COMMONALITY ANALYSIS FOR EXPLORATION LIFE SUPPORT SYSTEMS

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This paper investigates opportunities for commonality in exploration life support systems. Five different use cases are considered: life support in (1) an extravehicular activity suit for in-space use and on planetary surfaces, (2) the lunar lander, (3) a habitat for the lunar surface or Earth-Mars transit, (4) a pressurized rover, and (5) a Mars surface habitat. For each use case a quantitative analysis of architectural options is carried out and a set of interesting architectures is identified. Based on these interesting architectures, a set of interesting portfolios of system architectures, containing one interesting architecture per use case, is enumerated. Within these portfolios, a systematic analysis of opportunities for design and technology commonality is carried out. An assessment of the benefits and penalties of specific commonality opportunities is conducted, and a set of recommendations for interesting commonality opportunities and associated design implementations is derived. The results of these analyses indicate that the above portfolio of use cases will require the development of water regeneration, regenerative CO_2 removal, and oxygen regeneration technologies. Specific opportunities for commonality include the use of common CO_2 removal technology across all use cases, and the use of common water and oxygen regeneration systems for low-gravity use in lunar and Mars applications. Opportunities for reusing CEV carbon dioxide and humidity removal system designs on the lunar lander and as part of long-duration habitats were also identified.

INTRODUCTION

HUMAN exploration of the Moon and Mars, as well as of other potential deep space targets such as Near Earth Objects (NEO) or Phobos, will require the development of a number of new human spaceflight capabilities and associated space systems. Some of these systems are already under development, such as the Crew Exploration Vehicle (CEV) or the Ares I launch vehicle; others are in the planning stages, such as the lunar lander, the Ares V launch vehicle, and the lunar surface infrastructure [1, 2]. The sustained development and operation of these new systems requires significant resource expenditure and introduces significant developmental and operational risk; commonality in design, technologies, and operations offers the potential to improve life-cycle cost and risk properties. Specifically, commonality can (1) reduce overall development cost and risk through the intentional or unintentional reuse of designs from heritage systems, (2) reduce operational risk through increased operational experience with fewer custom designs, and (3) reduce operational cost through the maintenance of fewer dedicated production lines (with lower costs for associated capital equipment, manufacturing skills, and sustaining engineering) and the sharing of spare parts, as well as benefitting from learning curve effects and economies of scale through an increase in the number of repeated units per design. The downsides of commonality include potentially increased up-front cost and risk due to the additional requirements that common designs must satisfy in order to fulfill multiple use cases, as well as potentially increased system mass, volume, and power levels due to these additional requirements.

Portfolios of Complex Systems

A portfolio of complex systems can be defined as a set of complex systems which can each function independently but are grouped together to achieve a particular higher-level objective. An example of a portfolio would be an armored division – main battle tanks, repair vehicles, and fuel trucks are all complex systems which may operate on their own, but these complex systems are combined into a group to perform battlefield missions. A portfolio of crewed exploration systems typically consists of crew transportation elements, such as landers or the Crew Exploration Vehicle (CEV), crew residence elements, such as surface or transit habitats, and mobile exploration elements, such as pressurized rovers or Extravehicular Activity (EVA) suits. The entire portfolio has as its higher-level objective the exploration of the lunar and Martian surfaces.

For the purposes of this paper, a specific subset of complex exploration systems will be included in the portfolio to be examined. These systems are the Extravehicular Activity (EVA) suit, the lunar lander (the LSAM), the Small Pressurized Rover (SPR), a crew habitat for use either on the lunar surface or in transit to Mars (T-Hab), and a crew habitat for use on the surface of Mars (S-Hab). All of these systems, although possessed of varying degrees of mobility, will be referred to as "vehicles" in order to simplify terminology. Thus a portfolio is composed of several vehicles, and each vehicle has a number of technologies on board which deliver certain key life support functions. The choice of which technology option to use for each function defines a particular system architecture for that vehicle. For each vehicle there are a number of possible alternative system architectures, each based on the use of a set of specific life support technologies.

Benefits and Penalties of Commonality

Commonality may provide benefits to a portfolio by decreasing the operational cost (due to decreases in spares requirements), or by decreasing the development cost and risk (due to a reduced number of unique items to be designed and developed), or by decreasing the operational risk (due to a more rapid accumulation of runtime for any one item which is common than for a number of different items). Penalties from the inclusion of commonality in a portfolio may include increased up-mass requirements (either as non-optimized designs' excess mass of equipment or as a slightly increased mass of daily consumables). The basic trade examined in this paper is between development cost (as modeled based on the equipment mass of each portfolio's ECLS systems) and campaign mass requirements (a function of spares mass, consumables mass, and equipment mass). Campaign mass can also be converted to a cost metric by estimating the transportation costs of the required mass from the surface of Earth to the location where it will be used for exploration purposes, which allows the trading of development costs against transportation costs.

For the purposes of this paper, it is assumed that an opportunity for commonality exists if the same technology option is delivering the same function for different vehicles in the portfolio. For example, every vehicle must provide the function of atmosphere dehumidification. Two technology options available to deliver this function are desiccant silica gel and a condensing heat exchanger (CHX). If the EVA suit vehicle in a portfolio uses silica gel, but the surface habitat in the portfolio uses a CHX, then technology commonality does not exist. If both rely on silica gel, then commonality may exist (depending on the environmental conditions in which both vehicles operate).

This is a definition of commonality at the functional and technological level, which enables further commonality at lower levels, such as the component and part design levels. For early phases in the design of complex systems, many subsystems are not fully detailed, and as such commonality at the lower component, subassembly, or part levels is not possible to specify clearly, although commonality at the higher functional level enables this lower-level commonality. That is, for example, a molecular sieve used in the life support system of a transit habitat and the CEV may be designed and sized similarly for each of the two instantiations (functional and technological level commonality), with similar interfaces and requirements, but may also be assembled from the same components (lower-level commonality) and even be held together with the same size bolts (part-level commonality). At the maximum degree of commonality, the same unit would simply be used in both instantiations, but this design action cannot be immediately specified during early phases of the design process, although functional and technological commonality enables this action in later design phases.

MODELING APPROACH

In this paper, the vehicles examined are considered only in terms of environmental control and life support (ECLS) systems, with the other systems suppressed for clarity. Although a given number of types of vehicles make up a portfolio (five in this case), several instances of a vehicle may be included in a portfolio (for example, although all the EVA suits in a portfolio will use the same system architecture, more than just one physical EVA suit is required – each astronaut needs a separate suit). Including the actual number of instantiations for each vehicle enables life-cycle mass and cost trades between the different vehicles.

Figure 1 shows notional examples of the different vehicles in a portfolio:

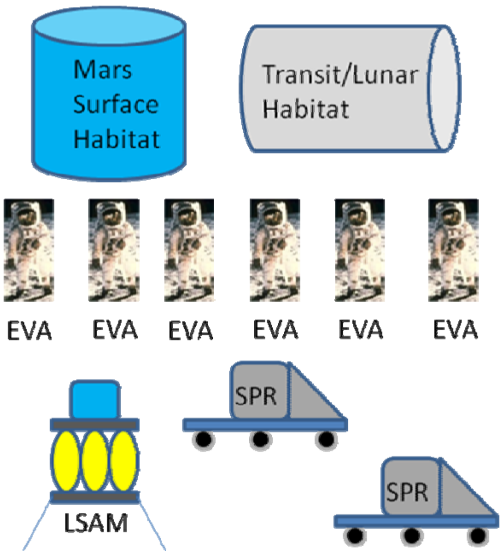


Figure 1. Notional Vehicles in the Portfolio.

Because each vehicle in the portfolio provides several life support functions, and each function can be delivered by several alternative technology options, many different system architectures (where a system architecture is a list assigning one technology option to each function) exist. These various system architectures are comprehensively enumerated for each vehicle, and metrics (including equivalent system mass, volume, and power, as well as development cost) are calculated for each system architecture. These system architectures are then down-selected based on relative ranking with respect to these metrics to a handful of interesting architectures for each vehicle.

The tool used to enumerate system architectures and calculate the metrics for each is Object-Process Network (OPN), a graphical programming environment which provides a meta-language that can be used to model the life support systems architecture space and generate architectures by constrained enumeration [3, 4]. Figure 2 shows a generalized OPN model for system architecture enumeration. Data on the performance of technology options, taken from a variety of sources [5-8], is incorporated into the model. The individual technology options each contribute to an overall equivalent mass for each system, using conversion factors for heat, power, and volume taken from [9]. Baseline campaigns, based primarily on the profile for a Mars mission but generalized to be applicable to other exploration missions as well, are assumed to allot crew sizes and usage timeframes. Logical constraints implemented in the OPN model also prevent certain infeasible combinations of technology options.

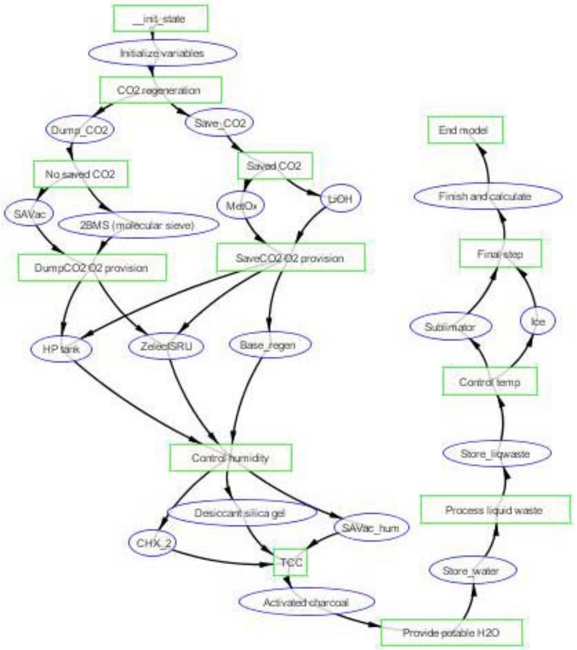


Figure 2. Example of Architecture Generator Model (see Appendix for full-size figure).

Models for system development cost and unit cost are taken from [10]. Because the cost information is only used for relative ranking of the architecture, cost results are normalized. Some specific details are derived from references; some (as in the scaling for a Zirconia electrolysis unit used in an ECLS system

[5]) are explicitly stated by the authors and adapted directly for this paper.

Once a set of interesting system architectures is selected, they are assembled into portfolios. The total number of possible portfolios is a combinatorial result of the number of vehicles in a portfolio and the number of interesting architectures for each vehicle; a complete analysis of the entire space of portfolios created is beyond the scope of this paper, so a few interesting portfolios will be identified and described.

Portfolios, once created, are screened for commonality opportunities, which are then visually displayed using an Excel-based commonality overlap matrix tool. A second Excel-based tool also calculates the benefits and penalties of commonality for each portfolio. Results for the interesting portfolios created appear in the following sections of this paper. More details on the methodology, as well as further case studies, appear in [8, 11].

ARCHITECTURAL ANALYSIS RESULTS

The results of the architecture down-selection process indicate that some technology options are an obvious choice in nearly any case, while other functions of some of the vehicles permit any of several technology options as choices of nearly equivalent value. It is these functions that provide the interesting options for commonality analysis.

It is immediately apparent from architectural analysis that potable water provision, and water recovery in general, is a very important step in maintaining a low campaign mass for all the instantiations, but especially for the two habitats. The single technology option for water provision which is most dominant is the multi-filtration (MF) option, as it recovers up to 99.9% of the water used, according to [7]. This technology is feasible on the T-Hab, the S-Hab, and the LSAM. It is assumed that water used by the EVA suit and the SPR is generally processed at a nearby habitat if possible, anyway, and so must simply be stored for a time by the SPR or EVA suit. The recovery of a maximal percentage of water is so critical to a low campaign mass because water makes up the bulk of the mass consumed by the crew every day. Crewpersons may each use up to 10 kg or more of water a day for washing, cooking, cleaning, and drinking, while the amount of food consumed by one crewperson (without counting the water in food) is less than a kilogram, less than a kilogram of oxygen is consumed by each crewperson, and the amount of mass consumed by packaging, trace contaminant control, and other supply categories during one day is usually significantly less than 1 kg as well. Therefore, a high water recovery percentage is critical, and the highest-performing technology option is a logical choice wherever possible.

Similarly, the two highest-performing technology options for the recovery of human liquid waste are of nearly equal importance to the performance of a long-term habitat, as the amount of liquid they process is about 1.5 kg per crewperson per day. The two highest-performing technologies for this function are the Vapor Compression Distillation (VCD) unit and Air Evaporation. Both are of approximately equal Technology Readiness Level (TRL) and use about the same amount of power, but the Air Evaporation system has a much higher recovery percentage of water (nearing 100%) than does the VCD (about 70%). For a crew of six, the VCD will have a daily consumable requirement of about 2.7 kg of makeup water, while the Air Evaporation unit will require about 0.5 kg of disposable felt pads daily. Because of this, the Air Evaporation system uses fewer consumables, and also becomes the preferred option.

It also becomes apparent from architectural analysis that regenerative carbon dioxide removal technologies are a positive development. The two habitats are obvious choices for regenerative carbon dioxide removal technology (much like Skylab was), as they would require tons of consumable lithium hydroxide to function over their lifetimes. The calculations related to using lithium hydroxide for vehicles with shorter usage times, such as the EVA suit and the SPR, however, are more complicated. The utility of a regenerative technology option is a trade between power system mass and consumables mass, as well as between simplicity of technology and low daily mass requirements. The break point usually depends on the use profile, that is, on the amount of time that the instantiation will be used during a campaign. For this analysis, a campaign usage profile based on a Mars surface exploration mission (but potentially applicable to lunar surface exploration missions as well) was assumed for the SPR.

Some interesting choices remain. For the transit habitat, Sabatier reactor, Advanced Carbon-forming Reactor System (a Sabatier unit with added methane-catalysis capability, called ACRS), and Zirconia electrolysis regenerative options for the reduction of carbon dioxide and the recovery of oxygen dominate the interesting system architectures. For the surface habitat, the Sabatier and zirconia electrolysis options used for in-situ resource utilization (ISRU, which here implies the extraction of oxygen from the surrounding environment) purposes dominate. This is logical, as ISRU effectively adds a negative component to the daily consumable mass requirement, which makes ISRU-containing architectures much more attractive. Performing ISRU using the carbon dioxide atmosphere on Mars is effectively trading a small additional power system mass for a permanently reduced need for makeup oxygen (not all the oxygen consumed can be regenerated from carbon dioxide exhaled, necessitating the use of makeup oxygen in non-ISRU circumstances). Although these technologies can help create a highly-closed ECLS system cycle on board the T-Hab, they can create an even higher effective closure level on board the S-Hab, thus making them very attractive options.

Although it has been noted that a regenerative technology option for carbon dioxide removal is very advantageous, the exact choice of technology option is not preconfirmed. The carbon, or 2-bed, molecular sieve (2BMS), the traditional 4-bed molecular sieve (4BMS), and the solid amine pressure-swing system (SAVac) are all still interesting technology options for more than one vehicle in the portfolio.

COMMONALITY ANALYSIS

Portfolio Creation

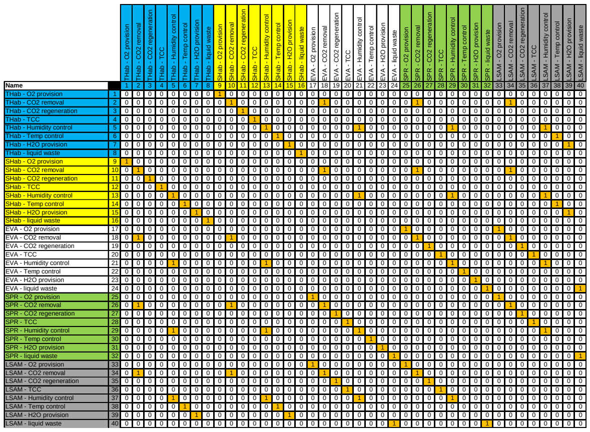
The end result of the down-selection to interesting architectures for each vehicle is the ability to combine these interesting architectures to create interesting portfolios of complex systems. Although the total number of portfolios that can be created is a combinatorial consequence of the number of interesting architectures found for each instantiation, widespread analysis of many different portfolios is too broad a topic to present in this paper. The main points can, however, be illustrated using just three portfolios.

One of the key points is that commonality always represents a trade between initial lifecycle costs (such as vehicle and system development costs) and downstream lifecycle costs, such as transportation costs (which are directly related to system lifecycle mass, here referred to as campaign mass). Any portfolio of complex systems that is to be analyzed for commonality should be analyzed on its own merits. However, some elements of this trade will become visible using just the three portfolios that follow.

The first portfolio uses a common carbon-dioxide removal technology. Carbon molecular sieves are, according to [12, 13], sufficiently small and lightly powered to be used in EVA suits, SPRs, and larger vehicles, such as the LSAM and habitats. Use of this technology option across all instantiations represents a case of maximum commonality.

The second portfolio uses the best of what are usually several closely competing technology options for each instantiation. Architectural analysis indicates that these are the carbon molecular sieve for the T-Hab and the S-Hab, as well as the SPR, but that the EVA suit slightly prefers the SAVac technology option, and for the selected use profile, the LSAM also uses SAVac, possibly enabling re-use of the CEV carbon dioxide and humidity removal system design on the lunar lander.

The final profile focuses on maximizing the maturity of the technology options selected. Predicting technology development over the next twenty years (the timeframe in which this portfolio is expected to fly) is difficult, so the relative maturity levels of these technology options are nearly certain to change, but the current relative levels of technological maturity can be used as a guideline. In this portfolio, the T-Hab uses a zeolite 4-bed molecular sieve (4BMS), the S-Hab uses a 2-bed molecular sieve, the LSAM uses a 4BMS, and the EVA suit uses SAVac, while the SPR actually uses lithium hydroxide (LiOH).



		THab - O2 provision	THab - CO2 removal	THab - CO2 regeneration	THab - TCC	THab - Humidity control	THab - Temp control	THab - H2O provision	THab - liquid waste	SHab - O2 provision	SHab - CO2 removal	SHab - CO2 regeneration	SHab - TCC	SHab - Humidity control	SHab - Temp control	SHab - H2O provision	SHab - liquid waste	EVA - O2 provision	EVA - CO2 removal	EVA - CO2 regeneration	EVA - TCC	EVA - Humidity control	EVA - Temp control	EVA - H2O provision	EVA - liquid waste	SPR - O2 provision	SPR - CO2 removal	SPR - CO2 regeneration	SPR - TCC	SPR - Humidity control	SPR - Temp control	SPR - H2O provision	SPR - liquid waste	LSAM - O2 provision	LSAM - CO2 removal	LSAM - CO2 regeneration	LSAM - TCC	LSAM - Humidity control	LSAM - Temp control	LSAM - H2O provision	LSAM - liquid waste
Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
THab - O2 provision	1	0	0	0	0	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	0	0	0	0	0	0	0	0	0	0	0
THab - CO2 removal	2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
THab - CO2 regeneration	3	0	0	0	0	0	0	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	0	0	0	0	0	0	0	0	0
THab - TCC	4	0	0	0	0	0	0	0	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	0	0	0	0	0	0	0	0
THab - Humidity control	5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
THab - Temp control	6	0	0	0	0	0	0	0	0	0	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	0	0	0	1	0	0
THab - H2O provision	7	0	0	0	0	0	0	0	0	0	0	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	0	0	0	1	0
THab - liquid waste	8	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	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - O2 provision	9	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	0	0	0	0	0	0	0	0	0	0	0	0
SHab - CO2 removal	10	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
SHab - CO2 regeneration	11	0	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	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - TCC	12	0	0	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	0	0	0	0	0	0	0	0	0	0	0	0
SHab - Humidity control	13	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
SHab - Temp control	14	0	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	0	0	0	0	0	0	0	0	0	0	0	1	0	0
SHab - H2O provision	15	0	0	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	0	0	0	0	0	0	0	0	0	0	0	1	0
SHab - liquid waste	16	0	0	0	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	0	0	0	0	0	0	0	0	0	0	0	0
EVA - O2 provision	17	0	0	0	0	0	0	0	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	1	0	0	0	0	0	0	0
EVA - CO2 removal	18	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
EVA - CO2 regeneration	19	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	1	0	0	0	0	0	0	0	1	0	0	0	0	0
EVA - TCC	20	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	1	0	0	0	0	0	0	0	1	0	0	0	0
EVA - Humidity control	21	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
EVA - Temp control	22	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	0	0	1	0	0	0	0	0	0	0	0	0	0
EVA - H2O provision	23	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	0	0	0	1	0	0	0	0	0	0	0	0	0
EVA - liquid waste	24	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	0	0	0	0	1	0	0	0	0	0	0	0	1
SPR - O2 provision	25	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	0	0	0	0	0	0	1	0	0	0	0	0	0	0
SPR - CO2 removal	26	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
SPR - CO2 regeneration	27	0	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	0	0	0	0	0	0	1	0	0	0	0	0
SPR - TCC	28	0	0	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	0	0	0	0	0	0	1	0	0	0	0
SPR - Humidity control	29	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
SPR - Temp control	30	0	0	0	0	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	0	0	0	0	0	0	0	0	0
SPR - H2O provision	31	0	0	0	0	0	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	0	0	0	0	0	0	0	0
SPR - liquid waste	32	0	0	0	0	0	0	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	0	0	0	0	0	0	1
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LSAM - CO2 regeneration	35	0	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	1	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - TCC	36	0	0	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	1	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - Humidity control	37	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
LSAM - Temp control	38	0	0	0	0	0	1	0	0	0	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	0	0	0	0	0	0
LSAM - H2O provision	39	0	0	0	0	0	0	1	0	0	0	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	0	0	0	0	0
LSAM - liquid waste	40	0	0	0	0	0	0	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	1	0	0	0	0	0	0	0	0

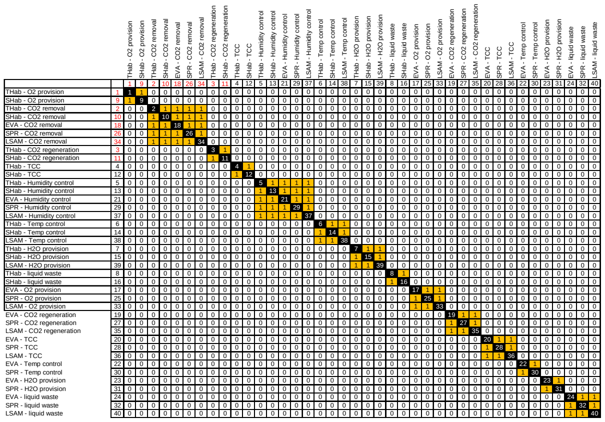
Figure 3. Commonality Overlap Matrix for First Portfolio.

Portfolio Results

The first portfolio displayed below features a common technology option for carbon dioxide removal (the carbon molecular sieve, or 2-bed molecular sieve). One of the Excel-based commonality analysis tools, designed to show the points where function, technology option choice, and sum of operating environments overlap, creates an output as seen in Figure 3. The top row and leftmost column list the various functions for each vehicle, color-coded by vehicle. Detailed breakdowns of the operating environment and technology option choices (not shown here; see [8, 11] for more detail) use mathematical overlay tools to create the overlap matrix, which highlights the points where the same technology option can be used in more than one vehicle with orange-filled boxes. Note that the matrix is symmetric.

Figure 4 shows the same information, sorted via the use of a Design Structure Matrix tool [14]. The functions are still arranged along the top and left side of the matrix, and overlapping points are still highlighted, but the blocks now indicate systems that can be made broadly common. For example, the large block in the upper-left corner of the matrix indicates the broadly common carbon dioxide removal technology option choice. This reshuffling of information assists in the visualization of the commonality opportunities.

Full-size versions of Figure 3 and Figure 4 appear in the appendix to this paper.



		THab - O2 provision	SHab - O2 provision	THab - CO2 removal	SHab - CO2 removal	EVA - CO2 removal	SPR - CO2 removal	LSAM - CO2 removal	THab - CO2 regeneration	SHab - CO2 regeneration	THab - TCC	SHab - TCC	THab - Humidity control	SHab - Humidity control	EVA - Humidity control	SPR - Humidity control	LSAM - Humidity control	THab - Temp control	SHab - Temp control	LSAM - Temp control	THab - H2O provision	SHab - H2O provision	LSAM - H2O provision	THab - liquid waste	SHab - liquid waste	EVA - O2 provision	SPR - O2 provision	LSAM - O2 provision	EVA - CO2 regeneration	SPR - CO2 regeneration	LSAM - CO2 regeneration	EVA - TCC	SPR - TCC	LSAM - TCC	EVA - Temp control	SPR - Temp control	EVA - H2O provision	SPR - H2O provision	EVA - liquid waste	SPR - liquid waste	LSAM - liquid waste
		1	9	2	10	18	26	34	3	11	4	12	5	13	21	29	37	6	14	38	7	15	39	8	16	17	25	33	19	27	35	20	28	36	22	30	23	31	24	32	40
THab - O2 provision	1	1	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	0	0	0	0	0	0	0	0	0	0	0
SHab - O2 provision	9	1	9	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	0	0	0	0	0	0	0	0	0	0	0
THab - CO2 removal	2	0	0	2	1	1	1	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	0	0	0	0	0	0
SHab - CO2 removal	10	0	0	1	10	1	1	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	0	0	0	0	0	0
EVA - CO2 removal	18	0	0	1	1	18	1	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	0	0	0	0	0	0
SPR - CO2 removal	26	0	0	1	1	1	26	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	0	0	0	0	0	0
LSAM - CO2 removal	34	0	0	1	1	1	1	34	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	0	0	0	0	0	0
THab - CO2 regeneration	3	0	0	0	0	0	0	0	3	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	0	0	0	0
SHab - CO2 regeneration	11	0	0	0	0	0	0	0	1	11	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	0	0	0	0
THab - TCC	4	0	0	0	0	0	0	0	0	0	4	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	0	0
SHab - TCC	12	0	0	0	0	0	0	0	0	0	1	12	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	0	0
THab - Humidity control	5	0	0	0	0	0	0	0	0	0	0	0	5	1	1	1	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
SHab - Humidity control	13	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	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
EVA - Humidity control	21	0	0	0	0	0	0	0	0	0	0	0	1	1	21	1	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
SPR - Humidity control	29	0	0	0	0	0	0	0	0	0	0	0	1	1	1	29	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
LSAM - Humidity control	37	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THab - Temp control	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - Temp control	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - Temp control	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THab - H2O provision	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - H2O provision	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - H2O provision	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THab - liquid waste	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - liquid waste	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - O2 provision	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
SPR - O2 provision	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	25	1	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - O2 provision	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	33	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - CO2 regeneration	19	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	19	1	1	0	0	0	0	0	0	0	0	0	0
SPR - CO2 regeneration	27	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	1	27	1	0	0	0	0	0	0	0	0	0	0
LSAM - CO2 regeneration	35	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	1	1	35	0	0	0	0	0	0	0	0	0	0
EVA - TCC	20	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	0	0	0	20	1	1	0	0	0	0	0	0	0
SPR - TCC	28	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	0	0	0	1	28	1	0	0	0	0	0	0	0
LSAM - TCC	36	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	0	0	0	1	1	36	0	0	0	0	0	0	0
EVA - Temp control	22	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	0	0	0	0	0	0	22	1	0	0	0	0	0
SPR - Temp control	30	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	0	0	0	0	0	0	1	30	0	0	0	0	0
EVA - H2O provision	23	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	0	0	0	0	0	0	0	0	23	1	0	0	0
SPR - H2O provision	31	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	0	0	0	0	0	0	0	0	1	31	0	0	0
EVA - liquid waste	24	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	0	0	0	0	0	0	0	0	0	0	24	1	1
SPR - liquid waste	32	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	0	0	0	0	0	0	0	0	0	0	1	32	1
LSAM - liquid waste	40	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	0	0	0	0	0	0	0	0	0	0	1	1	40

Figure 4. Sorted Commonality Visualization for First Portfolio.

Some results from this commonality analysis are unsurprising – for instance, it can be seen that the humidity control system should both be made broadly common, and that the processing system for human liquid waste may be made common between the EVA suit, the SPR, and the LSAM. Some of these revelations are essentially low-hanging fruit; because the common technology option for humidity removal is the best choice for all of the vehicles anyway, it is likely to be common with or without specific consideration. However, this visualization tool indicates the functional and technological commonality at an early stage of the design process, and permits designers to give consideration to commonality as the design progresses. The functional and technological commonality identified here for humidity control may serve to enable commonality at lower levels of the design as well.

Another Excel-based tool calculates total campaign mass for the portfolio, as well as total spares mass per year (based on a simple 10% replacement mass per year for all equipment model), and also tallies development cost for the portfolio. The tool estimates the benefits of commonality by applying an appropriate reduction in spares mass and development cost, based on the number of unique systems to be developed. In this way, the three tradable parameters for each portfolio can be listed.

Portfolio A: All 2BMS	
Total campaign mass	18910 kg
Spares mass per year	304.59 kg
Development cost	100%

Note that portfolio costs are normalized to the cost estimated for the first portfolio, so that relative values of cost, rather than absolute (which may not be accurately estimated, especially at such a high level of system design) can be traded.

The second portfolio examined uses the best possible option for each individual instantiation's carbon dioxide removal function, rather than a broadly common one.

Portfolio B: All best (EVA is lightest equip mass)	
Total campaign mass	16860 kg
Spares mass per year	268.65 kg
Development cost	104.6%

Notably, the development cost increases, although total portfolio campaign mass and spares mass per year drop. These values can be traded against one another for desired results when designing a portfolio of complex systems. This example illustrates the changes that commonality can bring to initial development cost and to downstream lifecycle costs.

Portfolio C: All mature technologies	
Total campaign mass	24080 kg
Spares mass per year	373.80 kg
Development cost	131.4%

A third portfolio, composed of the feasible technology options deemed most mature for every instantiation, is seen in the figures below. Note that this approach trades development risk and, to some extent, operational risk, against development cost and later lifecycle cost. Because risk is difficult to quantify, the exact value of this trade cannot be assessed, although the resulting commonality-related penalties and benefits can be calculated.

CONCLUSIONS

Recommendations for Development Strategy

The primary recommendation of this paper is that, when a portfolio of complex systems is being designed, some commonality analysis be conducted initially. This will clarify for the designers the benefits and penalties of commonality, if not precisely then at a relative level, and the designers will be able to trade initial development cost and risk for later lifecycle cost and risk (as embodied by lower total portfolio lifecycle masses and the speed at which object-years of operational experience are added on to working hardware) in a way that satisfies the needs of the particular design project at hand.

Technology Development Recommendations

Some technology development recommendations can be clearly made. The development of common water regeneration technologies, for use either on planetary surfaces or in microgravity habitats, is a critical element of the path to lower lifecycle costs for portfolios of exploration systems. It may also be possible to leverage design experience from the International Space Station water reclamation system for such a common exploration water reclamation system.

Regenerative CO_2 removal technologies are also clearly required, as non-regenerative technologies (like lithium hydroxide canisters) rapidly become mass-prohibitive. Several of these regenerative technologies, including carbon molecular sieves (also known as 2-bed molecular sieves), the traditional zeolite beds (4-bed molecular sieves), and solid amine vacuum-desorbed beds, are sufficiently competitive to merit greater attention from portfolio designers. One commonality opportunity of particular interest involves re-using the CEV carbon dioxide removal system design for long-duration habitat applications in vacuum (in-space transfer and lunar surface habitats, both of which are modeled as the T-Hab in the portfolio). Analysis indicates that the CEV carbon dioxide removal system design may also be an attractive choice for the lunar lander.

Carbon dioxide reduction technologies, which allow for the regeneration of oxygen, are also very important. Interestingly, the benefits from the technology options which completely close the air loop (at least theoretically) are not necessarily worth the additional mass they require in terms of power systems and the additional risk they bring in terms of development. That is, the Bosch and ACRS reactors are not as worth considering as are the tested Sabatier and Zirconia electrolysis systems. One additional recommendation along these lines is that these systems, if used to make a high-closure ECLS system for lunar exploration, can provide maximum benefit in terms of forward commonality to Mars exploration if they are made flexible enough to allow their adaptation to ISRU use for the Mars surface mission. The Martian atmosphere's free source of carbon dioxide can translate to a greatly reduced need for makeup oxygen if the already-existing carbon dioxide reduction systems are simply made less input-sensitive. The Zirconia electrolysis system in particular requires nothing but a source of power to produce a feed stream of usable oxygen for the crew, and on Mars this is well enough available to make this a very attractive option.

Final Summary

This paper has presented a method for commonality analysis, and carried out sufficient analysis to make certain specific recommendations related to overall development strategy and specific technology development and commonality opportunities.

It should be noted that the specific assumptions and constraints used in the analysis presented in this paper may change as the design and development of the exploration systems portfolio progresses. As such, parts of the analysis will have to be revisited also in order to confirm the continued validity of the commonality opportunities identified and described here. However, the authors are confident that commonality opportunities for water recycling and regenerative carbon dioxide and humidity removal will prove to be robust to changes in the assumptions.

ACKNOWLEDGMENTS

This paper was prepared at the Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, under a research grant from NASA's Exploration Systems Mission Directorate (ESMD). The authors would like to thank NASA for the support of this work.

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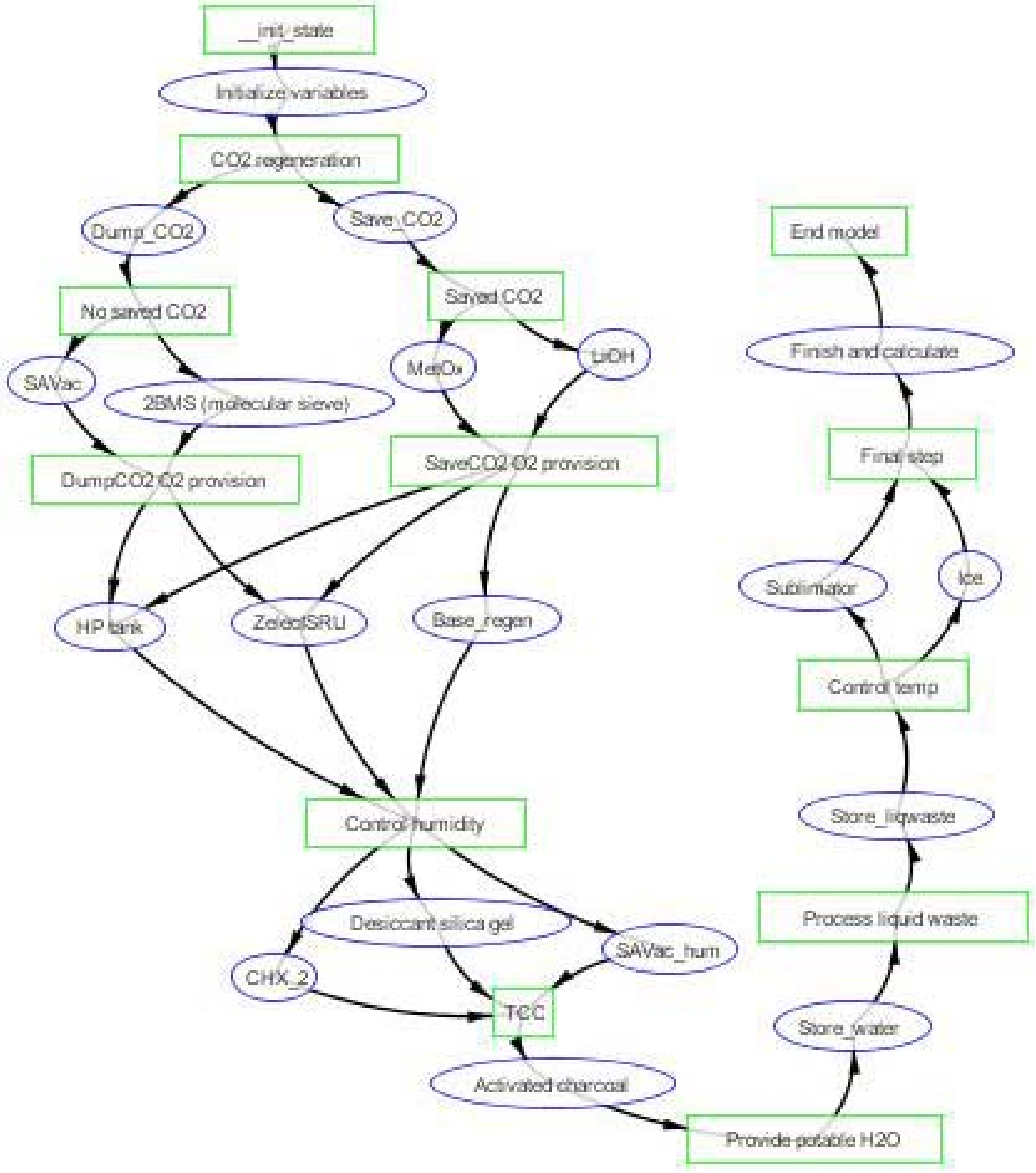
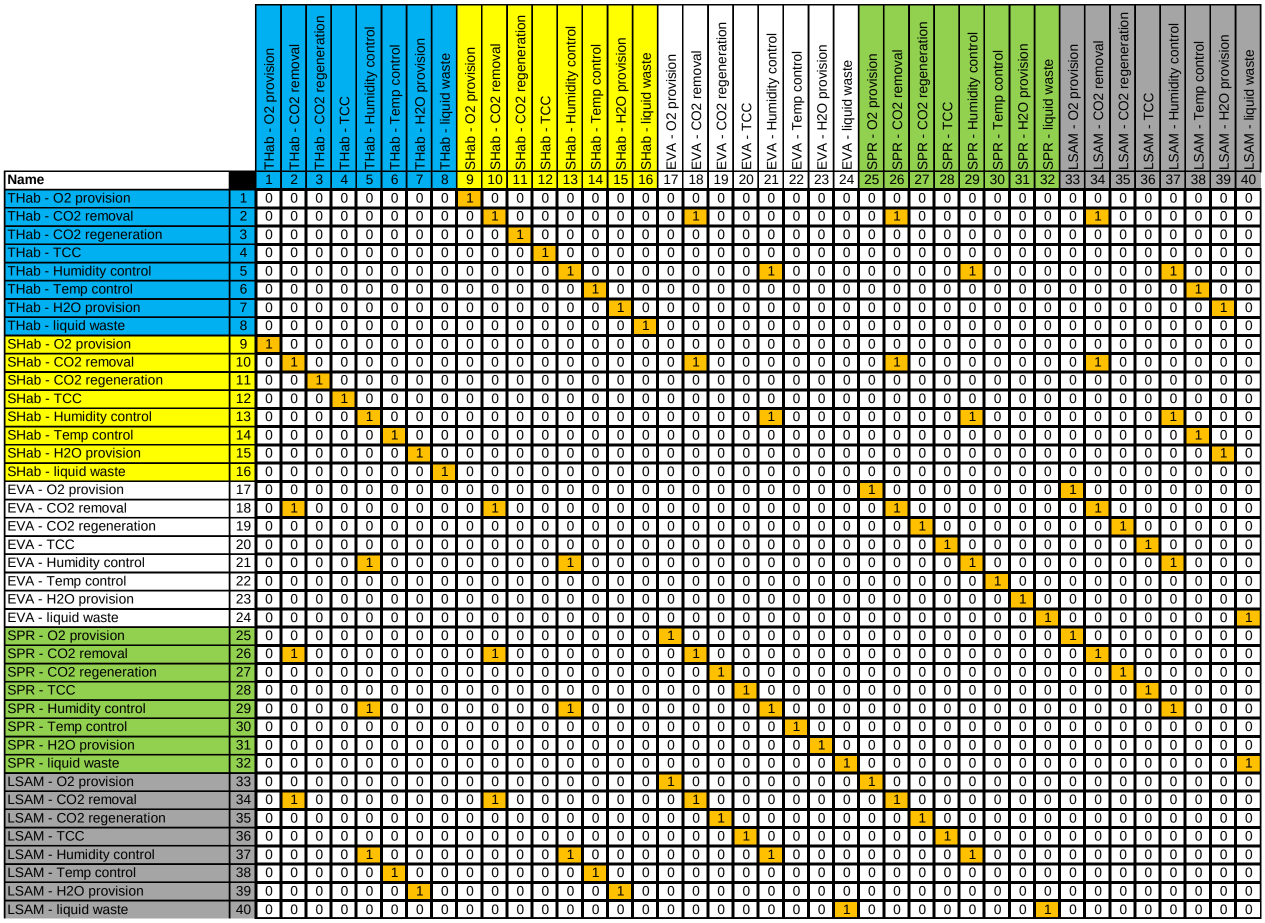
APPENDIX

Full-size version of Figure 2:



Full-size version of Figure 3:



Name		THab - O2 provision 1	THab - CO2 removal 2	THab - CO2 regeneration 3	THab - TCC 4	THab - Humidity control 5	THab - Temp control 6	THab - H2O provision 7	THab - liquid waste 8	SHab - O2 provision 9	SHab - CO2 removal 10	SHab - CO2 regeneration 11	SHab - TCC 12	SHab - Humidity control 13	SHab - Temp control 14	SHab - H2O provision 15	SHab - liquid waste 16	EVA - O2 provision 17	EVA - CO2 removal 18	EVA - CO2 regeneration 19	EVA - TCC 20	EVA - Humidity control 21	EVA - Temp control 22	EVA - H2O provision 23	EVA - liquid waste 24	SPR - O2 provision 25	SPR - CO2 removal 26	SPR - CO2 regeneration 27	SPR - TCC 28	SPR - Humidity control 29	SPR - Temp control 30	SPR - H2O provision 31	SPR - liquid waste 32	LSAM - O2 provision 33	LSAM - CO2 removal 34	LSAM - CO2 regeneration 35	LSAM - TCC 36	LSAM - Humidity control 37	LSAM - Temp control 38	LSAM - H2O provision 39	LSAM - liquid waste 40
THab - O2 provision	1	0	0	0	0	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	0	0	0	0	0	0	0	0	0	0	0
THab - CO2 removal	2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
THab - CO2 regeneration	3	0	0	0	0	0	0	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	0	0	0	0	0	0	0	0	0
THab - TCC	4	0	0	0	0	0	0	0	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	0	0	0	0	0	0	0	0
THab - Humidity control	5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
THab - Temp control	6	0	0	0	0	0	0	0	0	0	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	0	0	0	1	0	0
THab - H2O provision	7	0	0	0	0	0	0	0	0	0	0	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	0	0	0	1	0
THab - liquid waste	8	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	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - O2 provision	9	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	0	0	0	0	0	0	0	0	0	0	0	0
SHab - CO2 removal	10	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
SHab - CO2 regeneration	11	0	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	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - TCC	12	0	0	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	0	0	0	0	0	0	0	0	0	0	0	0
SHab - Humidity control	13	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
SHab - Temp control	14	0	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	0	0	0	0	0	0	0	0	0	0	0	1	0	0
SHab - H2O provision	15	0	0	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	0	0	0	0	0	0	0	0	0	0	0	1	0
SHab - liquid waste	16	0	0	0	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	0	0	0	0	0	0	0	0	0	0	0	0
EVA - O2 provision	17	0	0	0	0	0	0	0	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	1	0	0	0	0	0	0	0
EVA - CO2 removal	18	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
EVA - CO2 regeneration	19	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	1	0	0	0	0	0	0	0	1	0	0	0	0	0
EVA - TCC	20	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	1	0	0	0	0	0	0	0	1	0	0	0	0
EVA - Humidity control	21	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
EVA - Temp control	22	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	0	0	1	0	0	0	0	0	0	0	0	0	0
EVA - H2O provision	23	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	0	0	0	1	0	0	0	0	0	0	0	0	0
EVA - liquid waste	24	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	0	0	0	0	1	0	0	0	0	0	0	0	1
SPR - O2 provision	25	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	0	0	0	0	0	0	1	0	0	0	0	0	0	0
SPR - CO2 removal	26	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
SPR - CO2 regeneration	27	0	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	0	0	0	0	0	0	1	0	0	0	0	0
SPR - TCC	28	0	0	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	0	0	0	0	0	0	1	0	0	0	0
SPR - Humidity control	29	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
SPR - Temp control	30	0	0	0	0	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	0	0	0	0	0	0	0	0	0
SPR - H2O provision	31	0	0	0	0	0	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	0	0	0	0	0	0	0	0
SPR - liquid waste	32	0	0	0	0	0	0	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	0	0	0	0	0	0	1
LSAM - O2 provision	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - CO2 removal	34	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - CO2 regeneration	35	0	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	1	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - TCC	36	0	0	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	1	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - Humidity control	37	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
LSAM - Temp control	38	0	0	0	0	0	1	0	0	0	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	0	0	0	0	0	0
LSAM - H2O provision	39	0	0	0	0	0	0	1	0	0	0	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	0	0	0	0	0
LSAM - liquid waste	40	0	0	0	0	0	0	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	1	0	0	0	0	0	0	0	0

Full-size version of Figure 4:

		THab - O2 provision	SHab - O2 provision	THab - CO2 removal	SHab - CO2 removal	EVA - CO2 removal	SPR - CO2 removal	LSAM - CO2 removal	THab - CO2 regeneration	SHab - CO2 regeneration	THab - TCC	SHab - TCC	THab - Humidity control	SHab - Humidity control	EVA - Humidity control	SPR - Humidity control	LSAM - Humidity control	THab - Temp control	SHab - Temp control	LSAM - Temp control	THab - H2O provision	SHab - H2O provision	LSAM - H2O provision	THab - liquid waste	SHab - liquid waste	EVA - O2 provision	SPR - O2 provision	LSAM - O2 provision	EVA - CO2 regeneration	SPR - CO2 regeneration	LSAM - CO2 regeneration	EVA - TCC	SPR - TCC	LSAM - TCC	EVA - Temp control	SPR - Temp control	EVA - H2O provision	SPR - H2O provision	EVA - liquid waste	SPR - liquid waste	LSAM - liquid waste
		1	9	2	10	18	26	34	3	11	4	12	5	13	21	29	37	6	14	38	7	15	39	8	16	17	25	33	19	27	35	20	28	36	22	30	23	31	24	32	40
THab - O2 provision	1	1	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	0	0	0	0	0	0	0	0	0	0	0
SHab - O2 provision	9	1	9	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	0	0	0	0	0	0	0	0	0	0	0
THab - CO2 removal	2	0	0	2	1	1	1	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	0	0	0	0	0	0
SHab - CO2 removal	10	0	0	1	10	1	1	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	0	0	0	0	0	0
EVA - CO2 removal	18	0	0	1	1	18	1	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	0	0	0	0	0	0
SPR - CO2 removal	26	0	0	1	1	1	26	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	0	0	0	0	0	0
LSAM - CO2 removal	34	0	0	1	1	1	1	34	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	0	0	0	0	0	0
THab - CO2 regeneration	3	0	0	0	0	0	0	0	3	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	0	0	0	0
SHab - CO2 regeneration	11	0	0	0	0	0	0	0	1	11	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	0	0	0	0
THab - TCC	4	0	0	0	0	0	0	0	0	0	4	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	0	0
SHab - TCC	12	0	0	0	0	0	0	0	0	0	1	12	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	0	0
THab - Humidity control	5	0	0	0	0	0	0	0	0	0	0	0	5	1	1	1	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
SHab - Humidity control	13	0	0	0	0	0	0	0	0	0	0	0	1	13	1	1	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
EVA - Humidity control	21	0	0	0	0	0	0	0	0	0	0	0	1	1	21	1	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
SPR - Humidity control	29	0	0	0	0	0	0	0	0	0	0	0	1	1	1	29	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
LSAM - Humidity control	37	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THab - Temp control	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - Temp control	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - Temp control	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THab - H2O provision	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - H2O provision	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - H2O provision	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THab - liquid waste	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SHab - liquid waste	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - O2 provision	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
SPR - O2 provision	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	25	1	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAM - O2 provision	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	33	0	0	0	0	0	0	0	0	0	0	0	0	0
EVA - CO2 regeneration	19	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	19	1	1	0	0	0	0	0	0	0	0	0	0
SPR - CO2 regeneration	27	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	1	27	1	0	0	0	0	0	0	0	0	0	0
LSAM - CO2 regeneration	35	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	1	1	35	0	0	0	0	0	0	0	0	0	0
EVA - TCC	20	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	0	0	0	20	1	1	0	0	0	0	0	0	0
SPR - TCC	28	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	0	0	0	1	28	1	0	0	0	0	0	0	0
LSAM - TCC	36	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	0	0	0	1	1	36	0	0	0	0	0	0	0
EVA - Temp control	22	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	0	0	0	0	0	0	22	1	0	0	0	0	0
SPR - Temp control	30	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	0	0	0	0	0	0	1	30	0	0	0	0	0
EVA - H2O provision	23	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	0	0	0	0	0	0	0	0	23	1	0	0	0
SPR - H2O provision	31	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	0	0	0	0	0	0	0	0	1	31	0	0	0
EVA - liquid waste	24	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	0	0	0	0	0	0	0	0	0	0	24	1	1
SPR - liquid waste	32	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	0	0	0	0	0	0	0	0	0	0	1	32	1
LSAM - liquid waste	40	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	0	0	0	0	0	0	0	0	0	0	1	1	40