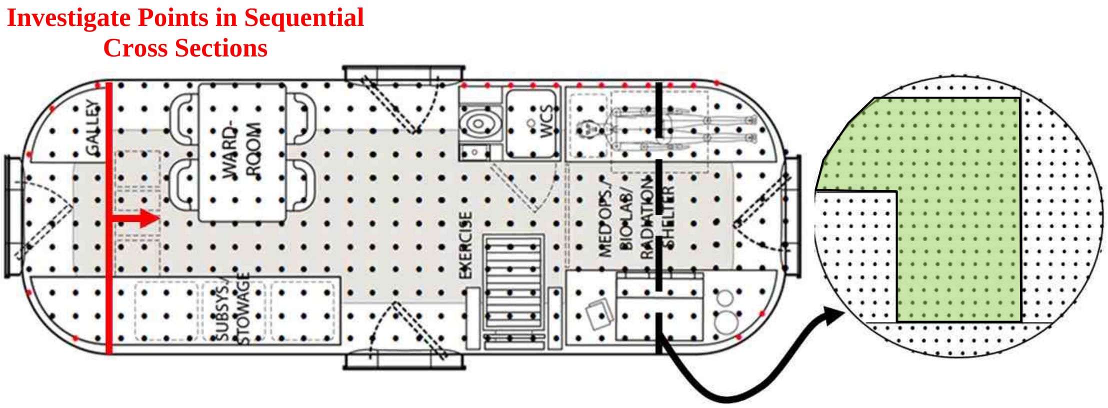


Figure 21: Orthogonal Cartesian Grid of Test Points for Iterative Evaluation Criteria Measurement Methods and Illustration of the Marching Grid Method

To illustrate this method, the following process is used to calculate habitable volume. A test point within the grid can be characterized as part of the habitable volume by testing whether it is within the free, accessible, and functionally usable volume. For this thesis, the following volumes are assumed not to be included in the estimate of habitable volume: the volume occupied by equipment, inaccessible volume behind wall-mounted racks, volume underneath the floor, volume above a ceiling, and volume that is inaccessible but not behind racks (e.g., above reach height, slots between racks, etc.). This definition of habitable volume is in agreement with the definition provided in the NASA, 2010. The Boolean tests used to determine if the point should be included in habitable volume are all point-hardware collision tests defined in the previous section with some half-space tests included for very simple ‘above’ or ‘below checks. The marching grid process used to perform habitable volume calculations is illustrated in Figure 22.

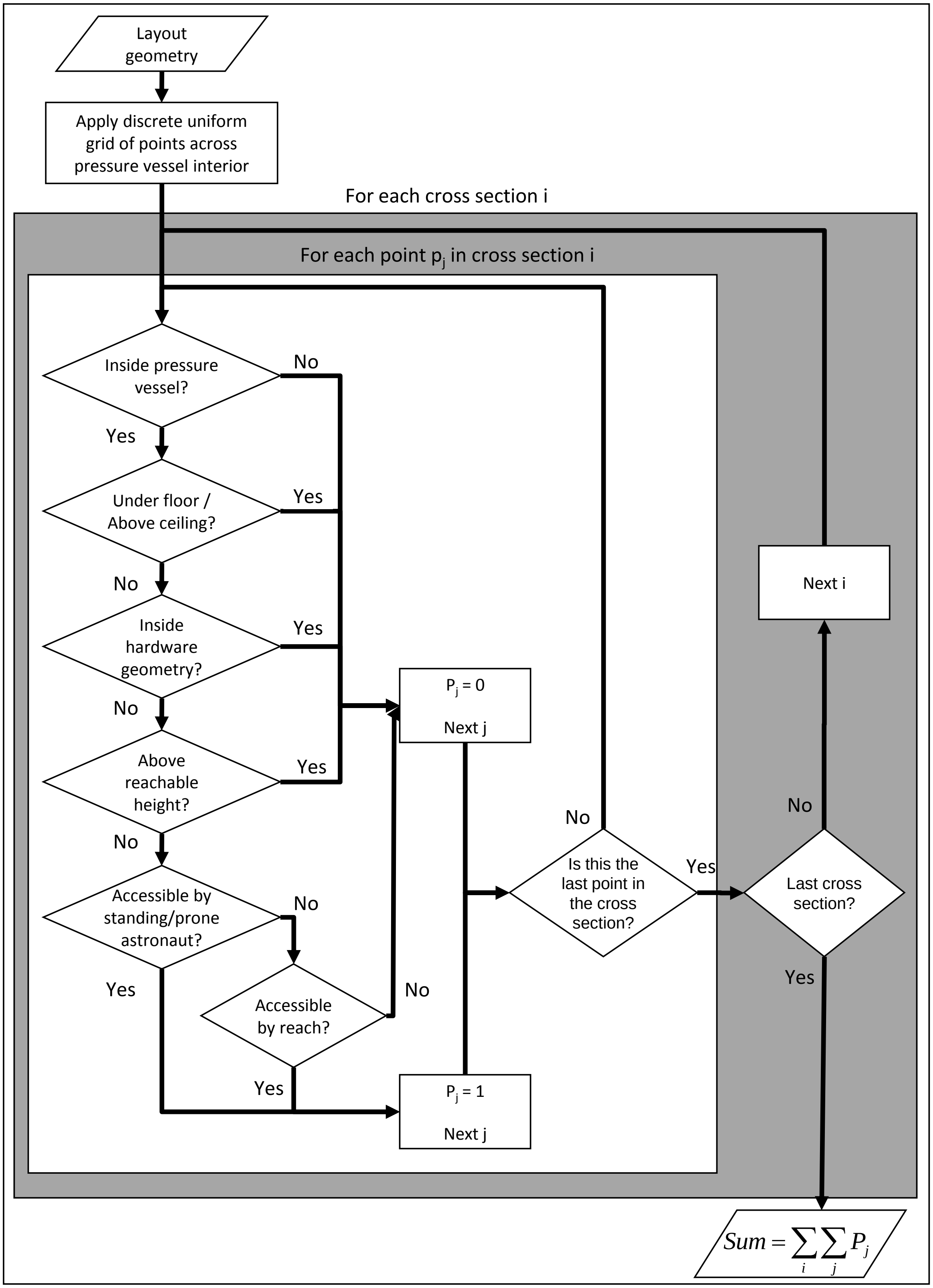


Figure 22: Process for Calculating Habitable Volume

The five Boolean tests used to specify the habitable volume from Figure 22 are as follows. The first test *restricts the number of points to those included within the pressurized volume of the habitat*. This can either be achieved during the selection of points to be investigated (e.g., any points outside the radius of a cylindrical pressure vessel could be eliminated) or by a collision detection test with the entire pressure vessel geometry. If points are outside the pressurized volume, they are excluded.

The second test *prevents inclusion of points below the floor or above the ceiling height from being considered*. This test primarily applies to habitats with some gravity and will be ignored for most microgravity habitats, as no floor or ceiling surface is typically defined. The test excludes all points in the half-spaces above the ceiling or below the floor

The third test determines if the point is physically located within a piece of hardware. ISA-GJK point-hardware tests are used to make this determination. Additionally, this process can be accelerated through the use of a simple bounding volume test known as the Axis Aligned Bounding Box test [Ericson, 2004], which determines if the maximum and minimum coordinates in one of the major axes directions overlaps the point being investigated. All points located within hardware are excluded from the count.

The remaining tests evaluate accessibility and exclude all points above the maximum reach height of an astronaut in a gravity environment and all cavities and voids that are anthropometrically inaccessible. The test for reach height is a simple half-space exclusion test as described in the second test. The test to include cavities and voids can be visualized as routing out the remaining volume to highlight the habitable volume. This is broken into two subtests, of which one must be passed to ensure that a point lies in the habitable volume.

1. The first step determines if the point is in a standing/prone astronaut accessible volume. This can be performed by using a test volume representing a crew operational envelope to show that an astronaut standing or laying down can occupy the point in space without interference from the pressure vessel or interior objects. Several positions and

orientations of the test volume relative to the investigated point may need to be tested. The test volume's shape and size will vary based upon the magnitude of the gravity environment. Test volumes can be tried in various orientations (with position constraints, such as "must be attached to floor in gravity environments" and orientation constraints, such as "vertical or horizontal for gravity environments") until at least one case is found with which the volume doesn't collide, as shown in Figure 23. One passing case is enough to prove that the point is not within a cavity or void. In order to prevent endless testing, discrete orientations and positions of the test volume relative to the point can be used.

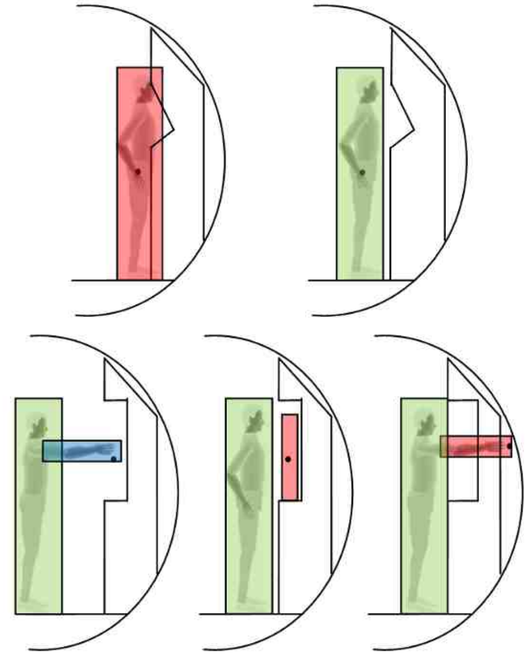
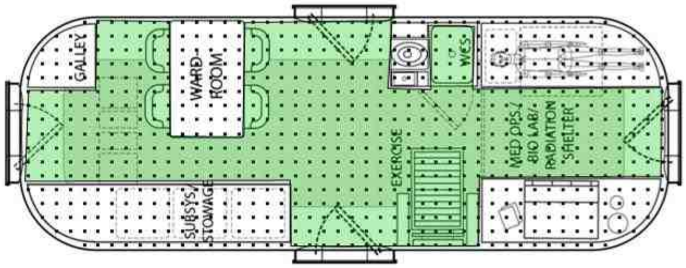


Figure 23: Illustration of Accessible Space for Habitable Volume Calculation

2. The second step assesses cavities for accessibility. A similar method to that in the first test is utilized for this assessment. A test volume representing the minimum length and maximum width of an arm must be tested in multiple positions to find at least one clear position where the test volume is free of collisions. The orientation of the tests could be restricted to preset search directions and positions to provide an exit criterion. The

additional stipulation of this test is that not only must the test volume contain the point being investigated, but it must also contain at least one point that has been classified as a standing/prone astronaut accessible point. This is illustrated in Figure 23. The green box indicates standing/prone astronaut accessible points and the black point is the point being tested. A blue box illustrates a passed test and a red box a failed test. Discrete orientations and positions may be used here to prevent endless testing as in the previous subtest.

Once the Boolean tests described above are used to remove non-habitable space, each point representing habitable volume adds the volume of a cube (equivalent to the cube of the distance between points in the grid) to a running total of the habitable volume. The resultant total is a numerical approximation of the habitable volume according to the definition provided by the four Boolean tests. Applying this process to the Scenario 12.0 PCM yields the volume indicated in Figure 24. The major achievement of this volume-estimation method is that it can be calculated automatically independent from user involvement. A similar method was developed for each of the volume-related evaluation criteria.



Resolution (m)	Number of points	Habitable Volume (m^3)
0.10	33600	33.6
0.05	269600	33.7
0.01	33720000	33.72

Figure 24: Calculation of Scenario 12.0 PCM Habitable Volume

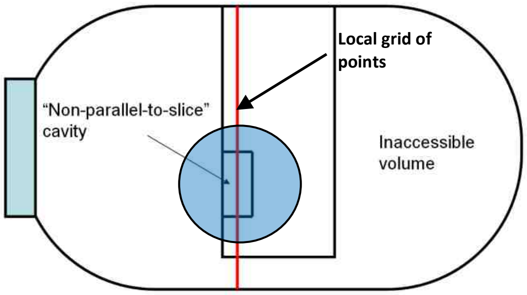


Figure 25: Illustration of Possible Marching Grid Algorithm Issues

As a whole this method accurately measures habitable volume within a spacecraft interior so long as the grid resolution is sufficiently dense to capture layout features. There are two potential limitations of this approach and both are illustrated in Figure 25. First, cavities that are accessible from some direction may be labeled inaccessible if not in the plane of the slice being investigated. To solve this: once the cavities are identified, points within the cavities should ideally generate a local 3-dimensional grid of points inside a sphere with radius equivalent to the length of the arm box and retest the points in this sphere for standing/prone astronaut accessibility. These points will be necessary for the second subtest to ensure arm accessibility in non-orthogonal directions for the point of interest. Essentially, a local test can be added to address this deficiency. The second limitation is the possibility that random layout generation can develop layouts where two zones of the standing/prone astronaut accessible volume do not have a sufficient translation path to translate between them. However, this problem is deemed to be out of scope in this thesis and layouts evaluated by this method are assumed to be reasonably designed concepts that do not contain such ambiguous regions. Making the method fully generic is part of the future work of which will be described in Chapter 5. Additional details of the calculation of habitable volume and practical examples can be found in Simon, Bobskill, & Wilhite 2012.

Methods utilizing this discrete grid of points can also be used for iterative methods of defining length-based evaluation criteria, particularly spatial vista and minimum aisle width. Spatial vista measures the maximum amount of volume that a crewmember can see within the habitat as shown in Figure 26. The point of origin from which the viewer's perspective originates is important to the find the maximum possible visible volume. The discrete points in the grid can be iterated through with some optimization method to converge to the point of view measuring the maximum spatial vista. Similarly, to quantify the minimum translation path width, points of origin must be on the translation path, which changes with every layout. The grid of points can be used with a robot path planning algorithm like A* or Djkstra's algorithm to construct a translation path from the available points. These algorithms iteratively, and directionally search for the simplest path between two points while avoiding objects. Then these identified points can be used as the points of origin for the measurement of translation path width as shown in Figure 27.

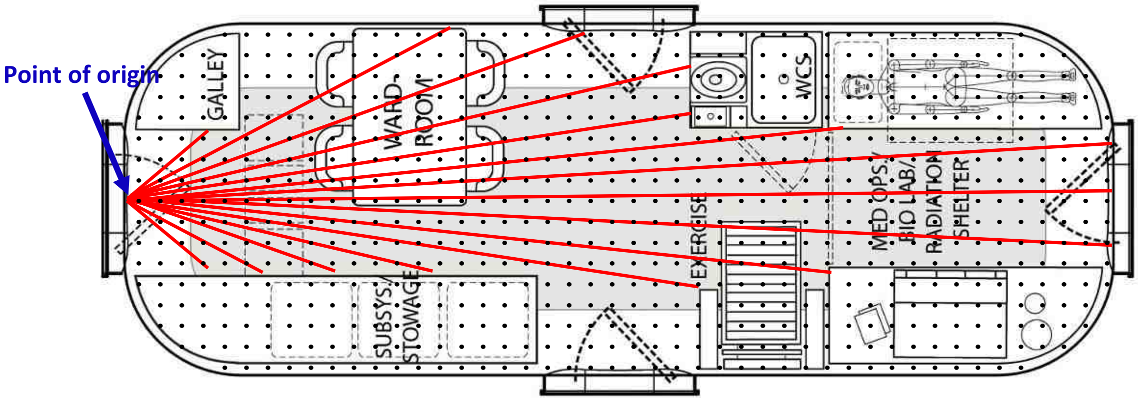


Figure 26: Use of Discrete Grid-based Iterative Method to Calculate Spatial Vista

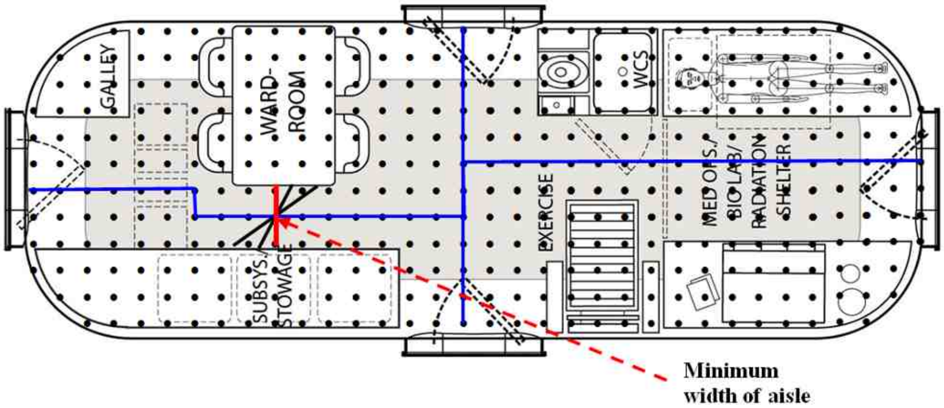


Figure 27: Use of Grid-based Iterative Methods to Measure Minimum Translation Path Width

It is important to note that for even moderately sized habitats, the assumed resolution of the grid necessary to get accurate measurements may include a computationally prohibitive amount of points. For example, a habitat with 3 m diameter and 7 m length may take as many as 60 million points to characterize the space. Storing data such as the location and exact characteristics of each of these points would be difficult. Two methods are taken to prevent this problem:

1. **Reduced grid resolution** to reduce the number of points which must be tracked. This is particularly important in finding the minimum translation path width which must keep track of the location of points in the translation path.
2. **Additive calculation with no data** can be used to eliminate the need for data storage. For example, when calculating habitable volume, the number of points passing each of the Boolean tests can be simply be counted using a running counter to determine the volume. Additional optimization or heuristic methods may be implemented in future work to speed this process further utilizing coherence and optimization algorithms.

3.3.3 Separation-Colocation Matrices [Simon & Wilhite, 2013]

Several evaluation criteria measure how well the functional relationships between systems are accommodated by their location. This can also be thought of as the degree to which conflicting or complementary hardware are separated or collocated, respectively. In spacecraft design and terrestrial architecture this is known as a functional relationships analysis and is typically characterized qualitatively using an adjacency diagram or bubble chart [Tullis & Bied, 1988; Fitts, 2002]. Each piece of hardware can perform multiple functions, so prior to any calculation of functional relationships accommodation of a layout, functions (such as Meal Preparation, Sleeping, Face cleansing, etc.) must be mapped to hardware (Galley, Crew Quarters, Hygiene, etc.).

After the mapping of functions to hardware is complete, an automatable calculation method utilizing two types of matrices has been identified in literature [Tullis & Bied, 1988]:

1. **Matrices capturing the functional relationships** are drawn from station crew schedules and crew preference elicitation [Tullis & Bied, 1988]. A library of these is documented in Tullis & Bied, 1988 which need only be mapped to the appropriate functions carried in any habitat concept. These provide guidance as to whether functions should be separated or collocated based upon specific criteria such as noise, hygiene, etc.
2. **Matrices of the distances between objects** can be defined based upon the layout and combined with the function relationships matrices to derive a measure of how successful the layout is at accommodating these functions. A simple implementation of this locates each function at the center of the piece of hardware it is mapped to and utilizes Euclidean distance to represent the separation of the functions. However, the distances included in these matrices need not be restricted to Euclidean distances. Some criteria desire visual separation or hygiene separation which can be augmented by partitions while others dealing with the length of shared consumable lines which run along the pressure vessel of the habitat behind equipment are best measured with some cylindrical mapping of Manhattan distance.

The structures of these matrices are shown in Figure 28. In order to derive a single measure of the overall effectiveness of a layout to capture these relationships, the Euclidean norm of the Hadamard Product (entry-wise product) of the R and D matrices was used. $\|[R \circ D]_{ij}\|$. While this quantity is not physically interpretable as any measurement, it can be compared to the range of possible values of this product determined by a design space exploration of the distance matrix for the specified pressure vessel geometry to gage its performance against possible values. Figure 29 shows an example of the calculation of the separation for privacy metric for the Scenario 12.0 PCM. The minimum and maximum possible values shown in this figure may be tracked over multiple layout evaluations to better define utility of this non-intuitive criterion.

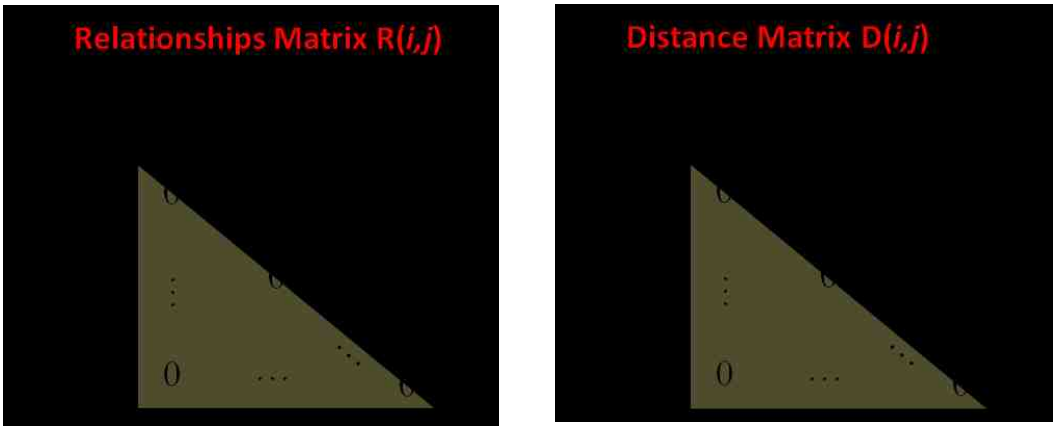
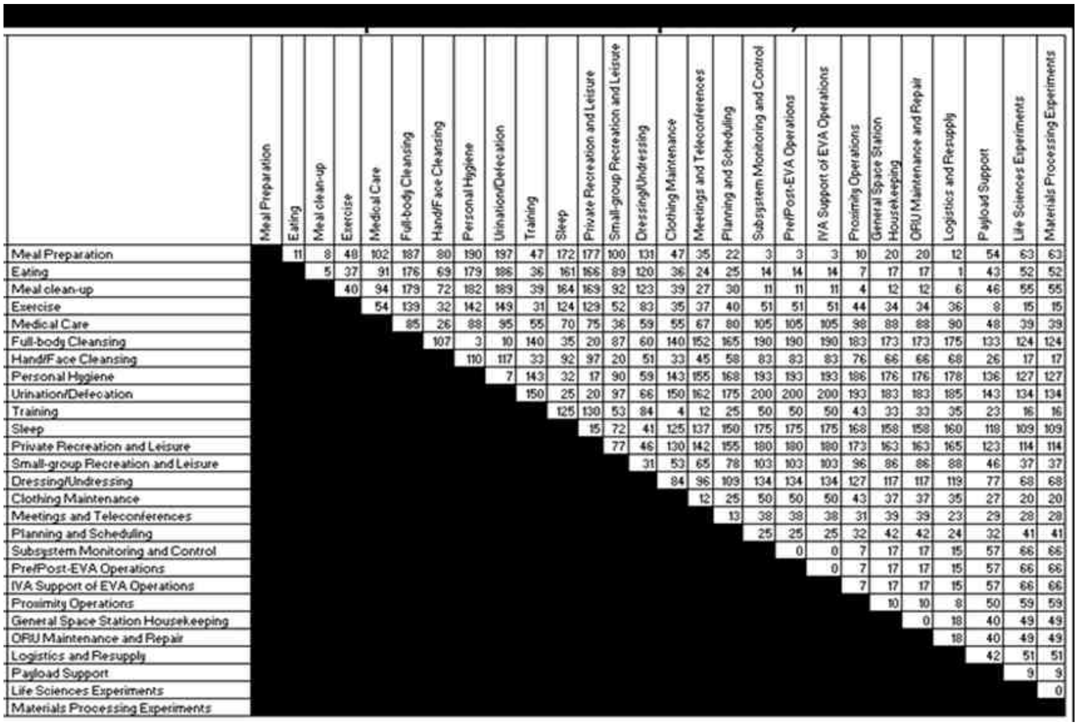
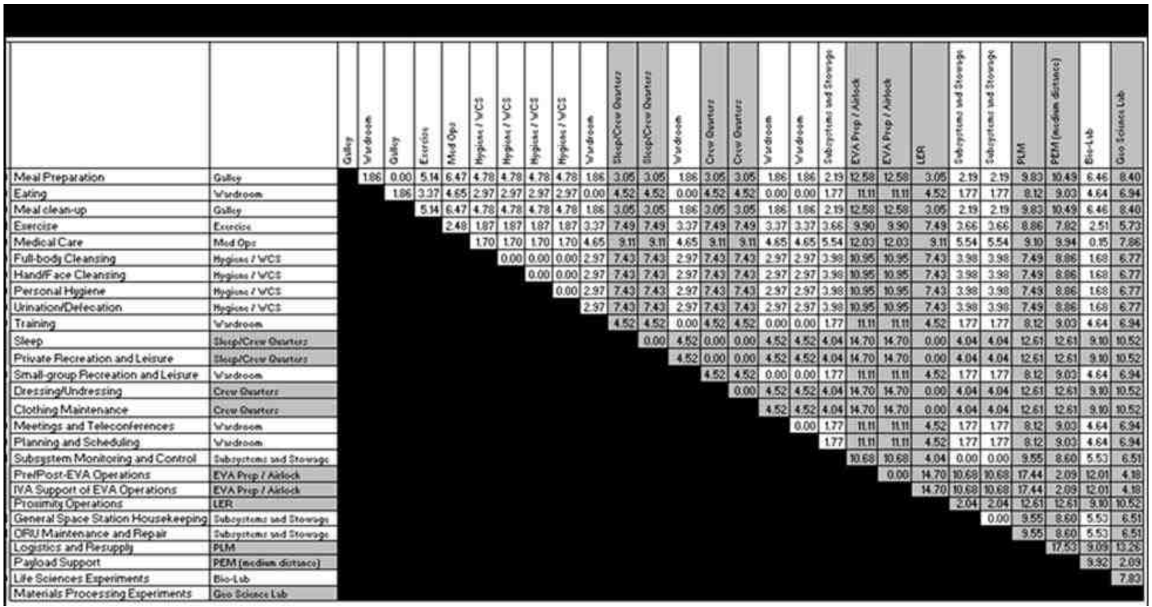


Figure 28: Functional Relationships and Distance Matrices

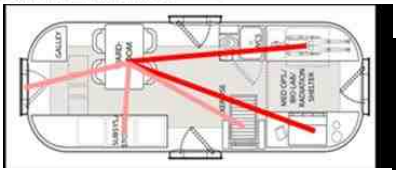
By implementing combinations of each of these three enabling mechanisms with logical definition-derived measurements, detailed automatically calculable algorithms have been created for each of the evaluation criteria in Figure 16. A description of each quantification method can be found in Appendix B. These algorithms are designed to be implementable in an object oriented programming language compatible with basic geometry modeling, and the software implementation of the method is described in Section 3.7.

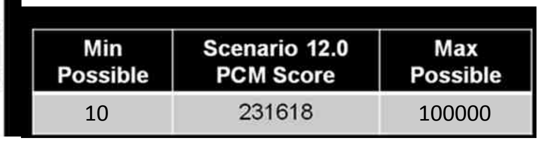


	Meal Preparation	Eating	Meal clean-up	Exercise	Medical Care	Full-body Cleansing	Hand/Face Cleansing	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation and Leisure	Small-group Recreation and Leisure	Dressing/Undressing	Clothing Maintenance	Meetings and Teleconferences	Planning and Scheduling	Subsystem Monitoring and Control	Pre/Post-EVA Operations	IVA Support of EVA Operations	Proximity Operations	General Space Station Housekeeping	ORU Maintenance and Repair	Logistics and Resupply	Payload Support	Life Sciences Experiments	Materials Processing Experiments
Meal Preparation		11	8	48	102	187	80	190	197	47	172	177	100	131	47	35	22	3	3	3	10	20	20	12	54	63	63
Eating			5	37	91	176	69	179	186	36	161	166	89	120	36	24	25	14	14	14	7	17	17	1	43	52	52
Meal clean-up				40	94	179	72	182	189	39	164	169	92	123	39	27	30	11	11	11	4	12	12	6	46	55	55
Exercise					54	139	32	142	149	31	124	129	52	83	35	37	40	51	51	51	44	34	34	36	8	15	15
Medical Care						85	26	88	95	55	70	75	36	59	55	67	80	105	105	105	98	88	88	90	48	39	39
Full-body Cleansing							107	3	10	140	35	20	87	60	140	152	165	190	190	190	183	173	173	175	133	124	124
Hand/Face Cleansing								110	117	33	92	97	20	51	33	45	58	83	83	83	76	66	66	68	26	17	17
Personal Hygiene									7	143	32	17	90	59	143	155	168	193	193	193	186	176	176	178	136	127	127
Urination/Defecation										150	25	20	97	66	150	162	175	200	200	200	193	183	183	185	143	134	134
Training											125	130	53	84	4	12	25	50	50	50	43	33	33	35	23	16	16
Sleep												15	72	41	125	137	150	175	175	175	168	158	158	160	118	109	109
Private Recreation and Leisure													77	46	130	142	155	180	180	180	173	163	163	165	123	114	114
Small-group Recreation and Leisure														31	53	65	78	103	103	103	96	86	86	88	46	37	37
Dressing/Undressing															84	96	109	134	134	134	127	117	117	119	77	68	68
Clothing Maintenance																12	25	50	50	50	43	37	37	35	27	20	20
Meetings and Teleconferences																	13	38	38	38	31	39	39	23	29	28	28
Planning and Scheduling																		25	25	25	32	42	42	24	32	41	41
Subsystem Monitoring and Control																			0	0	7	17	17	15	57	66	66
Pre/Post-EVA Operations																				0	7	17	17	15	57	66	66
IVA Support of EVA Operations																					7	17	17	15	57	66	66
Proximity Operations																						10	10	8	50	59	59
General Space Station Housekeeping																							0	18	40	49	49
ORU Maintenance and Repair																								18	40	49	49
Logistics and Resupply																									42	51	51
Payload Support																										9	9
Life Sciences Experiments																											0
Materials Processing Experiments																											



		Galley	Wardroom	Galley	Exercise	Med Ops	Hygiene / WCS	Hygiene / WCS	Hygiene / WCS	Hygiene / WCS	Wardroom	Sleep/Crew Quarters	Sleep/Crew Quarters	Wardroom	Crew Quarters	Crew Quarters	Wardroom	Wardroom	Subsystems and Stowage	EVA Prep / Airlock	EVA Prep / Airlock	LER	Subsystems and Stowage	Subsystems and Stowage	PLM	PEM (medium distance)	Bio-Lab	Geo Science Lab
Meal Preparation	Galley		1.86	0.00	5.14	6.47	4.78	4.78	4.78	4.78	1.86	3.05	3.05	1.86	3.05	3.05	1.86	1.86	2.19	12.58	12.58	3.05	2.19	2.19	9.83	10.49	6.46	8.40
Eating	Wardroom			1.86	3.37	4.65	2.97	2.97	2.97	2.97	0.00	4.52	4.52	0.00	4.52	4.52	0.00	0.00	1.77	11.11	11.11	4.52	1.77	1.77	8.12	9.03	4.64	6.94
Meal clean-up	Galley				5.14	6.47	4.78	4.78	4.78	4.78	1.86	3.05	3.05	1.86	3.05	3.05	1.86	1.86	2.19	12.58	12.58	3.05	2.19	2.19	9.83	10.49	6.46	8.40
Exercise	Exercise					2.48	1.87	1.87	1.87	1.87	3.37	7.49	7.49	3.37	7.49	7.49	3.37	3.37	3.66	9.90	9.90	7.49	3.66	3.66	8.86	7.82	2.51	5.73
Medical Care	Med Ops						1.70	1.70	1.70	1.70	4.65	9.11	9.11	4.65	9.11	9.11	4.65	4.65	5.54	12.03	12.03	9.11	5.54	5.54	9.10	9.94	0.15	7.86
Full-body Cleansing	Hygiene / WCS							0.00	0.00	0.00	2.97	7.43	7.43	2.97	7.43	7.43	2.97	2.97	3.98	10.95	10.95	7.43	3.98	3.98	7.49	8.86	1.68	6.77
Hand/Face Cleansing	Hygiene / WCS								0.00	0.00	2.97	7.43	7.43	2.97	7.43	7.43	2.97	2.97	3.98	10.95	10.95	7.43	3.98	3.98	7.49	8.86	1.68	6.77
Personal Hygiene	Hygiene / WCS									0.00	2.97	7.43	7.43	2.97	7.43	7.43	2.97	2.97	3.98	10.95	10.95	7.43	3.98	3.98	7.49	8.86	1.68	6.77
Urination/Defecation	Hygiene / WCS										2.97	7.43	7.43	2.97	7.43	7.43	2.97	2.97	3.98	10.95	10.95	7.43	3.98	3.98	7.49	8.86	1.68	6.77
Training	Wardroom											4.52	4.52	0.00	4.52	4.52	0.00	0.00	1.77	11.11	11.11	4.52	1.77	1.77	8.12	9.03	4.64	6.94
Sleep	Sleep/Crew Quarters												0.00	4.52	0.00	0.00	4.52	4.52	4.04	14.70	14.70	0.00	4.04	4.04	12.61	12.61	9.10	10.52
Private Recreation and Leisure	Sleep/Crew Quarters													4.52	0.00	0.00	4.52	4.52	4.04	14.70	14.70	0.00	4.04	4.04	12.61	12.61	9.10	10.52
Small-group Recreation and Leisure	Wardroom														4.52	4.52	0.00	0.00	1.77	11.11	11.11	4.52	1.77	1.77	8.12	9.03	4.64	6.94
Dressing/Undressing	Crew Quarters															0.00	4.52	4.52	4.04	14.70	14.70	0.00	4.04	4.04	12.61	12.61	9.10	10.52
Clothing Maintenance	Crew Quarters																4.52	4.52	4.04	14.70	14.70	0.00	4.04	4.04	12.61	12.61	9.10	10.52
Meetings and Teleconferences	Wardroom																	0.00	1.77	11.11	11.11	4.52	1.77	1.77	8.12	9.03	4.64	6.94
Planning and Scheduling	Wardroom																		1.77	11.11	11.11	4.52	1.77	1.77	8.12	9.03	4.64	6.94
Subsystem Monitoring and Control	Subsystems and Stowage																			10.68	10.68	4.04	0.00	0.00	9.55	8.60	5.53	6.51
Pre/Post-EVA Operations	EVA Prep / Airlock																				0.00	14.70	10.68	10.68	17.44	2.09	12.01	4.18
IVA Support of EVA Operations	EVA Prep / Airlock																					14.70	10.68	10.68	17.44	2.09	12.01	4.18
Proximity Operations	LER																						2.04	2.04	12.61	12.61	9.10	10.52
General Space Station Housekeeping	Subsystems and Stowage																							0.00	9.55	8.60	5.53	6.51
ORU Maintenance and Repair	Subsystems and Stowage																								9.55	8.60	5.53	6.51
Logistics and Resupply	PLM																									17.53	9.09	13.26
Payload Support	PEM (medium distance)																										9.92	2.09
Life Sciences Experiments	Bio-Lab																											7.80
Materials Processing Experiments	Geo Science Lab																											





Min Possible	Scenario 12.0 PCM Score	Max Possible
10	231618	100000

Figure 29: Example Calculation of the Separation for Privacy Evaluation Criterion for the Scenario 12.0 PCM [Tullis & Bied, 1988]

3.4 Constraints [Simon & Wilhite, 2013]

The final piece of the evaluation function which must be described is the implementation of constraints on the design problem specified by designer preferences, physical realizability or human/spaceflight standards. Constraints here are limits placed upon the physical location of interior equipment or evaluation criteria measurements. Table 16 lists a few of the constraints which apply to habitat interiors. The first group includes constraints which restrict the placement of equipment to certain locations. The first two constraints (hardware-hardware (also known as "non-overlap") constraint and the hardware-pressure vessel (also known as "container") constraint) within this group ensure that configurations investigated are physically realizable while the third places constraints on the overall placement to aid in integration of the habitat into the transportation stages and/or landers. The next three constraints are examples of minimum volumes which must be provided to meet human requirements. The final three are examples of constraints which are enforced by using the evaluation criteria values to check on specific measures found within human requirements. Many more constraints exist than can be covered in this table. Complete lists of these constraints are described in NASA standards of practice [NASA, 1995; NASA, 1999; Allen et al., 2003; and NASA, 2010].

Table 16: Constraint Types [NASA, 1995; NASA, 1999; Allen et al., 2003; NASA, 2010]

Constraint	Description	References
Constraints on Placement of Equipment		
Hardware-Hardware Overlap	Any two pieces of equipment must not be allowed to exist in the same space to ensure physical realizability	Tompkins et al., 2010
Hardware - Pressure Vessel Protrusion	Hardware must be contained within the pressurized volume specified	
Center of Gravity Constraints	There may be constraints upon the location of the center of gravity which can be calculated from the masses and positions of interior subsystems and structures. This is often a constraint for launch vehicle and lander payloads.	
Constraints on Required Minimum Volumes		
Minimum Habitable Volume	For missions of a specified number of crew, duration of mission, and gravity orientation, a minimum required habitable volume is required for crew health and operation efficiency. ____ indicates a minimum of 16.99 m3 per person for missions beyond LEO.	NASA, 2010; Celantano 1963; Allen et al., 2003
Required Volume for Specific Tasks	A minimum contiguous volume is required for several tasks within the pressurized volume, particularly for emergency situations. Examples of this are suit don/doff (min 1.19 m3) and incapacitated crew member suit removal. The volumes are well defined anthropometry found in spacecraft design standards.	NASA, 2010; Salvendy, 1997; Allen et al., 2003
Minimum Sleeping Volume	The minimum required volume for sleeping area (1.5 m3)	Allen et al., 2003
Other Constraints		
Translation Path-Hardware for Crew and Goods Translation	There is a requirement that two suited astronauts must be able to pass ion the translation path which dictates the minimum width of the translation path. Additionally, if goods are required to be handled or moved within the habitat, a path consistent with biomechanics should be provided for the pass-through.	NASA, 2010; NASA, 1995
Hatch-Hardware Clearance Constraints	There are requirements to ensure hatches swing paths are clear to ensure egress pathways or to ensure the ability to seal the hab by hatch closure in an emergency	NASA, 2010
Anthropometric Envelope Clearance for Critical Functions (Anthropometric envelope-hardware constraints)	Objects must be placed to accommodate certain critical functional envelopes or task volumes. These constraints can be implemented on an as needed basis.	NASA, 2010
Noise Exposure Limits	NASA standards provide noise exposure limits which must be considered in the placement of systems	NASA, 2010; Allen et al., 2003
Accessible front faces of critical high use systems (communication, temp control, fire extinguisher)	Emergency equipment such as fire extinguisher has constraints on their location and access which must be satisfied.	Fitts, 2002; NASA, 2010

One of the challenges in automated layout design is how to implement the constraints into the decision process to enable automation algorithms. There are three primary methods addressed in literature and covered in Section 2.3.2. The first option would be to declare a configuration unfeasible if interferences occur, and only evaluate feasible configurations. However, this makes automating the placement of interior components very difficult due to its effect on the design space, which becomes highly discontinuous and multi-modal for such hard constraints (e.g. if that concept is close to the optimum and small clearance problem caused it to be missed). Another way to enforce these constraints is to hard code placement algorithms to prevent collisions through discretization of the possible hardware locations or some logical placement order. This method is often used in facility layout problems to generate a database of feasible alternatives which can be evaluated to aid in selection. The third method to implement constraints is to accept their violation and either ignore or enforce them through their effect on objective function values. Ignoring constraint violations allows flexibility in the progression of hardware placement towards optimum configurations. Constraint violations can also be implemented by integration into the objective function through the use of penalty functions.

Penalty functions applied at the objective function level are the anticipated best method to implement these constraints. Penalty functions return increasingly large values as constraints are violated, which can be added from the unconstrained weighted sum of evaluation criteria to prevent layout designs which violate constraints from being acceptable. Interior penalty functions increase before the constraint is violated to enforce ‘hard’ constraints which must be met for feasible designs. Exterior penalty functions are used for ‘soft’ constraints where slight violations are acceptable. In general, exterior penalty functions are more consistent with the definition of the evaluation criteria and are anticipated to provide more flexibility in finding solutions. Additionally, all constraints can be relaxed during early iterations to prevent a lack of freedom for the optimization method to explore the design space and some schedule of the rate of increase of the penalty functions can be implemented to avoid local optima. For more information on external penalty functions see Vanderplaats, 1984.

3.5 Implementation of Designer Preferences [Simon & Wilhite, 2013]

Evaluation criteria measurements described in the previous sections each measure aspects of the effectiveness of the layout geometry. In order to make decisions as to whether additional layout iteration is required, these evaluation criteria must be combined into a single aggregate measure of the layout's performance on all objectives and its ability to meet all critical constraints. In order to assemble this objective function as described in Section 3.1.2.3, the detailed methods to capture and implement designer preferences are described here.

3.5.1 Utility Functions

As shown in Figure 13, Single-attribute Utility Functions (SUFs) are designer-specified functions which normalize the measured evaluation criteria values to some value between 0 and 1 where 1 is peak performance and 0 is the lowest possible. In most cases, linear relationships for these functions determined by the range of possible evaluation criteria values are acceptable. However, linear improvement in the value of an evaluation criterion does not always correspond to a linear improvement in the user's preference of that value. For example, at low values of habitable volume (e.g., 5 m^3/person) even slight volume increases may provide significantly improved human comfort, safety, or productivity. However, at high values (e.g., 40 m^3/person), even large increases in volume have diminishing returns as the volume becomes spacious to the point of being wasted. This diminishing return is reflected in the shape of the habitable utility function shown in Figure 30, which shows a negligible utility improvement past the value corresponding to the optimal amount of volume [NASA, 1995; Simon, Bobskill, & Wilhite 2012]. Several other types of possible utility functions are shown in Figure 31.

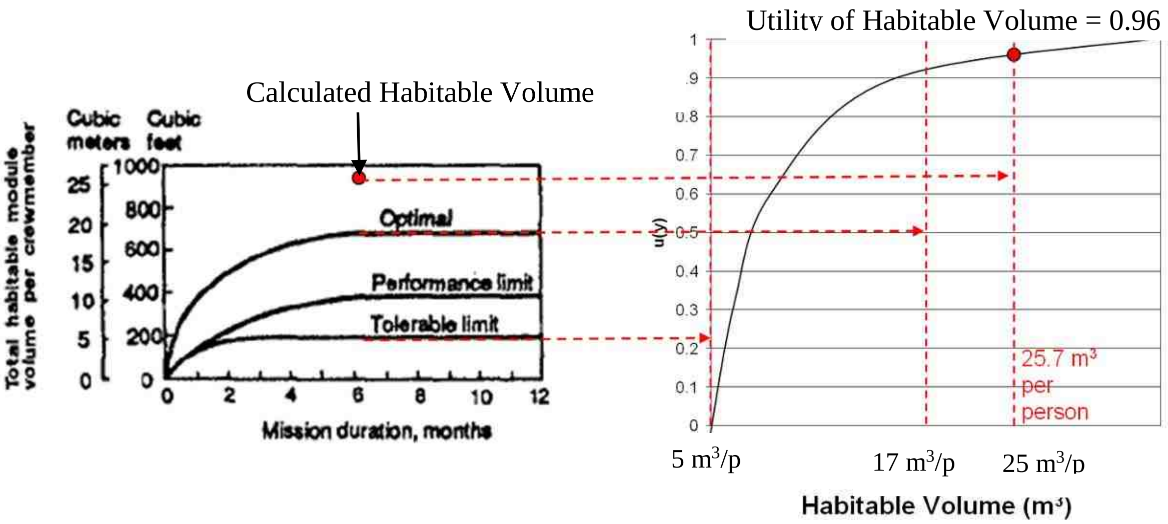


Figure 30: Illustration of Scenario 12.0 PCM Habitable Volume Requirements and Corresponding Utility Function [NASA, 1995; Simon, Bobskill, & Wilhite 2012]

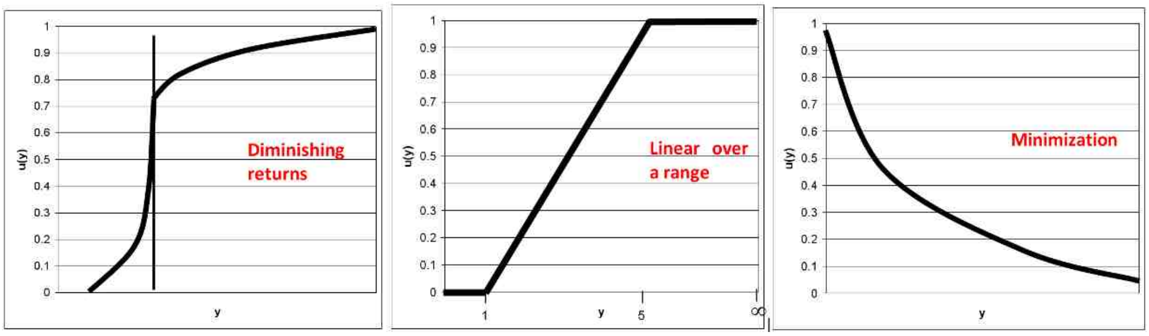
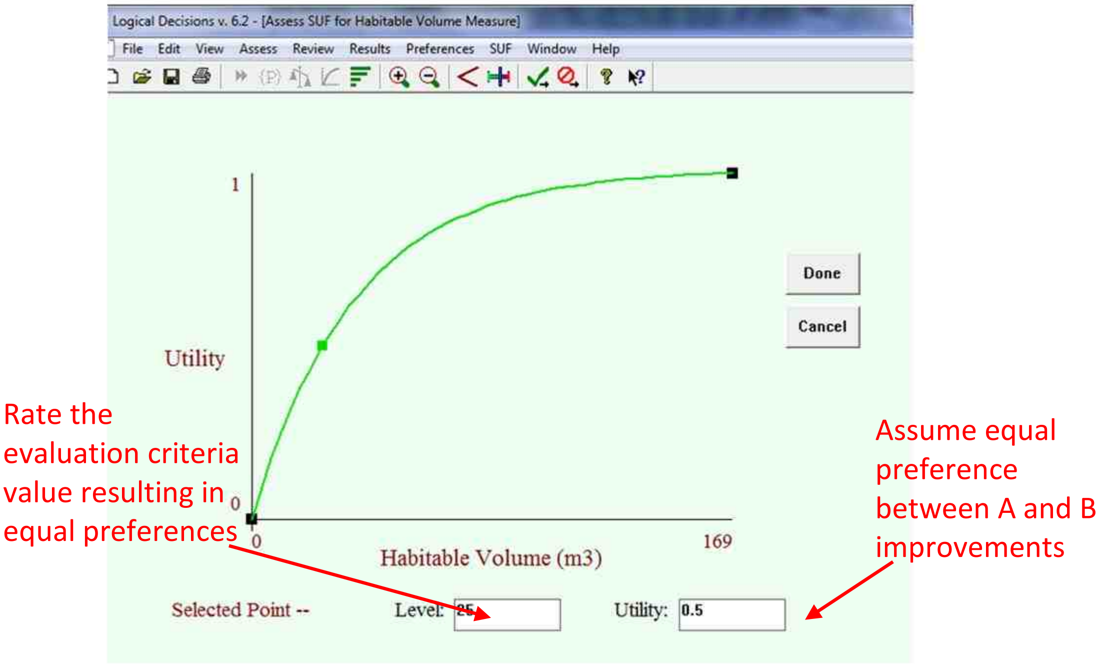


Figure 31: Types of Nonlinear Utility Function Shapes

Utility functions can capture designer preference of evaluation criterion value as a function of its value. Definition of these functions begins by assigning the best criterion value, X_{best}, to a value of 1 and the worst criterion value, X_{worst}, to a value of 0. The utility of a value between the best and worst values, U(X), is a function which can be defined in a few ways. Many structured, repeatable processes to define the utility curves are provided by the Logical Decisions for Windows® (LDW) software documented in Smith, 2007. The Mid-Preference Level Splitting was selected based upon its compatibility with the habitat layout design problem and its facility to capture designer rationale. This method uses expert questioning to identify the evaluation criteria value or level, 'L', where the improvement from the worst allowable value to L is equally preferred to an increase from L to the highest possible value (i.e., U(L) - U(L0) = U(L1) - U(L)). These preferences can then be captured with a curve fit through the specified points. This method is illustrated in Figure 32. The LDW software guides users through structured questions and can aggregate the responses of a group of experts [Smith, 2007]. The only weakness of this method is its inability to model discontinuous utility functions, which do not apply to the set of evaluation criteria used in this research.



Selected Point --

Level: 25

Utility: 0.5

Rate the evaluation criteria value resulting in equal preferences

Assume equal preference between A and B improvements

Figure 32: Demonstration of Mid-Preference Level Splitting Utility Function Definition [Smith, 2007]

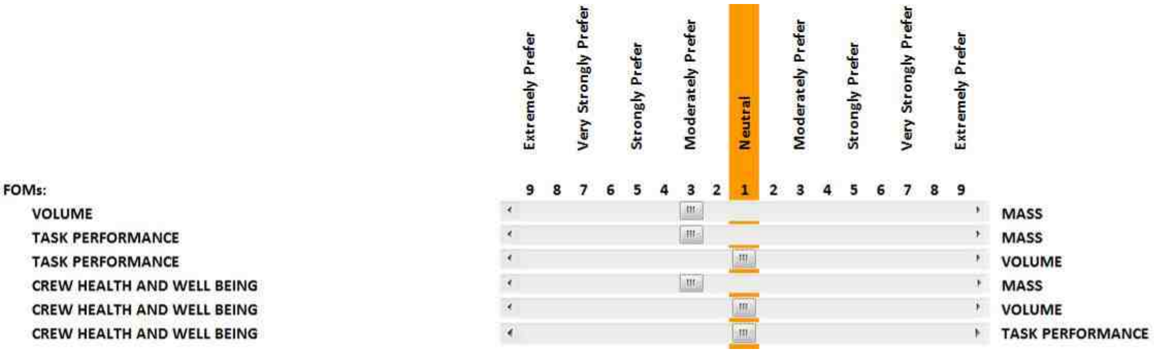
3.5.2 Relative Evaluation Criteria Weightings

Evaluation criteria weightings enable the designer to customize an objective function to their value model or the specific design problem they are investigating. For example, a designer focused on increased task performance efficiency or a design problem statement requesting a focus on task performance analysis may place less importance on mass related criteria than sequential tasks. Several methods for determining the relative importance of evaluation criteria investigated are shown in Table 17. Comparison of these methods showed that many of the methods were compatible with the design problem with varying levels of complexity and slightly different performance. The method chosen based upon these observations is the Analytic Hierarchy Process (AHP) [Saaty, 1980; Smith, 2007]. It was chosen because it is intuitive and simple to implement, so long as preferences show a certain level of consistency, which can be verified in the process of obtaining inputs.

Table 17: Alternative Multi-Criteria Decision Making (MCDM) Methods to Determine Relative Importance Weightings

Alternative Approach	Description	Limitations
Analytic Hierarchy Process (AHP) [Saaty, 1980; Smith, 2007]	• Uses pairwise comparisons on each possible pair of criteria to derive weightings	• Has difficulty dealing with inconsistent rankings • Assumes independent criteria
Analytic Network Process (ANP)	• Creates a network of information for interrelated criteria	• Difficult to explain to decision makers; Complex • Large amounts of information and time required • Verification of results impossible because of interrelated loops
“Smart” and “Smarter” Methods [Smith, 2007]	• Uses “swing weights” to order all alternatives, then converts “swing weights” to absolute weightings	• Difficult for criteria preferences aren’t well understood
Tradeoff Method [Smith, 2007]	• Uses pairwise comparisons between pairs of alternatives on selected criteria to indirectly derive relative importance	• Layout alternatives can seem similar • Some criteria are complex and not easily judged based upon top level data
Direct Entry Method [Smith, 2007]	• Directly enter in the weights based upon expert judgment	• Acceptable for certain simpler design problems, but problematic when dealing with more complicated design problems.

Analytic Hierarchy Process uses a full-factorial, user-defined set of pair-wise preference comparisons to numerically determine a normalized importance of each evaluation criterion [Saaty, 1980]. Pair-wise preferences for the each of the major evaluation criteria (mass, volume, etc.) from Figure 16 are captured based upon their influence on the final design via expert elicitation as shown in Figure 33. The pair-wise preferences for the sub-criteria are similarly captured based upon their importance as a measure of the top-level criterion to which they contribute. AHP uses the eigenvectors of a matrix built from these numerical pair-wise preferences to determine the overall weightings by the process described in Saaty, 1980. The resulting ranked list and overall weighting of each of the sub-criteria is provided in Figure 34 as a check to the validity of the preferences.



FOMs:
VOLUME — MASS
TASK PERFORMANCE — MASS
TASK PERFORMANCE — VOLUME
CREW HEALTH AND WELL BEING — MASS
CREW HEALTH AND WELL BEING — VOLUME
CREW HEALTH AND WELL BEING — TASK PERFORMANCE

Figure 33: Pair-wise Comparisons of Evaluation Criteria Preferences

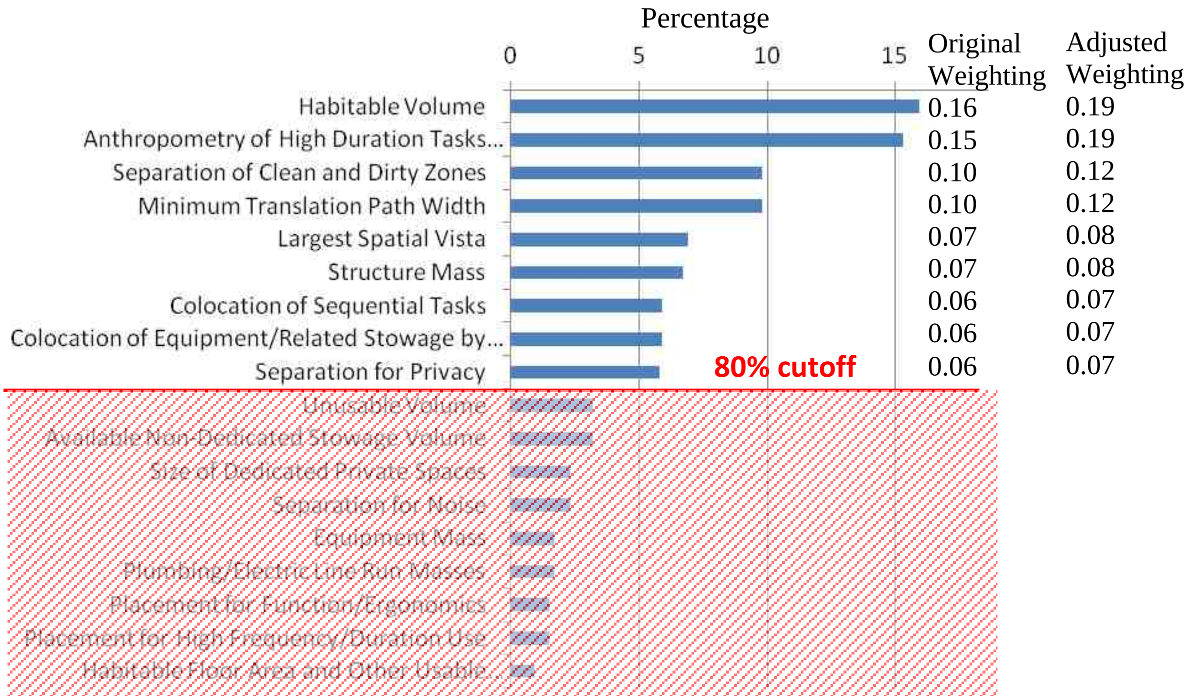


Figure 34: Relative Weighting of Each Criterion Based upon Pair-wise Comparisons

It is important to realize that these weightings are fully adjustable as part of the inputs to the quantitative evaluation process and that the current weightings are an example of possible weightings provided by the author based upon the Scenario 12.0 PCM design problem. In practice, a set of preset values elicited from experts for various mission types will be included for designers who are not completely comfortable with independent estimates. This is demonstrated in Chapter 4 when a habitation design expert provided the pairwise preferences for the criteria weightings on the cislunar habitat problem. It is also expected that the designer may desire to observe the impact of changing these preferences on the resultant configuration or to perform uncertainties to capture shifting priorities. For example, maximizing the importance of providing volume and reducing mass without considering task performance, quality of the volume or safety would result in placement of all of the equipment tightly packed in one or both ends of the habitat to maximize the adjacency of systems and maximize resultant volume. It is expected that the weightings may change several times as it becomes clear which evaluation criteria really discriminate concepts. By performing trades like these, it is possible to determine the robustness of certain designs to changes in designer preferences.

In order to focus on those criteria having the most impact to the overall objective function value, the list in Figure 16 can be reduced via a screening to include only the evaluation criteria accounting for 80% of the weighting as shown in Figure 34. These criteria can be renormalized based upon their original weightings and the weighting of the excluded criteria can be set to zero. These other criteria are still calculated and tracked, but they are effectively excluded from the objective function.

3.6 Software Implementation [Simon & Wilhite, 2013]

In order to implement the evaluation method and optimization algorithm, a software program was developed using C++ and OpenGL. These languages were primarily chosen because of the availability of collision detection libraries and the ability to generate a transferrable executable file to facilitate sharing. The code operates in the following order. First, the problem description information, such as the size of the pressure vessel, is defined. Then, information about the pieces of hardware to be included in the layout is read from objectList.csv input files. This file includes the geometry of these objects (as represented by matrices of vertices, face indices, and face normal vectors), geometry of simplified bounding box representations of the objects, geometry of reserved anthropometric volume to interact with each object, object mass, object volume, a mapping of what tasks are associated with each piece of hardware, a flag to identify those objects which should be designated as private space, and a matrix mapping power and consumable line mapping to objects. Additionally, the initial positions and velocities of hardware may be specified in this input file to model one layout or they may be procedurally generated to create a population of initial layouts. Other .csv files are also used to store functional relationship data (hygieneMatrix.csv, noiseMatrix.csv, privacyMatrix.csv, sequentialMatrix.csv) [Tullis & Bied, 1988], a list of tasks which must be performed (taskList.csv), and typical spaceflight durations of these tasks (taskDurations.csv). In the main program, all of the information about the objects and tasks is stored in structures which allow for colocation and facilitated access of geometry, position, and functional relationship data. Other input files capture the utility functions (utilitiesMatrix.csv) and criteria weightings (weightsMatrix.csv) which are collected from expert elicitation over the course of a few hours, but these inputs could also be pulled from libraries of previous runs in future code implementations. Examples of all of the .csv input files are provided in Appendix C. After all input information is captured; the process described in Chapter 3 is used to evaluate input layouts. Criteria and constraints are calculated to quantify the objective function. Images of the layouts are then rendered using the OpenGL visualization capability using transparent blue and yellow boxes to track the anthropometric reserved volumes and translation paths, respectively, and displaying key variables of interest.

In addition to evaluating single layouts, the tool is set up to generate and evaluate multiple alternative layouts. These populations of layouts are generated using Particle Swarm

Optimization (PSO) and the preprocessing algorithm described in the previous section. After a significant number of iterations, the resulting best layouts are visualized and recorded; and the code can be rerun with a different population of initial layouts to better explore the design space and search for other minima.

The following two chapters describe the implementation, strengths and weaknesses of the methodology described in Chapter 3 through demonstration of example layouts. Chapter 4 focuses on verification of the evaluation method for single layouts. Chapter 5 addresses implementation of the PSO algorithm described in Section3.6 and provides comments on the limitations of this method.

CHAPTER 4: EVALUATION PROCESS VERIFICATION

This chapter demonstrates the use of the habitat interior layout evaluation method described in Chapter 3 to evaluate a sample layout to verify that the method meets the goals set forth in Table 6. This chapter first describes the setup of a habitat interior layout design problem including capture of designer preferences and constraints. Then, the automated evaluation criteria calculation methods and constraints are used to quantify the habitat interior layout objective function described in Equation 1 and multiple layouts are compared for the assumed designer preferences. This chapter concludes with comments about the appropriateness of evaluation criteria calculations followed by comments describing the verification of the results and the evaluation process as a whole. Once again, it should be noted that this verification example was presented in Simon & Wilhite, 2013 and Simon, Bobskill, & Wilhite 2012, and large portions of results/text in this chapter are pulled from these references.

4.1 Example Problem: 180 Day Cis-lunar Habitat [Simon & Wilhite, 2013]

In order to demonstrate the habitat layout evaluation method, the cislunar habitat design problem introduced in Section 3.1 is used through the remainder of this dissertation. As previously mentioned, this habitat was chosen over the Scenario 12.0 Pressurized Core Module (PCM) for the verification example due a few factors. First, the two-dimensional PCM layout and the lack of PCM hardware, geometry, interfaces, and etc. data made it difficult to perform a complete layout. Additionally, there is substantial benefit in assessing the more politically relevant and microgravity-specific cislunar habitat, particularly for application to orbital Mars missions. The Scenario 12.0 PCM development process and timeline are used as points of comparison for the performance of the habitat interior layout evaluation method application to the cislunar habitat problem in Chapters 4 and 5. The following section starts with a description of the initial cislunar habitat design problem, followed by the explanation of the methods used to evaluate a few interior layouts.

Prior to sending humans on long-duration, crewed missions to Mars, several capabilities will be required to ensure that humans and spacecraft will be safe and productive/functional for long periods in deep space with little abort or resupply and communications delay [Simon, Wald, Howe, & Toups, 2015; Williams-Byrd, Arney, Hay, Simon, Rodgers, & Antol, 2015]. NASA is investigating the potential for a 180-day habitat placed in cis-lunar space to serve as a test platform for maturing systems and demonstrating technologies and operations which are incompatible with the International Space Station. In order to enable such a habitat design, an interior layout describing how all of the required functions can fit in the limited volume of this facility has been proposed. In order to demonstrate the habitat interior layout evaluation method and drive out necessary process improvements, the following design problem statement was created.

> *Evaluate the layout performance of a cis-lunar habitat designed to sustain four crew for 180 days in deep space in combination with an entry capsule. Assume the spacecraft is 4.5 meters in diameter and 6 meters long with one hatch on an endcap. Assume a pre-defined set of International Space Station rack-based hardware with standard anthropometric use envelopes, which is to be packaged within this habitat while maintaining a central translation path corridor.*

The topology of the notional baseline layout to be evaluated is shown in Figure 35. The positions of each of the subsystems are indicated by the rows which correspond to the standard wall, ceiling, and floor rack locations. The functions shown in this module (long duration accommodations such as crew quarters, medical, hygiene and galley; and closed loop life support) are focused on increasing crewed duration while functions in the notional attached module (entry capsule) are focused on increased EVA and science. Geometry and functional information was provided for each rack, including the geometry of anthropometric envelopes reserved for interacting with the hardware. Each of the objects was represented by a simplified rack geometry, which is a simplification that avoids concave geometry modeling. This geometry modeling is a first order approximation of a more complicated geometry consistent with conceptual design detail, but does limit the appearance of cavities which are described in Figure 25. The rationale behind this particular layout is to separate private/quiet and public/noisy spaces while collocating line runs and function stowage. Additionally, implementing a rack-based layout automatically preserves the translation path by forcing interior rack geometries to the habitat walls, which ensures that volume parameters such as habitable volume, spatial vista, and unusable volume perform moderately well. The evaluation criteria calculation results in the next section will be used to verify this rationale.

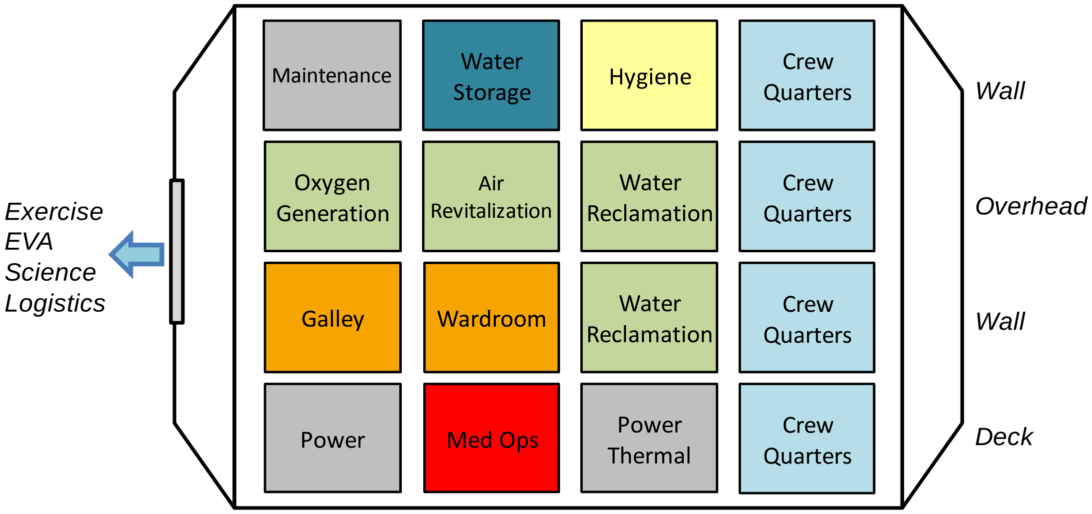


Figure 35: Notional Layout of Cis-Lunar Habitat Concept

The Initial Layout Generation Process from Figure 12 is performed first to define the hardware and functional information necessary for the evaluation. The design problem statement above specifies the design requirements, hardware, and other inputs described in Table 13: These are summarized in Table 18 and the tables in Appendix C. The hardware listed in this table were pre-specified for the cis-lunar habitat example, but could have been determined via functional decomposition from references mentioned in Chapter 3. The geometry of the hardware racks used in this example are similar to the geometry shown in Figure 14 (12 vertices, 14 faces), but with quadrilateral faces. The mapping of functions/tasks to these pieces of hardware is provided in Table 19; and the line run requirements, hardware masses, volumes, categorization as private space, and ratings of prioritized placement based upon high frequency/duration of use are provided in Table 20 as inputs to the Interior Layout Evaluation Process described in Figure 13. Additionally, more information on the subsystems used in this example problem is provided in Appendix C.

Table 18: Requirements, Hardware, and Inputs for Cis-lunar Habitat Layout Design Problem

Category	Specifics
Number of Crew	4 crew
Duration	180 days
Destination	Cis-lunar space
Gravity Orientation	Microgravity
Objectives	Extension of human duration/habitability
Launch Vehicle	Unspecified (diameter less than 5 m implies flexibility of NASA or commercial launch vehicle)
Required Hardware	4 Crew Quarters, Galley, Wardroom, Hygiene, Medical, Life Support (Air Revitalization, O2 Generation, Water Reclamation, Water storage), Power Thermal, Maintenance, EVA, Science, Logistics, Exercise
Geometric Features	Central translation path, 1 Axial end dome hatch, Pressure vessel (4.5 m diameter, 6 m long), Hardware modeled as International Standard Payload Racks (ISPRs)
Orientation	Horizontal like ISS

Table 19: Mapping of Cis-lunar Habitat Hardware to Function/Tasks

	Meal Preparation	Eating	Meal clean-up	Exercise	Medical Care	Full-body Cleansing	Hand/Face Cleansing	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation and Leisure	Small-group Recreation and Leisure	Dressing/Undressing	Clothing Maintenance	Meetings and Teleconferences	Planning and Scheduling	Subsystem Monitoring and Control	Pre/Post-EVA Operations	IVA Support of EVA Operations	Proximity Operations	General Space Station Housekeeping	ORU Maintenance and Repair	Logistics and Resupply	Payload Support	Life Sciences Experiments	Materials Processing Experiments
Oxygen Generation	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	0
Galley	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Power/Avionics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
ARS	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	0
Wardroom	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Medical	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Water Storage	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	0
Water Processor 1	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	0
WaterProcessor 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	0	0	0
Power/Thermal	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	0
Hygiene	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crew Quarters 1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Crew Quarters 2	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Crew Quarters 3	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Crew Quarters 4	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 20: Mapping of Hardware Information Feeding Evaluations

	Water line run required	Air line run required	Power line run required	Private space?	Mass, kg	Volume, m^3	Priority Placement rating
Oxygen Generation	1	1	1	0	843	1.57	0
Galley	1	0	1	0	412	1.57	1
Power/Avionics	0	0	1	0	1150	1.57	0
Maintenance	0	0	1	0	400	1.57	1
ARS	1	2	1	0	843	1.57	0
Wardroom	0	0	0	0	100	1.57	1
Medical	1	1	1	0	328	1.57	1
Water Storage	2	0	1	0	571	1.57	0
Water Processor 1	1	0	1	0	455	1.57	0
WaterProcessor 2	1	0	1	0	455	1.57	0
Power/Thermal	1	0	2	0	500	1.57	0
Hygiene	1	1	1	0	197	1.57	3
Crew Quarters 1	0	1	1	1	133	1.57	5
Crew Quarters 2	0	1	1	1	133	1.57	5
Crew Quarters 3	0	1	1	1	133	1.57	5
Crew Quarters 4	0	1	1	1	133	1.57	5

Before this evaluation begins, designer preferences and constraints are also defined. First, the evaluation criteria are weighted based upon the design problem context using the pairwise comparisons in the AHP method. Larry Toups, an architect and habitat design expert from NASA Johnson Space Center, performed pair-wise comparisons of the evaluation criteria according to the process described in Section 3.5.2. These pair-wise comparisons are used to create the prioritized list shown in Figure 36 where the weightings are expressed in percentages. Note that the weightings are different than those in Figure 34 because of the designer preference and the statement of the design problem. The criteria used to evaluate the cis-lunar habitat in this example are a reduced set making up the top 80% of the weightings. After removing the filtered criteria, the weightings shown in Figure 36 were renormalized to sum to unity.

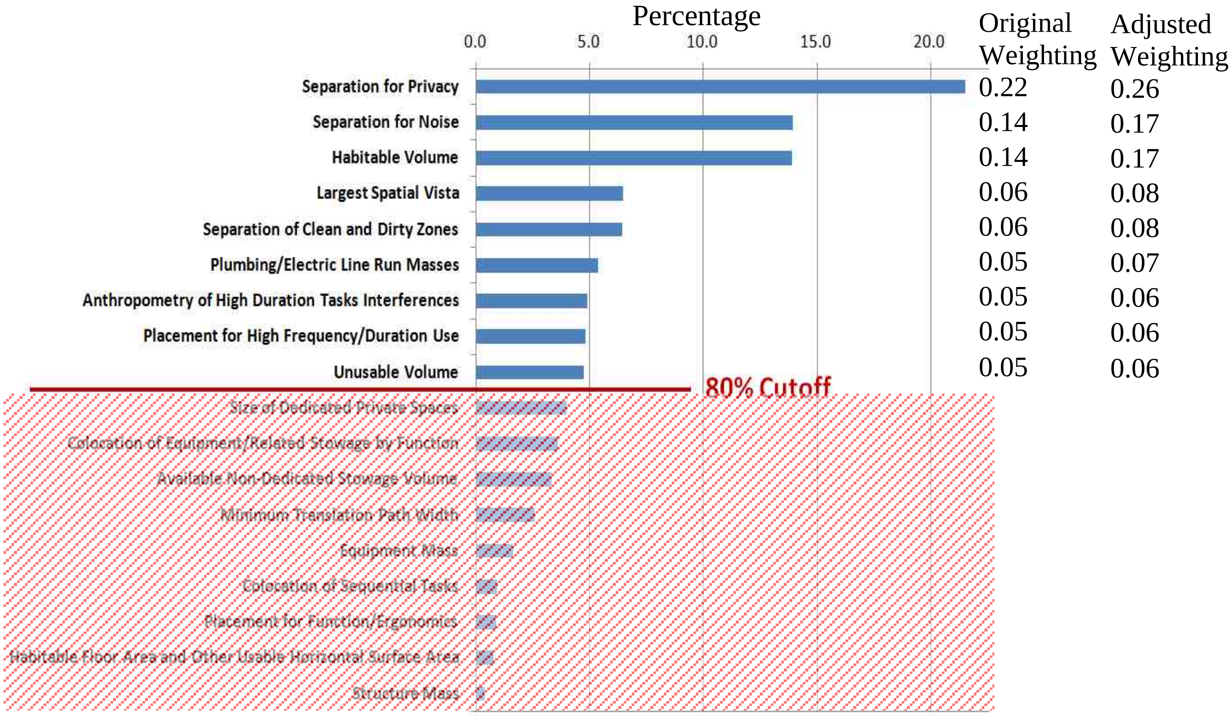


Figure 36: Prioritized List of Evaluation Criteria Weightings for the 180-day Cislunar Habitat Layout Problem

With the weightings defined, the utility functions are then defined for the reduced list of identified evaluation criteria. For this example, linear utility functions are assumed for all the criteria indicated in Table 21. Habitable volume ranges are set based upon human spaceflight design documents [NASA, 2010; Simon et al., 2011], but these ranges could be modified for this specific module layout if additional living volumes are assumed to be provided by connected modules. As the mission duration of the cislunar habitat is fairly short and the pressurized volume in the chosen pressure vessel is limited, the habitable volume utility function may be approximated as linear to reflect the general improvement of habitable volume utility over the range of feasible habitable volumes. The remaining criteria values ranges shown in Table 21 are determined based upon the range of values observed in a quick exploration of possible cislunar habitat layouts within the assumed pressure vessel geometry. For example, the largest spatial vista values range from 0 cubic meters to 3 cubic meters is an approximate range of the potential values possible when packaging the subsystems and logistics within the 4.5 meter diameter, 6 meter long habitat shell. Similarly, the non-dimensional separation criteria represent values achievable within this pressure vessel geometry. It should be noted that since these simplified linear utility functions were defined based upon these pressure shell dimensions and not based upon an absolute scale of designer-defined preference, only relative comparison of habitat layouts are enabled. For example, a value of 3 cubic meters for this example does not necessarily imply a desirable spatial vista. The use of data for absolute desirability determination is described further in the results section.

Table 21. Utility Function Values for Top 80% Criteria

Evaluation Criteria	Value for U=0	Value for U=1
Plumbing/Electric Line Run Masses	100 kg	0 kg
Habitable Volume	20 m3	100 m3
Unusable Volume	20 m3	0 m3
Largest Spatial Vista	0 m3	3 m3
Anthropometry of High Duration Tasks Interferences	30 interferences	0 interferences
Placement for High Frequency/Duration Use	0	1
Separation for Privacy	0	25000
Separation of Clean and Dirty Zones	0	900
Separation for Noise	0	28000

For simplicity, the constraints implemented in this example problem are hardware interferences (hardware-hardware and hardware-pressure vessel constraints) and clearance checks (“anthropometric envelope-hardware”, “hardware-translation path”, and “hardware-hatch clearance envelope”). Constraints are implemented based upon the number of interferences observed. For example, some multiple of the number of anthropometric reserved volume-hardware collisions is added to the unconstrained objective function to decrease desirability. These tests are implemented with the same ISA-GJK collision detection tests used for the evaluation criteria quantification methods.

4.2 Cislunar Habitat Interior Example Results

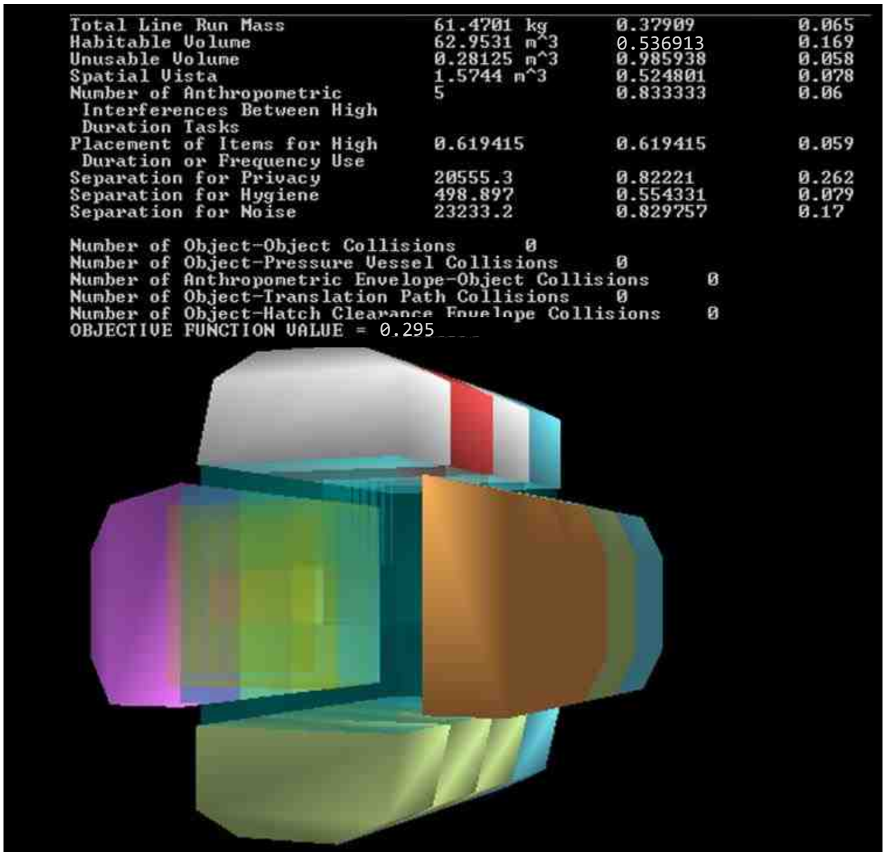
By performing each of the steps of the process illustrated in Figure 13, the habitat desirability objective function can be assembled as shown in Equation 6 and quantified for the baseline layout, A.

$$\begin{aligned}
Y_{\text{baseline}}(A) = 1 &- w_{\text{line runs}}U_{\text{line runs}}\left(X_{\text{line runs}}(A)\right) \\
&- w_{\text{habitable volume}}U_{\text{habitable volume}}\left(X_{\text{habitable volume}}(A)\right) \\
&- w_{\text{unusable volume}}U_{\text{unusable volume}}\left(X_{\text{unusable volume}}(A)\right) \\
&- w_{\text{largest spatial vista}}U_{\text{largest spatial vista}}\left(X_{\text{largest spatial vista}}(A)\right) \\
&- w_{\text{high-duration task interferences}}U_{\text{high-duration task interferences}}\left(X_{\text{high-duration task interferences}}(A)\right) \\
&- w_{\text{placement for high frequency/duration}}U_{\text{placement for high frequency/duration}}\left(X_{\text{placement for high frequency/duration}}(A)\right) \\
&- w_{\text{separation for privacy}}U_{\text{separation for privacy}}\left(X_{\text{separation for privacy}}(A)\right) \\
&- w_{\text{separation of clean/dirty zones}}U_{\text{separation of clean/dirty zones}}\left(X_{\text{separation of clean/dirty zones}}(A)\right) \\
&- w_{\text{separation for noise}}U_{\text{separation for noise}}\left(X_{\text{separation for noise}}(A)\right) \\
&+ P_{\text{object-object collisions}}(A) + P_{\text{object-pressure vessel collisions}}(A) + P_{\text{anthro envelope-object collisions}}(A) \\
&+ P_{\text{object-translation patht collisions}}(A) + P_{\text{object-hatch collisions}}(A) \qquad (6)
\end{aligned}$$

This objective function equation does not include screened items which are of lesser importance to the designer and utilizes the utility functions and adjusted weightings described in Figure 36 and Table 21. It should also be repeated that since the sum of the of the w*U(X(A)) terms sum to 1 at maximum utility, minimum values of the aggregate objective function Y(A) are preferred with overall values between 0 and 1 deemed feasible (free from constraint violations).

Using the software implementation of the automated evaluation criteria calculation methods described in Chapter 3 and Appendix B, the evaluation criteria values (X_i) for the baseline layout were automatically measured from the baseline layout geometry (as defined by the hardware geometry, location matrices, and orientation matrices). This layout is shown in Figure 37, and calculated evaluation criteria values (X_i) are shown in

Table 22 along with the associated utility values ($U_i(X_i)$), the evaluation criteria weightings (w_i) collected from the designer, and the number/degree of constraint violations (which feeds the penalty function calculations, P_j).



```
Total Line Run Mass            61.4701 kg      0.37909          0.065
Habitable Volume               62.9531 m^3     0.536913         0.169
Unusable Volume                0.28125 m^3     0.985938         0.058
Spatial Vista                  1.5744 m^3      0.524801         0.078
Number of Anthropometric       5               0.833333         0.06
 Interferences Between High
 Duration Tasks
Placement of Items for High    0.619415        0.619415         0.059
 Duration or Frequency Use
Separation for Privacy         20555.3         0.82221          0.262
Separation for Hygiene         498.897         0.554331         0.079
Separation for Noise           23233.2         0.829757         0.17

Number of Object-Object Collisions      0
Number of Object-Pressure Vessel Collisions     0
Number of Anthropometric Envelope-Object Collisions     0
Number of Object-Translation Path Collisions    0
Number of Object-Hatch Clearance Envelope Collisions    0
OBJECTIVE FUNCTION VALUE = 0.295
```

Figure 37: OpenGL Render of Cis-Lunar Habitat Layout Geometry

Table 22. Baseline Layout Objective Function Calculation

Evaluation Criteria	**Measured Value**	**Utility**	**Weightings**
Separation for Privacy	20555	0.82	0.26
Separation for Noise	23233	0.83	0.17
Habitable Volume	63.0 m^3	0.54	0.17
Spatial Vista	1.57m^3	0.52	0.08
Separation of Clean and Dirty Spaces	498.9	0.55	0.08
Total Line Run Mass	61.5 kg	0.38	0.07
Anthropometric Interferences between High Duration Tasks	5	0.83	0.06
Placement of Items for High Duration /Frequency Use	0.62	0.62	0.06
Unusable Volume	0.28 m^3	0.99	0.06
Constraints	**Measured Value**		
Number of Object-Object Collisions	0		
Number of Object-Pressure Vessel Collisions	0		
Number of Anthropometric Envelope-Object Collisions	0		
Number of Object-Translation Path Collisions	0		
Number of Object-Hatch Clearance Envelope Collisions	0		
OBJECTIVE FUNCTION VALUE	**0.30**		

Assuming the utility ranges are appropriate, the resultant utilities indicate that all evaluation criteria perform moderately well except line run mass, spatial vista, and separation of clean and dirty tasks. Inspection of the individual evaluation criteria values and comparison to hand calculated results verify that the automated evaluation criteria calculation methods are performing correctly. Additionally, inspection of the associated utility values indicate that the layout rationale described in Section 4.1 is achieving some of its goals, such as minimizing unusable volume and providing good separation for privacy and noise. Furthermore, the aggregate desirability value of 0.30 calculated using Equation 6 shows that this layout performs moderately well (minimum values are preferred).

However, the evaluation criteria utility function ranges defined in Table 21 were chosen based upon the ranges of possible values observed in the design space exploration of the assumed pressure vessel geometry. As a result, few conclusions can be drawn about whether the overall performance of the layout is acceptable on an absolute scale or not *for this design problem*. The determination of desirability on an absolute scale would require value ranges set from standards or human system design heuristics. Still, this example does show that utilizing the described evaluation method to compare multiple layouts (with the same set of assumptions and designer preferences) does allow for the determination of a relative desirability of the layouts, which can be used to guide iterations towards an optimal layout solution for the given design problem.

To demonstrate the ability to compare layout alternatives, an alternative layout shown in Figure 38 is created by exchanging the rack based locations of a few subsystems. This layout was designed to perform better on line run mass and anthropometric interference criteria at the expense of separation/colocation criteria. It is also anticipated to be a less favorable layout as the separation/colocation criteria weightings are relatively high. Table 23 and Table 24 show that these expectations proved to be true. This layout performs better on line run mass and anthropometric interferences due to the movement of the water storage, but at the expense of the separation-colocation criteria and placement for high duration/frequency of use. Because the separation-colocation criteria have relatively high weightings, the overall utility of Layout 2 is significantly decreased and the aggregate value of this layout decreases.

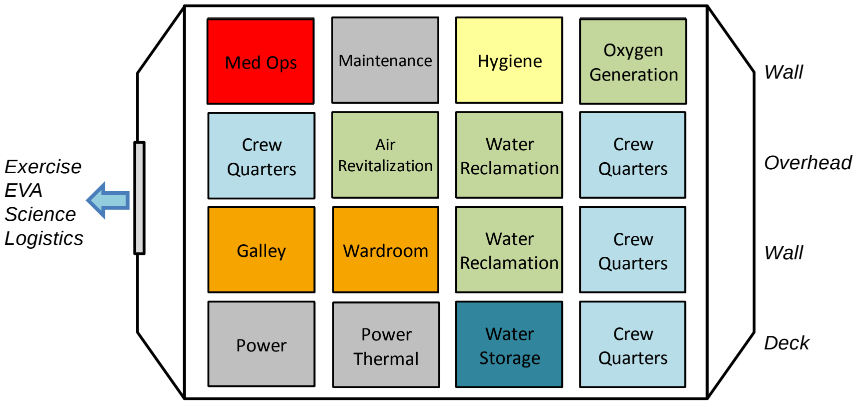


Figure 38: Alternate Layout of Cis-Lunar Habitat

Table 23: Alternative Layout Objective Function Calculation

Evaluation Criteria	**Measured Value**	**Utility**	**Weightings**
Separation for Privacy	13431	0.54	0.26
Separation for Noise	14351	0.51	0.17
Habitable Volume	63.0 m^3	0.54	0.17
Spatial Vista	1.57m^3	0.52	0.08
Separation of Clean and Dirty Spaces	313	0.35	0.08
Total Line Run Mass	44.6 kg	0.55	0.07
Anthropometric Interferences between High Duration Tasks	3	0.9	0.06
Placement of Items for High Duration /Frequency Use	0.51	0.51	0.06
Unusable Volume	0.31 m^3	0.98	0.06
Constraints	**Measured Value**		
Number of Object-Object Collisions	0		
Number of Object-Pressure Vessel Collisions	0		
Number of Anthropometric Envelope-Object Collisions	0		
Number of Object-Translation Path Collisions	0		
Number of Object-Hatch Clearance Envelope Collisions	0		
OBJECTIVE FUNCTION VALUE	**0.43**		

Table 24. Comparison of Two Evaluations for Cis-lunar Habitat Layouts (in criteria weighting order)

Evaluation Criteria	**Layout 1 Utility**	**Layout 2 Utility**
Separation for Privacy	0.82	**0.54**
Separation for Noise	0.83	**0.51**
Habitable Volume	0.54	0.54
Spatial Vista	0.52	0.52
Separation of Clean and Dirty Spaces	0.55	**0.35**
Total Line Run Mass	0.38	**0.55**
Anthropometric Interferences between High Duration Tasks	0.83	**0.9**
Placement of Items for High Duration /Frequency Use	0.62	**0.51**
Unusable Volume	0.99	0.98
OBJECTIVE FUNCTION VALUE	**0.30**	**0.43**

Finally, the timeframe for this evaluation should be mentioned. This evaluation was performed using the software implementation of the evaluation method as described in Section 3.6. Assembling the inputs, which includes collecting designer preferences and generating the initial layout, comprised the majority of the evaluation time. Collecting weightings and utilities took about two hours. Setting up the hardware geometry and initial layout information took an additional hour. Performing the evaluation of the baseline and alternate layouts by calculating the objective functions, checking constraints, and calculating Equation 6 took seconds. In comparison, the Scenario 12.0 PCM described in Chapter 3 and Howe & Sherwood, 2009 took several weeks to design and evaluate one to two layouts with a team of 10-20 people discussing the complex, interacting layout factors. Had this method and associated tool been available during that design effort, it could have tracked those conflicting objectives allowing for increased information facilitating faster and more comprehensive layout designs. Thus, the fast evaluation capability desired in Table 6 has been demonstrated here. It is possible to use this method and tool without any layout generation automation to investigate the design space using evaluation results as feedback to address particular design issues while tracking their impacts on other aspects of desirability.

4.3 Discussion of Evaluation Process Results

While Section 4.2 demonstrated that fast, quantifiable habitat layout evaluations capturing designer preferences and a comprehensive set of evaluation criteria are enabled by the methodology set forth in this thesis, there are several details about the method's implementation which must be discussed to address the performance and completeness of this evaluation. This section describes important factors which must be considered to ensure that evaluations performed are accurate, fast, and complete.

First, the accuracy and speed of evaluation criteria and constraint calculations are greatly affected by the number of test points used for numerical tests and the number of allowable hardware locations and orientations for geometry clearance tests. Increasing the number of test points (i.e., decreasing the Cartesian grid spacing to increase the number of test points) simultaneously yields more accurate estimates of evaluation criteria and longer calculation times. Additionally, as shown in the sample habitable volume calculations in Figure 39 and Figure 40, the relationship between the spacing of the grid and the fundamental dimensions of the hardware can cause complex, modal variances from the actual value, particularly when the hardware and grids are misaligned. A grid spacing of 0.05 m is anticipated to provide an appropriate balance between speed and accuracy for layouts with numerous or more complex objects. For the current example problem, centimeter accuracy was not deemed to be time prohibitive. Alternative approaches including use of an isometric grid are discussed in Simon, Bobskill, & Wilhite 2012.

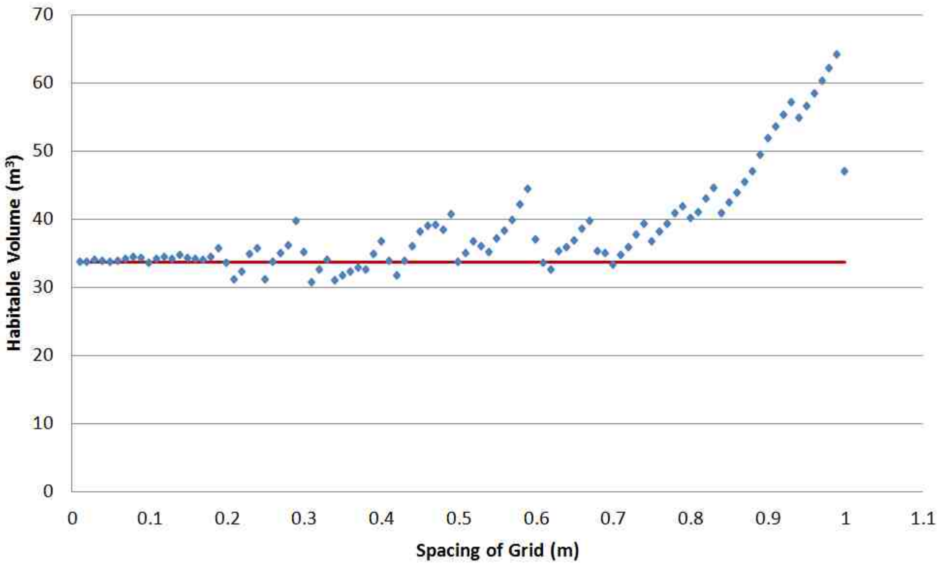


Figure 39: Habitable Volume Calculations using Various Grid Spacing for Scenario 12.0 PCM [Simon, Bobskill, & Wilhite 2012]

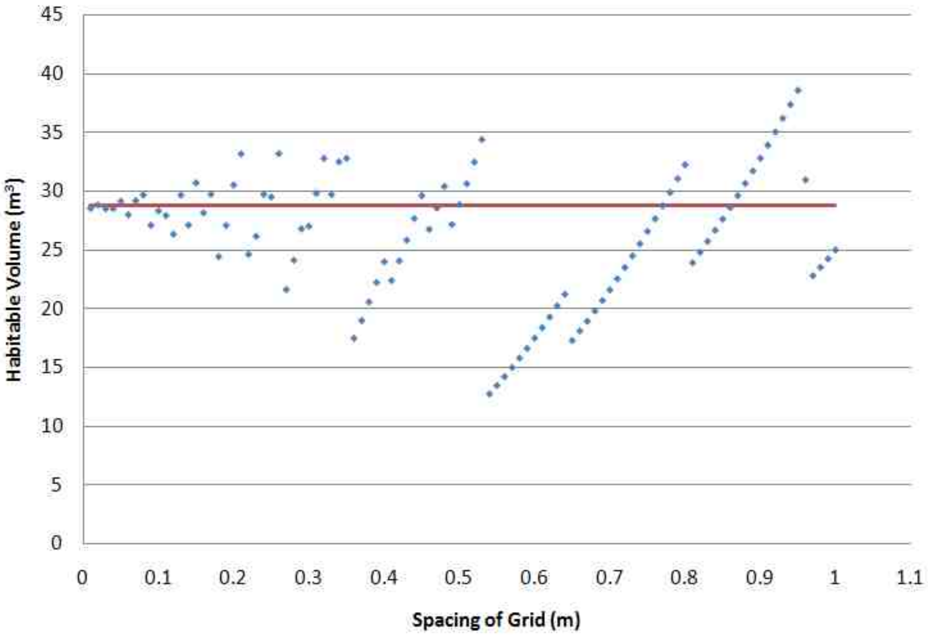


Figure 40. Habitable Volume Calculations using Varying Grid Spacing for ISS Destiny Module [Simon, Bobskill, & Wilhite 2012]

A second consideration is the simplifying set of assumptions used to facilitate fast layout evaluation which may or may not need to be corrected on future instantiations of this method. The current layout evaluation method implementation makes the following simplifying assumptions, each of which are commented on in the following list:

- **Fixed, user-specified translation paths** are used to ensure that there exist good paths between all hatches and every functional area of the habitat. This affects calculation of clearance constraints and the minimum translation path width constraint (which is met a priori in these layouts). Ideally, a path planning algorithm such as A* (as discussed in Section 3.3.2) would be used to determine a clear translation patch between hatches and yield more flexible interpretations of an adequate translation path, but the implementation of such an algorithm is complex and left to future design iterations.
- **Simplified separation/colocation distances** are assumed to be Euclidean distances to simplify the current analysis. As mentioned before in Section 3.3.3, most separation/colocation evaluation criteria would rely on Manhattan distance, or would

apply distance penalties/bonuses for use of a partition or door and additional bonuses for occlusion of line of sight. Future instantiations of this method will apply these penalties/bonuses for these design features.

- **Limited position/orientation checks** in volume characterization criteria are used to simplify/speed volume determination. These limited directions and orientations can potentially mischaracterize large portions of the interior volume, particularly for layouts where interior hardware are packaged in non-orthogonal orientations. Simon, Bobskill, & Wilhite 2012 demonstrates that for layouts with orthogonal hardware which are aligned with the slices taken by the Marching Grid Method, the accuracy of the estimates are adequate for layout comparison. In future instantiations of this method which implement other evaluation time saving methods and measures, additional orientations may be considered.

Finally, some final comments are made describing the completeness and realistic use of these evaluations. Based upon a review of the available literature, the evaluation criteria and constraints successfully capture the majority of the critical measures and concepts necessary to assess the desirability and acceptability of an interior layout. This can be demonstrated through the investigation of likely layout scenarios where a human designer would indicate an issue. For example, for objects placed randomly in a volume, it is likely that objects will be placed in the middle of aisles or open volumes far from the walls. Ideally, such hardware would require additional structural support, line runs, and more detailed translation paths for maintenance which might prevent a human designer from choosing such arbitrary placement. In this situation, the current criteria set would capture and penalize a layout containing a free floating object in the middle of an open volume through reduced volume criteria, increased structural mass, and increased line run mass. Furthermore, by implementing this preference through evaluation criteria instead of specific placement algorithms forcing objects along the walls, arbitrary restrictions on the available design space which would prevent potentially innovative layouts can be avoided.

Another situation which the current instantiation of the method would appear to be ill-equipped to handle is the placement of hardware preventing access to an area which would otherwise be deemed habitable. Without implementing the automated translation path determination algorithm and requiring access to a translation path as a Boolean test in the habitable volume calculation, this volume would be inaccurately characterized. However, implementing these refinements would enable the method presented in this thesis to correctly assess this layout as poor without manual intervention by a designer. Though there may be other situations where manual intervention by a designer seems necessary, creative applications of the methods described in this thesis are capable of correctly assessing most of these exceptions and will direct future improvements to the initial method presented here.

Still, there are two criteria which were identified that the current method chose not to implement: center of mass displacement and radiation protection due to layout arrangement. Center of mass displacement is simple to measure and was removed because it doesn’t inherently improve the desirability of layout. Instead of implementing this as a criterion, it was implemented as a constraint aimed at maintaining the center of mass within some acceptable range dictated by maneuvers such as planetary landing. Radiation protection is not as simple. Methods to measure this criterion are described in Simon et al. 2013b, and involve determining the mass of solid surrounding points within a habitat emphasizing uniformity in coverage. Implementation of this radiation assessment method into the layout evaluation method is planned as a future improvement. This and many other future improvements are discussed further in Chapter 6 under future work.

4.4 Verification

Based upon the results discussed in the Sections 4.2 and 4.3, the proposed systems engineering-based evaluation method described in this thesis greatly improves upon the currently available habitat interior layout methodologies by enabling fast evaluations capturing engineering and human factors concerns, designer preferences and important constraints; proving that the hypothesized solution to Primary Research Question is feasible. The proposed, comprehensive list of quantifiable evaluation criteria adequately captures the most salient habitat design concerns while enabling automated, quantitative calculation of the desirability of interior layout alternatives. The list of design constraints ensure that evaluated layouts are feasible for manufacturing and human spaceflight standards while the list of criteria weightings and customized utility functions ensure that the most influential criteria drive the overall value of any layout alternative. As a result of the specific implementation of these features, the resulting aggregate objective function closely aligns with designer rationale and has been shown to enable comparison between multiple layouts using a consistent designer value model.

At the same time, this evaluation framework has been specifically developed to maintain flexibility to identify innovative layout solutions outside of the traditional habitat interior design features which have been implemented on previous habitats, such as rack-based or wall based layouts. Furthermore, this evaluation framework is capable of adding any additional custom criteria using similar methods described in Chapter 3 to expand its ability to capture specific designer concerns and flexibly adapt to a range of habitat interior layout problems. In short, the proposed evaluation method has successfully addressed all but the last research question concerning automation while identifying possible areas for improvement.

This advancement in and of itself is a significant contribution to the field. For example, using the understanding of the established criteria weightings and objective function from the cislunar habitat example discussed in Section 4.2, the designer can manually adapt the baseline layout to create a third point of comparison layout. Since the top 4 criteria all respond well to increased volume, a larger volume habitat can greatly increase the relative objective function value. In order to maintain launch vehicle constraints, this could mean adding some length to the end of the habitat to better accommodate functional separations and desired interior volume. Furthermore, moving water processing and hygiene away from crew quarters and placing relatively quiet functions of logistics and maintenance adjacent to crew quarters would provide better functional accommodation of privacy and noise separations. A potential layout implementing these changes is shown in Figure 41. The designer rationale just described in this third layout example are a result of the transparency built into the structured evaluation framework, which can be used to aid early interior layout designs and inform manual layout iteration. Chapter 5 will describe efforts to implement an automated, iterative layout design process leveraging this transparency and characterize challenges to automating space habitat interior layout design utilizing the same example covered in this chapter.

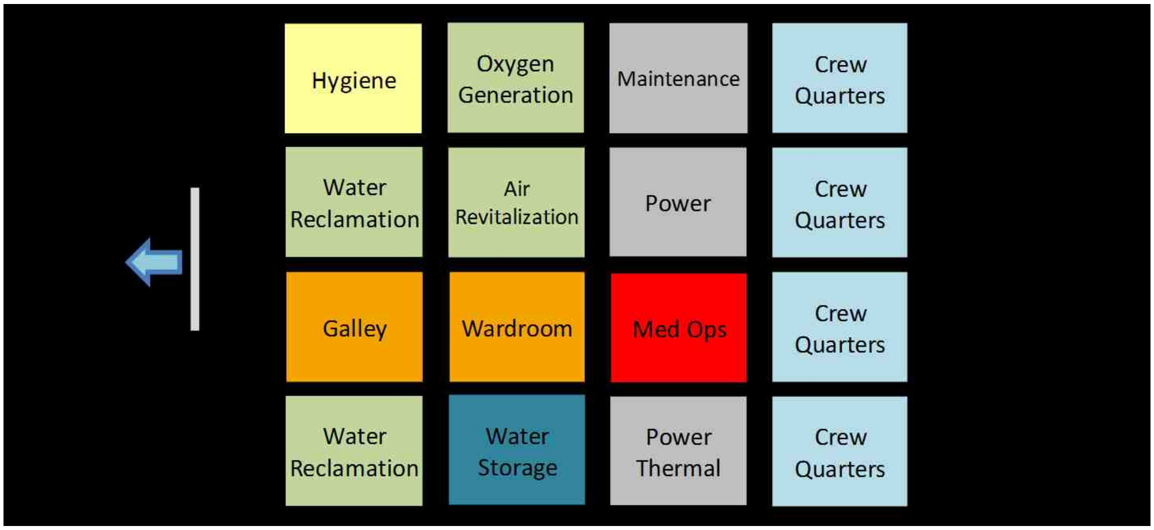


Figure 41: Manually Adjusted Next Layout Based upon Design Rationale from Objective Function Definition

CHAPTER 5: AUTOMATION OF LAYOUT DESIGN

This chapter utilizes the software implementation of the iterative layout evaluation method described in Chapter 3 to demonstrate the challenges of automating the development of desirable layout alternatives. In particular, the cislunar habitat example problem described in Chapter 4 is extended to allow for exploration of the layout design space and iterative improvement of layout concepts. This chapter first describes how the evaluation framework developed in Chapter 3 can be augmented to iteratively improve the habitat layout objective function using stochastic optimization and constraint implementation techniques. Then, the specific implementation of this method to improve cis-lunar habitat designs in an autonomous fashion is described, including the assumptions used to simplify the problem. Then resulting layouts and algorithm performance are discussed, including discussion of the challenges implementing the Particle Swarm Optimization algorithm and potential solutions applied to improve development of realistic layouts and/or improve convergence behavior. Finally, the effectiveness and limitations of the current implementation of the iterative improvement method are discussed, clarifying what enabling advancements have been made, identifying what continued work is required to fully realize automation of habitat interior layout generation, and describing what decisions can be informed by the current automation results.

5.1 Layout Design Automation

By assembling all of the components mentioned in Chapter 3 into the evaluation method illustrated in Figure 13 and demonstrated in Chapter 4, an automated layout evaluation capability is created which addresses the research questions in Chapter 1 and achieves the performance goals from Table 6. This layout evaluation methodology provides for a consistent basis of comparison between various layout alternatives and enables a quantitative evaluation of a single layout in seconds using automated calculation methods (not including initial collection of designer preferences and inputs which may take minutes to hours). What remains to be addressed is how this method enables automated, iterative layout improvement capable of finding layout concepts which are desirable according to the designer preferences. This sections describes an approach for automatically generating successive populations of layouts which are iteratively improved to identify those desirable solutions.

As described in Chapter 2, approaches in literature which automate layout design problems of similar complexity to the habitat interior layout design problem often apply stochastic optimization techniques to identify new layout alternatives for evaluation. The following method seeks to minimize the layout evaluation objective function (Equation 1) using Particle Swarm Optimization (PSO) to generate new layouts. In PSO, alternative concepts are treated as particles which move about the design space while tracking each particle's 'position' within the design space and its 'velocity', or movement direction and speed within the design space. Updates of the particle velocity are directed by two previous best positions: the position associated with the best objective function value achieved by that particle (personal best, pbest), and the position associated with the best objective function achieved by any particle (global best, gbest). The following steps and equations from Eberhart & Shi, 2001 guide the selection of 'positions' and 'velocities' for subsequent iterations. Variables from the habitat design problem from Equation 1 are substituted for the variables of the traditional PSO problem to place the problem in the context of habitat design. In particular, 'position' in the traditional PSO algorithm is replaced by a layout represented by the variable 'A'. This quantity is represented by a matrix containing the locations and orientations of all objects within a given layout.

1. Initialize a set of particles representing layouts, each with semi-random position/layout (A_i) and velocities (V_i)
2. Evaluate the objective function value for each layout, $Y(A_i)$ using Equation 1
3. Update pbest and gbest objective functions

$$IF \quad Y(A_{current}) < Y(A_{pbest}), \quad Y(A_{pbest}) = Y(A_{current}), \quad A_{pbest} = A_{current} \tag{2}$$

$$IF \quad Y(A_{current}) < Y(A_{gbest}), \quad Y(A_{gbest}) = Y(A_{current}), \quad A_{gbest} = A_{current} \tag{3}$$

4. Update velocity and position/layout based upon a combination of personal and global best targets

$$V_i = \omega V_i + \phi_{pbest} rand()\,(A_i - A_{pbest}) + \phi_{gbest} rand()\,(A_i - A_{gbest}) \tag{4}$$

$$A_i = A_i + V_i \tag{5}$$

where rand() is a random number between 0 and 1and ω, ϕ_{pbest}, and ϕ_{gbest} are constants referred to as tuning parameters which control the behavior of the PSO algorithm and are selected by the designer

5. Loop to step 2 and continue until desired layout is created

By implementing this algorithm, multiple layout concepts can be investigated, and subsequent iterations of these investigated layouts trend towards better values of the objective function. It should be noted that the intent of this thesis is to demonstrate that a stochastic optimization algorithm can be successfully applied, not to optimize the performance of any particular optimization algorithm through experimentation with tuning parameters. That said, there are several challenges to implementing this algorithm which are addressed in this thesis.

First, this method originally proposed the enforcement of constraints listed in Table 16 through penalty functions added to the evaluation objective function without a priori prevention of violated geometric constraints. However, preliminary investigation of the design space indicated that this approach works well for most constraints, but utilizing penalty functions exclusively for the non-overlap constraint requires careful refinement of optimization method tuning parameters (already described as out of scope) to enable good convergence. Alternate penalty function implementations are discussed in Section 5.3. For *a priori*, constraint violation prevention approaches, the following preprocessing method (dubbed the Simon-Arney

Preprocessing Algorithm) was proposed to provide some prevention of non-overlap constraint violations and improve convergence performance. This method has not been implemented, but is expected to facilitate convergence by limiting the evaluated solutions to only feasible solutions.

First, the PSO outputs a layout to be evaluated. Because of the high packing density of spacecraft interiors, this layout probably violates the non-overlap constraint with one or more overlapping objects which will result in a poor objective function value. This layout can be treated as a target (A_{target}), and an alternate layout close to the target layout which does not violate the non-overlap constraint ($A_{achieved}$) can be determined with the following algorithm.

1. Randomly generate a layout offset from A_{target} by a small amount and assign a velocity of moderate magnitude towards A_{target}
2. Check for the number of overlap constraint violations. If greater than 0, perform Step 3. If 0 then proceed to step 5.
3. For each pair of objects in the layout, if colliding, modify the components of the velocity along a line between the centers of the objects to create a reflection "pushing" the objects apart in an inelastic collision (i.e., apply a damping factor to the magnitude of the velocity)
4. Apply these velocity adjustments, move the object positions forward an iteration, and re check for collisions (i.e. perform steps 2-4)
5. Once all objects are deemed to be clear and stable, the resulting layout $A_{achieved}$ represents a close layout to the target which was achievable without constraint violation. Evaluate this layout using Equation 1 and continue with iteration using the PSO.

By implementing this algorithm, only layouts meeting the non-overlap constraints are evaluated, preventing the reliance on fine tuning of PSO tuning parameters. The key factor in successful implementation of this preprocessing algorithm is a reliable exit criterion to identify when no collisions are occurring and the resulting layout is somewhat stable. Several possible exit tests may be used, but two major ones should be investigated in future work to optimize runtime. They are the 1) “first available non-colliding” test (where the first non-colliding layout could be utilized as $A_{achieved}$) and the 2) “closest non-colliding (where a set number of iterations or an object velocity test can be used after many iterations of collision-based velocity updates to identify when object motion has settled on a non-colliding solution). The first available method is simpler requiring less iteration to find $A_{achieved}$ but it places a higher demand on the optimization as the first available non-colliding layout may be significantly different than A_{target}. Conversely, the closest non-colliding layout will closely resemble A_{target}, but will require more significant iteration and more complicated exit tests to find $A_{achieved}$. Other non-object-object constraints are still enforced using penalty functions on the objective function.

The second major challenge to PSO based layout improvement is convergence speed. The complexity of polyhedral objects being placed and the resolution of the grid in numerical volume estimation methods are the major speed limiters. These issues can be readily overcome through limiting details of interior objects, reducing grid size on numerical tests, better utilization of coherence in quantification methods, and multi-threading of independent calculations. Limiting details on interior objects and reduction of grid size for numerical tests are straightforward and are commented on in Chapter 4. Coherence (or previous iteration data) can be better leveraged in numerical estimation algorithms to speed estimates. For example, in the habitable volume estimation method, when testing for accessibility of a standing astronaut, a successful test automatically ensures that a number of points equal to the volume of an astronaut surrounding the test point are also accessible. If this information could be implemented into the algorithm, several tests in the Marching grid method could be eliminated at the expense of some additional memory to store the bounds of space already deemed accessible by previous tests. This improvement is left as future work. Finally, convergence can be accelerated by multi-threading or parallel processing independent calculations to make use of multiple processors on computing platforms. This is also left as future work and will be discussed in Chapter 6.

5.2 Automated Iterative Improvement of Cis-Lunar Habitat

In order to identify the potential issues and refine the automated layout improvement approach, an example problem was chosen. The following statement is the goal of this analysis: "determine whether an implementation of a stochastic optimization method can be developed which enables the automated, iterative improvement of habitat layout concepts resulting in an automated layout generation capability that can produce acceptable and favorable layout concepts". It was hypothesized that such a capability could be developed using a PSO or another stochastic optimization method such as genetic algorithms or simulated annealing. In this section, a PSO algorithm making use of the inertia parameter from Eberhart & Shi, 2001 is applied to the same cis-lunar habitat example utilized in Chapter 4 to investigate whether layout concepts identified by the algorithm are capable of automating early layout design.

The cis-lunar habitat example from the previous chapter focused on the evaluation of various layouts manually specified by a designer to understand and compare their relative performance. This problem can be extended by iterating upon an initial population of layouts to strategically investigate the design space, and eventually converge to a favorable layout using a PSO algorithm to specify subsequent layouts. Once again, it should be noted that this thesis seeks to prove that such an approach is feasible and will focus on proof of this feasibility, not optimization for streamlined performance or fast convergence. One possible proof of method feasibility is to demonstrate that an implementation that will converge to realistic layouts which have somewhat desirable objective function values. In order to demonstrate that this capability, the following simplifying assumptions are used for the cis-lunar example to reduce convergence time and make results more transparent. A fully generic implementation of this method is anticipated to perform similarly, albeit more slowly.

- Assume a fixed 1m x 1m translation path located along the axis of the habitat as shown in Figure 37. This will eventually be replaced by an automated translation path determination algorithm (the development of which is left to future work.)

- Assume that the orientation of racks are automatically adjusted in 90 degree increments based upon a radial quadrant they are located in to protect access to front faces. This purpose of this simplification is to limit the more exhaustive design space to those solutions more likely to perform well in the small radius pressure vessel. However, this limitation is likely to increase discontinuities in the design space and will be revisited later in this chapter.
- Similarly, orientations for numerical volume checks are also limited to 90 degree increments. Also, the grid spacing for the optimization run was set to 0.25 m. While, this only returns estimates within approximately 10% of the actual value, the speed increase for understanding convergence was deemed more important for this example.
- Initial layouts are randomly generated ensuring that the initial locations of the hardware are kept inside of the pressure vessel. This ensures that initial concepts do not violate the hardware-pressure vessel constraints to prevent extremely large objective function values for convergence performance.
- Constraints are implemented utilizing linear penalty functions based upon the number of violations. This allows violation of some constraints in the exploration of the design space [Szykman & Cagan, 1997]. Linear penalty functions allow some constraint violations to ensure the design space is fully explored. The slopes assumed are as follows
    - Hardware-hardware collision slope = 1/5
    - Hardware-pressure shell = 3/2
    - Hardware -anthropometric envelope = 1/20
    - Hardware-translation path = 1/5
    - Hardware-hatch clearance envelope = 1/5

  These slopes were qualitatively determined by inspection of the resulting best objective function values after several minutes of iteration, and do not represent an optimal setting. They do represent that packaging within the pressure shell is the most important constraint to aid overall algorithm convergence, followed by an equal preference between hardware-hardware, hardware-translation path, and hardware hatch clearance. Relatively low importance is placed upon hardware-anthropometric envelope constraints for this design example. These slopes should be optimized and can potentially be adjusted in future iterations of this method using a cooling schedule similar to that applied in simulated annealing to progressively firm up constraints as iterations progress, enabling early design space freedom. This is discussed more in the results later in this section.

With these assumptions defined, the PSO algorithm described in Section 5.1 can be executed for the cis-lunar habitat interior layout problem. This algorithm was run with the following PSO assumptions:

- PSO tuning parameters are set to $\omega = -0.002$, $\phi_{pbest} = 0.05$, $\phi_{gbest} = 2.7$. These were determined by experimentation and are not expected to optimize convergence times. The rationale for the current values reflect a focus on global best movement with moderate amounts of personal best and inertia to provide variability.
- Population size of 150, which is roughly three times the number of independent variables (3 dimensional positions of 16 objects = 48 independent variables).
- Maximum number of iterations was set to 200 to allow enough iterations to understand convergence behavior. In practice, the objective function values for the currently assumed penalty functions and tuning parameter values converges well before this number of iterations.

Initial results shown in Figure 42 and Figure 43 demonstrate that the objective function value is highly driven by the implementation of penalty function constraints. Since a worst possible layout may only have utilities totaling zero, objective function values greater than one (the acceptability threshold) occur when constraints are violated. In the cislunar habitat example results shown in Figure 42, the automated iterative values greater than one are caused by the highly dense interior which causes multiple constraint violations for every generated layout.

Essentially, this corresponds to a local minima in the design space where the PSO would require augmentation to escape. Furthermore, this minima is most likely caused by a poor combination of the fine balance between multiple factors influencing investigated layouts including: initial layout positions, initial layout velocities, penalty function implementation, and PSO tuning parameters.

If fully feasible layouts were chosen as the initial layouts, the velocities of particles in subsequent iterations would be more likely to also converge to feasible solutions. Alternatively, penalty functions must be implemented in a balanced manner to encourage good layouts. For example, if hardware-hardware or hardware-translation path penalties are too steep with respect to hardware-pressure vessel penalty function slopes, a local minima will exist with hardware outside the pressure vessel. Furthermore, the implementation of penalty functions counting the number of collisions does not distinguish for the severity of these collisions. For example, a layout with 20 barely interfering overlaps would be harshly penalized, whereas a layout with three collocated, totally overlapping subsystems would be preferred. Refinement of the penalty function definition utilizing penetration depth calculations should be investigated in future versions of the method. Finally, PSO tuning parameters are poorly chosen, the convergence performance can be slow and prone to settle in local minima. The next section describes these challenges further and proposes solutions to the local minima in parts of the design space where constraints are violated.

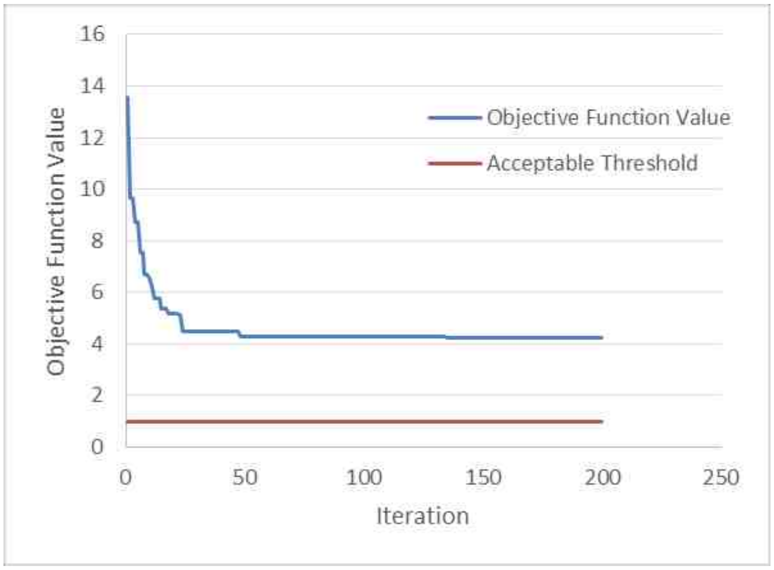


Figure 42: Baseline PSO Convergence Results for Cis-Lunar Habitat Design Example

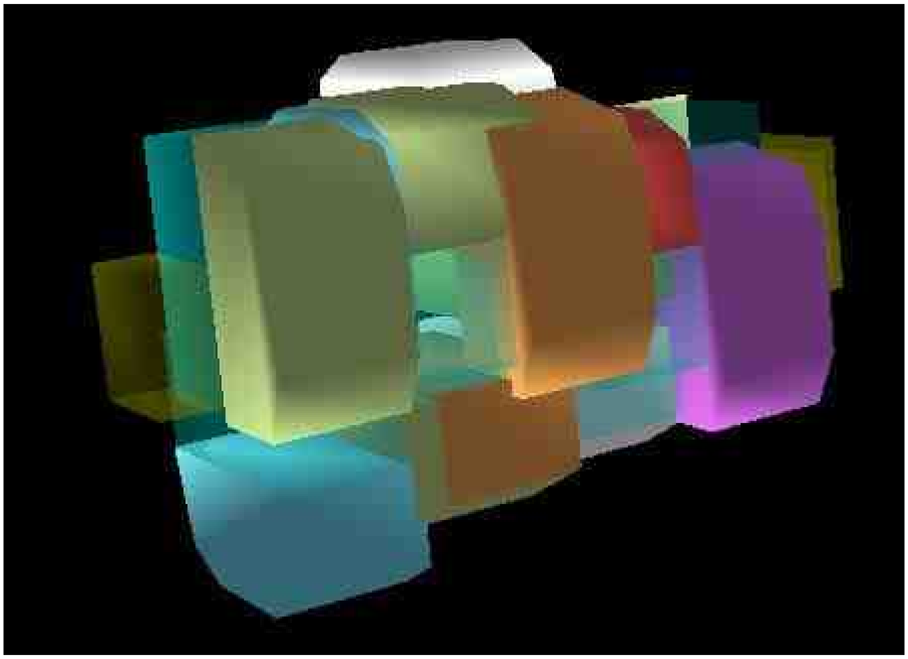


Figure 43: Resultant Cis-Lunar Habitat Layout for Baseline PSO Run

5.3 Design Space Exploration Results and Improvements

As demonstrated by the example from the previous section, there are several challenges to implementing a PSO-based automation method which must be addressed by some application of various techniques or fine tuning. These techniques must create the appropriate balance between constraint enforcement and freedom to explore the design space, while also preventing stagnation in multi-modal or discontinuous design spaces. Some of these methods are summarized in this section and Table 25.

Table 25: Techniques for Improving PSO Automating Layout Design

Technique	Description
Penalty Function Implementation	Balancing penalty function slopes with objective function values to enable slow convergence to feasible/desirable layouts.
Feasible Initial Layouts	Ensure that initial layouts are feasible layouts to seed the PSO with favorable concepts to direct later.
Constraint Violation Prevention (e.g., Simon-Arney Preprocessing Convergence Algorithm)	Prevent evaluation of layouts which violate harder feasibility constraints to ensure PSO only favorable concepts.
Discretization of Design Space to Combinatorial Optimization Problem	Like Constraint Violation Prevention, evaluates only feasible concepts, but further leverages rack structures to a small subset of possible positions.
Alternate Stochastic Optimization Method	Alternate stochastic methods such as simulated annealing or hybrid PSO algorithms better suited to deal with local minima, and accelerate convergence.

As mentioned in the previous section penalty function adjustments can be used to ensure that constraints are being applied equitably and that they are not steep enough to cause the design space to be discontinuous. The choice to use linear penalty functions in the previous section is not the only option, but was hypothesized to be less severe than a quadratic or higher power functions. The major issue with searching for the right balance of penalty functions is that the penalty function slopes are very design problem and geometry specific. For example, a design problem focused on packaging ISS racks within a tight launch vehicle envelope may require application of a steep hardware-translation path constraints whereas a more open layout concept without a specific launch platform can be more open in its search. Furthermore, even if augmented penalty function concepts are allowed to iterate, convergence behavior is slow (on the order of hours to days) without some additional logic to escape local minima.

In addition to slope adjustment, the fundamental formulation of the penalty functions in the objective function may need to be changed to enable good convergence performance. For example, use of additive linear penalty functions does allow for more flexible exploration of the design space, but does so at the cost of convergence performance. The additive nature of the penalty functions allows the stochastic optimization algorithm to choose layout alternatives where penalty functions are purposefully violated and their violation artificially creates favorable, but unrealizable utilities. A dynamic approach should be able to correct this phenomenon. The slope of the penalty functions could start fairly shallow to allow for traversal through the design space in early iterations, and then the slope could increase during later iterations to force feasibility and prevent the artificial utilities and constraint violations. This can either be implemented within the evolution of a single population of layouts or over multiple populations to identify advantageous penalty function slopes.

Feasible initial layouts can be used to speed convergence. For example, the rack based layouts presented in Chapter 4 could be included in the population of initial layouts to provide a well performing global target that can influence the layout population. Furthermore, implementing constraint violation prevention approach as described in Table 25, could further reduce convergence time by ensuring all layouts are feasible before evaluation. Several methods of constraint satisfaction can be implemented including ordered placement and discretization of the possible design space. These methods can be applied to ensure satisfaction of multiple criteria or can focus on the most critical ones addressing feasibility.

One such method was identified in the early development of the software implementation of the evaluation method. A program translating objects and reacting to collisions with elastic or inelastic collisions was developed to test out various collision detection algorithms. When this program detected a collision, it added separating increments to the component of the velocity in the direction of the vector formed between the objects positions away from the object encountered. This simple physics model can be implemented into a preprocessing algorithm which uses damped, inelastic collision handling to shift objects in infeasible layouts to nearby feasible layouts where no collisions occur. This Simon-Arney Preprocessing Convergence Algorithm first generates a layout slightly displaced from the PSO targeted layout with an initial velocity towards the PSO target layout. It then utilizes an inner loop which checks the hardware-hardware constraint (i.e." non-overlap" constraint) and applies simple inelastic collisions to "push" the objects apart until a layout is created which has no hardware-hardware constraint violations. This 'feasible' layout is then used as the new PSO target and is evaluated. In summary, this preprocessing algorithm would improve convergence behavior by dealing with hardware-hardware constraints a priori. There are several possible augmentations to this approach utilizing more refined logical operators and collision bounding volumes to speed the inner loop convergence, but these are left as forward work on a promising method for automated layout design.

The last constraint prevention method utilizes a discretized design space to limit possible locations of hardware to a much reduced set of locations known to not overlap. For example, the cis-lunar habitat problem implements an International Space Station (ISS) -derived rack structure with a common rack size. These racks could actually be assigned numbers and a combinatorial optimization approach could be used to quickly find an optimum, rack-based layout. The main reason this method is not applied is that it greatly restricts the available layout design space to a layout form. While this solves the cis-lunar problem easily, it makes the generic automation of habitat interior layout design unrealistic.

Finally, an alternate PSO algorithm or an alternate stochastic optimization method altogether could be implemented to deal with the local minima issue better than the current PSO algorithm. That is not to say that the current algorithm is incapable of identifying desirable and feasible layouts, but careful tuning is required for every design applications. Methods such as simulated annealing could more robustly address the local minima utilizing a cooling schedule or some other means of minima-escaping variation factor. Investigation of the other algorithms is left as forward work for future research.

5.4 Automation Effectiveness, Limitations, and Value

In summary, this chapter presented multiple methods for enabling automated improvement of habitat interior layouts which enable exploration of the habitat interior layout design space at conceptual design. In particular, these methods allow for much faster iteration of the designs that the manual process utilized by the Scenario 12.0 PCM designers, who iterated their initial layout over weeks to months using currently available methods. Further refinement of these methods and variations of them can be implemented to characterize the layout design space more effectively than these manual methods and increase designer knowledge of how the complex interactions between constraints and objective function values take place.

Even though the proposed method in Section 5.1 did not converge to physically realizable solutions, it is still considered feasible with the right application of PSO tuning parameters and more realistic constraint implementation. In particular, the choice to automatically adjust the orientation of the hardware based upon the radial position was observed to cause the design space to have additional modality and discontinuities which complicated the search for feasible solutions. Additionally, the replacement of number of collisions with a quantity like ‘total overlapping volume’ is expected to improve convergence to feasible layouts.

A combination of penalty function and PSO tuning with the implementation of a feasible layout seeding of the population is anticipated to speed convergence moderately, while implementation of the Simon-Arney Preprocessing Convergence Algorithm held in reserve to greatly speed convergence and generate better solutions at the expense of design freedom. In short, viability of the use of a stochastic optimization method to automate the design of interior layouts is suspected, but additional research is necessary to validate the hypothesis from Research Question 5.

Finally, implementation of the identified necessary improvements to fully enable layout automation is expected to enable the following analyses to inform designers and, ultimately, decision makers. If desirable objective function values can be obtained, then a family of promising layouts will be provided to designers to use in conceptual design phases and iterate the selection of equipment and internal geometry much earlier than was previously possible. If no desirable objective function is calculated for a given set of pressure vessel geometry and/or hardware, then trades and analyses results can be provided to habitat designers to either increase the size of the pressure vessel to better accommodate existing hardware, or to inform the selection of certain subsystems or accommodations which should perhaps be moved to another module to increase interior space or better accommodate functional desires. These level of analyses enable a more informed selection of the pressure vessel geometry and hardware complement at conceptual design, which may lead to less mass/cost growth due to changes in later design phases.

It should also be mentioned that there is inherent value in the current instantiation of the habitat interior layout evaluation method, even though it did not converge to feasible solutions in its current implementation. First, the current automation algorithm enables a structured exploration of the habitat interior layout design space. Every layout evaluated can be recorded and used to understand trends in subsystem placement and problem points where the designs are extremely unfavorable. Furthermore, by running the algorithm in an unconstrained mode, unconstrained relationship-adjacency diagrams representing designer preferences can be visualized which could inform a manual design. For example, if the unconstrained algorithm indicates that, for the defined evaluation criteria values and designer utilities, subsystems generally cluster into 3 separated zones, then a layout accommodating those separations can be manually defined if the designer agrees with that assessment. These products can inform decision makers on the feasibility of improving achieved layouts through either improved layout or larger pressure vessels to better accommodate packaged items.

As mentioned before, the current automated iteration algorithm can be used as a test bed to refine the formulation of the objective function; identifying the right slopes or implementation of penalty functions to ensure feasible solutions. Additionally, the current instantiation of the automation algorithm is expected to perform well for larger, less densely packed layouts, as the PSO can more readily address conflicting constraints. Finally, converged layouts from the current algorithms can be manually adjusted to eliminate collisions and serve as initial layouts for future iterations. For example, the layout in Figure 43 could be manually adjusted to eliminate collision detection and re-evaluated to determine layout effectiveness. This layout could also be used as the initial layout for another run of the iteration algorithm. This user-intervention approach common in facility layout problems and could be implemented until the desired algorithm improvements are successfully integrated.

CHAPTER 6: CONCLUSIONS AND FORWARD WORK

6.1 Conclusions

The primary goal of the research presented in this thesis was to develop a fast, comprehensive, and transparent method to quantitatively evaluate habitat interior layouts; enabling comparison of multiple layout concepts. A systems engineering trade study process was used to identify the gaps necessary to develop this capability. The following necessary improvements to the currently available process were identified:

- A comprehensive, automatically quantifiable set of evaluation criteria
- A mathematical, computer representation of layout geometry and subsystem characteristics consistent with criteria quantification methods
- A structured method to capture designer preferences
- A multi-criteria objective function providing an aggregate measure of overall layout effectiveness including treatment of interior design constraints

It was hypothesized in Research Question 1 that a structured, systems-engineering habitat layout evaluation process built around the assembly of a multi-criteria objective function capturing both engineering and habitability concerns could be 1) developed and 2) proven to be capable of accurately comparing multiple layout alternatives against a consistent set of designer preferences. The process presented in Chapters 3 and 4 of this thesis verifies this hypothesis is true by successfully developing and demonstrating implementations of each of the four gaps listed above and integrating them into an end-to-end evaluation process. Section 3.2 outlined the quantifiable evaluation criteria identification and the process used to map qualitative criteria to quantitative proxies. Together these advances confirm Hypothesis 2 by identifying a more comprehensive set of all quantitative evaluation criteria. Then algorithms/methods were developed (Section 3.3 and Appendix B) to automatically measure the resulting 18 evaluation criteria from a chosen mathematical representation of habitat geometry by utilizing a combination of automated analytical and numerical methods. These methods demonstrate that habitat layout performance can be quickly assessed with no additional designer input during calculation (confirming Hypothesis 3). Systems engineering methods such as Analytic Hierarchy Process and single attribute utility functions are implemented to capture a set of designer preferences (Section 3.5). By forcing designer preferences to be collected prior to evaluation criteria measurement, a consistent basis from which to assess multiple habitat layouts was developed and demonstrated with the cislunar example from Chapter 4. Furthermore, this separation of objective measurements from subjective designer preferences enables the investigation of thousands of layouts in the minutes required for "designer-in-the-loop" methods. These designer preference methods were identified from a survey of approaches consistent with the habitat layout problem formulation and implemented effectively, confirming Hypothesis 4. In Chapter 4, every step of this layout evaluation process was demonstrated by the evaluation of multiple designs of a cis-lunar habitat module, providing real-world examples to confirm Hypotheses 1-4. The evaluation process demonstrated met all speed and automation goals from Table 6.

In addition to the evaluation capability demonstrated in this thesis, implementation of a method to automate generation of desirable layout concepts was proposed featuring this habitat evaluation methodology. The intent of this automation research was not to solve or optimize the automated design problem, but rather to identify a promising method while addressing potential factors which would prevent automation. A Particle Swarm Optimization (PSO) algorithm used in commercial practice was applied to the cis-lunar habitat example from Chapter 4 to reveal the challenges of automating layout design and some potential solutions. It was determined that a fine balance of constraint satisfaction and evaluation criteria optimization was required, and that additional methods would be needed to augment the baseline algorithm to truly enable automation. The characterization of potential solutions and the presentation of a preprocessing algorithm to speed convergence were discussed, with recommendations for future projects. As a result of the information collected from the current automation attempt, it was determined that automated layout generation would be feasible and capable of creating both acceptable and desirable layout alternatives with the implementation of some of the potential PSO augmentations outlined in Table 25 (confirming Hypothesis 5). Furthermore, products and decision forming trades were identified for the automation method in its current state and projected for its completed state.

The results of this research are important for the conceptual design of spacecraft because automation of the interior layout design of a habitat was the major missing component preventing conceptual habitat design optimization. Other major contributions from this work include: a comprehensive, measurable set of evaluation criteria capturing both engineering and habitability concerns, automated methods of measuring them which are not apparent in current literature, and proof of the viability of PSO for automated habitat layout design. These capabilities will enable earlier identification of habitat sizing or interior design issues with defensible, quantifiable data. This will allow earlier changes to designs when design freedom is high and cost is low, and potentially reducing mass growth/habitability compromise from architectural issues discovered in later phases of design when human in the loop testing typically occurs. Furthermore, this automated layout generation capability will enable engineering research identifying effective form factors for habitat interiors (potentially different from the current practice) and assessing robustness of designs to multiple managerial preferences and requirements.

6.2 Future Work

So in summary, a method for habitat layout evaluation has been developed which is compatible with stochastic optimization methods, and preliminary automation of interior layout design has been advanced. There are several pieces of forward work to expand both the Evaluation and Generation steps of this method which will result in more complete, autonomous, and stable tools and methods for the habitat design community.

As mentioned in previous chapters, the current evaluation criteria measurement methods perform adequately, but further refinement is desired to make them more autonomous and to allow them to capture more detailed, generic interiors. Subtests for the volume estimation methods should be added to ensure complex geometric features such as cavities and protrusions don't introduce error into the estimate. These subtests can include additional orientations of test volumes representing standing/prone crew members or reaching appendages. Additionally, coherence from the previously evaluated points (specifically clearance of test volumes) should be used to speed these estimates. For separation/colocation criteria, more refined distances (such as Manhattan or radial distances) and the use of partition penalty/bonuses and/or line of sight occlusion tests should be implemented to provide a more accurate representation of design features commonly used to increase the perceived separation/colocation of functions. Finally, the minimum width of translation path criterion requires significant development. Automated translation path design algorithms such as the A* algorithm for robotic path planning should be implemented and used as test points for this numerically estimated length.

New criteria and constraints are also expected to be implemented as necessary. Criteria such as center of mass, layout efficiency for radiation protection, etc. are likely to be desired. Center of mass offset and minimal amounts of uniform radiation shielding can also be implemented as constraints on the design, though acceptable ranges for these may be hard to determine at conceptual design. In addition to the geometric criteria, some more perception based criteria focusing on form and shape [Wise et al. 1985] or criteria capturing the degree to which long duration countermeasures play into the evaluation should also be addressed [Simon et al. 2011]

In addition to refining the current evaluation criteria, alternate constraint approaches should be investigated to guide the layout alternatives to feasible design space. The number of violations was used in this work to determine the degree of infeasibility for a number of constraints. However, in practice this leads to optimizer decisions to violate one constraint, such as a pressure vessel constraint, by a significant distance to reduce the overall score through separation criteria.

Alternate constraint approaches or additional constraints should be investigated to capture the extent to which a constraint is violated. For example, a constraint placing thresholds on the amount of overlapping volume between all of the objects could be applied to provide a continual improvement function to enforce hardware-hardware collision constraints.

In addition to refining the evaluation criteria and constraint measurement methods, the designer input process should be streamlined to reduce the amount of time necessary to set up new design problems. Libraries of evaluation criteria ranges and previous designer preferences based upon certain missions and spaceflight requirements should be established, to enable a designer to utilize previously developed inputs when applicable. Multiple uses of this method and tool are expected to develop such libraries. Additionally, libraries of hardware geometries and functional information should also be established, particularly since the same basic pieces of hardware are often leveraged to reduce mission development and certification costs. A more streamlined geometry definition should also be identified to allow designers to specify new hardware without vertex and face normal representation.

Finally, the majority of forward work centers on fast, fully generic automated layout iteration leading to an automatic layout generation capability producing designs which are both feasible and desirable. Several alternate constraint handling and optimization approaches listed in Table 25 should be investigated. In particular, the Simon-Arney Preprocessing Convergence algorithm is anticipated to greatly speed convergence while generating all feasible solutions. Additionally, after investigation of PSO algorithms, simulated annealing approaches should be investigated as “cooling schedules” are anticipated to work well in this multi-modal design space. Multiple other methods from facility planning literature should also be investigated. In addition, the layouts evaluated in this thesis are pretty straightforward. Each of these methods should be demonstrated on a broad class of highly-constrained and less-constrained layouts with various shapes and sizes. It is anticipated that evaluation criteria measurement methods may need to be customized to deal with non-convex shapes such as toroids.

APPENDIX A: Glossary of Terms

Table 26: Term Glossary

Term	Definition
Accommodations	Configuration, arrangement,
Constraint	Limitations on the design space indicating human system or physical limits
Design Space	The full set of possible layouts which could be design that must be explored to understand performance on key variables.
Equipment	Used interchangeable with hardware; may be used specifically when referring to habitat subsystems
Evaluation Criteria	Measures which are critical for assessing the desirability of a layout concept.
Functions	Interchangeable with tasks
Hardware	Generically, interior objects to be packaged including subsystems, equipment, accommodations, or logistics
Layout	Arrangement of interior objects through specification of location and orientation of each object
Logistics	Goods which vary with mission duration. Item to be packaged
Penalty Function	A function used to 'penalize' the aggregate objective function for constraint violations
Subsystems	Habitat system used to perform a specific function, most commonly a habitat function generally unassociated with human tasks.
Tasks	Activities performed by the crew
Vehicle	Typically a launch vehicle or propulsive stage (not a habitat)

APPENDIX B: Evaluation Criteria Detailed Descriptions

Quantifiable

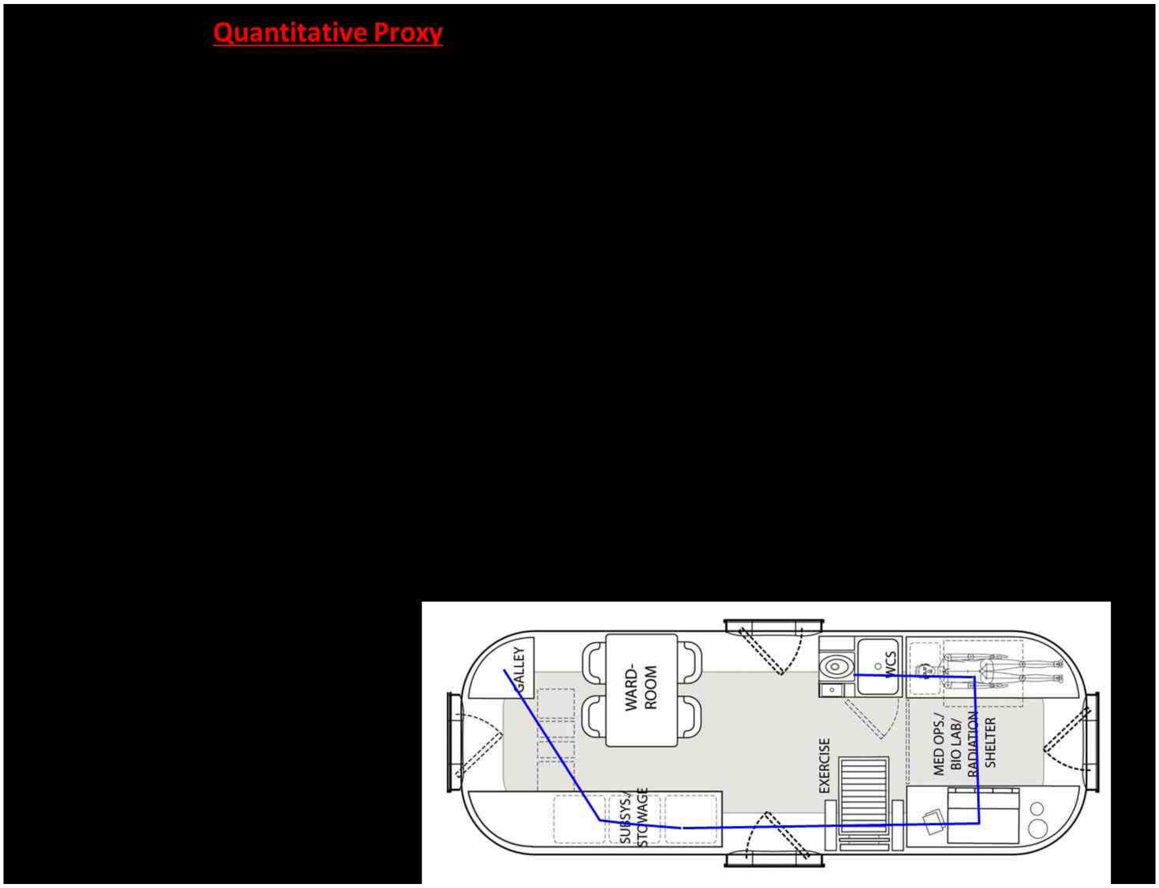
[redacted]

Figure 44: Evaluation Criterion One Pager: Structure Mass

Quantifiable

[redacted]

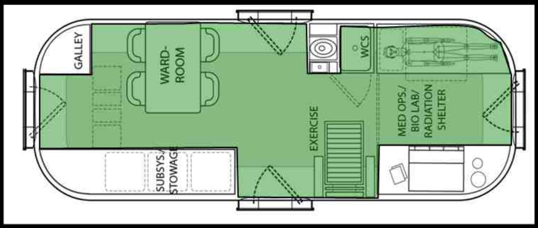
Figure 45: Evaluation Criterion One Pager: Equipment Mass

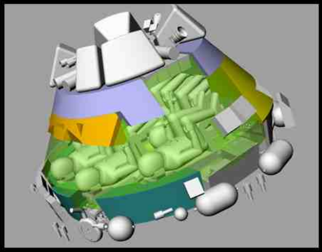


Quantitative Proxy

Figure 46: Evaluation Criterion One Pager: Line Run Mass

Quantifiable





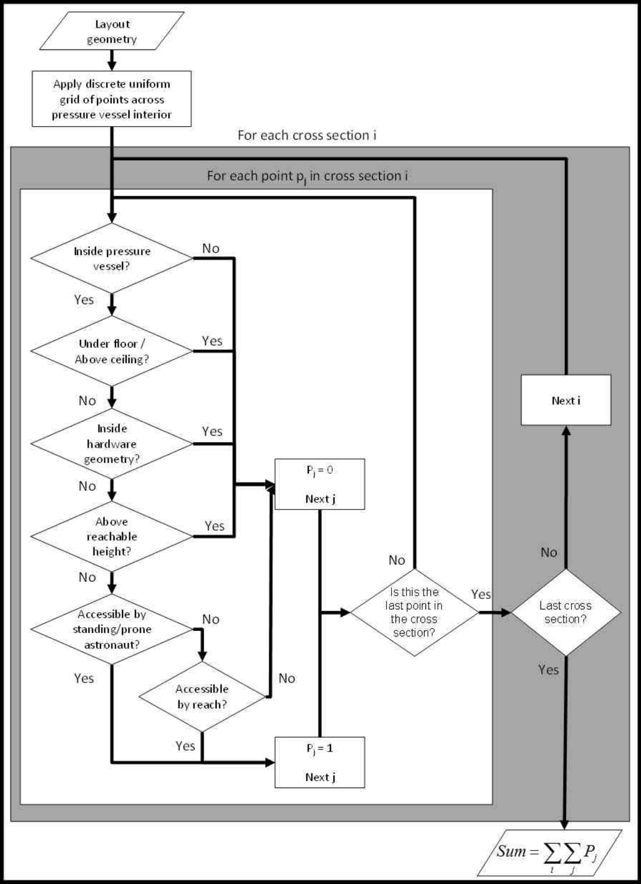
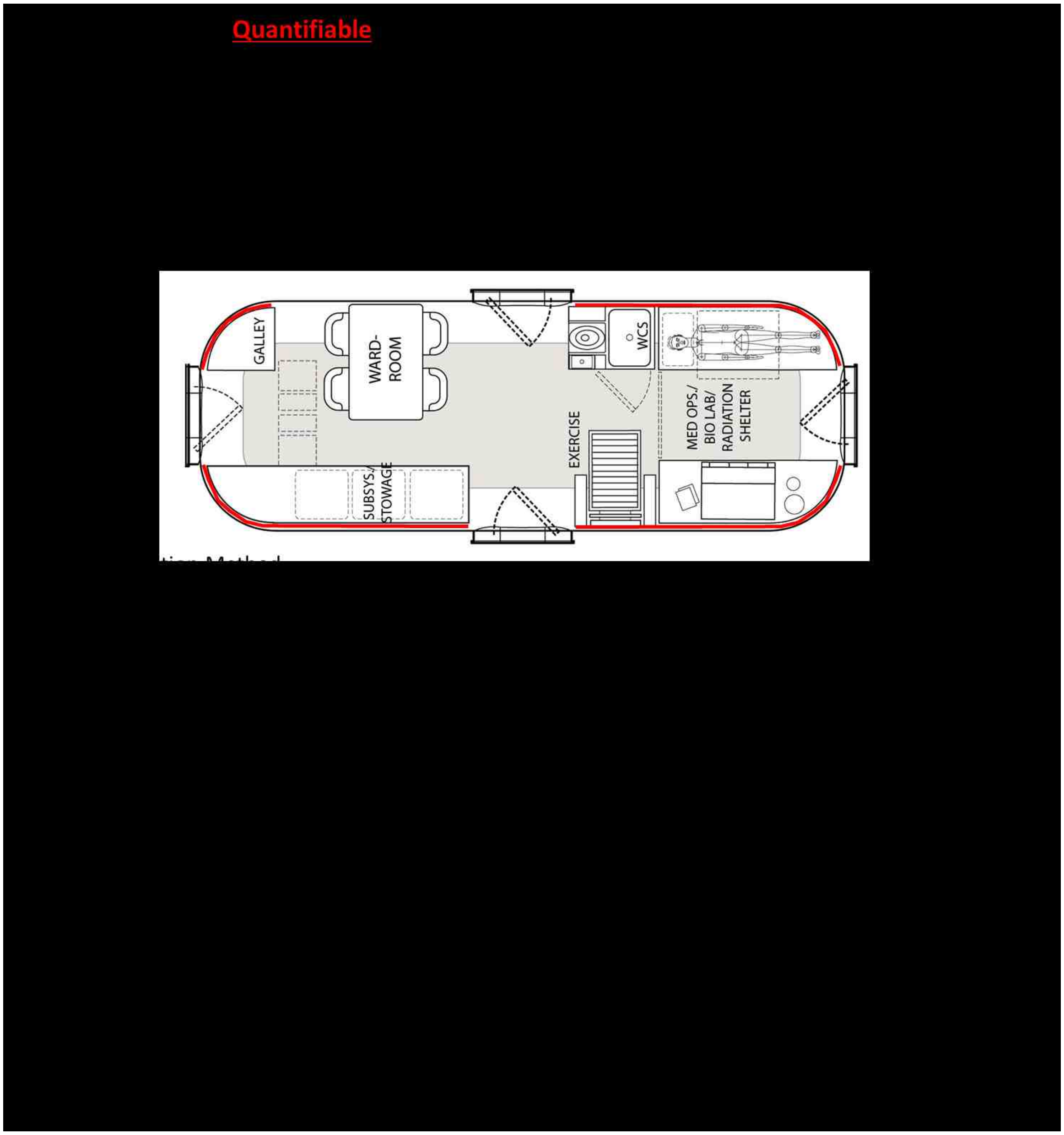


Figure 47: Evaluation Criterion One Pager: Habitable Volume



Quantifiable

Figure 48: Evaluation Criterion One Pager: Unusable Volume

Quantifiable

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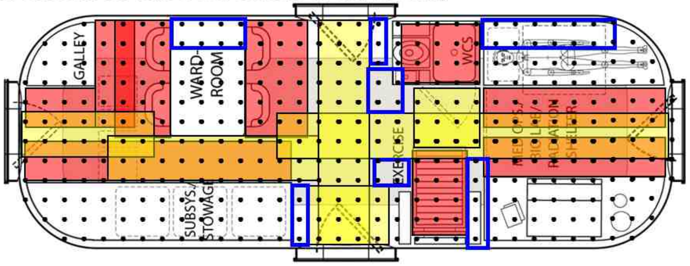
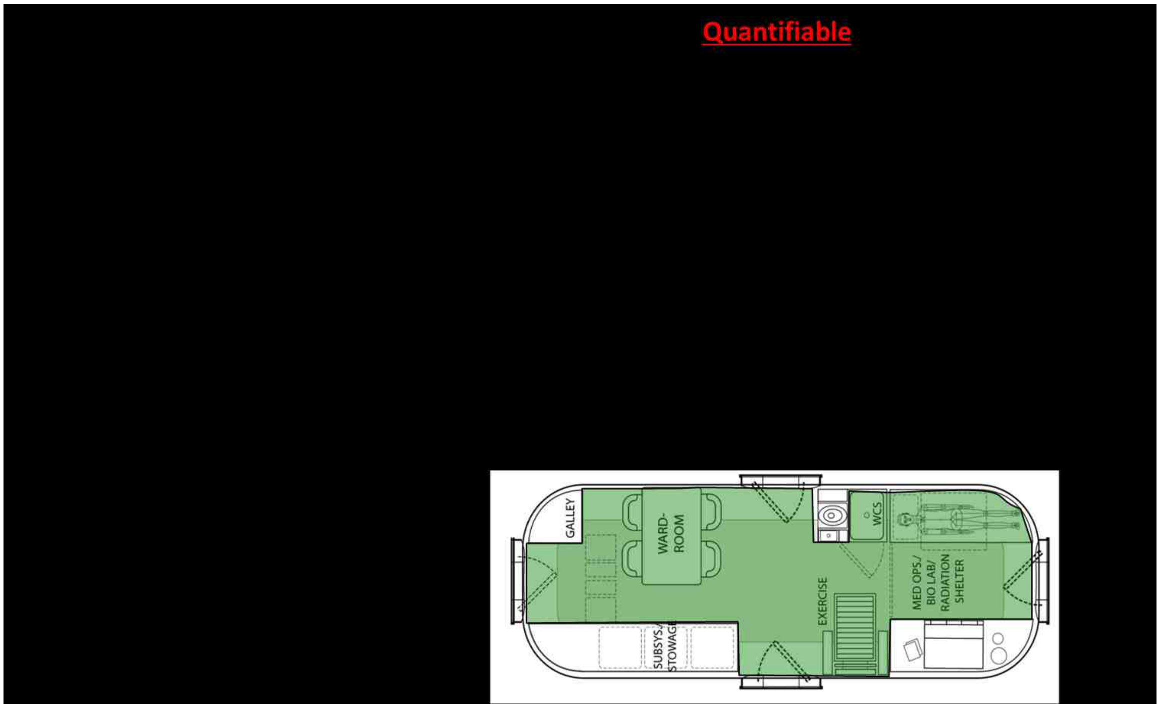
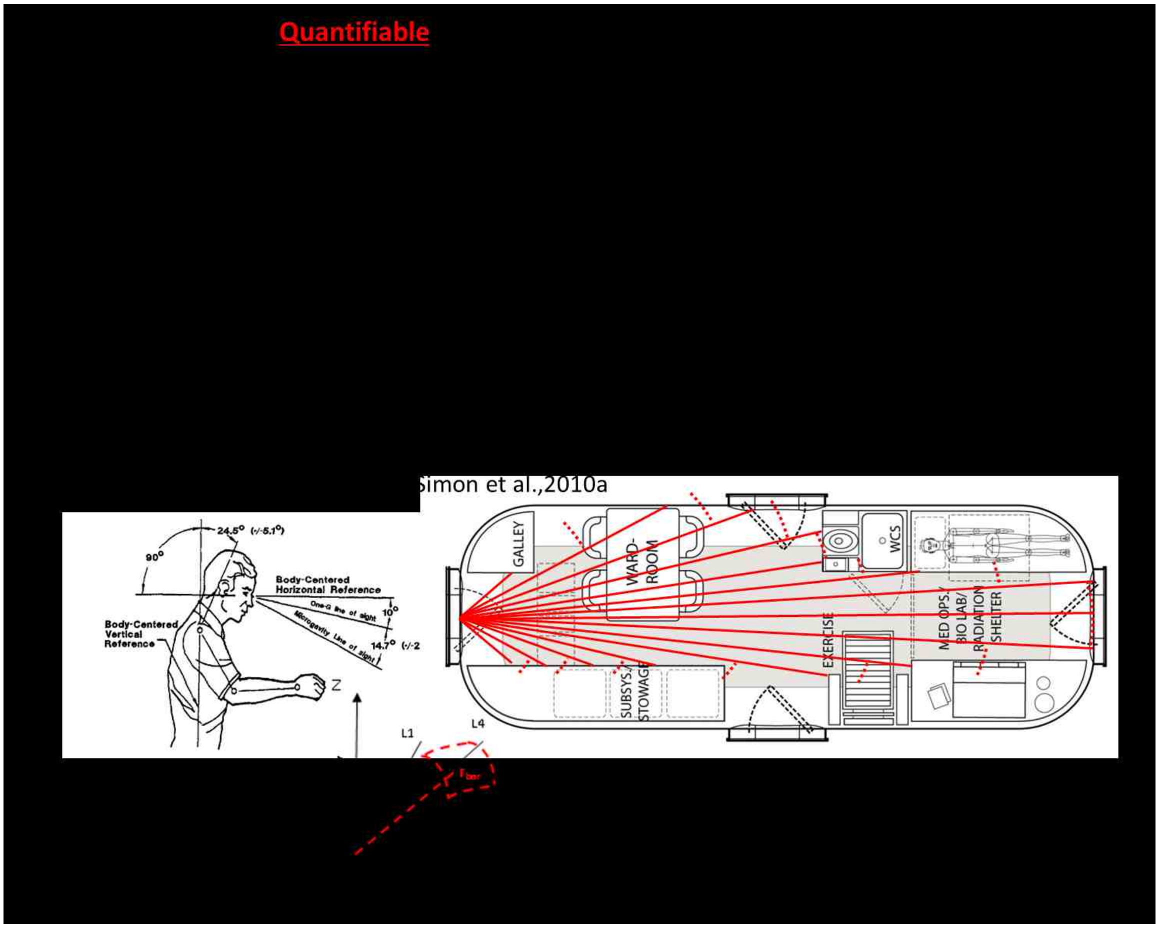


Figure 49: Evaluation Criterion One Pager: Available Non-dedicated Stowage Volume



Quantifiable

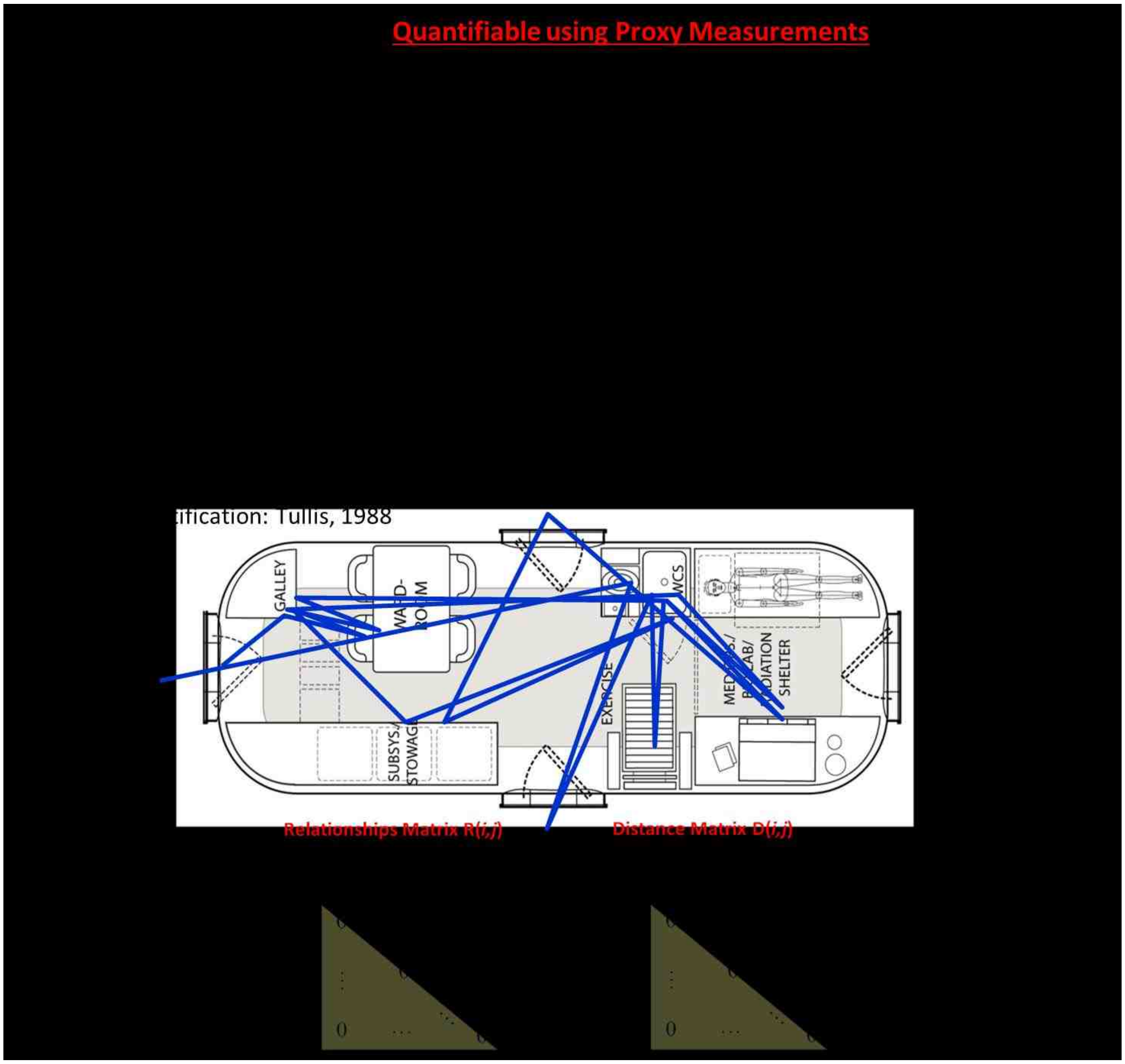
Figure 50: Evaluation Criterion One Pager: Habitable Floor Area



Quantifiable

Simon et al.,2010a

Figure 51: Evaluation Criterion One Pager: Largest Spatial Vista

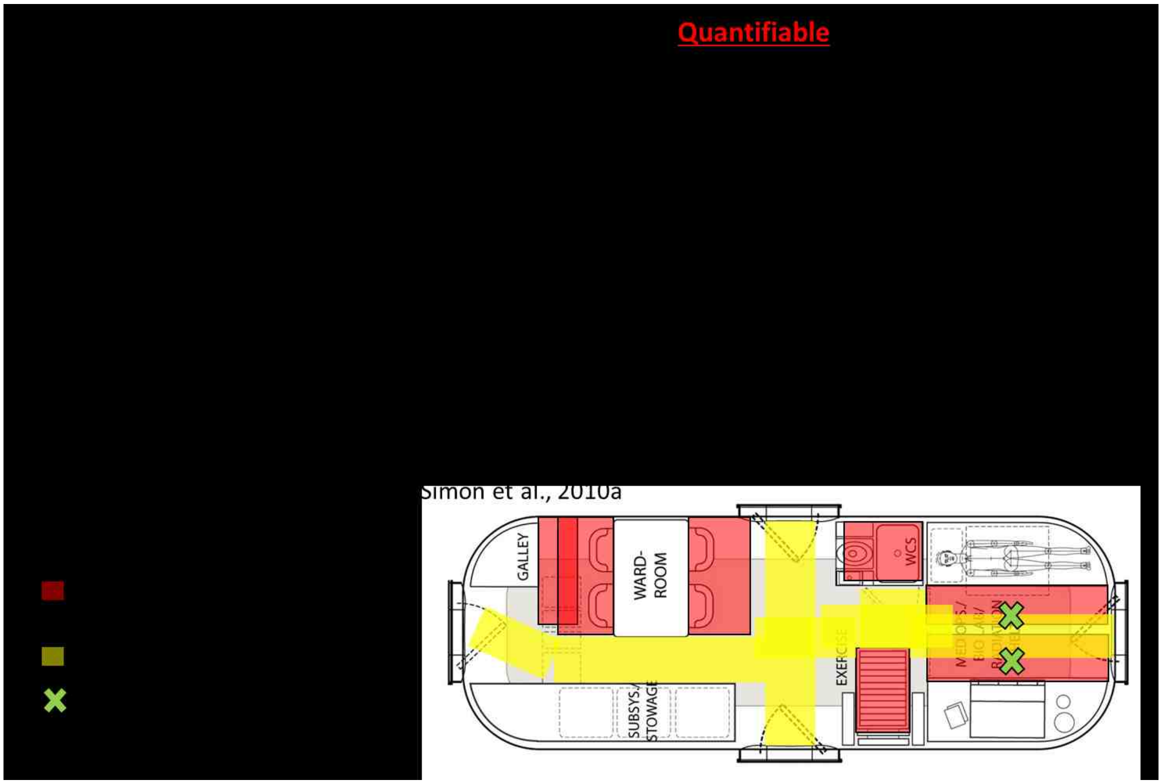

Quantifiable using Proxy Measurements

tification: Tullis, 1988

Relationships Matrix R(*i*,*j*)

Distance Matrix D(*i*,*j*)

Figure 52: Evaluation Criterion One Pager: Colocation of Sequential Tests



Quantifiable

Simon et al., 2010a

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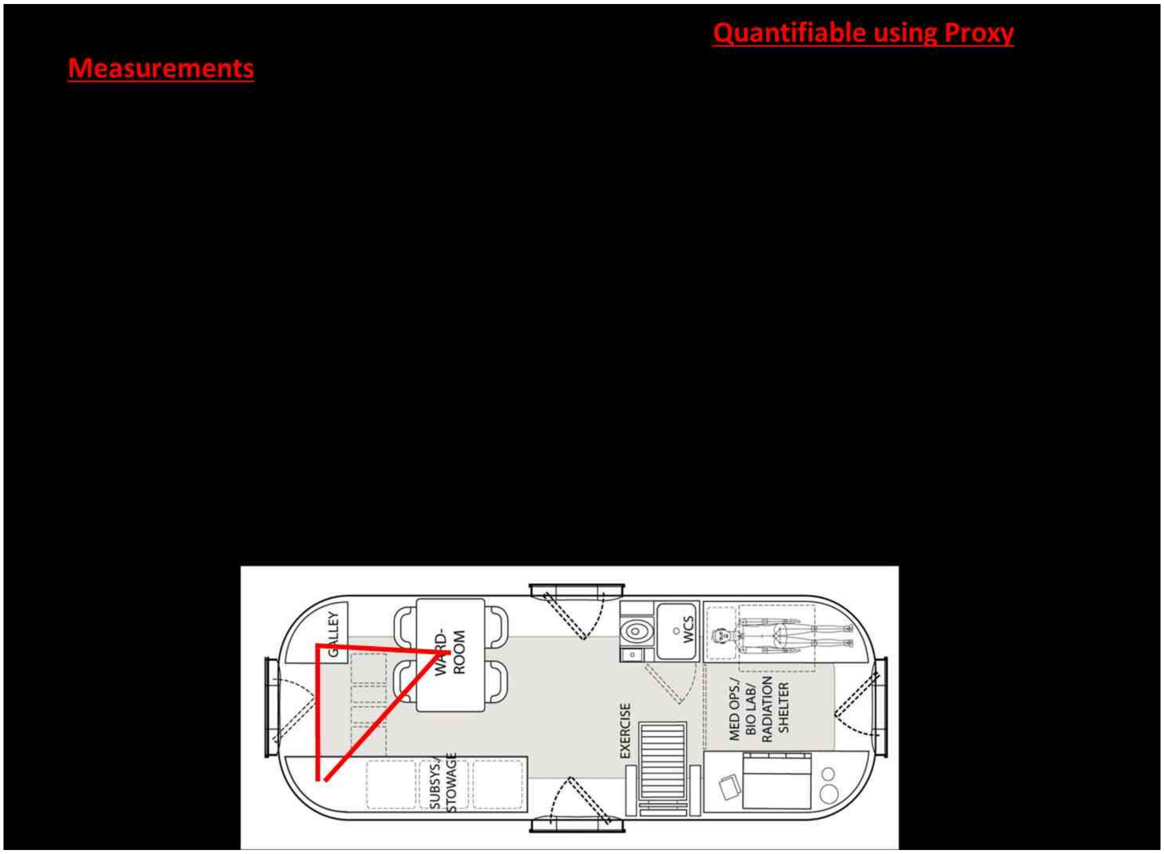
Figure 53: Evaluation Criterion One Pager: Anthropometry Interferences of High Duration Tasks



Quantifiable using Proxy Measurements

Figure 54: Evaluation Criterion One Pager: Colocation of Equipment / Related Storage by Function

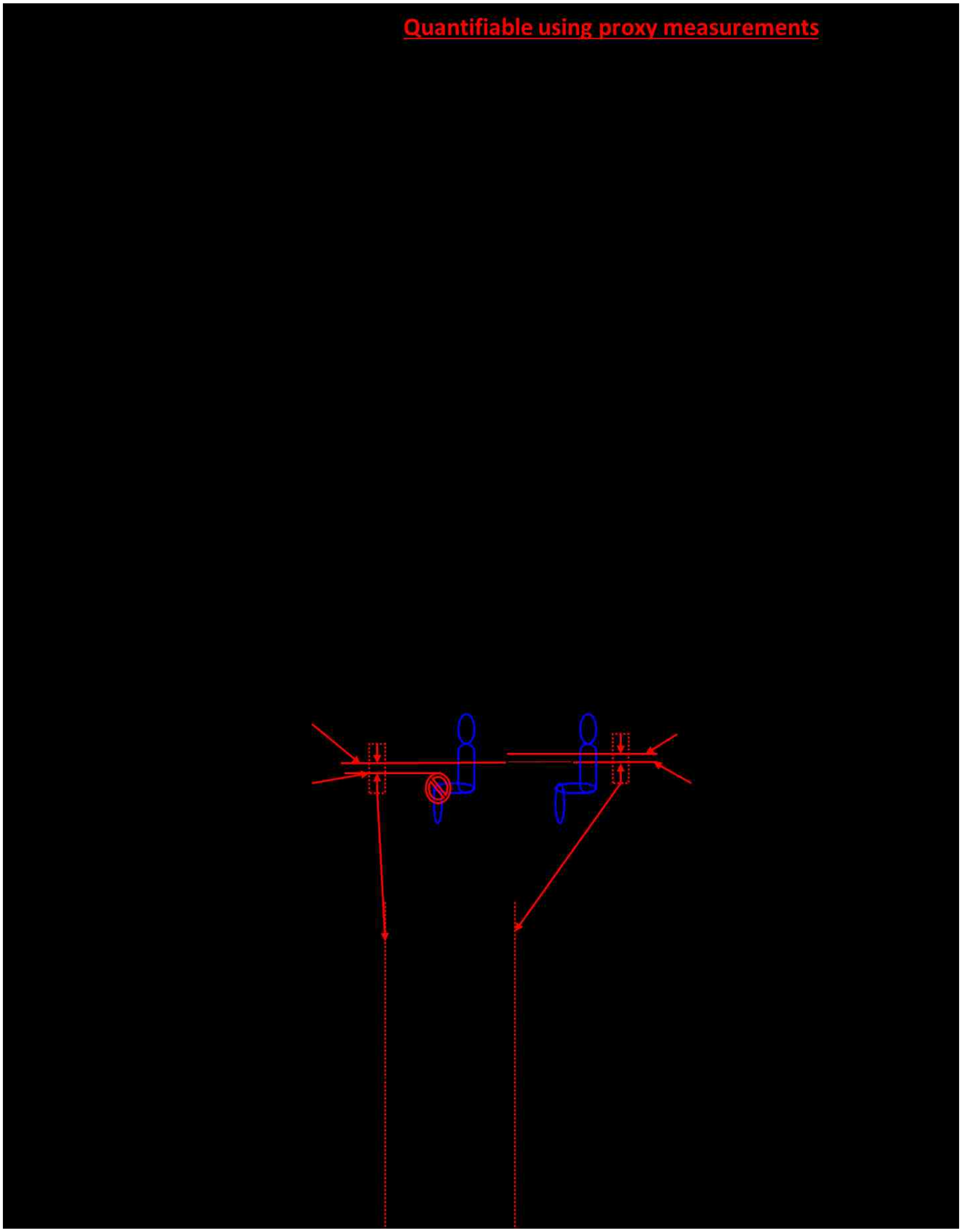
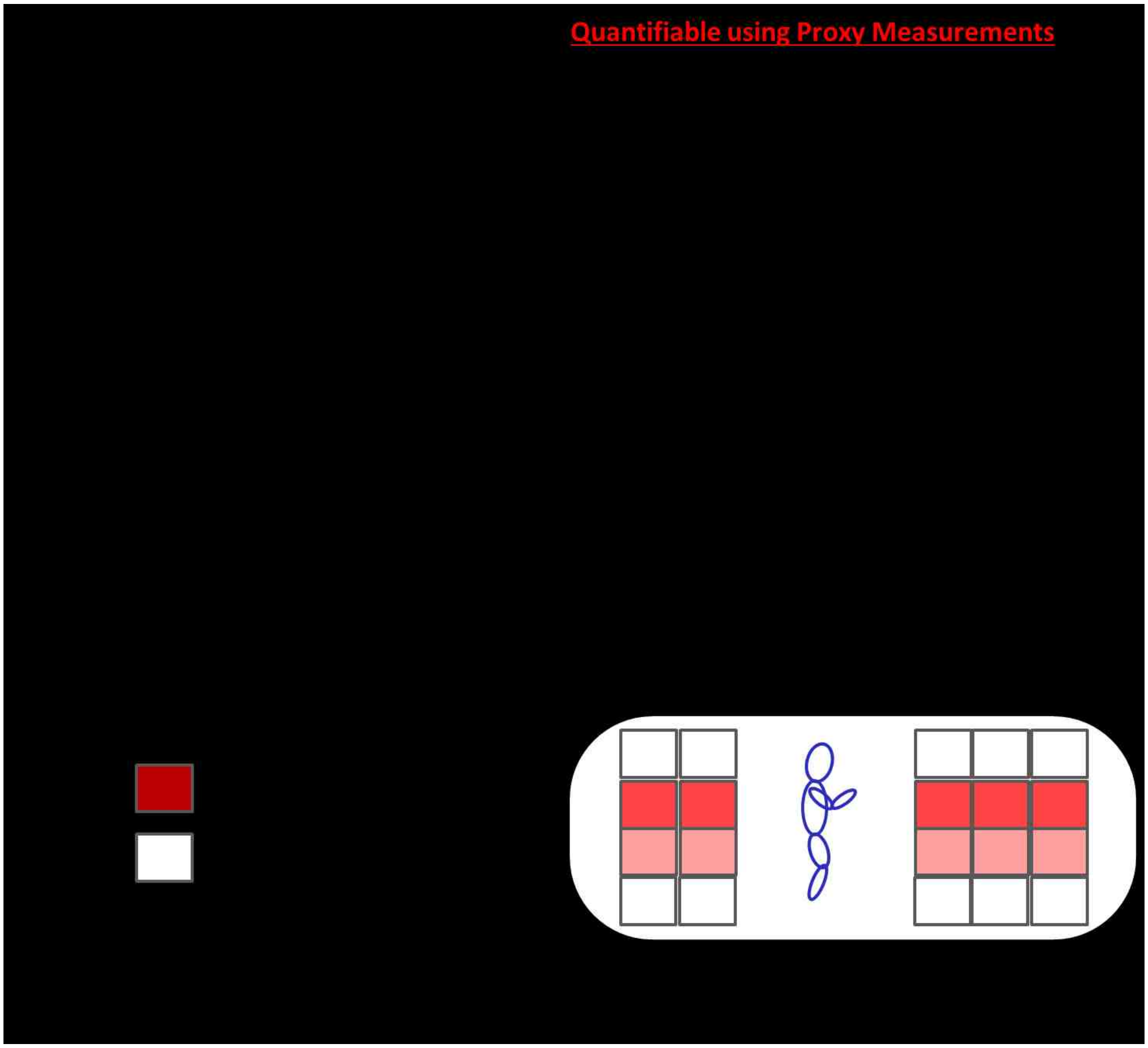
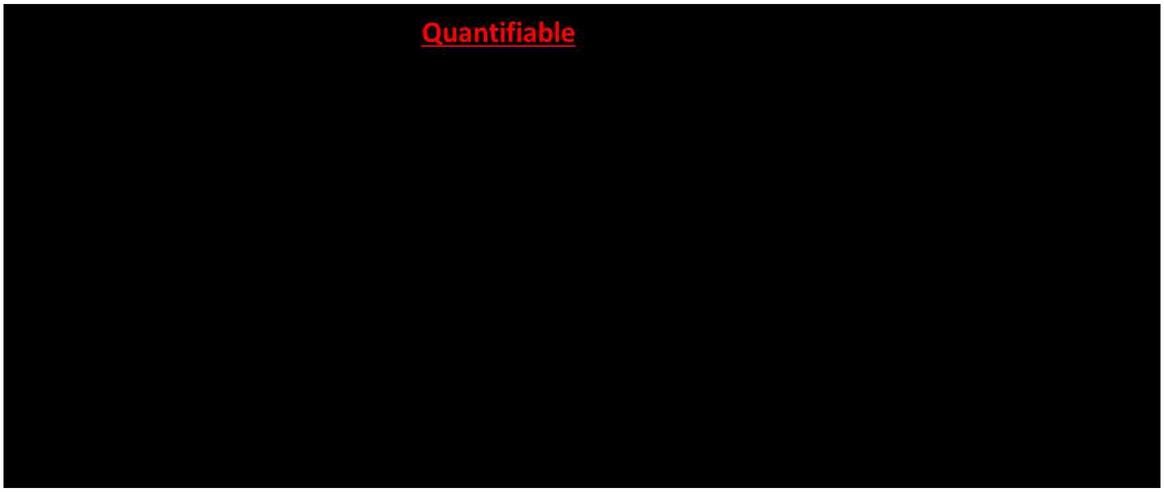


Figure 55: Evaluation Criterion One Pager: Placement for Function/Ergonomics



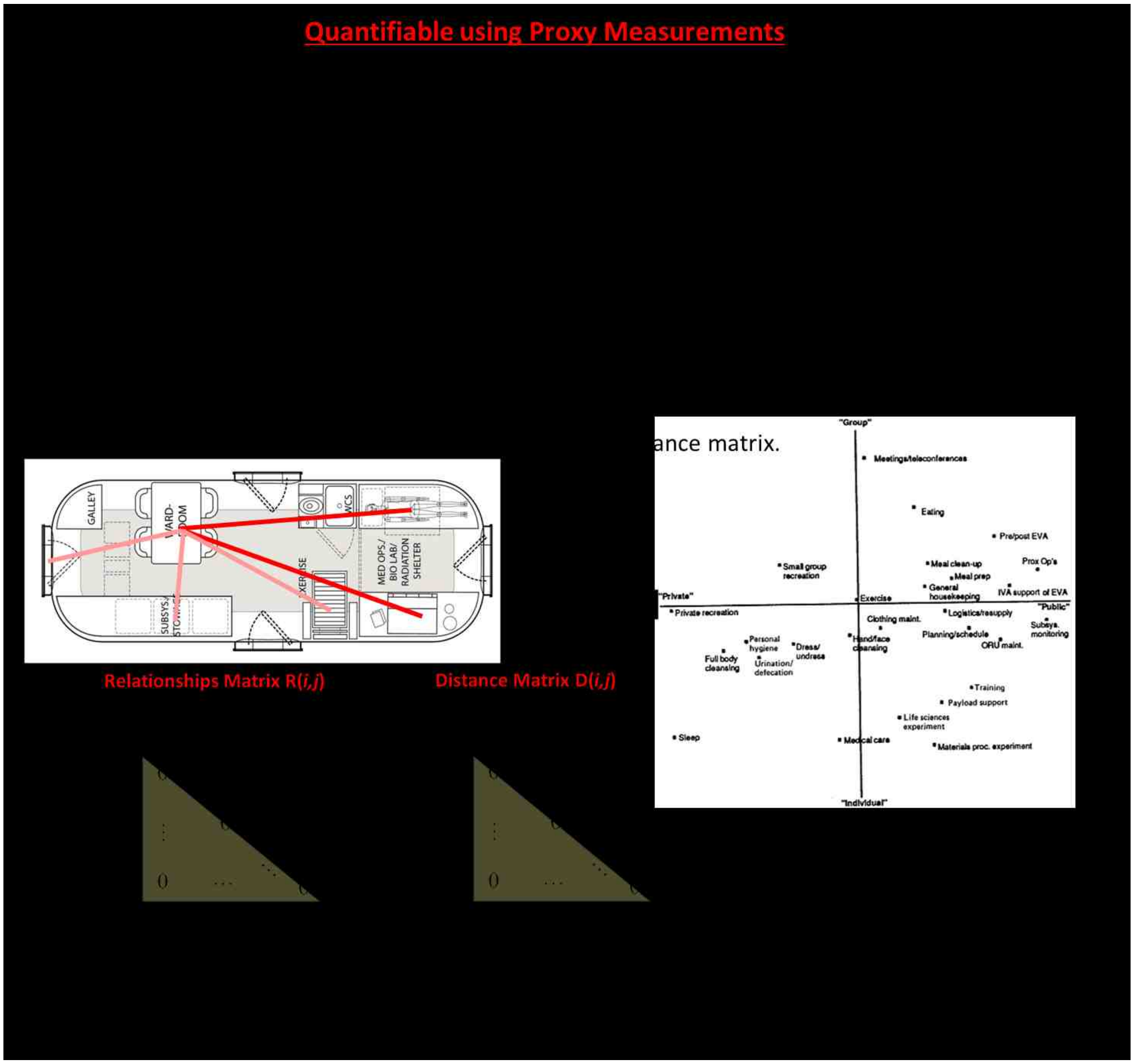
Quantifiable using Proxy Measurements

Figure 56: Evaluation Criterion One Pager: Placement for High Frequency/ Duration Use



Quantifiable

Figure 57: Evaluation Criterion One Pager: Size of Dedicated Private Space



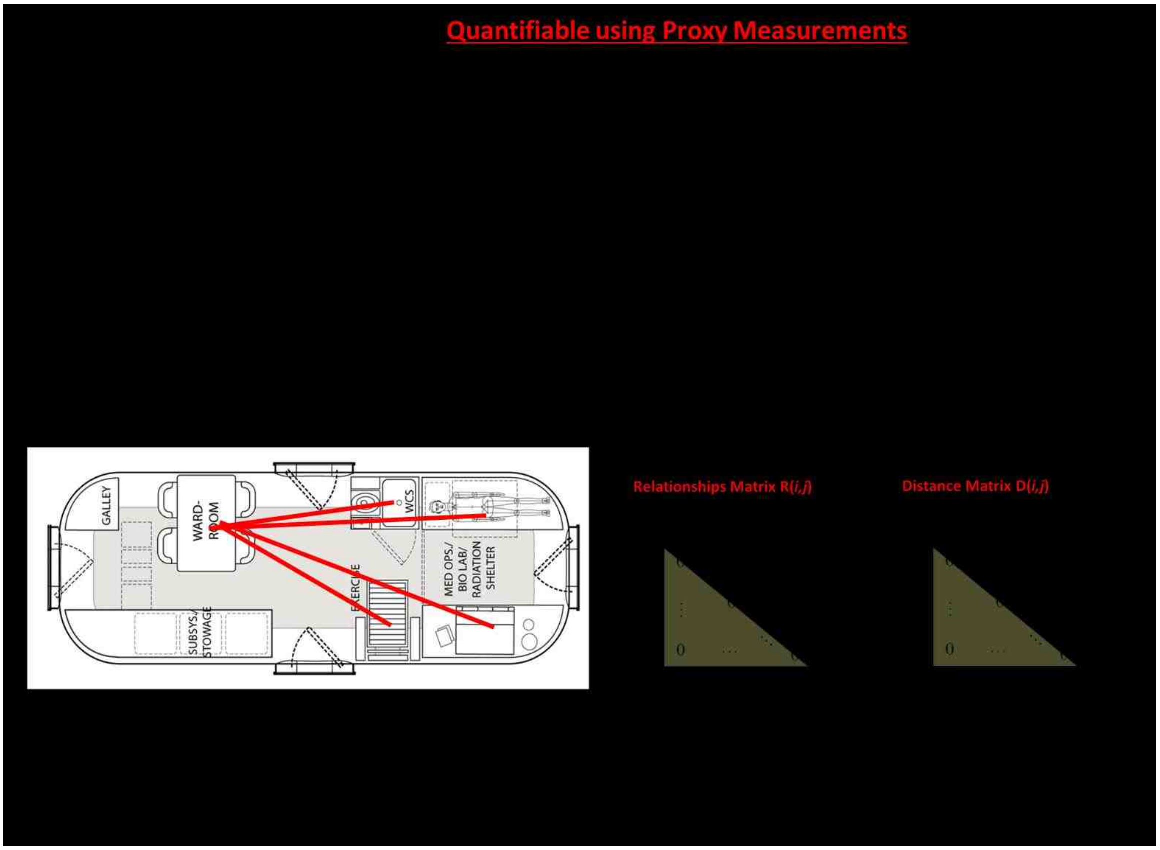
Quantifiable using Proxy Measurements

ance matrix.

Relationships Matrix R(*i*,*j*)

Distance Matrix D(*i*,*j*)

Figure 58: Evaluation Criterion One Pager: Separation for Privacy

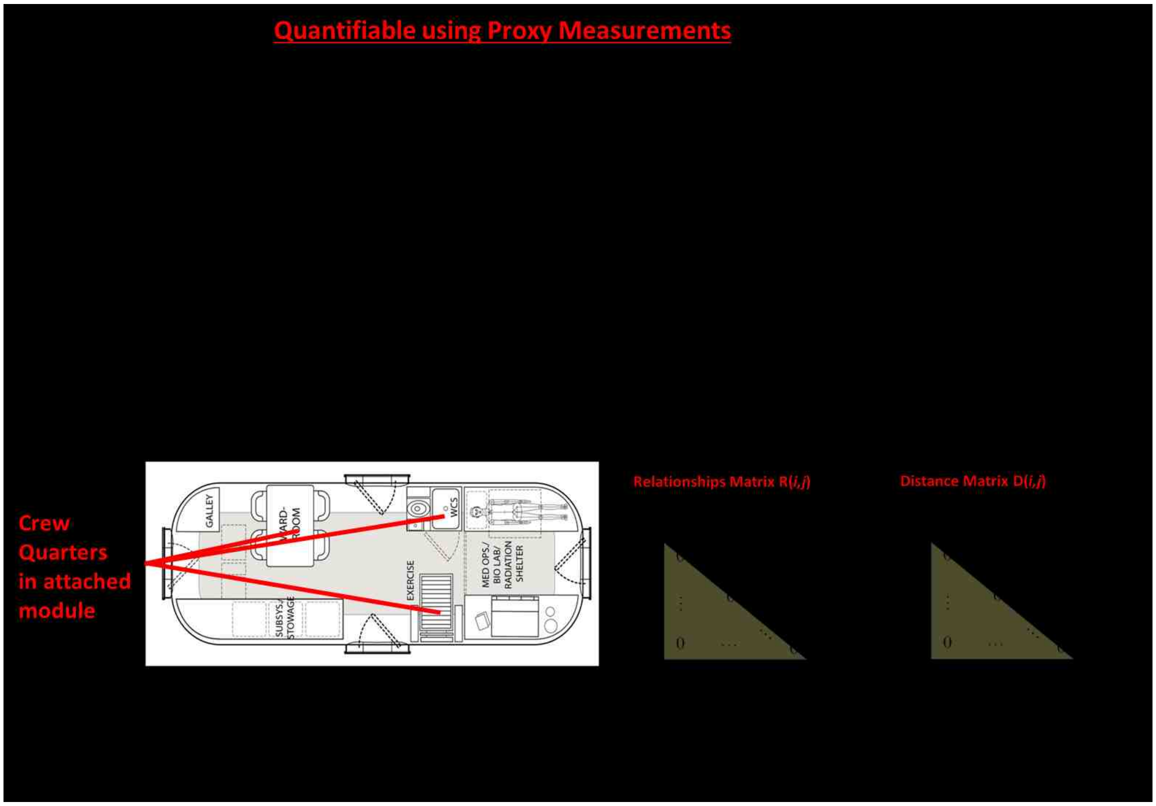


Quantifiable using Proxy Measurements

Relationships Matrix R(*i*,*j*)

Distance Matrix D(*i*,*j*)

Figure 59: Evaluation Criterion One Pager: Separation for Clean and Dirty Zones



Quantifiable using Proxy Measurements

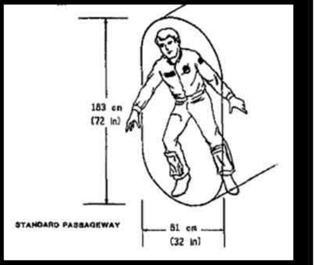
Crew Quarters in attached module

Relationships Matrix R(*i*,*j*)

Distance Matrix D(*i*,*j*)

Figure 60: Evaluation Criterion One Pager: Separation for Noise

Quantifiable



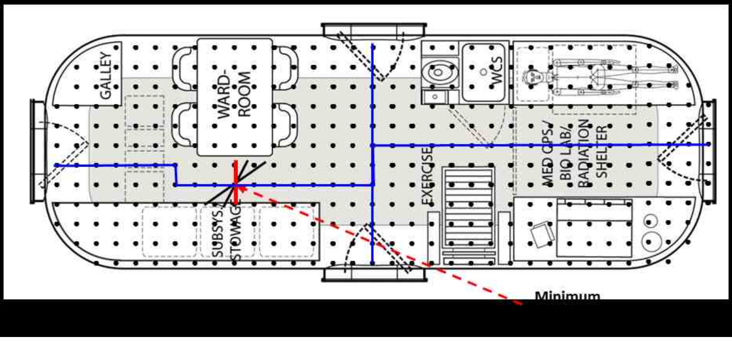


Figure 61: Evaluation Criterion One Pager: Minimum Translation Path Width

APPENDIX C. Definition of Hardware Information from Cis-Lunar Habitat Example Described in Chapter 4 and 5

Table 27: Mapping of Crew Tasks to Hardware (objectList.csv data)

	Meal Preparation	Eating	Meal clean-up	Exercise	Medical Care	Full-body Cleansing	Hand/Face Cleansing	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation and Leisure	Small-group Recreation and Leisure	Dressing/Undressing	Clothing Maintenance	Meetings and Teleconferences	Planning and Scheduling	Subsystem Monitoring and Control	Pre/Post-EVA Operations	IVA Support of EVA Operations	Proximity Operations	General Space Station Housekeeping	ORU Maintenance and Repair	Logistics and Resupply	Payload Support	Life Sciences Experiments	Materials Processing Experiments
Oxygen Generation	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	0
Galley	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Power/Avionics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
ARS	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	0
Wardroom	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Medical	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Water Storage	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	0
Water Processor 1	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	0
WaterProcessor 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	0	0	0
Power/Thermal	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	0
Hygiene	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crew Quarters 1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Crew Quarters 2	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Crew Quarters 3	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Crew Quarters 4	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 28: Mapping of Hardware Information Feeding Evaluations (objectList.csv data)

	Water line run required	Air line run required	Power line run required	Private space?	Mass, kg	Volume, m^3	Priority Placement rating
Oxygen Generation	1	1	1	0	843	1.57	0
Galley	1	0	1	0	412	1.57	1
Power/Avionics	0	0	1	0	1150	1.57	0
Maintenance	0	0	1	0	400	1.57	1
ARS	1	2	1	0	843	1.57	0
Wardroom	0	0	0	0	100	1.57	1
Medical	1	1	1	0	328	1.57	1
Water Storage	2	0	1	0	571	1.57	0
Water Processor 1	1	0	1	0	455	1.57	0
WaterProcessor 2	1	0	1	0	455	1.57	0
Power/Thermal	1	0	2	0	500	1.57	0
Hygiene	1	1	1	0	197	1.57	3
Crew Quarters 1	0	1	1	1	133	1.57	5
Crew Quarters 2	0	1	1	1	133	1.57	5
Crew Quarters 3	0	1	1	1	133	1.57	5
Crew Quarters 4	0	1	1	1	133	1.57	5

Table 29: Initial Hardware Locations and Bounding Volume Dimensions (objectList.csv data)

	Location			Dimensions		
	X, m	Y, m	Z, m	Depth, m	Height, m	Width, m
OGS	0	-1.65	-1.6	0.966	2.014	1.046
Galley	-1.65	0	-1.6	0.966	2.014	1.046
Power/Avionics	0	1.65	-1.6	0.966	2.014	1.046
Maintenance	1.65	0	-1.6	0.966	2.014	1.046
ARS	0	-1.65	-0.525	0.966	2.014	1.046
Wardroom	-1.65	0	-0.525	0.966	2.014	1.046
Medical	0	1.65	-0.525	0.966	2.014	1.046
Water Storage	1.65	0	-0.525	0.966	2.014	1.046
Water Processor 1	0	-1.65	0.525	0.966	2.014	1.046
Water Processor 2	-1.65	0	0.525	0.966	2.014	1.046
Power/Thermal	0	1.65	0.525	0.966	2.014	1.046
Hygiene	1.65	0	0.525	0.966	2.014	1.046
CrewQuarters 1	0	-1.65	1.6	0.966	2.014	1.046
CrewQuarters 2	-1.65	0	1.6	0.966	2.014	1.046
CrewQuarters 3	0	1.65	1.6	0.966	2.014	1.046
CrewQuarters 4	1.65	0	1.6	0.966	2.014	1.046

Table 30: Hardware Vertices before Translation Defining Polyhedral Rack Structure (objectList.csv data)

Hardware Vertices		
X, m	Y, m	Z, m
0.483	1.007	-0.523
0.483	1.007	0.523
0.483	-1.007	-0.523
0.483	-1.007	0.523
-0.267	-1.007	-0.523
-0.267	-1.007	0.523
-0.483	-0.575	-0.523
-0.483	-0.575	0.523
-0.483	0.397	-0.523
-0.483	0.397	0.523
-0.267	0.829	-0.523
-0.267	0.829	0.523

Table 31: Hardware Indices Defining Polyhedral Faces of Rack Structure (objectList.csv data)

Hardware Polyhedral Face Indices , vertices number			
0	1	3	2
2	3	5	4
4	5	7	6
6	7	9	8
8	9	11	10
10	11	1	0
0	2	4	10
4	6	8	10
1	11	5	3
5	11	9	7

Table 32: Hardware Face Normal Vectors Defining Polyhedral Faces of Rack Structure (objectList.csv data)

Hardware Face Normal Vectors, m		
1	0	0
0	-1	0
-0.432	-0.216	0
-1	0	0
-0.432	0.216	0
-0.178	0.75	0
0	0	-1
0	0	-1
0	0	1
0	0	1

Table 33: Separation Matrix for Clean and Dirty Spaces (hygieneMatrix.csv data) [Tullis & Bied, 1988]

Separation Matrix for Clean and Dirty Sys		Meal Preparation	Eating	Meal clean-up	Exercise	Medical Care	Full-body Cleansing	Hand/Face Cleansing	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation and Leisure	Small-group Recreation and Leisure	Dressing/Undressing	Clothing Maintenance	Meetings and Teleconferences	Planning and Scheduling	Subsystem Monitoring and Control	Pre/Post-EVA Operations	IVA Support of EVA Operations	Proximity Operations	General Space Station Housekeeping	ORU Maintenance and Repair	Logistics and Resupply	Payload Support	Life Sciences Experiments	Materials Processing Experiments
Crew Support	Meal Preparation		0	0	7	0	7	0	7	10	0	0	0	0	0	0	0	0	3	5	5	0	6	6	0	0	6	6
	Eating			0	7	0	7	0	7	10	0	0	0	0	0	0	0	0	3	5	5	0	6	6	0	0	6	6
	Meal clean-up				5	0	7	0	7	10	0	0	0	0	0	0	0	0	3	5	5	0	6	6	0	0	6	6
	Exercise					5	0	0	1	5	0	6	6	6	0	0	5	0	0	0	0	0	0	0	0	0	2	2
	Medical Care						2	0	0	8	0	0	0	0	0	0	5	0	2	2	3	0	3	3	0	0	8	8
	Full-body Cleansing							0	0	5	0	6	6	6	0	0	5	0	0	2	0	0	0	0	0	0	3	3
	Hand/Face Cleansing								1	5	0	6	6	6	0	0	5	0	0	2	0	0	0	0	0	0	2	2
	Personal Hygiene									5	0	6	6	6	0	0	5	0	0	2	0	0	0	0	0	0	2	2
	Urination/Defecation										0	10	10	10	0	0	10	0	0	3	0	0	0	0	0	0	6	6
	Training											0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
	Sleep												0	0	0	0	0	0	0	5	0	0	0	0	0	0	5	5
	Private Recreation and Leisure													5	0	0	0	0	0	5	0	0	0	0	0	0	5	5
	Small-group Recreation and Leis														0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dressing/Undressing															0	0	0	0	0	0	0	0	0	0	0	0	0
	Clothing Maintenance																0	0	0	0	0	0	0	0	0	0	0	0
Station Operations	Meetings and Teleconferences																	0	0	0	0	0	0	0	0	0	0	0
	Planning and Scheduling																		0	0	0	0	0	0	0	0	0	0
	Subsystem Monitoring and Contr																			0	0	0	0	0	0	0	0	0
	Pre/Post-EVA Operations																				0	0	0	0	0	0	0	0
	IVA Support of EVA Operations																					0	0	0	0	0	0	0
	Proximity Operations																						0	0	0	0	0	0
	General Space Station Housekee																							0	0	0	0	0
	ORU Maintenance and Repair																								0	0	0	0
	Logistics and Resupply																									0	0	0
Mission Operatio ns	Payload Support																										0	0
	Life Sciences Experiments																											0
	Materials Processing Experimen																											

Table 34: Separation Matrix for Noise Interference (noiseMatrix.csv data) [Tullis & Bied, 1988]

Separation Matrix for Noise Interference		Meal Preparation	Eating	Meal clean-up	Exercise	Medical Care	Full-body Cleansing	Hand/Face Cleansing	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation and Leisure	Small-group Recreation and Leisure	Dressing/Undressing	Clothing Maintenance	Meetings and Teleconferences	Planning and Scheduling	Subsystem Monitoring and Control	Pre/Post-EVA Operations	IVA Support of EVA Operations	Proximity Operations	General Space Station Housekeeping	ORU Maintenance and Repair	Logistics and Resupply	Payload Support	Life Sciences Experiments	Materials Processing Experiments
Crew Support	Meal Preparation		50	15	20	90	33	32	23	23	89	120	115	84	18	22	106	88	102	75	77	107	9	55	19	87	86	89
	Eating			58	68	126	76	67	58	56	129	153	154	126	44	57	162	##	150	123	123	155	54	109	61	131	129	141
	Meal clean-up				20	108	37	36	25	25	106	144	138	99	20	24	125	##	120	88	91	128	8	63	19	104	102	105
	Exercise					122	45	43	31	31	120	162	155	113	24	29	143	##	137	101	104	145	13	74	25	118	116	120
	Medical Care						116	98	94	89	132	129	140	136	71	92	179	##	157	145	142	159	109	152	108	141	137	161
	Full-body Cleansing							52	42	41	116	147	144	112	32	41	143	##	134	105	106	140	32	86	41	117	114	122
	Hand/Face Cleansing								39	37	98	122	121	95	30	37	122	##	114	91	91	119	32	76	39	99	97	105
	Personal Hygiene									30	93	120	117	89	24	30	113	94	107	83	84	113	21	65	29	93	91	97
	Urination/Defecation										89	114	11	85	23	29	108	90	102	79	80	107	21	63	28	89	87	92
	Training											142	153	144	71	91	188	##	166	151	148	169	106	154	107	149	145	168
	Sleep												142	151	91	119	200	##	172	168	162	171	148	188	143	156	152	183
	Private Recreation and Leisure													160	89	115	211	##	183	174	168	184	140	187	138	166	161	190
	Small-group Recreation and Leis														68	87	190	##	170	151	149	173	98	151	100	152	148	169
	Dressing/Undressing															23	86	71	81	63	64	85	16	50	22	71	69	73
	Clothing Maintenance																111	92	105	81	82	110	19	63	27	91	89	94
Station Operations	Meetings and Teleconferences																	##	222	196	193	227	123	193	127	198	193	219
	Planning and Scheduling																		182	161	158	185	103	159	106	162	158	180
	Subsystem Monitoring and Contr																			177	174	201	120	179	122	177	172	198
	Pre/Post-EVA Operations																				151	182	85	145	90	157	153	172
	IVA Support of EVA Operations																					178	88	146	93	154	151	170
	Proximity Operations																						120	186	129	180	175	202
	General Space Station Housekee																							57	13	103	101	103
	ORU Maintenance and Repair																								67	157	154	167
	Logistics and Resupply																									105	103	107
Mission Operations	Payload Support																										153	175
	Life Sciences Experiments																											171
	Materials Processing Experimen																											

Table 35: Separation Matrix for Combined Privacy Needs (privacyMatrix.csv data) [Tullis & Bied, 1988]

Separation Matrix for Combined Privacy n		Meal Preparation	Eating	Meal clean-up	Exercise	Medical Care	Full-body Cleansing	Hand/Face Cleansing	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation and Leisure	Small-group Recreation and Leisure	Dressing/Undressing	Clothing Maintenance	Meetings and Teleconferences	Planning and Scheduling	Subsystem Monitoring and Control	Pre/Post-EVA Operations	IVA Support of EVA Operations	Proximity Operations	General Space Station Housekeeping	ORU Maintenance and Repair	Logistics and Resupply	Payload Support	Life Sciences Experiments	Materials Processing Experiments
Crew Support	Meal Preparation		11	8	48	102	187	80	190	197	47	172	177	100	131	47	35	22	3	3	3	10	20	20	12	54	63	63
	Eating			5	37	91	176	69	179	186	36	161	166	89	120	36	24	25	14	14	14	7	17	17	1	43	52	52
	Meal clean-up				40	94	179	72	182	189	39	164	169	92	123	39	27	30	11	11	11	4	12	12	6	46	55	55
	Exercise					54	139	32	142	149	31	124	129	52	83	35	37	40	51	51	51	44	34	34	36	8	15	15
	Medical Care						85	26	88	95	55	70	75	36	59	55	67	80	105	105	105	98	88	88	90	48	39	39
	Full-body Cleansing							107	3	10	140	35	20	87	60	140	152	##	190	190	190	183	173	173	175	133	124	124
	Hand/Face Cleansing								110	117	33	92	97	20	51	33	45	58	83	83	83	76	66	66	68	26	17	17
	Personal Hygiene									7	143	32	17	90	59	143	155	##	193	193	193	186	176	176	178	136	127	127
	Urination/Defecation										150	25	20	97	66	150	162	##	200	200	200	193	183	183	185	143	134	134
	Training											125	130	53	84	4	12	25	50	50	50	43	33	33	35	23	16	16
	Sleep												15	72	41	125	137	##	175	175	175	168	158	158	160	118	109	109
	Private Recreation and Leisure													77	46	130	142	##	180	180	180	173	163	163	165	123	114	114
	Small-group Recreation and Leis														31	53	65	78	103	103	103	96	86	86	88	46	37	37
	Dressing/Undressing															84	96	##	134	134	134	127	117	117	119	77	68	68
	Clothing Maintenance																12	25	50	50	50	43	37	37	35	27	20	20
Station Operations	Meetings and Teleconferences																	13	38	38	38	31	39	39	23	29	28	28
	Planning and Scheduling																		25	25	25	32	42	42	24	32	41	41
	Subsystem Monitoring and Contr																			0	0	7	17	17	15	57	66	66
	Pre/Post-EVA Operations																				0	7	17	17	15	57	66	66
	IVA Support of EVA Operations																					7	17	17	15	57	66	66
	Proximity Operations																						10	10	8	50	59	59
	General Space Station Housekee																							0	18	40	49	49
	ORU Maintenance and Repair																								18	40	49	49
	Logistics and Resupply																									42	51	51
Mission Operations	Payload Support																										9	9
	Life Sciences Experiments																											0
	Materials Processing Experimen																											

Table 36: Colocation Matrix for Sequential Functions (sequentialMatrix.csv data) [Tullis & Bied, 1988]

	Colocation Matrix for Sequential Function	Meal Preparation	Eating	Meal clean-up	Exercise	Medical Care	Full-body Cleansing	Hand/Face Cleansing	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation and Leisure	Small-group Recreation and Leisure	Dressing/Undressing	Clothing Maintenance	Meetings and Teleconferences	Planning and Scheduling	Subsystem Monitoring and Control	Pre/Post-EVA Operations	IVA Support of EVA Operations	Proximity Operations	General Space Station Housekeeping	ORU Maintenance and Repair	Logistics and Resupply	Payload Support	Life Sciences Experiments	Materials Processing Experiments
Crew Support	Meal Preparation		42	0	1	1	0	12	3	3	0	0	0	3	5	0	2	3	1	0	0	0	2	0	1	0	2	2
	Eating			41	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Meal clean-up				5	1	0	1	2	1	2	0	1	6	2	1	1	7	0	0	0	1	2	1	0	4	2	1
	Exercise					1	3	2	1	5	0	0	1	1	2	0	2	0	1	0	0	0	0	0	0	1	0	0
	Medical Care						0	1	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
	Full-body Cleansing							0	9	4	0	1	1	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hand/Face Cleansing								1	21	1	2	1	2	1	0	0	1	3	0	1	0	1	1	0	0	3	1
	Personal Hygiene									13	0	6	2	1	7	0	0	1	0	0	0	0	0	0	0	0	0	0
	Urination/Defecation										3	2	8	2	8	0	4	2	4	3	0	2	0	3	3	4	2	4
	Training											0	2	1	0	0	0	3	0	0	0	0	0	0	1	0	3	0
	Sleep												1	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
	Private Recreation and Leisure													5	3	2	1	0	0	0	0	0	0	0	0	0	1	0
	Small-group Recreation and Leis														1	0	1	0	1	0	0	0	0	0	0	0	1	0
	Dressing/Undressing															1	0	2	0	0	0	0	0	0	0	0	0	0
	Clothing Maintenance																0	0	0	0	0	0	0	0	0	0	0	0
Station Operations	Meetings and Teleconferences																	2	1	0	0	0	2	0	0	1	1	2
	Planning and Scheduling																		3	1	1	0	0	0	2	2	1	1
	Subsystem Monitoring and Contr																			0	1	0	1	3	1	0	0	0
	Pre/Post-EVA Operations																				0	0	0	0	0	0	0	0
	IVA Support of EVA Operations																					1	0	0	0	0	0	0
	Proximity Operations																						0	0	0	0	0	0
	General Space Station Housekee																							0	2	0	0	0
	ORU Maintenance and Repair																								0	1	0	0
	Logistics and Resupply																									0	0	0
Mission Operations	Payload Support																										0	1
	Life Sciences Experiments																											2
	Materials Processing Experimen																											

Table 37: List of Crew Tasks (taskList.csv) and Daily Durations (taskDurations.csv) [Tullis & Bied, 1988]

Task	Duration, crew-minutes per day
Meal Preparation	15
Eating	20
Meal clean-up	5
Exercise	480
Medical Care	60
Full-body Cleansing	5
Hand/Face Cleansing	15
Personal Hygiene	20
Urination/Defecation	90
Training	90
Sleep	480
Private Recreation and Leisure	60
Small-group Recreation and Leisure	60
Dressing/Undressing	10
Clothing Maintenance	20
Meetings and Teleconferences	60
Planning and Scheduling	30
Subsystem Monitoring and Control	30
Pre/Post-EVA Operations	90
IVA Support of EVA Operations	240
Proximity Operations	60
General Space Station Housekeeping	30
ORU Maintenance and Repair	30
Logistics and Resupply	30
Payload Support	60
Life Sciences Experiments	480
Materials Processing Experiments	480

Table 38: Utility Function Calculation Inputs for the Cislunar Habitat Design Problem (utilitiesMatrix.csv data)

FOM	Utility Type	Minimum	Maximum	Value at Min	Value at Max
Structure Mass	Linear	0	1	0	1
Equipment Mass	Linear	0	1	0	1
Plumbing/Electric Line Run Masses	Linear	1	100	1	0
Habitable Volume	Linear	20	100	0	1
Unusable Volume	Linear	0	20	1	0
Available Non-Dedicated Stowage Volume	Linear	0	100	0	1
Habitable Floor Area and Other Usable Horizontal Surface Area	Linear	0	1	0	1
Largest Spatial Vista	Linear	0	3	0	1
Colocation of Sequential Tasks	Linear	0	500	0	1
Colocation of Equipment/Related Stowage by Function	Linear	0	1	0	1
Anthropometry of High Duration Tasks Interferences	Linear	0	30	1	0
Placement for Function/Ergonomics	Linear	0	1	0	1
Placement for High Frequency/Duration Use	Linear	0	1	0	1
Size of Dedicated Private Spaces	Linear	0	1	0	1
Separation for Privacy	Linear	0	27000	0	1
Separation of Clean and Dirty Zones	Linear	0	900	0	1
Separation for Noise	Linear	0	30000	0	1
Minimum Translation Path Width	Linear	0	1	0	1

Table 39: Evaluation Criteria Weights for the Cislunar Habitat Design Problem (weightsMatrix.csv data)

Evaluation Criteria	**Criteria Weighting**
Structure Mass	0
Equipment Mass	0
Plumbing/Electric Line Run Masses	0.065
Habitable Volume	0.169
Unusable Volume	0.058
Available Non-Dedicated Stowage Volume	0
Habitable Floor Area and Other Usable Horizontal Surface Area	0
Largest Spatial Vista	0.078
Colocation of Sequential Tasks	0
Colocation of Equipment/Related Stowage by Function	0
Anthropometry of High Duration Tasks Interferences	0.06
Placement for Function/Ergonomics	0
Placement for High Frequency/Duration Use	0.059
Size of Dedicated Private Spaces	0
Separation for Privacy	0.262
Separation of Clean and Dirty Zones	0.079
Separation for Noise	0.17
Minimum Translation Path Width	0

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