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# POTENTIAL APPLICATIONS OF MODULARITY TO ENABLE A DEEP SPACE HABITATION CAPABILITY FOR FUTURE HUMAN EXPLORATION BEYOND LOW-EARTH ORBIT

**Mr. Matthew Simon**
NASA Langley Research Center, United States, matthew.a.simon@nasa.gov

**Mr. Larry Toups**
NASA Johnson Space Center, United States, larry.toups-1@nasa.gov

**Mr. David Smitherman**
NASA Marshall Space Flight Center, United States, david.smitherman@nasa.gov

Evaluating preliminary concepts of a Deep Space Habitat (DSH) enabling long duration crewed exploration of asteroids, the Moon, and Mars is a technically challenging problem. Sufficient habitat volumes and equipment, necessary to ensure crew health and functionality, increase propellant requirements and decrease launch flexibility to deliver multiple elements on a single launch vehicle; both of which increase overall mission cost. Applying modularity in the design of the habitat structures and subsystems can alleviate these difficulties by spreading the build-up of the overall habitation capability across several smaller parts. This allows for a more flexible habitation approach that accommodates various crew mission durations and levels of functionality. This paper provides a technical analysis of how various modular habitation approaches can impact the parametric design of a DSH with potential benefits in mass, packaging volume, and architectural flexibility. This includes a description of the desired long duration habitation capability, the definition of a baseline model for comparison, a small trade study to investigate alternatives, and commentary on potentially advantageous configurations to enable different levels of habitability. The approaches investigated include modular pressure vessel strategies, modular subsystems, and modular manufacturing approaches to habitat structure. The paper also comments upon the possibility of an integrated habitation strategy using modular components to create all short and long duration habitation elements required in the current exploration architectures.

## INTRODUCTION

Habitats are the vehicles in which crew live and work during long duration missions in space. They must provide a pressurized environment and a complement of subsystems which deliver the functionality necessary to keep astronauts healthy and productive. In the context of habitat design, modularity is the buildup of a habitat with a complete set of required functionality through the assembly or recombination of multiple habitat modules or modular subsystems within the habitats. There are several potential benefits of these approaches over a “monolithic” habitat design which contains all subsystems necessary to support crew during the mission. First, multiple, smaller elements increase launch flexibility to alleviate launch vehicle mass or payload shroud dimensional constraints. Second, having multiple, separable pressurized modules or modular subsystems with common components can improve the safety of a spacecraft through increased redundancy and reduced spares requirements. Third, modularizing habitat approaches enables customization of the launched habitat size to mission duration and requirements, which can improve in-space propulsive performance and the overall cost of the mission. These and other improvements come at the potential cost of increased complexity and/or increased mass through excessive redundancy, additional structure and additional docking ports.

Two things drive a designer to the consideration of modularity in habitat design. First, assembly of a large habitat which exceeds available launch vehicle volume or mass requires a modular approach with in-space assembly. The primary example of this is the International Space Station (ISS) which was assembled over many years and launches. The added desire of reconfigurability and the eventual replacement of hardware also resulted in the use of a somewhat modular subsystem design on ISS and the International Standard Payload Rack (ISPR). As the destination of such a habitat is located further away from Earth or as cost constraints limit the selection of available launch vehicles to smaller options, modularity becomes more of a driver. For example, the use of commercially available expendable launch vehicles such as the Delta IV-H for the delivery of a large long-duration habitat beyond Low-Earth Orbit (LEO) would require a modular habitation strategy (or an advanced propulsion

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strategy). The second consideration which drives modularity is the desire to slowly buildup or upgrade a habitation capability for incrementally more lengthy or difficult missions. For example, if a campaign of missions of 30, 180, and 360 days were desired, delivering a 30 day habitat wouldn't meet the requirements for longer missions and delivering a 360 day design would be substantially over-capable for the 30 day mission. A 30 day habitat which could be upgraded by an additional module and logistics to achieve the 180 and 360 day capabilities could potentially save several launches and significant cost over the design of two separately customized habitats.

The following section describes the details of the various methods of adding modularity to habitat designs, with particular focus on the acceptable or advantageous allocation of functions across modules.

## CATEGORIES/TYPES OF MODULARITY

Approaches to modularity in habitat design can be categorized into four categories:

- Pressure Vessel Modularity
- Distributed Functions
- Modular Subsystems
- Commonality across Subsystems

Each is described here in detail, including identification of the reasons to select each approach and directions for concerning its application.

### Pressure Vessel Modularity

Pressure vessel modularity refers to the separation of a habitat pressure vessel into multiple pressure vessels or multiple modules for integration. These two basic variations of this type of modularity each have their own distinct advantages and disadvantages.

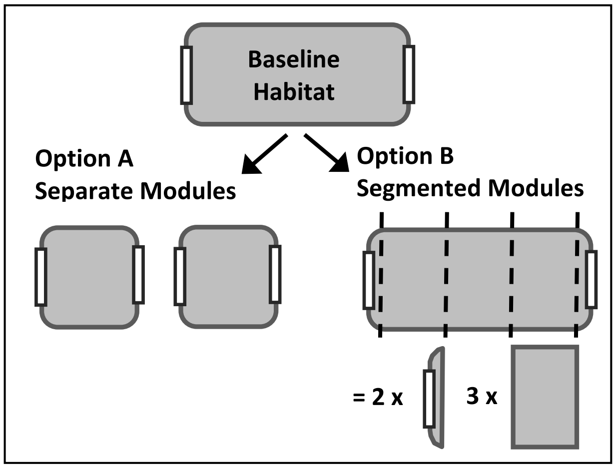

Figure 1: Pressure Vessel Modularity Options

Splitting a habitat into "separate modules" (Option A) is ideal when multiple launches are required, smaller or more affordable launch vehicles are desired, or multiple visits to a habitat with increasing durations are planned. Separate module approaches particularly trade well with smaller diameter habitats as the smaller modules can potentially leverage existing commercial launch vehicles by reducing individual module mass, saving cost by alleviating the necessity of a heavy launch vehicle for some missions. Separate modules with some docking or berthing capability are required for in-space assembly of a complete habitat through pre-deployment and assembly of modules in space. The major disadvantage to this strategy is the additional mass required by additional docking ports, pressure shell endcaps, and critical subsystems which must be present on every individually operable vehicle such as air circulation, power distribution, and thermal conditioning.

There are several strategies to make this method of modularity more effective. First, equipping these multiple modules with mobility could potentially enable multiple vehicle exploration of a destination. This strategy is also appealing when logistics deliveries are necessary, as the logistic modules could potentially serve as additional habitat modules. Another useful strategy is the use of an external airlock which would only be delivered on missions requiring substantial Extravehicular Activity (EVA). Pre-deploying either airlocks or logistics using highly efficient low thrust propulsion systems can save a substantial amount of mass compared to the fast chemical stages necessary to deliver crew in a timely manner. Additionally, repurposing the modules for the disposal of trash, waste, and unneeded equipment at the destination can potentially make up for the mass increases associated with multiple pressurized modules in propulsion savings.

Another modular pressure vessel strategy is Option B, a "kit of parts" approach to pressure vessel design referred to as the "segmented module" approach. In this approach, the pressure vessel is constructed of a number of identical cylindrical sections which are integrated and terminated with endcaps customized for the mission objectives (options include airlock/EVA endcap, docking endcap, driving endcap, etc). These modules are assembled on the ground and outfitted prior to launch. The two primary advantages of this strategy are 1) the potential mass savings achievable with customization of habitats for each mission and 2) the potential manufacturing and design cost savings resulting from the use of a standard set of core parts. The major disadvantage of this approach is that the "full capability habitat" necessary for long duration missions may weigh slightly more as a result of the interface structure necessary to integrate the pieces together unless some low mass assembly method is developed. This approach is may also increase the risk of leaks.

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## Distributed Functions

The distribution of the functions (and corresponding subsystems) across the various modules is an important consideration when considering a multiple module approach. The following list represents the basic functions provided by habitats, with italicized functions indicating those which must be present in every separate habitable module:

- Life Support
    - *Atmosphere Pressurization and Circulation*
    - Air Revitalization
        - CO2 Removal
        - CO2 Reduction
        - O2 Generation
    - Water Recovery
    - Waste Processing
- *Thermal Control*
- Avionics
    - Command and Control
    - Communications
- Power
    - Generation
    - *Conditioning*
    - *Distribution*
    - Storage
- *Fire Detection/Suppression*
- Crew Accommodations
    - Sleep/Crew Quarters
    - Galley
    - Wardroom
    - Hygiene
    - Waste Collection
    - Exercise
    - Housekeeping/Trash Management
    - Medical Care
- Workstations
- Radiation Protection Shelter
- Extravehicular Activity Prep.
- Suit Maintenance
- Vehicle Maintenance
- Science

A well-designed habitat considers the layout of these functions to properly balance habitat size, crew health, and productivity[1]. Three considerations need to be taken into account to assure the proper distribution of these functions across multiple modules: 1) the interrelationships between the functions themselves, 2) layout concerns addressing the use of volume, and 3) historical placement of subsystems.

Many functional interrelationships and habitability concerns[2,3] drive the separation or collocation of certain functions to improve crew health and productivity or to reduce mass. These include the:

- separation of work and recreation spaces
- separation of private and public spaces
- separation of clean and dirty areas
- separation of noisy and quiet areas
- collocation of related or sequentially used functions
- collocation of functions with shared equipment, resource supplies lines, waste streams (tools, power, water, hydrogen, etc)

The degrees of separation or collocation desired for each type of relationship can be determined by expert or astronaut elicitation[3] and by the results of crew survey/scheduling studies. Tullis and Bied capture many of these relationships in their analysis of a space station interior[3].

In addition to these functional relationship drivers, other layout-specific design factors affect the distribution of functionality across modules including:

- prevention of crowded space in any one module
- providing adequate space for the performance of all tasks, particularly high frequency or long duration tasks
- providing adequate translation paths to allow for safe egress in all contingency situations
- consideration of placement of micrometeoroid and radiation shielding when locating functions appropriately to take advantage of their locations
- avoiding complexity and excessive inter-module line runs

Placement of functions must also consider the distribution of functions from a mass perspective, not exceeding launch vehicle or propulsion stage capabilities. Equally sized modules allow for the smallest mass requirements for a number of splits modules. It is also anticipated common-sized modules will be desired to reduce manufacturing cost.

Historically in modular habitat studies certain functions tend to be grouped together in separate modules. Figure 2 illustrates some possible groupings with a basic notional proximity analysis. Proximity analyses and “bubble diagrams” are commonly used tools which capture functional interrelationships and historical precedents to inform designers in the layout process. This particular diagram summarizes the proximity of functions in historical spacecraft. From the one below, a clear trend in literature is the separation of work areas from crew quarters and recreational areas (illustrated by the notional red separation line). The blue separation line represents another possible separation more focused upon even distribution of available volume to enable similar sized modules as a cost reduction strategy.

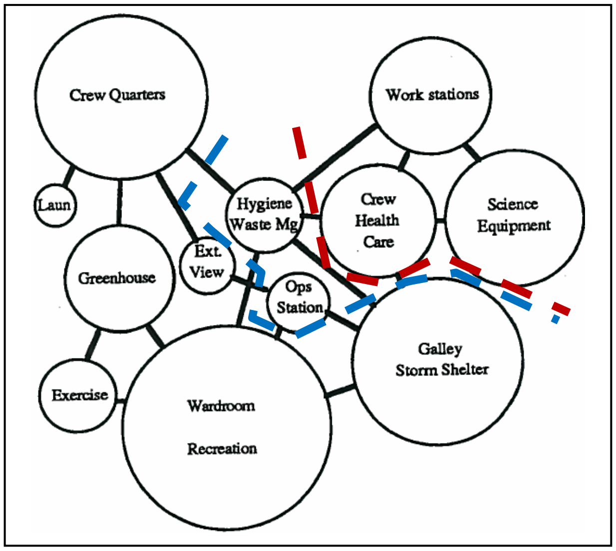

Figure 2: Historical Spacecraft Proximity Analysis and Sample Separations of Functions across Modules[4]

| Grouping Consideration | Functions to Group |
|---|---|
| Water Recovery Loop | Water Recovery, Waste Processing, Hygiene, Waste Collection, |
| Air Revitalization Loop | CO2 Removal, CO2 Reduction, O2 Generation |
| Sequential/Related Function: Exercise-Hygiene | Exercise, Hygiene |
| Waste Stream | Hygiene, Housekeeping/Trash Management |
| Shared Tools/Related Function/Historical | Medical, Science, Workstations |
| Shared Tools/Related Function: EVA and Maintenance | EVA Preparation, Suit Maintenance, Vehicle Maintenance |
| Related Function: Food | Galley, Wardroom |
| Radiation Protection | Crew Quarters, Radiation Protection |

Table 1: Synthesized Grouping Recommendations based upon Collected Considerations

Taking all of these considerations into account, several likely groupings of functions across modules become apparent. Table 1 lists the groups and driving rationales for their grouping. These groupings were derived from a qualitative interpretation of the multiple considerations in literature and designer opinion. These represent groups of functions which, in general, should not be placed in separate modules. However, they are not all necessarily hard constraints. As not all functions fall in this list of obvious groupings, some functions can be separated from others without compromising their function or adding substantial complexity, so long as their new location does not violate one of the separation requirements. Table 2 lists the critical separations between certain functions. These indicate that these functions should not be adjacent or closely located. It also indicates that while the functions may be located in the same module, there is a benefit to separating them across modules if possible.

| **Work** | **Recreation** |
|---|---|
| Science | Wardroom |
| Workstations | Exercise |
| **Private/Quiet** | **Public/Noisy** |
| Crew Quarters | Wardroom |
| **Clean** | **Dirty** |
| Crew Quarters | Hygiene/ Waste |
| Galley | Exercise |
| Medical | EVA Prep (on surface) |

Table 2: Critical Separation of Functions[2,3]

Based upon these critical grouping and separation concerns, 2, 3, and 4 module configurations can be created, either qualitatively or with a more rigorous numerically defensible analysis[3]. There is no generic allocation of functions to modules however, as the need for and size of modular approaches are very mission specific (destinations and delta V's play a significant role in the selection of a launch vehicle, which in turn determines the habitat). It was observed that more than four modules for most habitat designs become unnecessarily complex and a significant mass driver.

<u>Modular Subsystems</u>

Regardless of whether the habitat is a "separate module", "segmented module", or conventional "monolithic" design, there are potential benefits to modularizing the subsystems. There are basically two types of subsystem modularity:

1. Multiple small subsystems for full capability
2. Scarred subsystems designed for upgrade

'Multiple small subsystems for a full capability' refers to the use of many smaller, less capable pieces of hardware which can be combined to achieve an overall end-state capability. An example is the use of many smaller sorbent beds for the "scrubbing" of carbon dioxide (CO2) out of the atmosphere instead of one large one. There are two major advantages to this strategy. First, this allows for easy scaling of the capability customized to the habitat size and mission.

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For example, if a habitat is to perform both a short and long duration mission, the initial CO2 removal subsystems could include two sorbent beds saving mass over the full capability of four beds. Second, it allows for use of a common technology and subsystem components across all habitable vehicles (i.e. similar systems on entry vehicle, roving vehicles, suits, large habitats). This allows for a substantial reduction in the amount spares required across all elements. For example, if the CO2 removal sorbent beds were common for the entry vehicle, habitat, and suits, then the entry vehicle and suit beds could serve as backups to the habitat during most of the mission.

‘Scarred subsystems designed for upgrade’ refers to the forward thinking strategy of designing of subsystems (especially subsystem interfaces) for the planned integration of performance enhancing components later in the lifecycle of the habitat. This strategy is particularly appealing when the upgrade to an enhanced capability would normally require a full replacement of the current systems, resulting in wasted equipment (e.g. upgrading life support systems from open loop to closed loop systems). ISS is an example of the successful application of this strategy. The ‘scarring’ strategy was used to upgrade the CO2 removal system on ISS to include compression of CO2 for CO2 reduction and a “water save” feature for water reclamation from the sorbent beds. The system was ‘scarred’ for integration of the new hardware, which made update of the systems relatively easy. The important consideration for carrying out this ‘scarring’ strategy successfully is to ensure that the subsystems are designed so that additional modules add additional capability and that layouts and hardware concerns are considered early in this design.

Several subsystems are especially well catered to these two subsystem modularity strategies. Table 3 shows the subsystems/functions which should consider the use of these strategies in the design of short and long duration habitats.

| **Multiple Smaller Subsystems** | **Scarring for Upgrade** |
|---|---|
| CO2 Removal | CO2 Removal |
| Water Recovery | CO2 Reduction |
| Thermal Control | O2 Generation |
| Power Generation | Water Recovery |
| Power Storage | Waste Processing |
| | Thermal Control |
| | Communications |
| | Power |
| | Hygiene |
| | Medical Care |

Table 3: Subsystems/Functions Compatible with Modularization

Commonality across Subsystems

At the lowest level of modularity, there are opportunities to reduce mass, cost, spares, and tools through enforcing common components across subsystems. Even an improvement like using only 3 to 4 sizes of bolts has the potential to save hundreds of kilograms and thousands of dollars through reduced tools and spares requirements. Care must be taken to design systems and missions so that this commonality can be enforced. For example, choosing to operate a long duration habitat at the same atmospheric pressure as the entry vehicle enables the possibility for one design, development, certification and manufacturing process for components like fans, pumps, filters, etc. Though these considerations cannot be readily traded early in the design process, their potential impact for cost and mass reduction are worth investigation in future efforts.

## PRACTICAL MODULARITY EXAMPLE

The benefits of these modular approaches can be illustrated through a practical example: an evolvable habitat at Earth-Moon Lagrange Point 2 (E-M L2) which will first demonstrate technologies necessary for sending humans to a Near Earth Asteroid (NEA) then could be reused as the transit habitat for that NEA mission. In this example, a few potential options to implement modularity are discussed with rationale for each choice, and the impacts to mass or cost are shown where applicable. This is not meant to be an exhaustive trade study, but an illustration of the potential benefits of modularity.

### Tools and Assumptions Used for Comparison of Approaches

In this example, a parametric mass estimating tool, EXAMINE[5] (Exploration Architecture Model for IN-space and Earth-to orbit), is used to model the various modular habitat options and track mass improvements. This tool takes mission and habitat configuration parameters as inputs and determines masses, volumes, and powers of the resultant concepts for comparison purposes using historical and physics-based estimation methods. In this analysis, the assumptions for sizing habitat subsystems and outfitting are consistent with the NASA Human Spaceflight Architecture Team (HAT) assumptions and literature[6], with the modification of the following assumptions which are specific to this study:

- 4.27 m diameter pressure shell (compatible with Expendable Launch Vehicle (ELV) shrouds)
- Habitable volume required is based upon a phasing from Celentano’s “Performance Limit” curve[7] and the HAT habitable volume recommendation[8] (Figure 3)

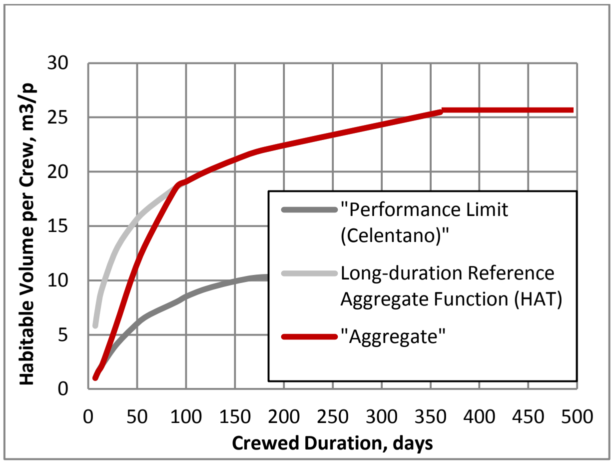

Figure 3: Habitable Volume per Crew Recommendation from HAT[7,8]

- Assumes that part of the entry vehicle habitable volume is usable to offset the required habitable volume of the habitat
- Crew accommodations complement appropriate for duration consistent with Larson and Pranke[9]
- Assumes Reaction Control System (RCS) is required to maintain L2 orbit
- 1000 kg fixed spares plus 500 kg linearly variable over a year
- Assumes a fixed 12 x 4 hour 2 person EVAs per mission (fixed for study)
- Closed-loop Life Support assumes ISS technologies
- Open-loop Life Support assumes Lithium Hydroxide (LiOH) canisters for CO2 Removal, storage for O2 and Water, disposable clothes, and no shower.

As a final note before presenting the example, cost comparisons for the approaches in the example problem are captured considering EXAMINE's masses combined with qualitative comments based upon the particular modularity strategy application.

Example Campaign Description

The following example is analyzed in depth: Assume the habitat(s) will support four crew and nominal EVAs at the destination with the following cadence of durations: a 30 day initial capability at E-M L2 followed by an upgrade to at least 180 days at E-M L2 followed by another upgrade to enable at least 360 days transit to an easy NEA. In order to satisfy these requirements, approaches must provide all subsystems and logistics necessary to perform the missions while maintaining sufficient habitable volume consistent with Figure 3. Several pressure vessel options are available to meet these goals, which can each be further enhanced with the use of distributed functions and modular subsystems. The modularity *options* addressed in this example are illustrated in Figure 4 to better communicate the configurations. Each option described in this section and is compared against the "monolithic solutions" to demonstrate its advantages and disadvantages.

Non-Modular Approaches to Example Campaign

Two non-modular approaches are possible. The first (*Option A*) involves the delivery of single-use habitats customized for each mission. This is not a sustainable strategy (three custom designed habitats are prohibitively massive and expensive), but the masses and the performance of each design provides a useful basis of comparison for modular approaches. The second non-modular approach (*Option B*) involves a large pressure vessel capable of performing the 360 day mission when outfitted appropriately, but which could be outfitted lightly for the shorter missions. This module would be equipped with all of the long duration subsystems necessary for the longest duration and could be reused for each mission by delivering logistics with crew (which may not be possible for large amounts of pressurized logistics). This approach trades the large mass and volume required to the launch of a 360 day pressure vessel against the benefit of only delivering one modules with one set of subsystems applicable to all missions.

Table 4 indicates the performance parameters for the custom-designed "monolithic" habitat concepts for each of the durations as a basis of comparison for the modular concepts. As mentioned above, *Option A* represents a good fit for habitable volume, but developing three habitats is very massive and requires a highly capable launch vehicle to deliver the 360 day habitat.

| **Duration, days** | **Habitable Volume Required, $m^3$** | **Mass of Monolithic Design, kg** | **Life Support Closure** |
|---|---|---|---|
| 30 | 25 | 17,000 | Open |
| 180 | 88 | 24,307 | Partially Closed |
| 360 | 110 | 28,784 | Partially Closed |
| Total Mass for 3 Missions | | **70,091** | |

Table 4: Performance Parameters for the *Option A*: "Monolithic, Custom Designed" Baseline Habitats

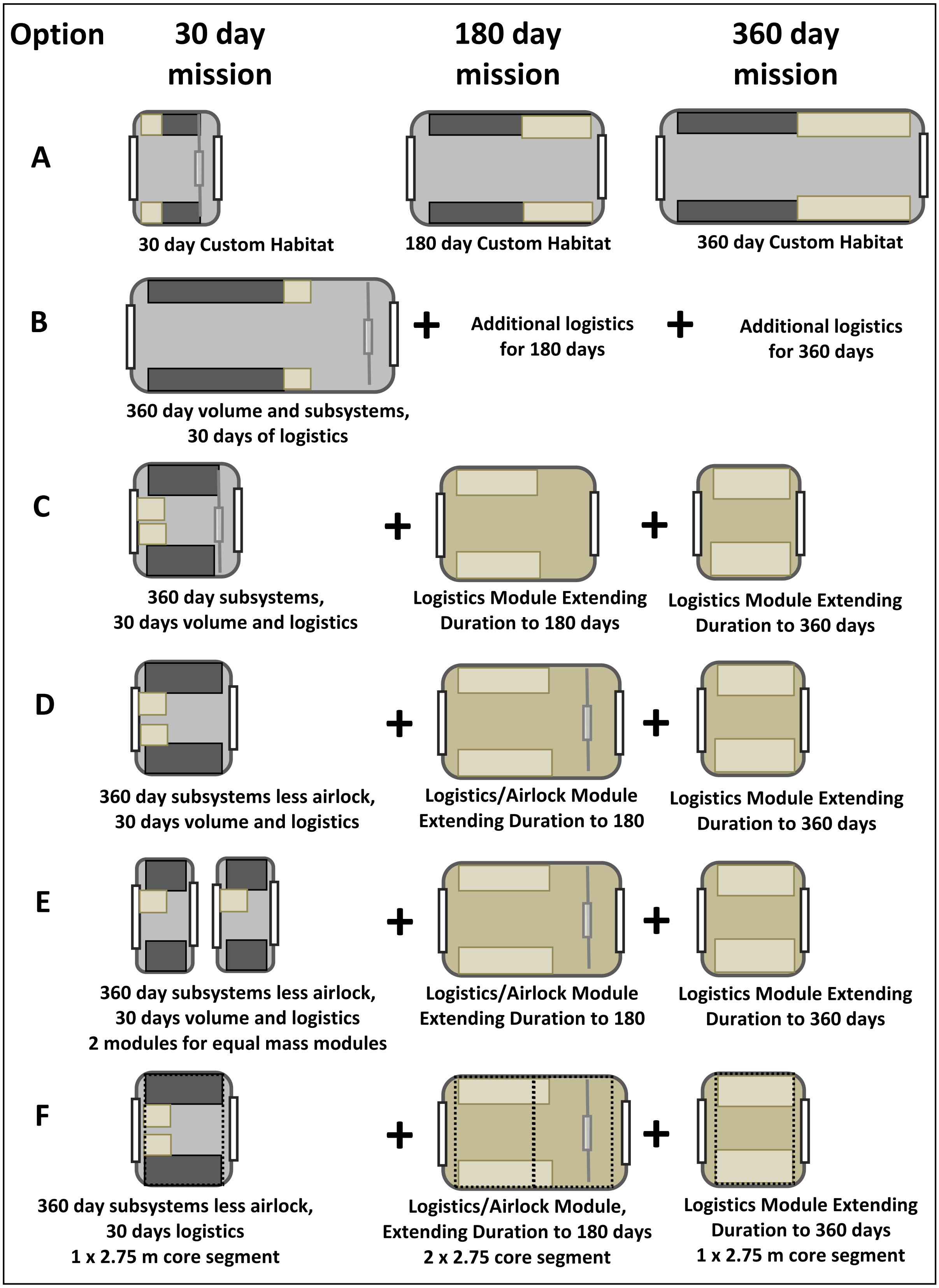

Figure 4: Example Approaches for 30-180-360 Day Example (Images not to scale)

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Table 5 shows the performance for the same missions in Table 4 assuming that the one 360 day habitat is used for all three missions. Here "Habitable Volume Provided" indicates the habitable volume available at the time of the mission assuming no space is reclaimed from the removal of trash on previous missions. The mass delivered for the mission column describes the required launch vehicle capability for each mission. For the second and third missions, this represents the mass of logistics beyond the dry mass of the vehicle, assuming that fixed spares, radiation protection, and ECLSS consumables are additive across missions, not requiring replacement each mission. This approach shows a reduction of the required mass delivery capability of the launch vehicle from 28,784 kg to 23,454 by reusing and re-outfitting a 360 day habitat.

| **Duration, days** | **Habitable Volume Provided, m$^3$** | **Mass Delivered for Mission, kg** | **Mass of Outfitted Habitat, kg** |
|---|---|---|---|
| 30 | 127 | 23,454 | 23,454 |
| 180 | 116 | 6,243 | 25,837 |
| 360 | 110 | 9,190 | 28,784 |
| Total Mass for 3 Missions | | **38,887** | |

Table 5: Performance Parameters for *Option B*: "Monolithic" 360 Day Pressure Vessel Outfitted Uniquely for Mission

Modular Approaches to Example Campaign

There are thousands of modular habitat trade variations which could improve upon aspects of the habitat performance across the example campaign. Four approaches are presented to demonstrate the impact of modularity strategies:

*Option C:* Core Habitation Module + Logistics Modules
*Option D:* Core Habitation Module + Logistics/Airlock
*Option E:* Core Habitation Modules + Logistics/Airlock: Equal Mass Modules Variant
*Option F:* Core Habitation Module + Logistics/Airlock Modules: Segment Module Approach

*Option C:* Core Habitation Module + Logistics Modules

The first modular approach (*Option C*) is similar to *Option B*, except that logistics modules are used to deliver additional habitable volume along with logistics. These additional modules decrease the required size of the 30 day habitat and allow for customization of habitable volume to mission durations similar to *Option A*. This 30 day habitat still maintains non-modular 360 day subsystems, but only provides 30 days of logistics storage and habitable volume for the first mission, augmenting the habitat thereafter with additional logistics modules. For this option, it is assumed that only maintenance and spares items and radiation protection are additive, not requiring replacement after the first mission. The use of logistics modules in *Option C* make it a more practical solution than *Option B* as the amount of pressurized logistics required to support longer durations is difficult to package within the crew transfer vehicle. The size and shape of these logistics modules can vary as long as the minimum habitable volume and logistics for the mission are provided. Table 6 shows that *Option C* further reduces the maximum required launch capability to 21,687 kg. Performing a more detailed scrub of logistics to prevent complete replacement some logistics categories would reduce the mass of the second and third logistics carriers further, making this an even more advantageous solution. The overall increase of outfitted mass of Option C compared to Option B shows that adding modularity to reduce required performance of launch vehicle increases the in-space propulsion system requirements to maneuver a larger stack. Typically this penalty for using modularity is a function of how many separate modules are used.

| **Duration, days** | **Habitable Volume Provided, m$^3$** | **Mass Delivered for Mission, kg** | **Mass of Outfitted Habitat, kg** |
|---|---|---|---|
| 30 | 25 | 21,687 | 21,687 |
| 180 | 88 | 8,826 | 26,262 |
| 360 | 110 | 10,832 | 34,399 |
| Total Mass for 3 Missions | | **41,345** | |

Table 6: Performance Parameters for *Option C*: Core Habitation Module + Logistics Modules

*Option D:* Core Habitation Module + Logistics/Airlock

*Option C* is a favorable concept, but a more equal distribution of mass between the three modules provides more potential benefit to reduce required launch vehicle capability. *Option D* attempts to achieve this by offloading the airlock capability from the 30 day core habitat to the first logistics vehicle. Table 7 shows the results of this trade. Further shuffling of the functionality across modules is possible, but significant changes may compromise on the functionality of the initial habitat. For example, In *Option D*, the delay of the airlock delivery prevents EVAs on the first flight.

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| Duration, days | Habitable Volume Provided, $m^3$ | Mass Delivered for Mission, kg | Mass of Outfitted Habitat, kg |
|---|---|---|---|
| 30 | 25 | 18,163 | 18,163 |
| 180 | 88 | 11,131 | 25,750 |
| 360 | 110 | 11, 014 | 33,584 |
| Total Mass for 3 Missions | | **40, 308** | |

Table 7: Performance Parameters for *Option D*: Core Habitation Module + Logistics/Airlock Modules

### *Option E:* Core Habitation Modules + Logistics/Airlock: Equal Mass Modules Variant

Designing equal mass modules is the best way to reduce required launch vehicle capability, particularly with the delivery of more modules. Designing these modules becomes a balance of number of launches, size of launch vehicle, and ensuring that the modules remain habitable. *Option E* is a variation of *Option D* that splits the initial habitat into two modules, which should result in approximately equal mass modules. If it is assumed that these two modules do not support crew independent of one another, the mass and habitable volume may be equally split (ignoring the complexity of mapping functions and volumes required for tasks as a simplifying assumption). For every split, additional hardware must be added to the two resulting modules to maintain a sealed environment and allow for connection to the module which had been split off. Additional hardware required includes:

- 2 pressure shell endcaps (82 kg each)
- 2 ring frames (54 kg each)
- 2 docking mechanisms (120 kg each)
- 2 hatches (53 kg each)
- 1 docking tunnel (134 kg)

After adding appropriate margins, the total mass penalty added for the split is 1066 kg. Table 8 shows the performance of this approach, assuming that the mass penalty for the splitting the module is equally distributed between the resulting two modules. *Option E* shows that with additional modularity and the cost of an extra launch, the launch vehicle capability required can be reduced to just 11 metric tons. This approaches the capability of a Delta IV Heavy to E-M L2 with a small upper stage, which might be feasible with more work on the distribution of functions and reclamation of space from trash disposal.

| Duration, days | Habitable Volume Provided, $m^3$ | Mass Delivered for Mission, kg | Mass of Outfitted Habitat, kg |
|---|---|---|---|
| - | 12.5 | 9,615 | - |
| 30 | 25 | 9,615 | 19,229 |
| 180 | 88 | 11,131 | 26,816 |
| 360 | 110 | 11, 014 | 34,650 |
| Total Mass for 3 Missions | | **41, 375** | |

Table 8: Performance Parameters for *Option E*: Core Habitation Module + Logistics/Airlock Modules: Equal Mass Modules Variant

### *Option F:* Core Habitation Module + Logistics/Airlock Modules: Segment Module Approach

*Option F* implements the segment module approach mentioned previously. Instead of focusing on reducing the required launch vehicle capability through equal distribution of the mass, this modularity approach seeks to construct habitats out of identical pressure vessel "building blocks" to reduce manufacturing cost. This incurs a penalty of a less optimal evolution of habitable volume across missions, but the differences may be minor if enough segments are used. Option F shows a modification of Option D using four cylindrical barrel segments instead of the custom length barrels used in Option D. Option D modules had barrel lengths of 2.5 m, 5.66 m, and 2.55 m respectively. Option F replaced these with a common barrel length of 2.75 m, using one segment for the first and third modules and two segments for the second module resulting in barrel lengths of 2.75 m, 5.5 m, and 2.75 m respectively. For the second module a 5% pressure vessel mass penalty was added to account for the split in the barrel section. Table 9 shows that for a little extra mass and habitable volume on early missions, significant cost savings through manufacturing can be gained with little impact to the design.

| Duration, days | Habitable Volume Provided, $m^3$ | Mass Delivered for Mission, kg | Mass of Outfitted Habitat, kg |
|---|---|---|---|
| 30 | 32 | 18,312 | 18,312 |
| 180 | 93 | 11,132 | 25,879 |
| 360 | 110 | 10,983 | 33,685 |
| Total Mass for 3 Missions | | **40, 427** | |

Table 9: Performance Parameters for *Option F*: Core Habitation Module + Logistics/Airlock Modules: Segment Module Approach

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Final Comments on Example

As evident from the approaches presented, slight changes to the design approach for habitats can improve launch vehicle performance, in-space propulsion performance, cost, and complexity of the overall campaign to enable human exploration missions, particularly in the context of a campaign of missions. More substantial improvements are possible through the application of more distributed functions, modular subsystems and common components.

Most of the approaches presented here focused on reducing the required launch vehicle capability, but some proposed launch vehicles would provide a large payload capacity alleviating this concern. However, manifesting habitats on the same launch vehicle with other architectural elements, such as in-space propulsion stages or surface elements, will limit the available volume within the shroud. Modular approaches, including partially inflatable concepts, can be applied to volume limited problems as well, providing significant advantages in packaging efficiency and integrated launch stack length.

## FORWARD WORK

This paper is intended to provide a summary of modular approaches to habitation, informing future investigators of the options available and their general benefit. It also sets the stage for a study to create an integrated habitation strategy across all habitable elements in the HAT architectures. Desired future work includes modifying existing tools to run modularity trades automatically without much of the manual modification used for the example. This automatic modular habitat framework should also be equipped to optimize each modular strategy (e.g. segment module design) for a particular mission or set of missions. This will enable the best instantiations of each modular strategy to be compared, allowing for a fully informed choice between which ones to implement.

Finally, the approaches investigated in this paper represent a small fraction of the modular habitation trade space. Additional considerations warranting study include:

- Use of mixed inflatable and rigid pressure shells to improve packaging efficiency
- The impact of sizing modules for disposal during the mission to improve propulsion performance
- Capturing the benefit of reclaiming space through trash compaction, disposal, and reconfiguration of interior layouts.
- The actual performance of modularized subsystems and their impact on habitat designs
- Non-segment module modular construction methods
- Application of modularity principles across all habitable vehicles in an architecture including: rovers, habitats, entry vehicles, landers, etc.

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