A Framework for the Architecting of Aerospace Systems Portfolios with Commonality

by

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Abstract

Aerospace systems are increasingly being developed as part of portfolios, or sets of related aerospace systems whose design and production is controlled by a single organizational entity. Portfolios enable synergies across the constituent systems that can reduce portfolio life-cycle cost and risk; one important synergy is commonality between the systems in the portfolio. Commonality in the form of technology and design reuse between and within systems can lead to significant benefits in life-cycle portfolio cost and risk; however, commonality usually incurs up-front and life-cycle cost and risk penalties due to increased design complexity. A careful trade-off of these benefits and penalties is required in order to assess the net benefit of specific commonality opportunities in the portfolio. This trade-off needs to be carried out during the architecting stage of the portfolio life-cycle when the leverage to improve life-cycle cost and risk is greatest.

Existing analysis methodologies are generally focused on commonality as indicated by similarities in design parameters and therefore have limited applicability during the architecting stage. This thesis provides a framework for the identification and assessment of commonality opportunities in aerospace systems portfolios during the architecting stage. The framework consists of a set of principles which are intended to provide general guidance for the portfolio architect, a methodology that transforms a solution-neutral description of an aerospace systems portfolio into a set of preferred portfolio design solutions with commonality, and a heuristic commonality screening tool which is integrated into the methodology.

The framework was applied to three case studies: commonality analysis for a portfolio of future and legacy exploration life support systems, for the historical Saturn launch vehicle portfolio, and for a portfolio of future lunar and Mars surface pressurized mobility systems. The case studies demonstrate the broad applicability of the methodology and provide insights into the impact of commonality on key portfolio metrics. Results indicate that commonality can enable life-cycle cost savings of 10% or more, dependent on the type of systems in the portfolio. The results further indicate that commonality can enable significant reductions in the number of custom development projects that need to be carried out in the portfolio; reductions of 50% or more were observed, dependent on the type of systems in the portfolio. As each project carries developmental risk and cost overhead, the reduction of the number of projects and the associated simplification of the portfolio must be considered a strong driver for commonality in aerospace systems portfolios.

Thesis Supervisor: Edward F. Crawley
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Nomenclature

R	Set of portfolio requirements
P	Aerospace systems portfolio
C	Set of portfolio constraints
PDS	Portfolio design solution
SDS	System design solution
δ	Operational overlap fraction for commonality analysis
k	Design parameter overlap factor for commonality analysis
F_k	Upper bound for the number of feasible architecture alternatives for the future use case k in the portfolio
n	Number of portfolio internal functions
a_i	Number of technology choices for portfolio function i
P	Upper bound on number of portfolio design solutions without commonality
E	Number of pair-wise commonality checks for each portfolio design solution
m	Number of future use cases in the portfolio
l	Number of legacy use cases in the portfolio

$C_{LC\_Use\_Case}$	Portfolio use case life-cycle cost
$C_{DDT\&E}$	Use case design, development, test, and evaluation cost
C_{Units}	Use case cumulative unit production cost
C_{Spares}	Use case cumulative spare part production cost
$C_{Transportation}$	Use case cumulative transportation cost
$m_{DDT\&E}$	Use case mass of equipment, spare part, and consumables units that need to be developed for a portfolio function
C_{1st_unit}	Cost for production of the first unit of a system
LR	Learning rate for system production
f_i	Transportation cost factor to destination I [$/kg]
$m_{Life\text{-}cycle}$	Life-cycle mass of a life support system including equipment, spare part, and consumables mass
$C_{LC\_Portfolio}$	Portfolio life-cycle cost for a particular PDS
$n_{Portfolio}$	Number of custom development projects in a PDS
n_{Units_flown}	Number of system units flown over the life-cycle
$n_{Portfolio}$	Number of crew members on a vehicle
Δt	Cumulative duration of vehicle / element usage
$m_{Equipment}$	Subsystem equipment mass
m_{Power}	Subsystem mass associated with power overhead

$m_{Thermal}$	Subsystem mass associated with heat rejection overhead
m_{Volume}	Subsystem mass associated with pressurized volume overhead
$m_{Consumable}$	Subsystem consumables mass per person and per day
$tare_{Consumable}$	Overhead factor to account for the storage mass associated with a specific consumable
m_{Spares}	Subsystem spare part mass normalized per person per year
$tare_{Spare\_Parts}$	Overhead factor to account for the storage mass associated with a specific spare part
n_{Spares}	Number of spare parts over the mission duration
$C_{Engine\_DDT\&E}$	Rocket engine design, development, test, and evaluation cost
$C_{Fuselage\_DDT\&E}$	Rocket fuselage design, development, test, and evaluation cost
$C_{Engine\_1st\_unit}$	Rocket engine production cost for the 1st unit
$C_{Fuselagee\_1st\_unit}$	Rocket fuselage production cost for the 1st unit
$m_{Propellant}$	Rocket propulsion stage propellant mass
$m_{Payload}$	Launch vehicle payload mass
$m_{Fuselage}$	Rocket propulsion stage fuselage mass
m_{Engine}	Rocket engine mass

n_{Engine}	Number of rocket engines per propulsion stage
Δv	Rocket stage delta-v capability
I_{sp}	Rocket engine specific impulse
g_0	Gravity at Earth sea level
α	Empirical engine scaling factor
$Thrust_{Engine}$	Engine thrust
T/W	Thrust-to-weight (force) ratio of a rocket stage at ignition
β	Empirical fuselage scaling factor
$Volume_{Propellants}$	Propulsion stage propellant volume
$V_{Reference}$	Empirical reference volume for fuselage sizing
OTF	Rocket engine oxidizer to fuel mass ratio
$\rho_{Oxidizer}$	Oxidizer density
ρ_{Fuel}	Fuel density
$C_{Lifecycle\_lunar}$	Life-cycle cost of the lunar surface mobility system
$C_{Lunar\_DDT\&E}$	Design, development, test, and evaluation cost of the lunar surface mobility system
C_{Lunar_units}	Cumulative unit cost of the lunar surface mobility system
$C_{Lunar\_transportation}$	Cumulative transportation cost of the lunar surface mobility system

$C_{Lifecycle\_Portfolio}$	Mobility portfolio lifecycle cost (Moon + Mars)
$C_{Lifecycle\_Mars}$	Life-cycle cost of the Mars surface mobility system
$C_{CrewCab\_DDT\&E}$	Crew cabin development cost
$m_{CrewCab}$	Crew cabin inert mass
$C_{Chassis\_DDT\&E}$	Chassis development cost
$m_{Chassis}$	Chassis inert mass
$C_{CrewCab\_1st\_unit}$	Crew cabin 1st unit production cost
$C_{Chassis\_1st\_unit}$	Chassis 1st unit production cost
$m_{Transportation\_lunar}$	Cumulative mobility system mass transported to the lunar surface including equipment and consumables
$n_{Vehicles}$	Number of surface mobility vehicles per use case
$m_{Vehicle}$	Surface mobility system mass including crew cabin and chassis
$m_{Consumables\_lifecycle}$	Cumulative life-cycle consumables mass per surface mobility vehicle
$m_{Structure\_crewcab}$	Structure mass of the crew cabin
$m_{CO2\_removal}$	Mass of the vehicle CO_2 removal equipment
$m_{Humidity\ removal}$	Mass of the vehicle humidity removal system
$m_{Avionics\_Comm}$	Mass of the vehicle avionics and communications systems
$m_{Thermal\_control}$	Mass of the vehicle active thermal control system

$m_{Supplementary\_power\_generation}$	Mass of the vehicle supplementary power generation system (power generation on traverse)
$m_{Energy\_storage}$	Energy storage system mass on the vehicle
$m_{Chassis\_Wheels\_Drives}$	Mass of the vehicle chassis, wheels, and drive units
$n_{Traverses}$	Number of surface traverses carried out per vehicle
$m_{Water\_Cons.}$	Water consumables mass per person per day
$m_{Oxygen\_Cons.}$	Oxygen consumables mass per person per day
$m_{Food\_Cons.}$	Food consumables mass per person per day
$m_{Humidity\_Removal\_Cons.}$	Humidity removal consumables mass per person per day
$m_{CO2\_Removal\_Cons.}$	Consumable mass for CO_2 removal per person per day
$\Delta t_{Traverse}$	Duration of the surface mobility traverse
ε	Mobility energy requirements normalized per unit mass and distance
$E_{Traverse\_Energy}$	Habitation and mobility energy required for vehicle traverse
$D_{Energy\_Density\_Storage}$	Energy density (mass-based) of the energy storage system
$m_{Vehicle\_Loaded}$	Mass of the surface mobility vehicle loaded with the crew and all consumables required for the traverse
γ_{Duty_Cycle}	Fraction of the day that the supplementary power generation is available

$P_{Supplementary}$	Supplementary power generated on the vehicle
$P_{Habitation}$	Power required for habitation on the vehicle
$P_{CO2\_removal}$	Power required for carbon dioxide filtering
$P_{Humidity\_removal}$	Power required for humidity removal
$P_{Avionics\_comm}$	Power required for avionics and communications systems on the vehicle

1. Introduction

1.1 Motivation

This doctoral thesis provides a framework for systems architects to improve the life-cycle cost and risk properties of aerospace systems portfolios through use of commonality. Aerospace systems are technical systems that have at least one key element which nominally operates in the Earth's atmosphere (without physical connection to the ground) or in space [MW-09] [LW-99]. Portfolios of aerospace systems are sets of aerospace systems which are interrelated by a common purpose. Commonality is the concept of reusing elements of existing aerospace systems for future aerospace systems or reusing elements between future aerospace systems [Wai-87]. The last decades have seen an increasing trend towards the development of portfolios of aerospace systems rather than the development of individual aerospace systems [NASA-1977] [ESAS-05] [Yod-07] [ULA-07] [Air-08]; see also Subsection 1.1.1 and Appendix I.

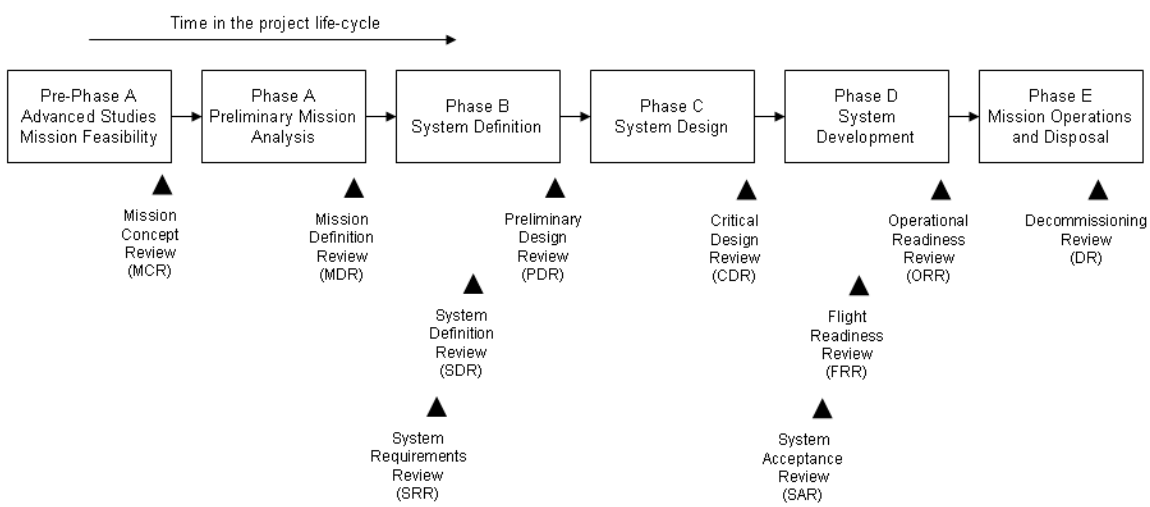

Figure 1: Overview of the project life-cycle for major NASA systems, adapted from [NASA-SP-610S]

A similar trend can be observed in many other industrial domains with complex technical products, such as product families and platforming approaches in the automotive industry [SSJ-06]. Product families generally refer to sets of technical products which have the same basic functionality but differ in optional functionality or scale; platforming refers to the process of defining common modules (the "platform") between systems in a product family.

The development of individual aerospace systems, be it for purposes of air or space transportation, defense, or other applications, is typically a complex enterprise of several years duration with expenditures measured in hundreds of millions of dollars or billions of dollars by the time the system is ready for mission operations [MAB-02] [BBC-01] [JPL-03]. Aerospace systems generally exhibit high complexity due to a large number of system elements as well as a high degree of interconnectivity between these elements; this complexity results in significant developmental and operational risk and must be actively managed over the entire life-cycle of the system [LW-99] [Fie-99] [NASA-SP-610S]. The life-cycle of aerospace systems proceeds along a staged process with multiple phases which are governed by milestones: see Figure 1 for an overview of the NASA system project life-cycle based on [NASA-SP-610S] as well as [Fie-99] for an overview of aircraft life-cycle phases. These phases incorporate an initial architecting phase where the system concept is developed and key technologies are chosen, subsequent detailed design activities, usually leading to the development and test of one or multiple engineering models and prototypes prior to manufacture, operation, and disposal of the 1st (and sometimes only) flight unit.

The high costs and risks associated with the development, production, and operation individual aerospace systems provide the motivation for developing methods to improve these life-cycle properties (i.e. to reduce life-cycle cost, developmental risk, and operational risk). The organization of aerospace systems into portfolios enables the systematic use of synergies between the individual systems to reduce the overall life-cycle cost and risk of the portfolio when compared to developing the constituent systems individually. These synergies manifest themselves in the form of common subsystem or component designs, common testing and training procedures and infrastructure, and common manufacturing infrastructure, among others. Experience with past aerospace systems portfolios [Wai-87] [Bell-67] [Sie-93] [EM-94] [deWe-06] [CT-88] [KB-06] [SW-07] [CB-06] suggests that synergies in the form of commonality can, under the right circumstances, lead to significant reductions in life-cycle cost and risk.

In the following subsections, the concepts of aerospace systems portfolios, commonality in aerospace systems, and systems architecting will be defined in more detail and their significance will be further explored.

1.1.1 Aerospace Systems Portfolios

The term ***portfolio*** as used in this thesis is borrowed from the strategic management literature [Hen-73] [MW1-08]; in this context it stands for a set of aerospace systems which exhibit an ***intentional interrelationship***. It is further assumed that all systems in an aerospace systems portfolio are at some level of organizational hierarchy ***controlled by a single organizational entity***: this entity can be exclusively based on a single organization (either commercial or governmental) or can be a joint entity created through cooperation between different commercial and / or governmental organizations (a joint venture). The concept of a single controlling entity is crucial to the ability to realize the benefits of cross-portfolio synergies: without a single entity that controls the design and production of each of the systems in the portfolio as well as the associated workforce and expenditures, synergies such as specific opportunities for commonality cannot be guaranteed to be implemented. Cases of past implementation of commonality investigated for this thesis feature single controlling entities, either commercial or governmental [ULA-07] [Air-08] [NASA-1975] [EM-94] [Cro-80].

Two basic types of aerospace systems portfolios can be distinguished based on the type of relationship between the systems in the portfolio: for the first type the systems in the portfolio are related by ***similarity or identity in externally delivered function***, i.e. the systems "all do the same things". It is assumed that while the systems provide the same externally delivered function there is ***no intentional competition*** between the systems in the portfolio.

Examples for the first type include the following families of systems (see also Figure 2):

- The Delta IV launch vehicle family [ULA-07]; see also Figure 4 below. Externally delivered function: launch of 10+ metric tons (mt) payloads into Low Earth Orbit (LEO) or Geostationary Transfer Orbit (GTO). Synergies exploited in this portfolio include common rocket engines (e.g. RS-68), common propulsion stage structures and propellant feed systems (e.g. common booster core), common avionics systems, as well as associated common production / manufacturing lines and testing facilities.

- The Airbus A320 commercial aviation aircraft family [Air-08]; externally delivered function: mid air-range transport of passengers and cargo. Synergies within the portfolio include the use of common cockpits including avionics and training simulators, common wings and fuselage sections, common gas turbine engines and Auxiliary Power Units (APUs) and the manufacturing infrastructure associated with these components.

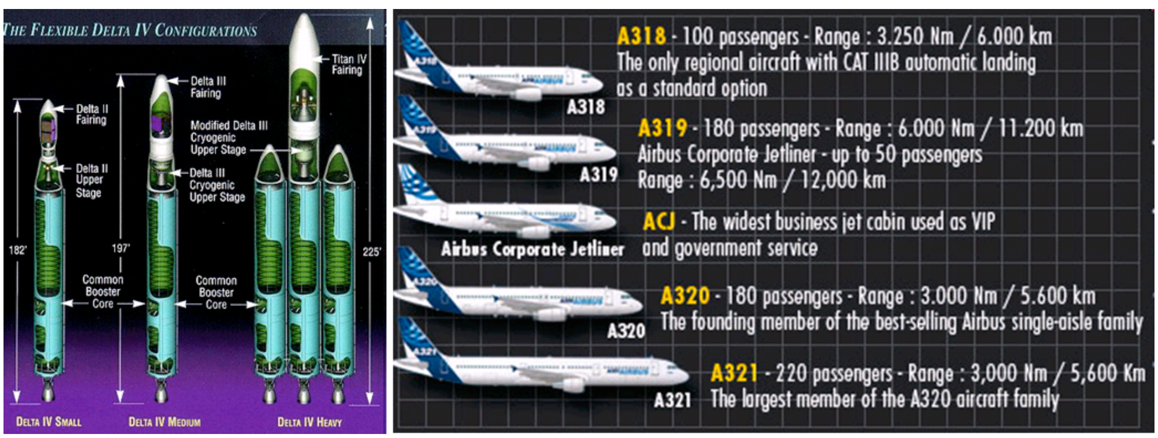

Figure 2: Examples for aerospace systems portfolios where the systems exhibit identical externally delivered functions: Delta IV launch vehicle family (left); A320 commercial aircraft family (right)

For the second type of portfolio the systems in the portfolio are related because their ***externally delivered functions are complementary*** and enable the portfolio as a whole to provide a higher-level externally delivered function. In these portfolios, commonality does not occur at the system-level but at the subsystem- or component-level. Examples for this would be commonality between life-support or power subsystems of different systems in the portfolio: while the externally delivered functions of two vehicles in the portfolio can be quite different (orbital operations vs. planetary landing), the subsystem functionality of sustaining a habitable environment for the crew and providing life support consumables for the duration of the mission is identical and enables common implementations with the associated synergies..

Examples for the second type of portfolio include (see Figure 3):

- The systems developed to carry out the Apollo lunar landing missions [NASA-1975] and the Apollo Applications Program (namely the Skylab space station program) [NASA-1977]. Synergies utilized include the use of a common guidance computer on the Apollo Command & Service Module and on the Lunar Module, the use of a retrofitted Saturn IVB upper stage as pressure vessel for the Skylab orbital workshop, as well as the use of common space suit equipment for the Apollo lunar landings and the Skylab program.

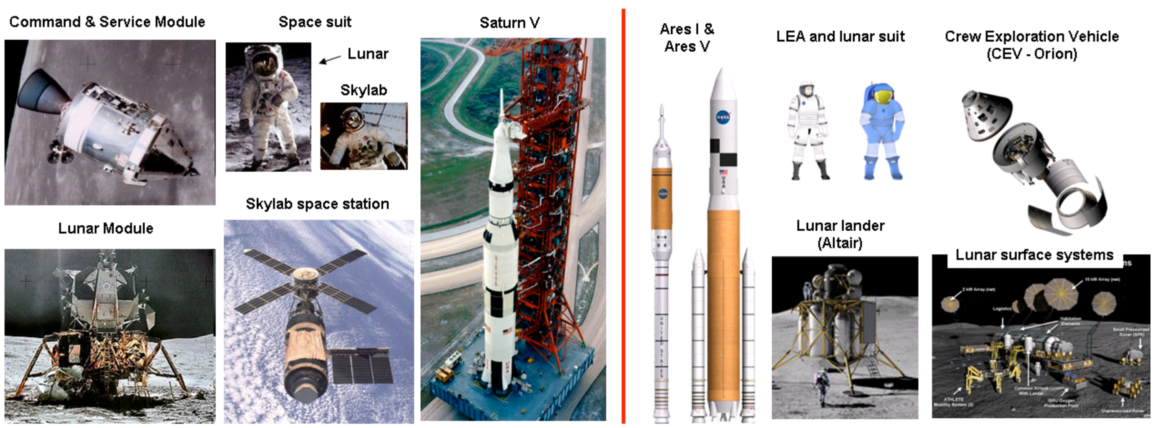

Figure 3: Examples for aerospace systems portfolios where the systems exhibit complementary externally delivered functions

- The systems currently under development for NASA's Project Constellation which are envisioned to provide a renewed lunar exploration capability at the end of the next decade [ESAS-05] [Yod-07]. Synergies identified to date include use of common solid rocket boosters as well as the use of a common upper stage engine on the Ares I and Ares V launch vehicles. As many of the elements envisioned for the lunar exploration systems portfolio are still in the early stages of development, this portfolio represents a timely opportunity for identifying further synergies and commonality opportunities.

Additional examples for historical aerospace systems portfolios of both types are described in Appendix 1. Aerospace systems portfolios of both types can be expected to play a key role in the future development of aircraft and spacecraft.

1.1.2 Commonality in Aerospace Systems Portfolios

For the purposes of this thesis, commonality in aerospace systems portfolios is defined as the possession of shared features or attributes by two or more systems in the portfolio [MW2-08]. It is important to note that this definition of commonality does not discriminate with regard to the developmental status of the systems in question, i.e. whether a system has already been developed (legacy system), is currently under development, or is planned for future development.

Commonality has long been recognized as an important tool for improving the life-cycle cost and risk properties of aerospace systems portfolios [Wai-87] [Bell-67] [Sie-93] [EM-94] [WHNC-05] [HWNC2-05] [deWe-06] [CT-88]. Major benefits achievable through commonality within aerospace systems portfolios are:

- ***Reduced overall development effort and risk***, leading to both reduced development cost and a shortened development schedule for the portfolio [Wai-87] [WHNC-05], i.e. to benefits in the non-recurring parts of the portfolio life-cycle. The mechanism for achieving these benefits is the reuse of designs, either intentionally or opportunistically from legacy designs. If implemented properly, the reuse of design will reduce the design effort required for the later designs in the portfolio, leading to a development cost reduction.

- ***Reduced fixed recurring and variable recurring cost*** [Wai-87] [WHNC-05] [Cro-80]: reuse of existing manufacturing, production, testing and training infrastructure leads to reduced fixed recurring cost (sometimes also called “standing army cost”), and economies of scale and learning curve effects through increased purchasing volumes of common components as well as reuse of manufacturing and production processes leads to reduced variables recurring cost in the portfolio.

- ***Decrease operational risk of the portfolio*** [CT-88] [KB-06] [SW-07] [CB-06] through accumulation of more operational experience with the common elements. This is a particularly attractive benefit of commonality for space systems for which generally very few units are built and operated. Each additional common unit that is operated provides a significant increase in operational experience.

- ***Reduction in the number of dedicated spares required for system operation***, which can lead to a significant reduction of logistics mass and spare part cost [CT-88] [KB-06] [SW-07] [CB-06]. It is easy to understand why common spare parts would lead to these benefits: if each spare part was unique, one would have to provide at minimum one unit each to protect against failures. If common spare parts are used, one unit may protect against several possible failures, thereby reducing the number of spare parts that need to be kept.

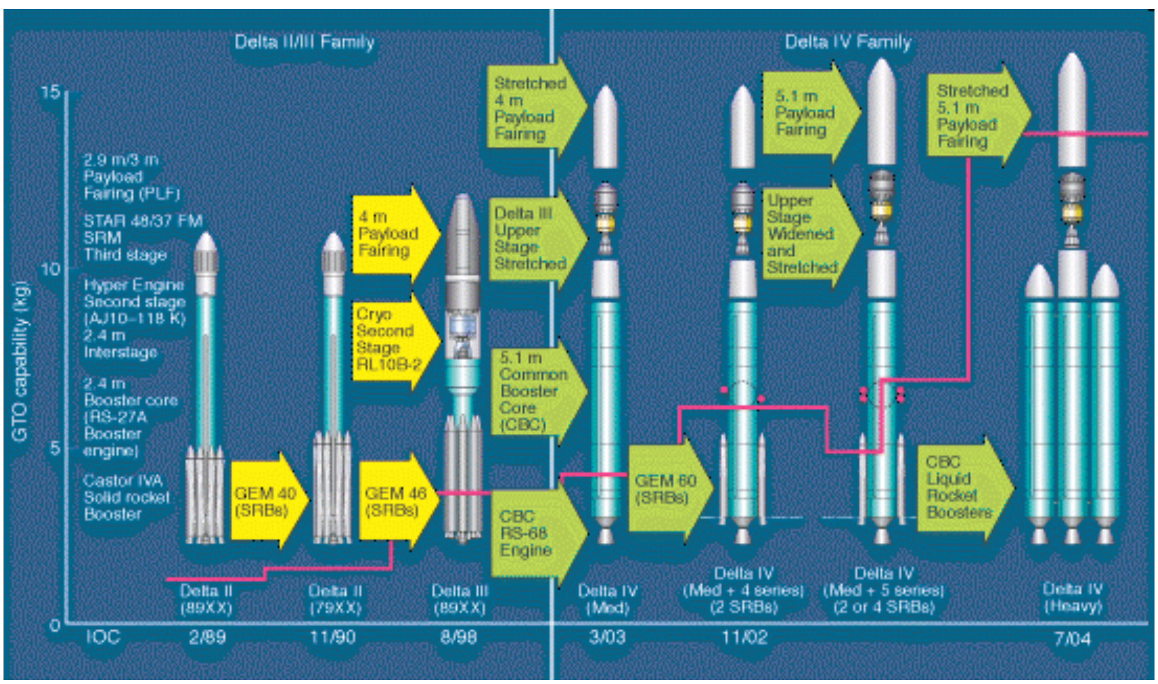

Figure 4: Design reuse and commonality in the Delta-IV launch vehicle family (note: the Delta II configuration is being phased out and the Delta III configuration was never fully operational)

Figure 4 shows how commonality was implemented in the above-mentioned Delta IV portfolio of launch vehicles. Within the Delta IV family, a common booster core first stage based on the RS-68 engine is used; this is an example for ***intentional commonality*** through reuse of engine and fuselage designs which was incorporated in the portfolio during the architecting phase. Commonality is implemented intentionally if the choice of common elements is made while all the systems including the common element are in the architecting phase.

Also, variants of the Delta III upper stage are used as upper stages; each based on the common RL-10B-2 engine. Reuse of the proven RL-10B-2 upper stage engine design as leads to a significantly more rapid accumulation of operational experience with regard to propulsion systems than could have been achieved if custom engine designs were used for all four variants. The payload fairing is also a heritage design based on the Delta III fairing, albeit stretched to 5.1 m for the higher-performance members of the family. The RL-10B engine and the fairing are examples of ***unintentional commonality*** through reuse of a heritage system from the Delta III program: a system elements which was designed for a legacy system without consideration for future systems happens to be usable for a future system which is still in the architecting stage; its design is reused in order to decrease development cost and risk of the future system. Both intentional and unintentional (legacy) commonality play an important role in the Delta IV portfolio; both of these forms of commonality should therefore be considered in future analyses of aerospace systems portfolios. In fact, case study research in the aerospace industry performed by Ryan Boas [Boas-08] indicates that unintentional commonality in the form of legacy reuse is an attractive form of commonality because it avoids penalties on the common element due to commonality at the time it is being designed.

Commonality as implemented in the Delta IV portfolio leads to benefits in the form of a single design and production line for all common booster cores (as opposed to 4 different designs with associated custom production lines), to a single sea-level engine design and production line for all vehicles (as opposed to 4 custom designs and production lines). While the portfolio includes 2 custom upper stage designs, the upper stage engine is common in all cases and is a legacy design and does not require a new production line; this reduces the number of production lines associated with the upper stages to 3 (2 for the stages and one for the engine) as opposed to 8 custom production lines in case of 4 completely custom launch vehicle systems (4 for the upper stages and 4 for the associated engines). This high-level review of the Delta IV portfolio would suggest that these commonality opportunities should lead to a reduction in non-recurring cost in excess of 50% as well as to significant learning curve benefits in the form of reduced unit production cost due to more than doubling the number of units produced per vehicle element (stage or engine). Additional risk and safety benefits would be expected due to the increased operational experience with fewer common stage and engine designs.

The potential advantages of commonality with regard to life-cycle cost and risk reductions are usually accompanied by the following potential disadvantages if commonality is intentionally designed into the portfolio from the start [deWe-05] [GOB-00] [WHNC-05] [deWe-06] [Boas-08]:

- ***Increased up-front development cost and risk*** for the first systems in the portfolio to incorporate common elements (up-front overhead of commonality). As a common element must satisfy the requirements from all systems it is a part of, it may require a more complex design than each corresponding custom design. This increased design complexity may lead to increased development cost and risk for the first system to incorporate the common element when compared to using a custom element at the beginning of the portfolio life-cycle.

- ***Additional complexity of the common element design*** may also lead to an increase in infrastructure, testing, and training requirements which in turn manifest themselves in increased fixed recurring cost for the first system to incorporate the common element.

- The increase in complexity due to additional design requirements can also cause an ***increase in production and operations cost for the common element*** compared to a custom element, leading to an increase in variable recurring cost over the lifecycle of the portfolio.

- Increased design complexity may also lead to ***increased operational risk associated with the common elements***, leading to an overall increase in operational risk over the life-cycle of the portfolio.

The above qualitative discussion of the cost and risk impact of commonality on aerospace systems portfolios highlights that the benefits of commonality tend to manifest themselves over the life-cycle of the portfolio, for example in the form of decreased cumulative development cost and risk, decreased cumulative fixed and variable recurring cost, decreased re-supply demand due to a decreased need for custom spare parts, and decreased cumulative operational risk. The penalties of commonality, on the other hand, may occur up-front (for example in the form of increased up-front development cost and risk for the common elements) as well as over the life-cycle (for example in the form of increased operational cost and risk for the common elements). This indicates a fundamental tension and ***trade-off between the long-term benefits and the short- and long-term penalties of commonality***. Based on the qualitative discussion above, it is not obvious under what conditions the benefits will dominate the penalties: the outcome of the trade depends on many technical and operational details which are only known after the architecture has been defined for each of the systems in the portfolio. The potentially significant net benefit of commonality on the one hand and the uncertainty regarding the actual net benefit of commonality that can be realized for a specific aerospace systems portfolio on the other hand provide a strong motivation for the development of approaches that allow for an assessment of the potential of commonality for a given aerospace systems portfolio, taking into account technical and operational details for each system in the portfolio. The framework outlined in this thesis (see Chapter 2) represents one possible way of carrying out this assessment.

In addition to the difficult trade-off between the benefits and penalties of commonality opportunities for the portfolio, there are also challenges related to the implementation of commonality over the life-cycle of the portfolio. Experience with large-scale development programs suggests that commonality tends to diminish due to "naturally occurring" divergence in portfolio designs over time [BC-07] [Boas-08] and that commonality solutions need to conform to the organizational constraints of the enterprise involved in development, implementation and operation of the portfolio [ANM-04]. In addition, a review of major human spaceflight programs at NASA and in industry and of the associated space systems portfolios suggests that commonality needs to be actively managed in order to be implemented effectively; lack of high-level management support may lead to a rapidly diminishing degree of commonality in portfolio system designs [Boas-08] [Quinn-08].

So far we have implicitly assumed that all the systems in the portfolio have mostly overlapping development, production / operational phases. For aerospace systems portfolios in general, this assumption may not hold because the life-cycle phases may be significantly offset in time. The degree of overlap between the different life-cycle phases in turn has an impact on the trade-off between benefits and penalties of commonality as well as on divergence of commonality over time. In order to gain a qualitative understanding of the impact of offset between development and production / operational phases we consider the simple case of a portfolio consisting of two aerospace systems and three possible cases of offset (see Figure 5):

<table>
<tr><td rowspan="3">Case 1</td><td>Time unit</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td></tr>
<tr><td>System 1</td><td colspan="9">Development</td><td colspan="11">Production / operations</td></tr>
<tr><td>System 2</td><td></td><td colspan="9">Development</td><td colspan="10">Production / operations</td></tr>
<tr><td rowspan="3">Case 2</td><td>Time unit</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td></tr>
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<tr><td rowspan="3">Case 3</td><td>Time unit</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td></tr>
<tr><td>System 1</td><td colspan="7">Development</td><td colspan="7">Production / operations</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>System 2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="7">Development</td><td colspan="6">Production / operations</td></tr>
</table>

Figure 5: Three basic cases of project relative development and operations / production phasing

In Case 1, both the development and the production / operations phases for System 1 and System 2 overlap mostly or completely (case with a slight offset is shown). In this case, the motivation for designing commonality intentionally into the system is the possibility of realizing all of the above benefits. An example for Case 1 would be the Ares I and CEV–Orion projects in the NASA Constellation portfolio described in Section 1.1.1. The case study on commonality opportunities in the historical Saturn launch vehicle family described in Chapter 4 is an example for Case 1.

In Case 2 the development phases do not overlap, but the production / operations phases do. The main motivations for intentional commonality in this case are possible reductions in operational cost and risk as well as in developmental risk. Reductions in portfolio development cost may also be achieved, although the offset between development phases and the corresponding advancement of technologies may make design commonality less desirable from a system performance stand-point. The unintentional reuse of designs from System 1 in System 2 becomes feasible and attractive in this case because penalties on System 1 are not incurred. An example for Case 2 would be the Ares I and Ares V projects in the NASA Constellation portfolio described in Section 1.1.1.

In Case 3 neither the development nor the production / operations phases overlap for Systems 1 and 2. In this case there are no fixed recurring cost benefits of commonality (one-time capital expenditures are assumed to be non-recurring), although reductions in portfolio operational and developmental risk may still occur. As for Case 2, intentional design commonality may be less attractive than in Case 1 because of technology advances during the time offset between developments. Unintentional reuse is also attractive for this case because it eliminates penalties for System 1. An example for Case 3 would be the NASA STS and Ares I projects [MPIM-08]. A special instantiation of Case 3 would be design evolution over several generations of a product or system (see Salyut space station portfolio in the appendix). The pressurized surface mobility system case study for applications on the lunar and Mars surface described in Chapter 5 is an example for Case 3.

The exploration life support systems case study described in Chapter 3 has elements of Cases 1-3: different pairings of systems in the portfolio are either developed concurrently or sequentially, and are also operated either concurrently or sequentially. For a more detailed discussion of the impact of the relative phasing of project life-cycles on the intentional and unintentional reuse of designs and on the benefits and penalties of commonality refer to [Boas-08].

1.1.3 The Leverage of Early Design Decisions (Systems Architecting)

As discussed above, the advantages of intentional commonality typically materialize over the entire life-cycle of the portfolio, whereas the disadvantages and challenges may result in both up-front and recurring penalties. Careful examination of the "net benefit" of commonality is therefore required before commonality can be adopted as part of a specific aerospace systems portfolio and the designs of the constituent systems. However, it is important to realize that the stage at which commonality is considered in the architecting and design process of the portfolio can also have a major effect on the result of the trade-off between the benefits and penalties of commonality: design freedom with regard to the architectures for the systems in the portfolio can be used to decrease the penalties of commonality and thereby improve the net benefit of specific commonality opportunities. It is therefore necessary to understand when design freedom to mitigate the penalties of commonality is available during the development of complex systems.

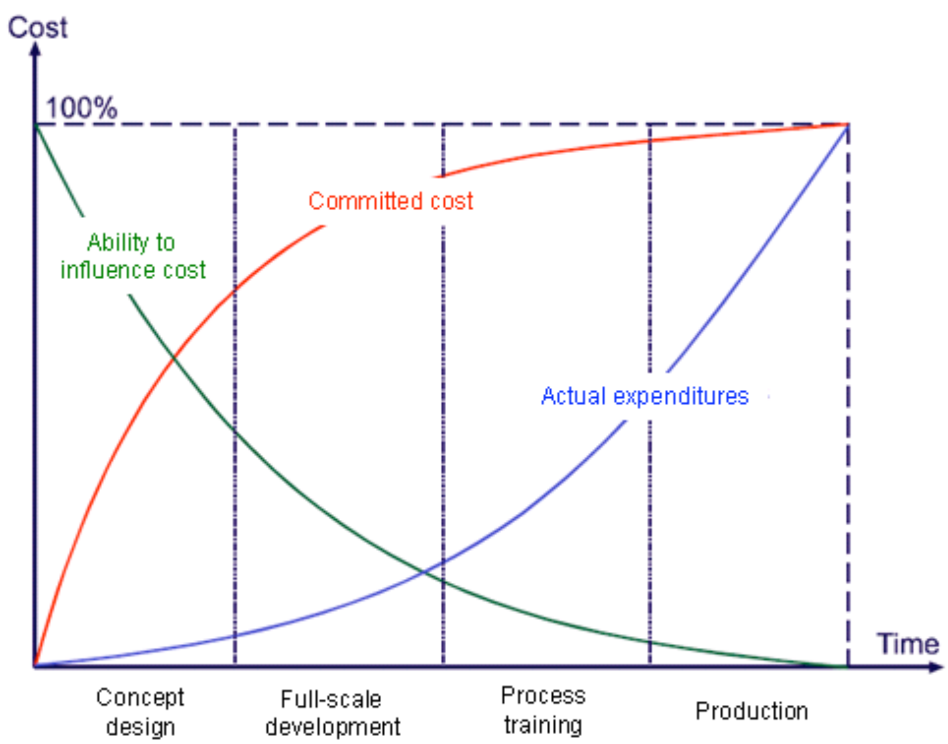


Figure 6: Notional representation of resource expenditure and commitment during the life-cycle for a complex system (adapted from [SCNF-99]); concept design corresponds to the architecting phase.

The diagram in Figure 6 shows a notional model of the resource expenditure and commitment during the life-cycle of a complex system [SCNF-99][Wai-87]: the majority of life-cycle cost is committed very early during conceptual design (i.e. when the architecture and concept of the system are being determined) and the ability to influence life-cycle cost is already greatly diminished once full-scale development (preliminary and detailed design) begins. The actual resource expenditure follows an opposing trend: during conceptual design expenditures are low; the majority of resources are expended during full-scale development.

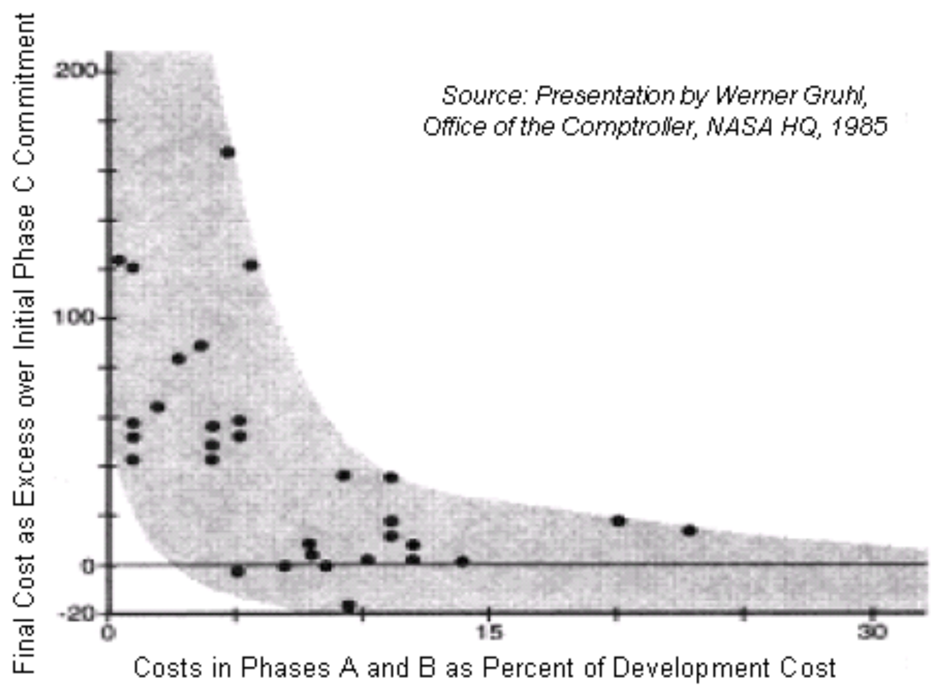


Figure 7: Program cost overrun as a function of resource expenditure during the early design phases (adapted from [NASA-SP-610S])

In the diagram in Figure 7 [NASA-SP-610S], the cost overrun of aerospace programs is plotted over the fraction of the total development cost expended during the early phases of system design (Phases A and B of the life-cycle shown in Figure 1). There is a clear trend towards lower overruns for programs that spent more resources (in a relative sense) up-front. There is also clear evidence from design and development practice in many industries that investment in the early phases of design pays off in reduced overall development time and resource expenditures, such as observed in the Toyota product development process for automotive vehicles [SWL-99] [LM-06]. The generally accepted mechanism for life-cycle savings in spite of higher up-front investment is that resource-intensive iterations in later development phases are avoided by more comprehensively exploring the architecture and design space early on. This provides a clear case for the value of systematic investigation of the architecture space for the systems in an aerospace systems portfolio, as well as for the assessment of commonality opportunities between these systems.

These observations underscore the pivotal role of the early phases of design (beginning with the architecting phase) in determining the life-cycle properties of a complex system or by extrapolation of a portfolio of systems. This suggests that there exists significant leverage to mitigate the penalties of commonality during the architecting phase of the portfolio because of the design freedom available at the time; the architecting phase is therefore the most suitable phase for assessing commonality opportunities in an aerospace systems portfolio. The framework developed in this thesis is aimed at exploiting the leverage during the architecting phase of an aerospace portfolio to identify and assess opportunities for commonality based on technical and economical factors, and also to provide a basis for shifting the trade between the benefits and penalties of specific commonality opportunities towards a higher "net benefit" of commonality.

1.2 General Problem Statement

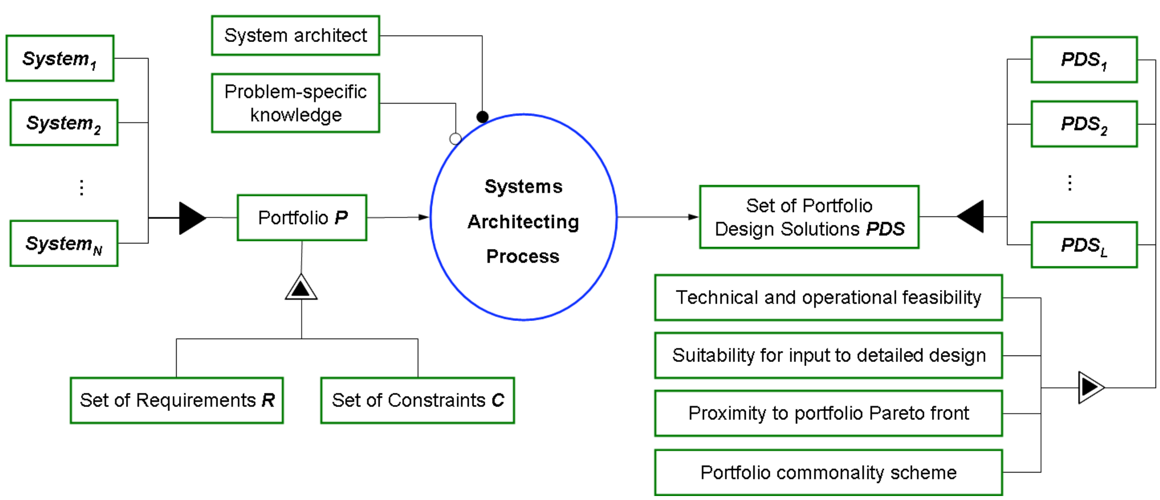


Figure 8: Black box representation of the general problem statement

Summarizing the above discussion, we can state that commonality offers great potential for improving the life-cycle properties of aerospace systems portfolios. However, in order to be implemented with maximum net benefit, commonality must be considered during the architecting stage of the portfolio and it must be managed actively and according to realistic expectations (loss of net benefit due to divergence) over the life-cycle of the portfolio. The system architect responsible for an aerospace systems portfolio with commonality is faced with four very different challenges when trying to find an effective design solution:

1. The creative challenge of finding good technically and operationally feasible design solutions for each of the systems in the portfolio,

2. The challenge of identifying opportunities for commonality that are technically and operationally feasible,

3. The challenge of evaluating economic (benefits vs. penalties), managerial and organizational feasibility of technically and operationally feasible commonality opportunities, and

4. The challenge of selecting one or several portfolio architectures that can serve as the basis for more detailed engineering development activity.

Formally, these challenges can be described by the following general problem statement: given a set $\boldsymbol{R = \{R_1, R_2, \ldots, R_K\}}$ of $\boldsymbol{K}$ solution-neutral requirements for an aerospace systems portfolio $\boldsymbol{P = \{System_1, System_2, \ldots, System_N\}}$ including $\boldsymbol{N}$ systems (also called use cases) related by a set of $\boldsymbol{M}$ constraints $\boldsymbol{C = \{C_1, C_2, \ldots, C_M\}}$, find a set of $\boldsymbol{L}$ portfolio design solutions $\boldsymbol{PDS = \{PDS_1, PDS_2, \ldots, PDS_L\}}$ for the portfolio. Each portfolio design solution in $\boldsymbol{PDS}$ must contain a set of $\boldsymbol{N}$ systems design solutions $\boldsymbol{SDS = \{SDS_1, SDS_2, \ldots, SDS_N\}}$ for each of the systems in the portfolio and a description of the extent of commonality within and between systems design solutions. In addition, each portfolio design solution in $\boldsymbol{PDS}$ must have the following attributes:

- Its systems design solutions must be technically and operationally feasible.

- It serves as input to more detailed design and development activities. In particular, it must provide a concept, selection of technologies for internal functionality, an operational description, as well as quantitative design information related to system scale for each of its system design solutions.

- It should be located close to or on the overall cost, risk, and performance Pareto front (or Pareto fronts) for the portfolio. For the purposes of this thesis, the Pareto front is defined as the set of portfolio design solutions with commonality that are not dominated by any other solution, i.e. that are equal to or better than all other portfolio design solutions with regard to at least one portfolio metric. This definition conforms with the definition provided by Smaling [Sma-05].

- It provides an explicit description of how commonality is being utilized for the portfolio design solution in terms of what functions, technologies, operations and elements of form are affected by commonality. This property of the portfolio design solution requires explicit search for commonality opportunities within each portfolio design solution.

Figure 8 provides a black box visualization of this general problem statement (which is also in a way a requirements statement for the portfolio architecting approach developed in this thesis) in the form of an Object-Process-Diagram [Dori-2002].

The research hypothesis for this thesis is that systems architecting processes which conform to the description in Figure 8 exist and enable comprehensive identification and evaluation of commonality opportunities by the portfolio architect during the earliest stages of portfolio design. This has the potential to significantly improve the way portfolios of aerospace systems are being architected and designed by allowing for the trade-off between the benefits and penalties of commonality to occur as early as possible. The general research objective is therefore to develop processes that conform to Figure 8 and to demonstrate their applicability by carrying out case studies with regard to commonality opportunities in specific aerospace systems portfolios. In Section 1.3 an assessment of the state of the practice with regard to existing systems architecting processes for portfolios with commonality is carried out as a basis for defining specific thesis objectives to address gaps in the state of the practice.

1.3 Assessment of the State of the Practice

This section provides a review of the state of the practice that is relevant to systems architecting of portfolios of complex systems with commonality. References concerning the general benefits and penalties of commonality as well as on the importance of conceptual design were provided in the introduction above. Specifically, four bodies of literature are covered in this review:

- Function-based engineering design and modularization,
- Platforming based on multi-disciplinary optimization (MDO)
- Commonality and standardization in the technology management literature, and
- General commonality and platforming literature which covers methodologies not captured in the three above categories as well as architecture-level case studies with regard to aerospace systems portfolio commonality.

The focus of the literature review is on publications describing practically applicable methodologies, tools, or strategies for the architecting of aerospace systems portfolios with commonality, and therefore by necessity the review is not all-encompassing with regard to the field of commonality analysis in complex systems.

Prior to discussing individual references in the four categories, it is useful to provide a more concrete definition of what the “systems architecting” process or phase represents in the context of this doctoral thesis. A general technical system (Figure 9) provides externally delivered functionality to the system stakeholders (and thereby delivers value) by using the system operating process which in turn requires the system internal functionality (what the system does specifically), the system form (hardware or software), and the system operator as instrument objects. System internal functionality and system form are related through technology choices for the individual internal functions and operating processes associated with these technology choices; the operating processes in turn use elements of form as instrument objects. The elements of form are described by design parameters which capture the scale and characteristics of the elements of form and the form elements are related through the system structure. The description of the system as shown in Figure 9 is the system architecture; the mapping of internal function to form without consideration for the details of the technology choices and operating processes is generally referred to as system concept.

It is important to note that the model of systems architecture shown in Figure 9 assumes that for each system considered a one-to-one mapping of internal functions to elements of form can be created by aggregation of lower-level functions and elements of form (we might call this attribute of the system “function-to-form modularity”). However, this does not mean that modularity in internal functionality (as captured by the relationships between internal functions) or physical modularity in system form (as capture by the system structure) is required for this model to apply.

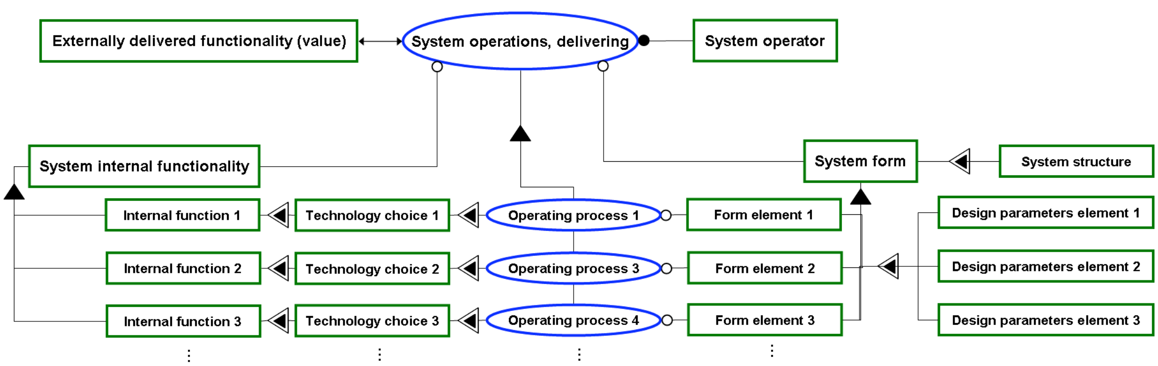


Figure 9: Overview of the system architecture of a technical system

For the context of this thesis, the system architect is assumed to define the internal functions, associated technology choices and operating processes as well as the elements of form of the system with associated design parameters and structure (i.e. the “architecture” of the system) based on a solution-neutral description of the externally delivered functionality. By extension, the portfolio architect defines the architecture of each of the systems in the portfolio. By contrast, during the design phases following the architecting phase, the design effort is typically concentrated on refining design parameters for the elements of system form. When analyzing the methodologies for commonality analysis proposed in the literature it is important to assess whether they are applicable during the architecting phase (i.e. proceed from a solution-neutral description of the systems in the portfolio), or whether they require the system architecture to be known and are mainly concerned with commonality as expressed by similarity in design parameter values.

1.3.1 Function-Based Design and Modularization

This field of the practice has its roots in the mechanical engineering design literature: the seminal book by Pahl and Beitz "Engineering Design – A Systematic Approach", the German textbook on the systematic design of technical products [PB-96], provides an excellent introduction to the field. Pahl and Beitz provide two approaches to commonality and standardization in technical systems: one based on size ranges, and one based on functional modularization of products made possible by a classification of internal functionality into basic, special, auxiliary, and adaptive functions. The size range approach (first method) is based on the use of similarity laws for scaling design parameters to accommodate different customer requirements without having to change the system architecture of the technical product; given that the architecture is assumed to be fixed and has to be known in order to apply similarity laws for scaling this approach is not helpful for commonality analysis during the architecting stage. The size-range approach has been applied to mechanical engineering products such as electric motors or electro-mechanical pumps. The second method of enabling the use of modules which are common between different technical systems by clustering identical functions together (in particular special, auxiliary, or adaptive functions) is suitable for use during the architecting phase; however, the proposed method does not directly take into account the impact of function clustering on system / portfolio metrics such as mass, cost, developmental or operational risk. Given that for aerospace systems, these metrics can be significantly affected by changes in the allocation of functions to system modules, the methodology as proposed is not suitable for use in the systems architecting of aerospace systems portfolios without adding explicit consideration of system and portfolio metrics.

Otto and Wood provide a more formalized and generalized version of the Pahl & Beitz modularization approach for general system function structures [OW-01]. This functional modularization approach is further expanded upon in the area of platforming in the much-cited text on product platforms and product platform design by Meyer and Lenherd [ML-97]. However, both the Otto & Wood and Meyer & Lenherd methodologies suffer from the same drawback as the Pahl & Beitz approach: they do not explicitly take into account system or portfolio metrics during the clustering process and therefore may not be easily applicable to aerospace systems portfolios.

Thomas provides a partially automated version of the functional clustering algorithm [Tho-89] which is applied to investigating commonality opportunities between space station berthing mechanisms with different interfacing capabilities (data, electricity, fluids, etc.). The "penalty" of commonality is analyzed by counting the number of functions allocated to each berthing mechanism for custom and for common implementations; the overhead in functions for the common case represents the commonality penalty. Thomas shows that by increasing the number of berthing mechanism variants that are designed the overhead in functionality across the berthing mechanism "portfolio" can be reduced; this is an intuitively expected result. Quantitative attributes of the mechanisms such as mass, cost, or developmental risk are not taken into account in the analysis. Note that Thomas provides another methodology in his work which is based on clustering of functions and investigating the quantitative attributes of the common and custom design solutions which is described in Section 1.3.4 below.

Zhang at al. [ZTB-06] use a two-layered approach with a function- and a behavior-layer and a behavioral modularity matrix for another partially automated approach to commonality within a product portfolio. The approach is demonstrated for an example of designing electro-mechanical terminal cut-off mechanisms for use in the automotive industry. The approach is implemented in a software tool and allows for the comprehensive analysis of functional and behavioral modularization options, but requires the architectures of the different mechanisms to be known, i.e. it is in its present form not applicable during the architecting phase. Also, the quantitative attributes of the mechanisms (number / type of parts, mass, etc.) are not taken into account in the analysis.

Perhaps the most relevant work in this field of literature is that by Reinhart, Schaefer, Fricke et al. [RSF-01] on modularization of commercial airship functionality (specifically for the “Cargolifter” airship): their approach is focused on finding an assignment of functionality to a series of increasingly capable airships that provides for incremental build-up of technological capabilities while providing revenue and staying robust to changes in the market environment. However, it seems that the fundamental Cargolifter architecture which incorporated the basic functionality (see Pahl & Beitz terminology above) is assumed to be set and known at the start of the methodology described in the paper. The task then is less to use the methodology to architect the airship portfolio, but to assign added functionality to the different airships in the portfolio that follow the baseline model in a way that is cost-effective and robust under a variety of future conditions.

Summarizing, the strength of the approaches in this field of function-based modularization and standardization is that they do not require detailed design knowledge about the systems in the portfolio and that they are therefore generally applicable during the systems architecting phase. These approaches also stress the importance of qualitative criteria to be used for identifying opportunities for commonality such as the requirement for identity in internal system functionality. The limitation of these approaches with regard to aerospace systems is that they tend to be limited to low-complexity systems (such as power tools, docking mechanisms, mechanical assemblies, etc.) or at least low-complexity representations of systems, and that function-based methodologies typically do not include explicit consideration for quantitative benefits or penalties of commonality opportunities. Given that the trade-off between the benefits and penalties of specific commonality opportunities must be based on a quantitative assessment of the overall impact on life-cycle cost and risk, function-based methodologies in their present form are not applicable to this trade-off.

1.3.2 Platforming Based on Multi-Disciplinary Optimization (MDO)

This field of commonality research is likely the most mature of the four fields covered in this review. Approaches in this field make use of the standard formulation of MDO problems for solving the portfolio design problem: the design is governed by a system of objective functions that relate design variables to figures of merits (such as weight, cost, etc.). These objective functions are then minimized given a system of equality and inequality constraints; commonality between systems in the portfolio is defined as similarity or identity in design variable values. Fellini et al. [FPW-00], Willcox and Wakayama [WW-02], and Toupet et al. [TMF-05] provide good examples for this approach.

Gonzalez-Zugasti et al. [GOB-00] outline an approach that includes a negotiation model in addition to the optimization approach with the goal to make the approach more applicable to conceptual design of planetary spacecraft.

Messac et al. [MMS-00] suggest the use of a Product Family Penalty Function (PFPF) that penalizes design parameters that are not common throughout the product family while optimizing the desired objectives; in addition they propose use of physical programming as a more efficient means of solving particular classes of platforming problems.

Simpson et al. [SMM-01] introduce the Product Platform Concept Exploration Method (PPCEM) which starts with a market segmentation grid for the products in the portfolio and then uses design principles and meta-modeling to set up the MDO problem. PPCEM represents a two-stage approach where the design variables in the platform are identified prior to the optimization of the custom parameters, whereas single-stage approaches perform the identification and optimization of the custom parameters at the same time, resulting in higher complexity for the optimization. The PPCEM approach is expanded upon in [FLD-06], [KCS-06], and [NCS-02].

Fellini and Kokkolaras [FK-02] introduce a Sharing Penalty Function (SPF) for products which have mild variation across design parameters to aid the selection of design variables for the platform; the approach is applied to platforming of automotive body structures. Khajavirad et al. [KMS-07] describes a single-stage approach based on the use of genetic algorithms which provides superior results compared to two-stage approaches; the approach is applied to the design of a general aviation aircraft family. Simpson, Siddique and Jiao [SSJ-06] provide a comprehensive review of the field.

In general, using MDO for finding commonality within a systems portfolio is a powerful approach due to the ability to investigate a large space or design alternatives. However, the MDO approaches investigated are focused on varying design parameter values and commonality opportunities are identified based on identity or similarity in design parameter values. This means that the architecture of the systems in the portfolio has to be known before the existing MDO methodologies can be applied, i.e. they are not suitable for use during the architecting phase. Also, due to the focus on commonality as evidenced by similarity or identity in design parameter values the commonality opportunities are associated with system form and not explicitly with system internal functionality, technology choices, and operating processes. Commonality opportunities with regard to system form are of significance for manufacturing cost because identical manufacturing systems can be used to produce identical elements of form. However, it is not clear how design parameter commonality relates to savings in design and development cost if commonality in internal functionality, technology choices, and operating processes is not investigated.

1.3.3 Commonality & Standardization in Technology Management

A high-level review of the treatment of commonality, platforming and standardization in the field of technology management has been carried out. The first interesting insight was that the technology management literature falls into two parts: the general technology and product portfolio management literature part, and the information technology management part. For aerospace systems portfolios primarily the former is relevant.

Standard texts on technology management [Kha-00] [BCWM-03] mention commonality, platforming and standardization as important tools for improving life-cycle properties of product and technology portfolios, but provide little in the way of actionable guidance (i.e. methods and tools) for identifying opportunities for technology commonality during architecting or design of the portfolio.

Cooper et al. [CEK-01] specifically distinguish technology platforms / commonality and marketing platforms from product design platforms, and suggest a strategic bucket funding approach for a project portfolio including platform projects in order to protect funding longer-term platform projects.

The most applicable work found in this area is by Dickinson, Thornton, and Graves [DTG-01] who provide a quantitative optimization-based methodology for the management of a portfolio of interdependent projects; the interdependence could represent commonality. However, the approach requires quantitative information on the kind of interdependence between the systems in the portfolio (i.e. impact of commonality opportunities) as input; this would make the methodology applicable only after the output from the systems architecting process described in Figure 8 is available. While not directly applicable during the systems architecting stage, the above works in the technology management literature do underscore the importance of the portfolio model for aerospace systems as a useful way of framing the commonality analysis problem.

1.3.4 General Methods for Commonality and Platforming

Thomas [Tho-89] provides a quantitative clustering-based commonality approach which was developed for the initial US space station designs; the method requires quantitative descriptions of concepts (i.e. is intended for the preliminary and detailed design phases), and includes explicit consideration for the benefits and penalties of commonality. The approach can also be used for qualitative function-based clustering during conceptual design (see above).

Martin and Ishii [MI-02] propose the QFD-based Design For Variety (DFV) method which includes two indices: the generational variety index (GVI), a measure for the amount of redesign effort required for future designs of the product, and the coupling index (CI), a measure of the coupling among the product components. Both indices are used for designing a decoupled basic product architecture from which common variants can be easily generated; the approach is applied to the design of a family of water-coolers.

Kalligeros [Kal-06] developed a method for identifying system components that can be standardized based on their robustness to changes in functional requirements and changes in other design variables. The limitation of this approach is that it requires a description of the system concept as input, and identifies commonality opportunities purely based on design parameter sensitivity to changes in requirements (the insensitive design parameters are candidates for commonality / standardization). The strengths of this approach are that it is amenable to mathematical treatment and can be coupled with real options analysis.

Liebeck [Lie-03] describes a commonality concept for the Blended Wing Body (BWB) aircraft architecture and introduces the concept of common components versus "cousin" components (changes in skin gage and hole locations allowed, but the geometry must remain identical), and also recognized the importance of "process" (i.e. operational) commonality.

Caffrey et al. [CSHC-02] examine strategies for the development of common spacecraft avionics systems based on a market-grid and associated development approaches (horizontal / vertical leverage, beachhead strategy) and recommends interface standardization, open architecture, and modularization as tools for supporting commonality.

Hodson [Hod-07] takes spacecraft avionics systems commonality analysis further and recommends commonality identification based on common internal functional and operational requirements, as well as a modular stack-based approach for hardware commonality.

Given the diversity of methodologies discussed in this subsection it is difficult to provide an assessment that captures the advantages and disadvantages of each methodology. However, it is possible to identify the reliance on information about the system architecture of the systems in the portfolio as a general feature of the general platforming and commonality analysis methodologies investigated. Requiring partial or complete knowledge about the architecture of each system in the portfolio makes application of these methodologies during the architecting phase difficult, and also results in a focus on commonality as evidenced by identity or similarity in design parameter values (much as for the MDO methodologies discussed above). However, it is interesting to note that the general platforming and commonality literature provides interesting contributions with regard to identifying opportunities for commonality other than those evidenced by design parameter commonality: [Hod-07] suggests that similarity or identity in internal functionality and operational environments can provide useful guidance on implementing commonality in avionics systems. This idea is the basis for a heuristic tool for the systematic identification of commonality opportunities developed in Chapter 2.2.

1.4 Research Gap and Specific Thesis Objectives

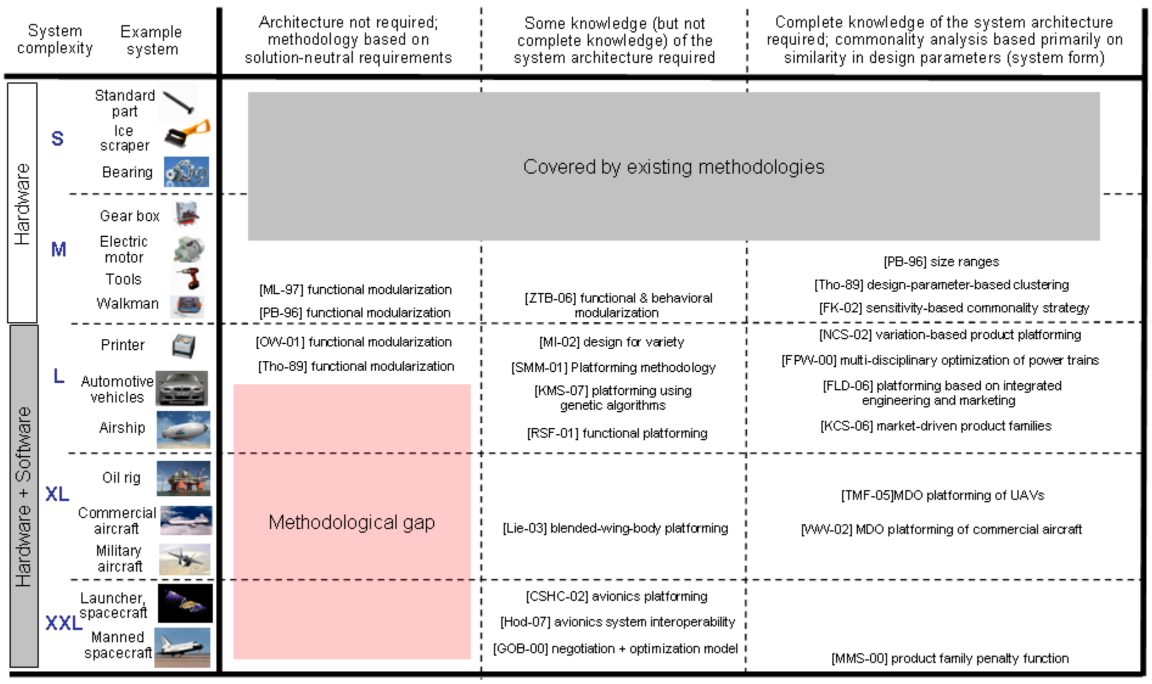


Figure 10: Research gap with regard to the applicability of methodologies investigated in the review of the state of the practice (see Section 1.3); note that methodologies applicable to higher-complexity systems are also applicable to all lower-complexity systems in the same column

The preceding review of the state of the practice in the different areas allows for a strategic assessment of the processes available to a system architect faced with the challenge of designing and implementing an aerospace systems portfolio with commonality. A number of gaps in the state of the practice of the field of architecting portfolios of aerospace systems with commonality were identified:

- Existing methodologies for commonality analysis are mostly ***limited to application during the detailed design phases*** (i.e. require system architectures as input) for portfolios of high-complexity systems, or are limited to portfolios of low-complexity systems if applicable during the systems architecting phase (see Figure 10). This indicates the need for a methodology that is applicable to systems architecting of portfolios high-complexity systems because of the potentially high pay-off of considering commonality during the architecting of aerospace systems portfolios.

- Existing methodologies are generally focused on individual parts of the systems architecting and commonality analysis process such as comparative analysis of point-design alternatives or identification of commonality opportunities based on design parameter similarity. Few methodologies allow for requirements analysis with regard to solution-neutral requirements or for an assessment of the use cases to be included in the portfolio. This indicates a ***gap with regard to the integration of all analysis steps*** required for commonality analysis in aerospace systems portfolios from requirements analysis to the identification, evaluation, and selection of specific commonality opportunities into a single methodology with a clear flow of information from one step to the next.

- Existing commonality analysis methodologies tend to be ***focused on commonality as defined by similarity or identity in design variable settings*** compatible with multidisciplinary optimization approaches. While this type of commonality is of particular relevance for benefits in design and manufacturing, other types of commonality such as functional, operational, or technology commonality are not being considered explicitly in the analysis.

Four specific thesis objectives were defined to address the gaps identified in the state of the practice of the systems architecting of aerospace systems portfolios with commonality. The definition follows the layered approach to systems architecting developed by Maier [Maier-2009] and Crawley [Cra-05-1] including the layers of principles, methods, and tools, each building upon the other.

Principles are the underlying and long enduring fundamentals that are always (or almost always) valid [Cra-05-1]. An example for a principle would be the strategy of achieving a reduction of complexity through “divide and conquer”; this principle was already recognized by the Romans (“divide et impera”). Principles have an approximate half-life of centuries or millennia.

Methods are the organization of approaches and tasks to achieve a concrete end, which should be solidly grounded in principles, and which are usually or often applicable [Cra-05-1]. Methodologies are systems of methods which have been interconnected to achieve some high-level functional capability beyond the capability of the individual methods. An example for a methodology would be the Architectural Decisions Graph approach developed by Willard Simmons [Sim-08]. Methods have an approximate half-life of centuries or decades.

Tools are the contemporary ways to facilitate process, and are sometimes applicable [Cra-05-1]. An example for a tool would be an algorithm implemented in software that allows for the automated analysis and clustering of Design Structure Matrices (DSM). Tools have an approximate half-life of years.

According to this layered approach to systems architecting, the following four specific thesis objectives were derived to close the above gaps in the state of the practice:

- To compile and develop a set of ***universally applicable principles*** for the three aspects of commonality analysis: the creative aspect of designing aerospace systems with and without commonality, the identification of commonality opportunities from a technical perspective, and the evaluation of economic and managerial feasibility of commonality opportunities.

- The ***development of a classification of commonality types*** (including but not limited to design and manufacturing commonality) and a high-level characterization of their associated benefits and penalties, as well as a tool for identifying these commonality types for use during conceptual design.

- To ***develop a methodology for the architecting of aerospace systems portfolios*** that serves as a tool for the system architect to translate solution-neutral statements of stakeholder requirements for the systems in the portfolio into conceptual design solutions that are feasible from a technical, operational, and economic perspective and explicitly consider commonality.

- The ***demonstration of this methodology through application*** to portfolio architecting problems of practical significance. These application case studies should be diverse in nature to demonstrate broad applicability of the framework.

The following is the subset of the above publications and approaches that are most relevant to and will be extended by work on the proposed research objectives: [RSF-01], [Tho-89], [SMM-01], [Kal-06], and [Hod-07].

1.5 Thesis Outline

This thesis consists of six chapters, including this introduction which provides an introduction to and motivation for the topic of aerospace systems architecting and commonality, a summary of the general problem statement, a review of the state of the practice in the field, and a description of the research gap and derived thesis objectives.

Chapter 2 covers the systematic approach to and framework for commonality analysis in aerospace systems portfolios and thereby provides one implementation of the systems architecting process template described in the general problem statement in Figure 8. The framework itself consists of two parts: (1) a set of universally applicable principles which summarize the intellectual foundation of the framework but do not provide specific guidance on how to carry out the analysis, and (2) a specific methodology with associated tools for the actual applied systems architecture and commonality analysis. Chapter 2 first describes the general research approach taken by the author, then provides discussion of 9 systems architecting principles that were synthesized from the literature, and then concludes with a detailed description of the architecting methodology and its individual steps and their complexity.

In Chapter 3, a case study on commonality in a human exploration life support system portfolio is provided. This worked-through case study is intended as a tutorial on the application of the systems architecting and commonality analysis framework developed in Chapter 2. Investigated are system architectures and commonality opportunities for a set of life-support systems for multi-person habitats, including both future use cases such as lunar and Mars surface habitats, as well as legacy systems such as the CEV and ISS life support systems. The results of this case study are two-fold: a set of specific and actionable recommendations with regard to commonality opportunities in future exploration life support systems is developed, and the effectiveness of the framework with regard to systematically identifying and evaluating commonality opportunities is demonstrated.

Chapter 4 is devoted to a description of results from the second application case study. This study is focused on the analysis of commonality opportunities within the historic Saturn launch vehicle family which included systems for launch into LEO as well as the Saturn V used for the manned lunar missions of the 1960s and 1970s. This case study is unique in that it is focused on a portfolio of propulsion systems for which a design reference in the form of the historical Saturn launch vehicle portfolio exists. The results from the case study can therefore be compared to the portfolio design solutions that were actually implemented.

Chapter 5 provides a description of results from a third application case study; the methodology is applied to an analysis of commonality opportunities within lunar and Mars surface pressurized mobility systems for human exploration. The case study investigates mobility system architectures over a range of technology choices for the functions of life support, power generation, energy storage, and mobility provision. As for Chapter 3, a set of specific and actionable recommendations with regard to commonality opportunities for future surface mobility systems is developed.

Chapter 6 is the conclusion section of the thesis which includes a summary of the work presented in the thesis and a review of major findings and insights from the case studies (both with regard to the methodology and with regard to the system architectures and commonality opportunities investigated). Chapter 6 further includes a discussion of the thesis contributions, and suggestions for future work to extend the framework for systems architecting and commonality analysis developed in this thesis and enhance its effectiveness in application to aerospace systems portfolios.

The Appendix following the Bibliography provides additional examples for aerospace systems portfolios with associated descriptions, as well as supplementary material for each of the three case studies described in Chapters 3, 4, and 5. In addition, a description of the contents of the CD attached to this thesis is provided.

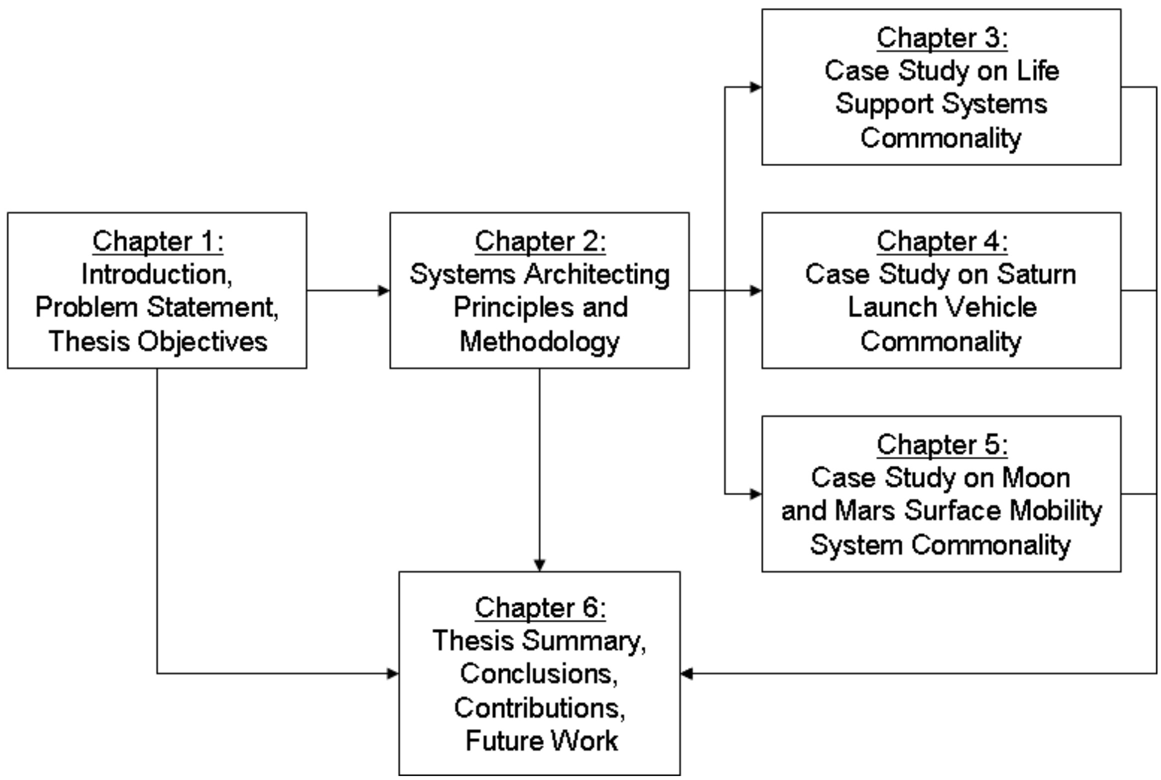


Figure 11: Thesis roadmap with information flow between the thesis chapters

The information flow between the thesis chapters is illustrated in the thesis roadmap in Figure 11: Chapter 2 builds on the derivation of the problem statement and thesis objectives in Chapter 1 and provides the framework that is applied in the case studies in Chapters 3, 4, and 5. Chapter 6 provides a summary of the major results and conclusions from the thesis and states the thesis contributions; in addition suggested topics for future work are described.

2. Systems Architecting Principles and Methodology

This chapter is devoted to the development of a framework for systems architecting and commonality analysis for aerospace systems portfolios that satisfies the conditions of the general problem description (see Figure 8) and of the specific thesis objectives as outlined in Sections 1.2 and 1.4. The goal is to provide a framework that can be used by a systems architect to translate the solution-neutral description of an aerospace systems portfolio into a set of portfolio design solutions with commonality. The portfolio design solutions should be technically and operationally feasible, they should be suitable as input for more detailed design phases, they should be located within proximity of the overall portfolio Pareto front with regard to the portfolio metrics, and they should explicitly consider opportunities for commonality in internal functions, technology choices, operations, and design parameters (to be captured in a commonality scheme for each of the portfolio design solutions). This framework should be applicable during the earliest stages of design, commonly referred to as the "systems architecting phase". A four-pronged approach was taken by the author towards the development of such a framework:

- The acquisition of first-hand experience in systems architecting and commonality analysis for aerospace systems

- The development of a set of systems architecting principles for aerospace portfolio commonality

- The development of a generic methodology for the identification and evaluation of specific commonality opportunities in aerospace systems portfolios

- The application of the framework to specific case studies within the astronautical engineering domain and subsequent refinement of the framework

The ***acquisition of first-hand experience*** in systems architecting and commonality analysis for aerospace systems: this was achieved through systems architecting and engineering consulting work for the NASA Office of Program Analysis and Evaluation (PA&E) and for NASA's Exploration Systems Mission Directorate (ESMD). The consulting work encompassed comprehensive enumeration and evaluation of architectures, conceptual design, and technology and commonality analysis for:

- Human lunar and Mars exploration systems, including launch vehicles, the Crew Exploration Vehicle (CEV) in-space transportation, planetary landing and surface systems, as well as the comparative analysis of mission modes.

- The Altair lunar lander which in NASA's Earth Orbit Rendezvous / Lunar Orbit Rendezvous (EOR/LOR) [ESAS-05] mission mode serves the function of transporting crew from lunar orbit to the lunar surface and back, as well as delivering cargo to the lunar surface on dedicated unmanned missions.

- Lunar surface systems in general, including habitation systems, surface power generation and energy storage systems, surface mobility systems, logistics systems, and infrastructure for surface assembly of assets.

Commonality was explicitly considered in these analyses, leading to the development of comprehensive commonality strategies for the entire exploration enterprise as well as for individual infrastructure element such as surface power systems and life support systems. A number of papers and repots summarize the results of these applied systems architecting and commonality studies which the author was involved in, see [CER-05] [HWC-08] [CHHC-08] [CuHHC-08] [HGMC-08] [HHHC-08] [GHC-08] [HSWC-07] [HWC-07] [HWSC-06] [HWC-06] [WHC-05] [WHNC-05] [BAH-05] [HWNC-05] [WHC-05] [HW-05] [Hof-04].

The ***development of a set of systems architecting principles*** for aerospace systems portfolio commonality: systems architecting principles capture observations regarding the properties and architecture of complex systems which have long-lasting and general validity [Maier-2009] [Cra-05-1]. They serve to provide general guidance to system architects for the formulation of architecting problems, for distinguishing architecturally relevant decisions from detailed design decisions, and for informing the selection of preferred architecture alternatives (among other uses). The set of principles developed for the architecting and commonality analysis of aerospace systems is based on synthesis of work in the literature on complex systems as well as on observations from the author's systems architecting and commonality analysis experience for astronautical systems (see above). The set of principles is discussed in Section 2.1.

The ***development of a generic methodology*** for the identification and evaluation of specific commonality opportunities: the methodology is intended to be a step-by-step process that a systems architect can follow when faced with the early design phase for an aerospace systems portfolio and with the task of identifying commonality opportunities between and within the systems in the portfolio. The methodology therefore provides more specific guidance for the systems architect than architecting principles, but is therefore also more limited in its applicability and validity. The methodology includes a newly-developed heuristic tool for the identification of commonality opportunities which are feasible from a technical and operational perspective. This tool can be applied in an automated fashion in order to screen a large number of candidates for commonality opportunities; this capability for automation is crucial to the practical applicability of the tool, as well as of the entire methodology. Section 2.2 contains a detailed description of the individual steps of the methodology, of their linkage to the architecting principles, as well as of the heuristic tool.

The ***application of the framework to case studies*** was carried out by analyzing commonality opportunities in three different portfolios of astronautical systems of either future or historical significance; these three case studies are described in Chapters 3, 4, and 5. While the application already required an initial version of the framework, it also informed the further development and refinement of the framework through identifying strengths and weaknesses in practical analysis of real aerospace systems portfolio and through identification of additional desirable capabilities for the framework. The development of the framework was therefore an iterative process; the primary test case study for refinement of the framework was the exploration life support systems case study described in Chapter 3. The Saturn launch vehicle family and planetary surface mobility systems case studies were mostly the pure application of the framework in its final form.

2.1 Systems Architecting Principles

A set of nine systems architecting principles for commonality in aerospace systems portfolios was synthesized based on previous work available in the literature as well as on the first-hand experience in applied systems architecting and commonality analysis for astronautical systems gained by the author. Works of the literature are cited in the descriptions of the individual principles where appropriate. The set of nine principles is divided into three subsets:

1. Principles related to the architecting (and to some extent also to the design) of aerospace systems without consideration for commonality between systems

2. Principles related to the aspects of commonality related to technical and operational feasibility, as well as to different types of commonality

3. Principles related to the management of commonality in existing or future aerospace systems portfolios

The individual principles in each subset are described in the subsections below; each subsection maps to one subset of systems architecting principles.

2.1.1 Principles Related to Aerospace Systems Architecting

***Principle 1:* Equal external system requirements enable equal system design solutions**

In system design theory it is generally assumed that the choice of design solutions for a technical system is exclusively driven by the need to fulfill specific requirements provided by the customer or system stakeholders [PB-96] [Suh-01]; these requirements can either be functional requirements stating ***what*** the system is supposed to do, performance requirements specifying ***how well*** the systems is supposed to accomplish a specific function, or operational requirements specifying the operating environments and regimes that the system has to provide its functionality in. Based on this external requirements-driven approach to system design, identical functional, performance, and operating requirements for two systems would lead to the exact same technology choices and design implementations for the two systems; unless two design implementations have exactly the same metric values but use different technology choices or operating processes (which is very unlikely), there could not be a motivation for choosing different design implementations. A possibly exception for the deliberate choice of divergent design solutions even if the external requirements are identical would be the need for protection against common cause failures; an example for this situation is the design of the space shuttle guidance system which features different computer designs with identical requirements [KSC-88] in order to achieve redundancy and protect against common cause failures of all guidance computers.

The practical significance of Principle 1 lies in its applicability and potential as a heuristic for identifying candidate opportunities for common technology choices, common operating processes, and common elements of system form: commonality opportunities may be feasible and beneficial if the functional, performance, and operational requirements for two systems are ***similar but not necessarily identical***. The degree of similarity (perhaps better called "overlap") in requirements can be used to judge the likelihood of the occurrence of beneficial commonality: if a high degree of overlap exists, the likelihood for beneficial use of commonality is high. The degree of similarity or overlap required for specific commonality opportunities can be varied to investigate the sensitivity of and identify robust commonality opportunities.

Principle 2: ***Solution-neutral requirements and metrics are the basis for effective system design***

In Principle 1 we have established that system design is driven by functional, performance, and operational requirements. If these requirements can only be fulfilled by a small set of or a single technology or design choice, then the design analysis will not necessarily result in the most effective design solution because an insufficient number of alternatives for the design will be considered feasible (i.e. the space of designs will be too small). This situation can best be described by the term solution-specific requirements which are usually based on making assumptions about the system form or internal functionality, rather than basing requirements purely on externally delivered functionality [Cra-05-1]. An example for solution-specific requirements would be to require a specific number of wheels or a specific energy storage technology for a planetary exploration ground vehicle; the correct way to formulate requirements in this case would be to specify a vehicle payload and range capability and leave the choice of internal functionality and associated technologies open to the system architect or designer for analysis. Solution-specific requirements are often derived by using a previous architecture (heritage architecture) as the basis for writing requirements; this approach is in particular often taken if there are severe resource constraints (time, budget) on the architecting phase. The resulting exploration of the architecture space is then generally constrained to the vicinity of the heritage architecture and may result in local optimization instead of global optimization.

A similar argument can be made for the metrics used to compare architecture alternatives for a given system: good metrics should measure objective attributes such as cost, risk, and performance properties of the system architecture alternatives, rather than measuring whether or not an architecture provides a particular internal functionality or utilizes a particular technology choice or operating process.

It is important to note that the definition of what solution-neutrality means is always only relative to the level of analysis being conducted: at the top-level solution-neutral requirements and metrics are defined by the system stakeholders / beneficiaries. As the analysis proceeds to lower levels of system design with increased design resolution (for example to individual subsystem design), the choice of internal functions, technology choices, operating processes, and elements of form at the higher level will become fixed requirements and specifications for the lower-level analysis and constrain the way solution-neutral requirements and metrics can be defined for the lower-level design analysis. At any level, a definition of solution-neutrality therefore requires careful analysis of the analysis assumptions to be made.

***<u>Principle 3:</u>* Comprehensive investigation of the architectural space enables the informed selection of a set of "good" architectures**

Traditionally, design space exploration is either carried out manually and involves the exploration of a limited number of concepts selected based on expert judgment [PB-96], or it is carried out in automated fashion and involves optimization, i.e. the numerical selection of a preferred concept based on minimization of one or more objective functions [deWe-05].

Expert judgment may lead to the choice of a design solution that represents a global optimum, but no guarantee can be made of the global optimality because the space of solutions is not known comprehensively. A similar argument can be made for optimization approaches: given that most design problems feature discrete variables (e.g. discrete choices of design features or technologies), the analytical derivation of a global optimum is often not possible and the analysis must rely on numerical analysis using heuristic algorithms such as simulated annealing or genetic algorithms [deWe-05]. While repeated application of these algorithms with differing initial conditions can provide a degree of certainty with regard to finding the global optimum, the identification of the actual global optimum cannot be guaranteed for arbitrary architecting or design problems.

In addition, the selection of a single perceived global optimum, either through expert judgment or through optimization does not provide insight into other good design solutions which may only be slightly worse with regard to the metrics used for comparing design solutions. As the selection of preferred design solutions for a system is often influenced by non-quantifiable properties as much as by quantifiable metrics; knowing a range of "good" design solutions is therefore generally considered to be better than just knowing "the best" design solution [Sma-05] [SWL-99]. This observation could be considered a separate principle, but for the purposes of this thesis we will consider this concept of "good" architecture or design part of Principle 3.

The answer to these limitations of traditional design approaches is the comprehensive enumeration and evaluation and ranking of design alternatives across the entire design space. This way, all optima (both global and local) can be identified and a robust set of "good" design solutions can be chosen based on the quantifiable metrics. We use the term "good" architecture or design solution because of the influence of non-quantifiable externalities which contribute the selection process in addition to the quantitative metrics defined prior to the analysis. A selection of a single or multiple preferred design solutions is then possible based on the non-quantifiable properties. Examples for comprehensive design space exploration are provided in the literature [SKC-05] [HWSC-06]. Tools specifically developed for supporting the comprehensive investigation of architecture-level design spaces are the Morphological Matrix methodology described by Pahl and Beitz [PB-96], Ben Koo's Object Process Network (OPN) [Koo-05], and the Architectural Decision Graph (ADG) [Sim-08] developed by Willard Simmons.

Principle 4: ***Sensitivity analysis and associated design iterations enable informed concept selection***

Once a comprehensive investigation of the architectural space has been carried out, it is not neccessarily clear which assumptions and requirements drive the ranking of concepts with regard to the metrics used for ranking architectural alternatives. Varying requirements and assumptions can provide important insights into the driving factors in architecture ranking, and may also lead to the elimination of requirements and assumptions that only marginally impact the design, thereby leading to a simplification of the architecting problem [HWSC-06] [Sim-08]. In addition, a more informed selection of preferred design solutions may be achieved by the selection of a concept that is robust to changes in requirements and assumptions and is consistently ranked well in all likely scenarios of future system usage. The value of architectural robustness to changes in requirements and assumptions is investigated in detail in the literature on design for changeability [SF-99].

Principle 5: ***Choosing non-optimal system design solutions may enable superior portfolio-level design solutions***

The life-cycle cost, risk, and performance properties of a portfolio of aerospace systems are determined by the properties of each of the constituent systems. In case the constituent systems are coupled, as for example through common element designs and technology choices, the properties of the systems can be traded against each other. It may, for example, be necessary to select a system design solution which is non-optimal when viewed individually in order to enable commonality in design with another system in the portfolio. The implementation of this commonality opportunity then may result in significant improvement of the portfolio life-cycle properties. This illustrates that it is necessary to consider more design solutions than the best-ranked one for each of the constituent systems of an aerospace portfolio in order to enable effective architecting of the portfolio. This principle has been explicitly recognized and implemented in the fuzzy-Pareto-front approach developed by Smaling [Sma-05] [Sma-07].

It is interesting to note that this principle is somewhat different from the points on "good" architecture made above: for an individual system, non-quantifiable externalities are the reason for choosing non-optimal architectures or design solutions. For a portfolio of systems, non-optimal individual architectures or design solutions can lead to portfolio-level optimality due to synergies like commonality, even if non-quantifiable externalities are not present in the selection process.

2.1.2 Principles Related to the Technical Aspects of Commonality

<u>Principle 6:</u> Commonality opportunities for complex systems can be classified by a set of distinct types

The review of the state of the practice of commonality analysis for aerospace systems portfolios (see Chapter 1) showed that existing commonality analysis methods tend to be focused on commonality as identity in ***design parameter values***; other types of commonality between aerospace systems are generally not considered explicitly. While this formulation can be used to capture commonality opportunities that are relevant to decreasing cost and risk in detailed design and manufacturing, it does not address the causes for commonality or customization within a particular portfolio: similarities or dissimilarities in internal functional and operational requirements, and in technology choices for the internal functions. If two systems are designed to the exact same functional and performance requirements, there is no need for two customized solutions (see Principle 1). This indicates the need for a more systematic classification of commonality types that takes into account the causes for commonality or customization in the analysis process.

Commonality type

Common feature	Functional commonality	Operational commonality	Technology commonality	Design commonality	System reuse	Variable functionality	Implementation commonality
Internal functions	X	X	X	X	X		
Operating processes		X	X	X	X		
Technology choices			X	X	X		
System form				X	X	X	X
System instance					X	X	

Figure 12: Overview of different commonality types based on the systems architecture model descried in Figure 9 in Chapter 1

Figure 12 shows a general classification of commonality types based on similarity with regard to the major aspects of system architecture as defined in Figure 9 in Chapter 1: system internal functionality, technology choices, operating processes, design parameters, and form structure. Seven commonality types are distinguished based on different degrees of similarity between these aspects of system architecture:

- **Functional commonality** requires only identity in system internal functionality between two systems; technology choices, operating processes and system form can be different.

    - **Non-aerospace example:** a plastic whistle and a grass whistle (grass leaf between fingers) provide the same internal functions but are different in operations, technology, and design.

    - **Aerospace example:** a lithium hydroxide canister and a 4-bed molecular sieve system both provide the internal function of carbon dioxide removal from a spacecraft cabin atmosphere, but the two systems are very different in operations, technology, and design.

- **Operational commonality** requires identity in the operating processes between two systems in addition to identity in internal functionality.
    - **Non-aerospace example:** humans learn to drive automotive vehicles based on standardized operations (and associated interfaces), although the vehicles utilize quite different technologies (internal combustion, hybrid, electric propulsion) and designs.
    - **Aerospace example:** the Gemini missions provided operational experience with extravehicular activities (EVA) in preparation for the Apollo EVAs; however, the space suit systems were quite different in terms of technologies and design.
- **Technology commonality** requires identity in the technology choices associated with the internal functions in addition to identity of the internal functions between two systems.
    - **Non-aerospace example:** different steel whistle designs utilize the same general geometrical arrangement of features and the same material, but may differ in exact size.
    - **Aerospace example:** different instantiations of the Centaur upper stage share the same technology for propulsion (expander cycle engine) and fuselage (common bulkhead design), but differ in their exact design specifications.
- **Design commonality** requires identity in form structure and similarity in design parameter values between two systems in addition to the requirements for technology commonality. This is the most studied form of commonality (see also Section 1.3).
    - **Non-aerospace example:** identical steel whistles from the same production line, standardized machine elements such as screws

    - **Aerospace example:** use of the same upper stage design on the Saturn IB and Saturn V vehicles (the so-called S-IVB stage)

- **System reuse** is identical to design commonality but requires that the same system instance be used multiple times for the same externally delivered function.
    - **Non-aerospace example:** reuse of the same automotive vehicle for multiple drives
    - **Aerospace example:** reuse of the same space shuttle orbiter for multiple missions

- The commonality type of **variable functionality** is intended to capture the case of using the same instance of system form for different purposes (hence different functions, technologies, and operating processes).
    - **Non-aerospace example:** use of a box which is intended for transportation of items as a seat
    - **Aerospace example:** wet workshop concept for the Skylab space station (an S-IVB upper stage would be used as active upper stage on a Saturn IB launch vehicle and then retrofitted to serve as the habitation volume for Skylab in orbit).

- **Implementation commonality** is identical to variable functionality but does not require the same instance of the system form to be used.
    - **Non-aerospace example:** acquisition of a musical instrument such as a piano purely as an element of room furnishing, not for making music
    - **Aerospace example:** the Skylab workshop as implemented and flown (a S-IVB stage which was designed and produced for use as an upper stage was retrofitted on Earth into the habitable volume for Skylab and subsequently launched as payload)

It should be noted that this classification of commonality types is just one of many possible classifications, but it has the advantages of being compatible with the model of system architecture used for this thesis (described in Figure 9 in Chapter 1). Each of the above commonality types may have specific benefits and penalties during certain stages of the system life-cycle; while it is not possible to describe what these benefits and penalties would be exactly, it is useful to investigate opportunities for these commonality types in aerospace systems portfolios. The classification will also serve as the basis for the development of a commonality analysis tool described in Section 2.2 below.

<u>Principle 7:</u> The different commonality types for complex systems form a logical hierarchy

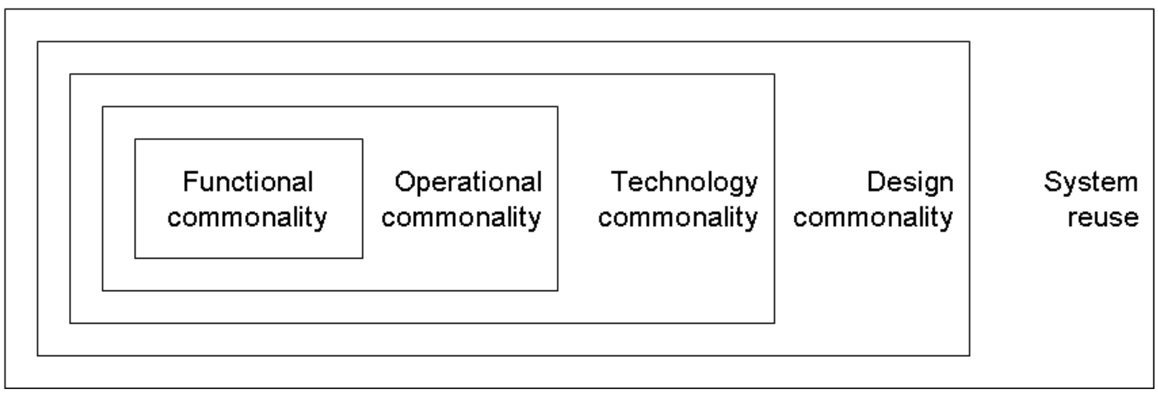


Figure 13: Hierarchy of certain commonality types in the form of a Venn-diagram

Given the definition of commonality types in Principle 7, the types functional, operational, technology, design commonality, and reusability form a hierarchy in the sense that the preceding commonality type is a precondition for the succeeding one (see Figure 13). This observed hierarchy within the commonality types can be used to more efficiently identify commonality opportunities: functional overlap is assessed first; if functional overlap is satisfactory, then operational overlap is assessed, and so on. Using this branch-and-bound approach the number of system pairs that need to be investigated for commonality opportunities can be reduced significantly compared to a comprehensive combinatorial analysis.

Variable functionality and implementation commonality are not part of the hierarchy because they do not require identical internal functions, operating processes, and technology choices. However, it would be possible to create a second hierarchy between system reuse, varying functionality, and implementation commonality. In addition, design commonality requires implementation commonality. These additional hierarchies could be used to further decrease the complexity of screening for commonality opportunities and should be explored as part of future work.

2.1.3 Principles Related to the Management of Commonality

Principle 8: ***The actual net benefits of commonality opportunities are smaller than envisioned benefits due to the occurrence of divergence***

Research by Boas and Crawley [BC-07] shows that during the development of portfolios of complex systems commonality that was architected into the system during the early phases of design has a tendency to diminish during preliminary and detailed design. There are multiple mechanisms for this so-called "divergence" phenomenon between common system designs in the portfolio, including sacrifice of commonality for short-term cost and schedule gains as well as changes in requirements resulting from insight gained during the design and testing of the actual system [Boas-08]. The impact of the observation of divergence in aerospace and automotive programs and the associated portfolios is that projected benefits of commonality during the architecting phase must be regarded as upper limits to the cost and risk benefits that will actually materialize, and that in addition to pure technical and economic feasibility, managerial feasibility of commonality also needs to be considered.

Principle 9: ***Continuous active portfolio-level management of commonality is required to realize the benefits of commonality***

The tendency for commonality in aerospace systems portfolios to diminish over time due to the occurrence of divergence indicates the need to actively preserve and perhaps even re-introduce commonality during the course of design and testing of the systems in the portfolio. Given that the systems in the portfolio which are designed and tested first usually carry the penalties of commonality, there is not necessarily strong incentive for the preservation of commonality on the system-level of management. This indicates that active portfolio-level management support of commonality is the best way of ensuring that a maximum extent of commonality is realized in the final implementation of the portfolio. Studies of historical US human space flight and defense programs by Ryan Boas and Shawn Quinn are the basis for this observation [BC-07] [Boas-08] [Quinn-08]. In addition to active management of commonality, enforcement of commonality through a potentially modified contracting process is crucial to the success of commonality.

2.2 Description of the Portfolio Architecting Methodology

The generic methodology for the architecting of aerospace systems portfolios described here represents one possible instantiation of a process that satisfies the general problem statement described in Chapter 1.2 (see Figure 8). The methodology is intended to transform a portfolio description based on a set of systems, requirements and constraints into a set of portfolio design solutions which include the implementation of commonality opportunities where technically and operationally feasible.

The methodology consists of four major steps: portfolio definition (Step 1), architecture analysis without commonality (Step 2), commonality screening (Step 3), and sensitivity analysis and preferred portfolio selection (Step 4); see Figure 14 for a visual description of the methodology showing the inputs and outputs of each step. In Step 1, the portfolio scope is determined in terms of system use cases included in the portfolio, externally delivered functionality is defined for each of the use cases, and solution-neutral metrics to be used for relative ranking of portfolio design variants are introduced. In Step 2, a comprehensive analysis of architecture alternatives is conducted for each of the future use cases in the portfolio (for legacy use cases the architecture is already known), leading to the selection of a set of preferred architectures for each use case in the portfolio. A sensitivity analysis of the architecture ranking with regard to architecture analysis assumptions may be carried out to assess the robustness of the preferred architecture alternatives. Commonality is not considered during this architecture analysis step, i.e. the architecture analyses for the individual systems in the portfolio are uncoupled and can be carried out in parallel. Based on the preferred architecture alternatives for each use case, a set of preferred portfolio design solutions without commonality can be enumerated combinatorially to serve as input to the commonality analysis.

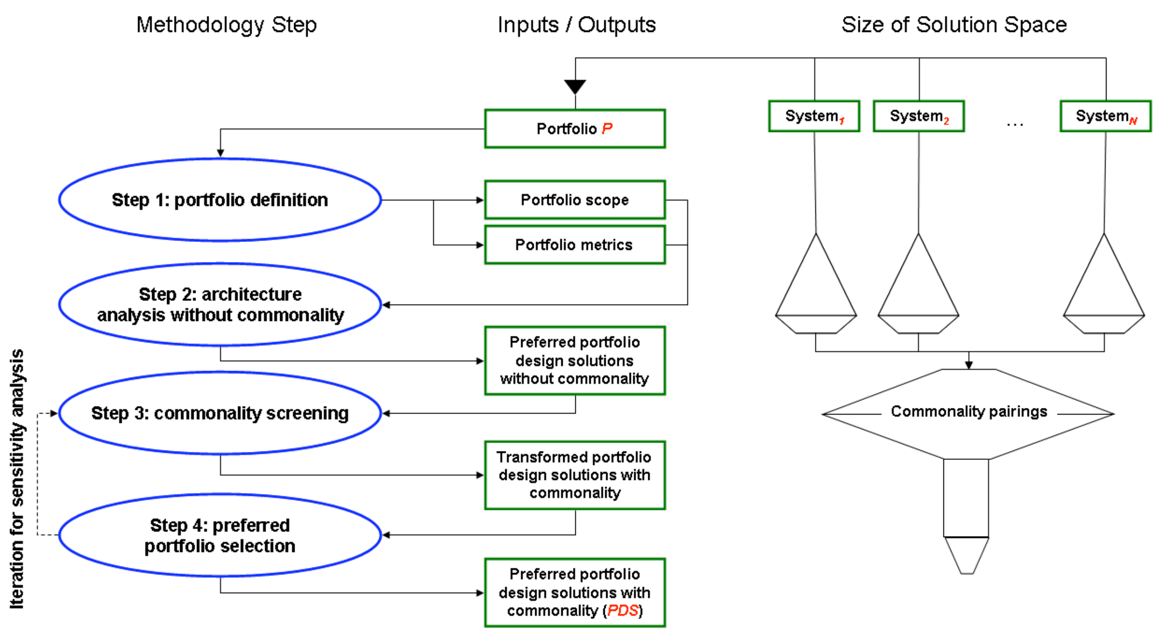


Figure 14: Generic methodology for the architecting of aerospace systems portfolios with commonality; the size of the solution space is graphically represented on the right-hand side.

The commonality screening process in Step 3 comprehensively investigates the potential for technology and design commonality for all pairs of systems for each internal function for each of the portfolio design solutions. If all criteria for commonality are satisfied, then the commonality opportunity is implemented, resulting in the minimum possible number of custom designs required per portfolio design solution. The specific criteria for commonality screening differ from case to case but the following criteria should be considered for every type of portfolio:

- <u>**Criterion 1:**</u> the two systems or subsystems in question must have the **same internal function**, for example both subsystems must exhibit the internal function of "CO_2 removal from cabin atmosphere" in order to have a common implementation. This criterion can be assessed using the hierarchy of commonality types shown in Figure 13 and described in Principle 7.

- **<u>Criterion 2:</u>** the two systems or subsystems in question must utilize the **same technology choice** associated with the internal function, for example both subsystems with the internal function of "CO_2 removal from cabin atmosphere" must utilize 4-bed molecular sieve technology in order to have a common implementation. This criterion can be assessed using the hierarchy of commonality types shown in Figure 13 and described in Principle 7.

- **<u>Criterion 3:</u>** in addition to Criteria 1 and 2, the two subsystem implementations also need to be **operated in similar environments** in order to ensure that requirements originating from these environments overlap. The similarity in operational environments is measured by calculating the number of common operational environments between two systems and then dividing this number by the number of total operational environments for each system. If both of these fractions are larger or equal to than a threshold $\boldsymbol{\delta}$, then the requirement for operational similarity is fulfilled. The value for $\boldsymbol{\delta}$ is obviously an arbitrary choice, and therefore needs to be subject to sensitivity analysis.

- **<u>Criterion 4:</u>** an additional criterion for the feasibility of specific commonality opportunities is **similarity in the quantitative design parameters**. If the design parameter values are within a factor ***k*** (the so-called overlap parameter) of each other, then commonality is feasible. The value for the overlap parameter ***k*** is obviously also arbitrary and therefore needs to be subject to sensitivity analysis.

These four general heuristic criteria must be customized for a specific portfolio in order to carry out a portfolio-specific commonality screening analysis; see also the descriptions of the customization of the commonality criteria for the thesis case studies in Section 3.3, 4.3, and 5.3. The output of Step 3 is a transformed set of portfolio design solutions with commonality opportunities implemented where technically and operationally feasible ("maximum commonality" transformation for each portfolio design solution).

In Step 4 a selection of portfolio design variants is carried out based on the life-cycle properties of the original (no commonality or only accidental commonality without utilization of commonality benefits) as well as the transformed set of portfolio design solutions with commonality. Step 4 may also include an analysis of the sensitivity of the transformed portfolio to changes in key parameters and assumptions made for the heuristic commonality criteria (Criterion 3 and 4) in Step 3; this is implemented in the form of iterations between Steps 3 and 4 (see Figure 14).

On the right-hand side of Figure 14, the size of the design solution space is shown for the four steps of the methodology. During Step 1 the space of design solutions is "empty" because no design solutions for the use cases in the portfolio exist at this point. In Step 2, a design space is created for each of the use cases in the portfolio based on the constrained enumeration of architecture alternatives. At the end of Step 2, the size of the solution space is decreased through selection of preferred architecture alternatives for each system in the portfolio. These preferred architecture alternatives are the basis for the enumeration of preferred portfolio design solutions without commonality. The number of preferred architecture alternatives is limited by the data management and processing capabilities of the computing systems available; ideally all architecture alternatives would be included in the comprehensive commonality screening in order to fully capture the possibility of portfolio-level synergistic effects of individually inferior architecture alternatives. Given current computing capabilities and portfolio sizes and scopes (5-10 functions for 5-10 systems) on the order of 10 – 100 preferred architecture alternatives can typically be chosen. The commonality screening process in Step 3 results both in an expansion and a contraction of the solution space as common variants of functional implementations are investigated for their economic benefit. The contraction leads to a set of portfolio design solutions which has the exactly same number of elements as the set without commonality at the beginning of Step 3. In Step 4, this number of portfolio design solutions is further reduced through selection of a set of preferred portfolio design solutions with commonality which is intended as input to more detailed design phases.

Table 1 shows how the architecting principles derived in Section 2.1 relate to the four steps of the generic architecting methodology. Principle 1 applies both to Step 1 and Step 3: in Step 1 the principle can be used to identify significant overlap in use cases and can therefore aid in defining the portfolio use case scope; in Step 3 the principle is the basis for identifying opportunities for commonality based on similarity in requirements.

Principle 2 applies to Step 1: the portfolio definition also includes the creation of metrics to evaluate individual architecture alternatives as well as portfolio design solutions. Principle 3 applies to Step2 and to Step 3: in Step 2 the space of feasible architecture alternatives is comprehensively investigated for each of the future use cases in the portfolio; in Step 3 all logically feasible opportunities for commonality are investigated, although only those opportunities that also satisfy the commonality criteria are actually implemented. Principle 4 applies both to Step 2 and to Step 4: in Step 2 the sensitivity analysis is carried out for individual future use cases in the portfolio; in Step 4 the sensitivity analysis applies to the entire set of portfolio design solutions. Principle 5 is used for Step 2 and Step 4: in Step 2 sub-optimal architecture alternatives are intentionally selected because of the possibility of portfolio-level synergisms; in Step 4 a set of preferred portfolio design solutions with commonality may be selected to be carried forward into more detailed design phases. Principles 6 and 7 apply only to the commonality screening process in Step 3. Principles 8 and 9 are relevant to the selection of preferred portfolio design solutions with commonality, taking into account divergence and associated reductions in the benefit of commonality over the life-cycle.

Table 1: Mapping of architecting principles for aerospace systems portfolios with commonality to the steps of the portfolio architecting methodology

Architecting Principle		Architecting Methodology			
		Step 1	Step 2	Step 3	Step 4
1	Equal external system requirements enable equal system design solutions	X		X	
2	Solution-neutral requirements and metrics are the basis for effective system design	X			
3	Comprehensive investigation of the architectural space enables informed concept selection		X	X	
4	Sensitivity analysis and associated design iterations enables informed concept selection		X		X
5	Choosing non-optimal system design solutions may enable portfolio-level benefit		X		X
6	Commonality opportunities for complex systems can be classified by a set of distinct types			X	
7	Commonality types for complex systems form a logical hierarchy			X	
8	Actual benefits of commonality are smaller than envisioned due to divergence				X
9	Continuous active management is required to realize the benefits of commonality				X

In the following subsections, a more detailed description of the four steps of the methodology is provided with particular emphasis on the linkage to the above architecting principles, the associated substeps, and specific tools available to the system architect. In addition, an assessment of the complexity of the design analysis is provided for each step.

2.2.1 Step 1: Portfolio Definition

Step 1 is similar to what is generally called requirements analysis: the portfolio architect carries out an enumeration of potential future use cases and their functionality based on stakeholder needs. Then, a selection of future use cases to be included in the portfolio is made based on likely future developments and needs. The architect also defines solution-neutral requirements for each of the use cases based on stakeholder needs and on the capabilities of current and future technologies. Legacy use cases must also be considered in order to include the possibility of retroactive commonality.

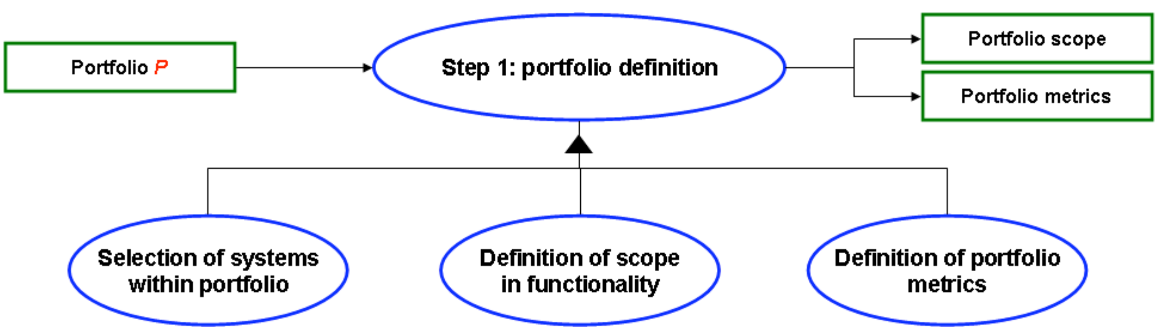


Figure 15: Overview of Step 1 of the generic architecting methodology

The definition of solution-neutral metrics for the comparison and ranking of architecture and portfolio design alternatives is the second important activity in Step 1. The metrics should in some way reflect the cost, developmental risk, operational risk and safety, and performance properties of architectures and portfolio design solutions. Cost must usually be considered in its different forms: design, development, test and evaluation (DDT&E) cost, unit production cost, spare parts cost, transportation cost, as well as life-cycle cost which is typically a combination of the individual costs. Learning curve effects should be considered for the calculation of unit and spare parts cost [NASA-SP-610S].

Developmental risk typically translates into cost, although it is sometimes also regarded as a separate metric.

For operational risk and safety and for performance "iso"-approaches are often employed [WJ-06]. This means that the architecture or portfolio characteristics in this regard are held constant across all architecture or portfolio variants considered (e.g. the payload and delta-v performance for all launch vehicle architectures considered for the same use case in a portfolio of launch vehicles would be identical). The "iso"-risk or "iso"-performance approach is convenient because it reduces the number of metrics that need to be considered for the relative ranking of architectures or portfolio design solutions and for the selection of preferred alternatives.

A variety of tools are applicable to Step 1, including Functional Flow Block Diagrams (FFBD [NASA-SP-610S]) for the qualitative analysis of individual mission use cases, parametric cost estimating relationships [Isa-02] and learning curve models for the calculation of the different cost contributions. In case the immediate stakeholders for the portfolio are not known, a systematic analysis of relative stakeholder importance based on modeling of stakeholder interactions may also be required [Cam-07]. Expert judgment may also sometimes be required in order to choose between alternative ways of writing requirements and calculating metrics.

2.2.2 Step 2: Architecture Analysis without Consideration for Commonality

In Step 2, architectural alternatives are investigated for each use case in the portfolio without consideration for commonality between or within the use cases (see Figure 16). This attribute of Step 2 is very important: portfolios without commonality necessarily represent the performance optimum for the given use cases and are therefore important references against which portfolios with commonality must be compared in order to assess the impact of commonality.

It is interesting to not that commonality (especially technology commonality, less likely for design commonality) may exist "accidentally" between performance-optimal architecture alternatives for the different use cases; the benefits from exploitation of this commonality are, of course, not included in the evaluation at this point. These commonality opportunities will be identified in the comprehensive commonality screening as part of Step 3.

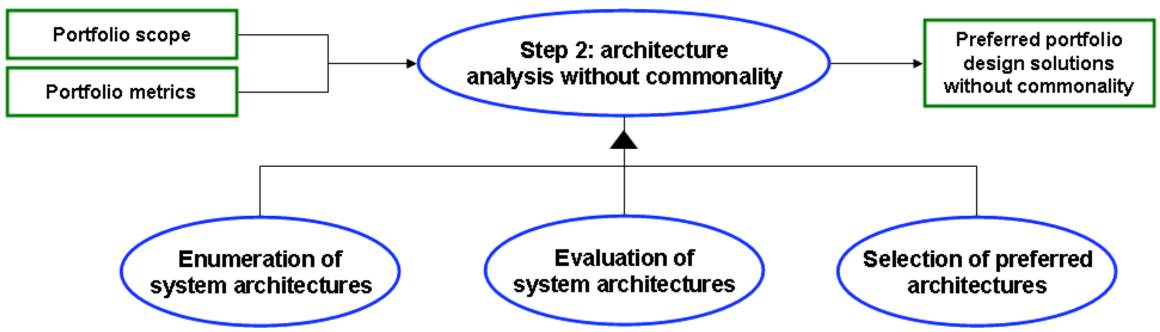


Figure 16: Overview of Step 2 of the generic architecting methodology

The architecture analysis is carried out in a specific order: first, architecture alternatives are enumerated based on a set of internal functions, associated technology choices and constraints between these different choices. This enumeration creates a hyperspace of feasible architecture alternatives for each of the use cases; feasibility is ensured through constraints which apply during the enumeration.

Given $\boldsymbol{n}$ internal functions with technology choices $\boldsymbol{a_1, a_2, \ldots a_n}$, an upper bound $\boldsymbol{F}$ for the number of feasible architecture alternatives for the future use case $\boldsymbol{k}$ in the portfolio can be calculated (Equation 1), assuming that the choice of technologies is unconstrained and the technology choices are the same for all use cases:

$$F_k = \prod_{i=1}^{n} a_i \qquad \textbf{Equation 1}$$

The upper bound for the number of feasible portfolio design solutions without commonality $\boldsymbol{P}$ consisting of $\boldsymbol{m}$ future use cases is therefore (Equation 2), again assuming that technology choices are unconstrained and identical for each use case:

$$P = \prod_{k=1}^{m} F_k = \prod_{k=1}^{m}\left(\prod_{i=1}^{n} a_i\right) \qquad \textbf{Equation 2}$$

The results from Equation 1 and Equation 2 are upper bounds because they assume that all combinations of technology assignments are feasible; constraints may not permit certain combinations of technology choices and would therefore reduce the number of feasible concepts for each system and for the portfolio.

This hyperspace of concepts is subsequently comprehensively evaluated with regard to the metrics defined in Step 1, and a set of preferred architecture alternatives which are ranked well with respect to all metrics is selected (see also Principle 5). Smaling's K-factor method for the fuzzy Pareto frontier [Sma-05] or manual analysis can be used to select the set of preferred architecture alternatives for each system in the portfolio. The method used will determine how many interesting concepts are selected for each system in the portfolio; however, due to practical reasons this number should be on the order of 10 interesting architecture alternatives per use case. The interesting architectures for each system in the portfolio are used to enumerate a set of $\boldsymbol{P_{Interesting}}$ portfolio design solutions without commonality for the following commonality analysis on Step 3.

There are a number of tools that can be used for the enumeration and evaluation of architecture alternatives for the future use cases in the portfolio. The specific tool to be used depends on the size of permutations in the architecting problem, the degree to which the architecture analysis is constrained, and the need for numerical analysis as part of the evaluation of the architecture alternatives: for problems of low to modest size (for example 2-5 use cases with 5 internal functions each) with modest needs for numerical analysis (some iteration require for sizing of components) explicit enumeration in a spreadsheet tool is all that is required, whereas for more constrained problems with modest need for numerical analysis tools such as Object Process Networks (OPN) [Koo-05] may be most appropriate. For problems of large size with significant need for numerical analysis direct encoding as a Valued Constraint Satisfaction Problem (Valued CSP) [RN-02] would be preferred; for two of the cases studies in this thesis (Chapter 3 and Chapter 4) the architecture analysis was implemented in Java.

Steps 1 and 2 of the framework have been applied to a number of space systems architecting studies, for example [WHC-05] [HWSC-06] [HWC-07].

2.2.3 Step 3: Commonality Screening

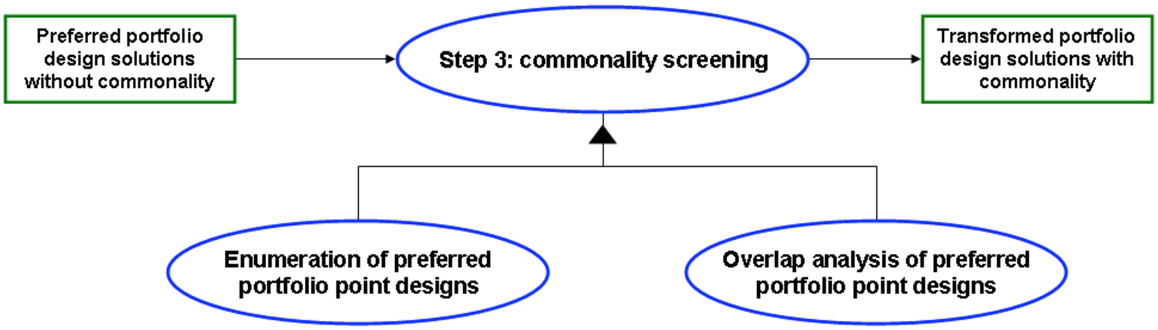


Figure 17: Overview of Step 3 of the generic architecting methodology

In Step 3 (see Figure 17), a comprehensive pair-wise assessment of architectures within each portfolio design solution is carried out with regard to similarity in internal functionality, operational requirements, technology choices associated with internal functionality, and quantitative design parameters (which approximately correspond to design variable settings or specifications in the MDO literature).

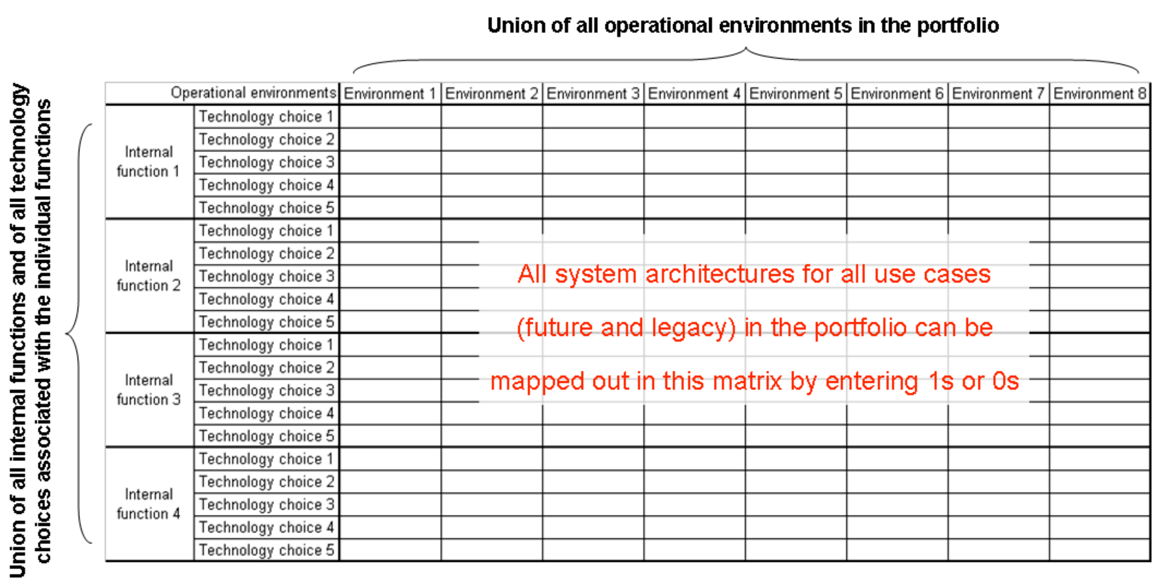
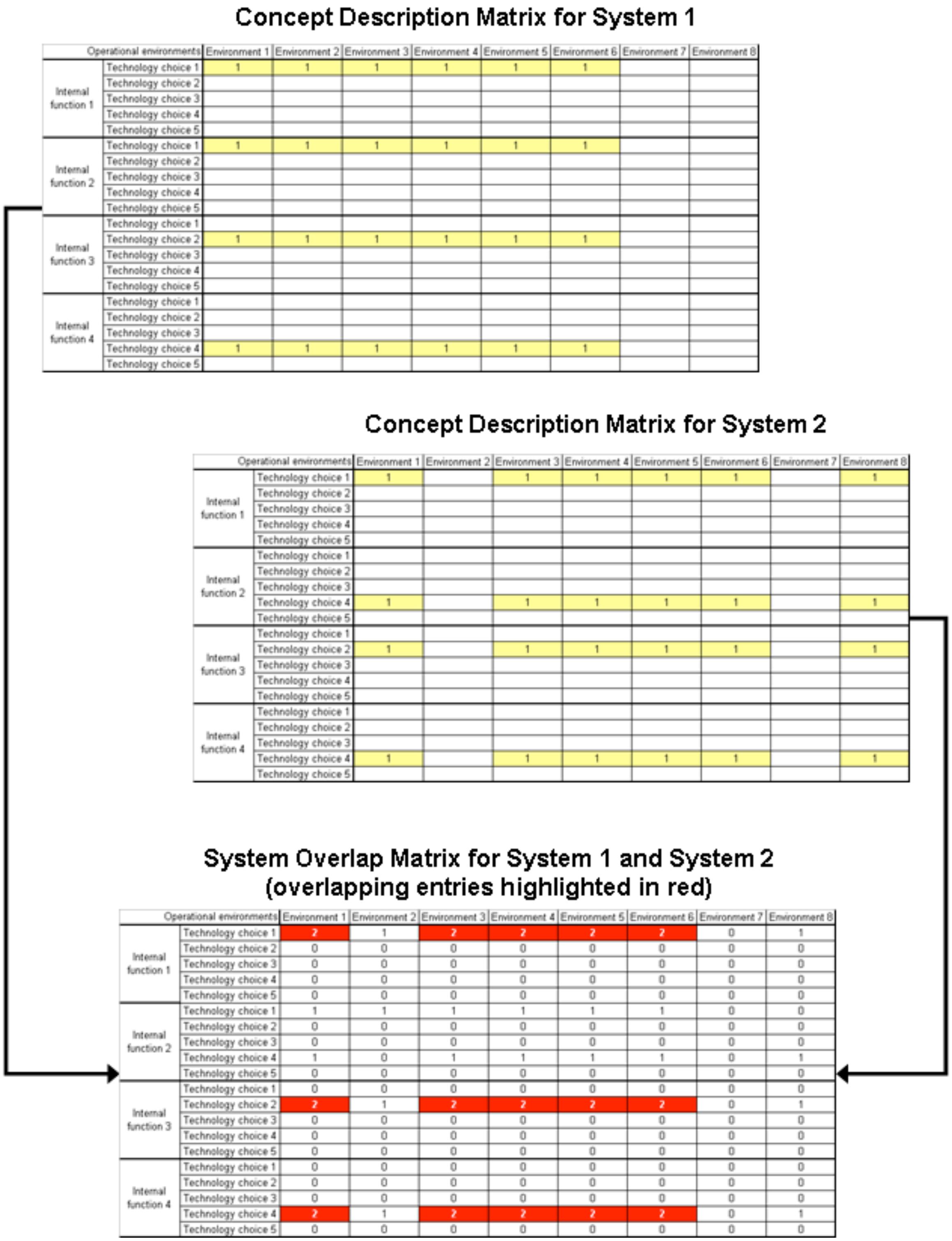


Figure 18: Concept Description Matrix (CDM) template with 4 internal functions, 5 technology choices per function, and 8 operational environments

To that end, a novel matrix tool using Principle 7 as a heuristic for the identification of commonality opportunities is employed (see Figure 18): the matrix allows mapping out a system concept with its internal functionality and associated technology choices (a vertical Morphological Matrix) and performance parameters, as well as operational building blocks capturing the operational requirements levied on the system. By making the sets of functionality, technology choices, operational building blocks, and performance parameters the unions of all corresponding sets for the preferred architecture alternatives across the portfolio design solutions, a standardized matrix can be created and used to capture any architecture alternative in the portfolio (when only capturing one alternative, the matrix is called Concept Description Matrix - CDM) [HWWC-07] [HWC2-07].

CDMs for two different use cases in the same portfolio design solution are then analyzed for overlap by determining which fields of the matrices have identical entries; this can be visualized as a process of overlapping the two CDMs, leading to a System Overlap Matrix (SOM). For each function, the number of overlapping fields is then normalized with the total number of entries for that function, resulting in two normalized overlap fractions which capture operational overlap for each function. The portfolio architect then specifies a minimum operational overlap fraction $\boldsymbol{\delta}$ for both systems: if the overlap fraction for each system is larger than this value then commonality is possible. This allows for an assessment of above Criteria 1, 2, and 3 for the feasibility of commonality opportunities.

Figure 19 shows a graphical representation of this overlap process for assessing Criteria 1, 2, and 3: the individual CDMs for system 1 and system 2 are shown above the SOM. In the CDMs, yellow fields mark the entries indicating implementation of a particular function with a specific technology choice in a specific operating environment. The SOM entries are calculated by adding up the entries from the two CDMs; an entry of “2” in a field in the SOM therefore means that both CDMs had entries for this field. This means that fields in the SOM with entries of “2” indicate overlap between the CDMs and therefore between the systems. By counting all the fields with entries of “2” for a specific function we can determine the degree of overlap for that function and therefore assess the validity of Criteria 1, 2, and 3 for that function.



Concept Description Matrix for System 1

	Operational environments	Environment 1	Environment 2	Environment 3	Environment 4	Environment 5	Environment 6	Environment 7	Environment 8
Internal function 1	Technology choice 1	1	1	1	1	1	1		
	Technology choice 2								
	Technology choice 3								
	Technology choice 4								
	Technology choice 5								
Internal function 2	Technology choice 1	1	1	1	1	1	1		
	Technology choice 2								
	Technology choice 3								
	Technology choice 4								
	Technology choice 5								
Internal function 3	Technology choice 1								
	Technology choice 2	1	1	1	1	1	1		
	Technology choice 3								
	Technology choice 4								
	Technology choice 5								
Internal function 4	Technology choice 1								
	Technology choice 2								
	Technology choice 3								
	Technology choice 4	1	1	1	1	1	1		
	Technology choice 5								

Concept Description Matrix for System 2

	Operational environments	Environment 1	Environment 2	Environment 3	Environment 4	Environment 5	Environment 6	Environment 7	Environment 8
Internal function 1	Technology choice 1	1		1	1	1	1		1
	Technology choice 2								
	Technology choice 3								
	Technology choice 4								
	Technology choice 5								
Internal function 2	Technology choice 1								
	Technology choice 2								
	Technology choice 3								
	Technology choice 4	1		1	1	1	1		1
	Technology choice 5								
Internal function 3	Technology choice 1								
	Technology choice 2	1		1	1	1	1		1
	Technology choice 3								
	Technology choice 4								
	Technology choice 5								
Internal function 4	Technology choice 1								
	Technology choice 2								
	Technology choice 3								
	Technology choice 4	1		1	1	1	1		1
	Technology choice 5								

System Overlap Matrix for System 1 and System 2
(overlapping entries highlighted in red)

	Operational environments	Environment 1	Environment 2	Environment 3	Environment 4	Environment 5	Environment 6	Environment 7	Environment 8
Internal function 1	Technology choice 1	2	1	2	2	2	2	0	1
	Technology choice 2	0	0	0	0	0	0	0	0
	Technology choice 3	0	0	0	0	0	0	0	0
	Technology choice 4	0	0	0	0	0	0	0	0
	Technology choice 5	0	0	0	0	0	0	0	0
Internal function 2	Technology choice 1	1	1	1	1	1	1	0	0
	Technology choice 2	0	0	0	0	0	0	0	0
	Technology choice 3	0	0	0	0	0	0	0	0
	Technology choice 4	1	0	1	1	1	1	0	1
	Technology choice 5	0	0	0	0	0	0	0	0
Internal function 3	Technology choice 1	0	0	0	0	0	0	0	0
	Technology choice 2	2	1	2	2	2	2	0	1
	Technology choice 3	0	0	0	0	0	0	0	0
	Technology choice 4	0	0	0	0	0	0	0	0
	Technology choice 5	0	0	0	0	0	0	0	0
Internal function 4	Technology choice 1	0	0	0	0	0	0	0	0
	Technology choice 2	0	0	0	0	0	0	0	0
	Technology choice 3	0	0	0	0	0	0	0	0
	Technology choice 4	2	1	2	2	2	2	0	1
	Technology choice 5	0	0	0	0	0	0	0	0

Figure 19: Assessment of overlap between two CDMs using the SOM. Fields with a value of“2” (marked in red) in the SOM indicate overlap in internal functionality, technology choice, and operating environment; all other entries indicate that there is no overlap.

Criterion 4 must be assessed separately based on quantitative design parameters of the subsystem implementation such as mass, thrust, volume etc.

Applying this commonality screening based on pair-wise comparison of functions for all use case pairs in the portfolio (future and legacy use cases) results in the comprehensive investigation of all possible commonality opportunities for all portfolio design solutions without commonality. An upper bound for the total number of pair-wise commonality checks that needs to be carried out, ***E***, can be calculated given the number of interesting portfolio design solutions without commonality, $P_{Interesting}$, the number of internal functions per use case, ***n*** (with ***a*** technology choices per function), the number of future use cases, ***m***, and the number of legacy use cases, ***l*** (Equation 3):

$$E = \binom{m+l}{2} \cdot n \cdot P_{\text{int}\,eresting} \qquad \textbf{Equation 3}$$

E signifies the expansion of the solution space shown in Figure 14 during Step 3. The computational tools used for the implementation of the comprehensive commonality screening process of Step 3 are similar to the tools used for Step 2; in addition, the SOM / CDM heuristic tool is used.

2.2.4 Step 4: Selection of Preferred Portfolio Design Solutions

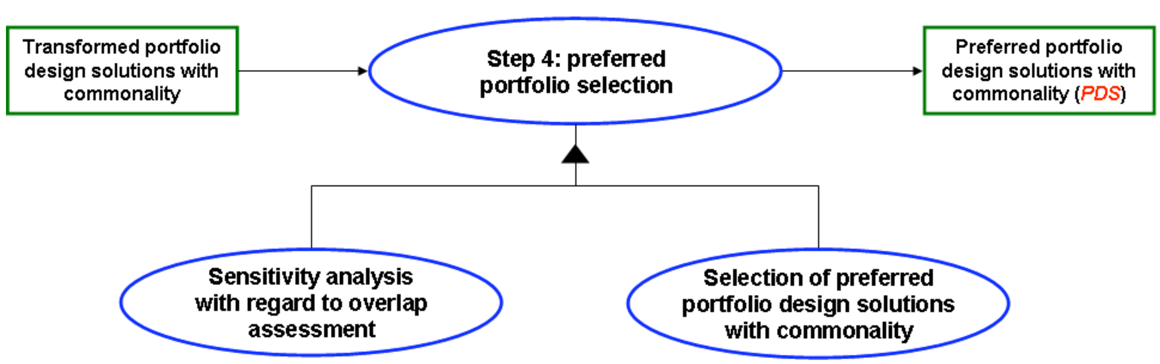


Figure 20: Overview of Step 4 of the generic architecting methodology

The last step of the framework (see Figure 20) consists of the selection of preferred portfolio design solutions based on the evaluation of results from the commonality screening process in Step 3. In order to arrive at a robust selection of preferred portfolio design solutions with commonality, a sensitivity analysis with regard to the overlap requirements for commonality in Step 3 is carried out; this effectively means that Step 3 is repeated for different settings of the overlap fraction. When comparing the preferred technology choices for each setting of the overlap parameter, technology choices (and by extension commonality opportunities) which are robust to changes in the overlap fraction can be identified, as well as functions for which robust technology choices do not exist.

The portfolio design solutions with commonality are ranked with regard to the values of the portfolio metrics (if an iso-approach is chosen these are primarily metrics for life-cycle cost and developmental risk). Principle 5 is applicable to Step 4 as it is to Step 2 in the sense that the selection of a range of well-ranked portfolio design solutions with commonality is preferable compared to the selection of just the best-ranked portfolio design solution because of the potential for slightly “sub-optimal” solutions to be superior with regard to non-quantitative selection criteria.

2.2.5 Methodology Complexity Example

For the purposes of demonstrating the complexity of the calculations and assessments in the framework we apply the above equations to an idealized example. Suppose we are designing an aerospace systems portfolio with 4 future use cases; for each of the 4 systems the space of feasible concepts can be described using 5 internal functions with 4 technology choices each. The upper bound on the number of portfolio design solutions without commonality is (Equation 4):

$$P = \prod_{k=1}^{4} \left(\prod_{i=1}^{5} a_i \right) = \left(4^5\right)^4 \approx 1.1 \cdot 10^{12} \qquad \textbf{Equation 4}$$

We decide to manually select 5 preferred architecture alternatives for each future use case in the portfolio, i.e. the number of interesting portfolio design solutions without commonality for input to Step 3 is:

$$P_{Interesting} = 5^4 = 625 \qquad \textbf{Equation 5}$$

Given 2 legacy use cases to be considered in the portfolio and the 5 internal functions per use case, we can calculate the total number of commonality pairings that need to be evaluated, given 2 legacy use cases also with 5 internal functions:

$$E = \binom{4+2}{2} \cdot 5 \cdot 625 = 15 \cdot 5 \cdot 625 = 46875 \qquad \textbf{Equation 6}$$

This simplified example illustrates the relative size of the expansion and contraction of the portfolio design solution space over the course of applying the methodology; it also suggests that partial automation of the methodology is essential to enable the analysis of practically relevant aerospace systems portfolios.

In order to demonstrate the effectiveness of the framework in transforming a solution-neutral description of the portfolio into a set of portfolio design solutions with commonality according to the general problem statement (Figure 8), the methodology has been applied to three diverse case studies of aerospace systems portfolios with commonality:

- The first case study is about life support systems for multi-person human space exploration habitats; it is described in Chapter 3.
- The second case study investigates commonality opportunities in the historical Saturn launch vehicle family; it is described in Chapter 4.
- The third case study analyzes commonality opportunities in future planetary surface mobility systems for human exploration; this case study is described in Chapter 5.

3. Case Study 1: Commonality in Space Exploration Life Support Systems

In this section we provide a step-by-step description of the application of the commonality analysis methodology from Section 2.2 to a real-world aerospace portfolio architecting problem in the area of life support systems for human space exploration. The detailed description is intended as a tutorial for future users of the commonality analysis methodology and tools which are described in a more generic way in Section 2.2.

Life support systems are essential for the survival of the crew in the inhospitable environment of space. The life support system of a human spacecraft provides the metabolic conditions required for immediate survival of the crew (such as oxygen partial pressure, atmospheric temperature and humidity) as well as consumables required for the duration of the mission by the crew (such as food, water, breathing oxygen). The size of the human spacecraft where the life support system is operating can vary significantly from a single-person-sized space suit to a habitat for six or more people (as for example on the International Space Station or on the space shuttle orbiter).

The origins of life support systems can be found in equipment developed to enable human operations in inhospitable terrestrial environments: diving and submarine operations, high-altitude and high-speed flight, as well as civilian and military operations in unprepared terrain. In these domains technologies have been developed for storing and disseminating breathing oxygen, pressure regulation in enclosed atmospheres, management of body nitrogen content (for avoiding the bends during de-pressurization), removal of carbon dioxide and other toxic trace gases from enclosed atmospheres, and long-term food storage, to name only a few technologies.

Space life support systems are different from terrestrial life support systems primarily in the availability of external resources for sustaining the crew: aircraft can in most cases utilize oxygen from the Earth's atmosphere and can be re-supplied on the Earth's surface after a relatively short mission durations, and submarines make use of the surrounding water (also for producing breathing oxygen). Terrestrial field operations make use of atmospheric oxygen and oftentimes rely on locally sourced water which may need to be purified prior to consumption. Spacecraft typically operate in resource-starved environments and need to store or recycle a significant fraction of the consumables required for the mission; this is true even for “resource-rich” space environments such as on the lunar surface or on Mars.

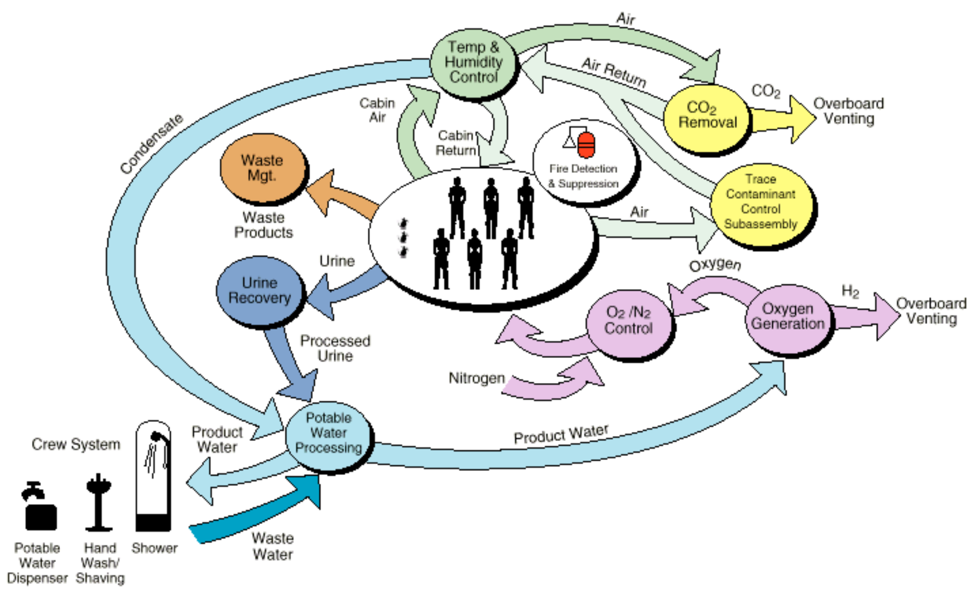


Figure 21: Overview of the life support system of the International Space Station [credit NASA]

Figure 21 provides an overview of the life support system planned for the US Orbital Segment (USOS) of the ISS, a multi-person long-duration system with a total life-time of two decades or more. It is apparent that a large number of interrelated functions need to be performed, leading to significant apparent design complexity. In addition, the provision of every function requires advanced technology making the system technology-enabled. This indicates that it is justified to regard the conceptual design of life support systems portfolios as a system-architecture-level problem.

The following case study is concerned with life support systems for multi-person (4 – 6 crew members) spacecraft that are likely to be used in the exploration enterprise. Single- or two-person spacecraft such as space suits or pressurized rovers for planetary surface mobility are not considered because their mobile use leads to different design drivers than for multi-person habitats. The following subsections correspond to the 4 steps of the systems architecting and commonality analysis methodology introduced in Section 2.2.

3.1 Definition of the Exploration Life Support Systems Portfolio

As mentioned above, this analysis is concerned with multi-person life support systems for exploration habitation applications. Step 1 of the methodology involves determining portfolio scope in terms of mission use cases and system functionality, as well as defining quantitative metrics for the subsequent architecture and commonality analysis.

Three human spaceflight mission types are considered in the life support systems analysis as part of a future life support development program (legacy missions such as to the ISS do not need to be developed): missions to the lunar surface, missions to Near Earth Objects (NEOs), and missions to the surface of Mars. Additional mission types such as lunar flyby missions, missions to lunar orbit, missions to the Earth-Sun L1/L2 point for telescope servicing [Thr-07], and Venus and Mars flyby and orbit missions have been proposed in the literature [TM-X-52311] [TR-67-600-I-I] [Zubrin-96] [NASA-88] [IAA-04] [PS-08]. However, as these missions do not provide scientific samples return they would likely be carried out on an opportunistic basis and would reuse life support system hardware designed around the more frequent use cases of missions to the Moon, NEOs, and Mars. Missions to main-belt asteroids, to the surface or orbit of Mercury, and to the outer planets must be considered beyond the scope of human spaceflight for the foreseeable future due to the excessive energy requirements for a round-trip.

Missions to the lunar surface include both short-stay missions similar to the Apollo missions (also called sorties) and repeated visits to an outpost with long-duration stays. Short stay missions involve only the lunar transportation system which, based on the NASA Exploration Systems Architecture Study (ESAS) and the Earth Orbit Rendezvous / Lunar Orbit Rendezvous (EOR/LOR) mission mode [ESAS-05], consists of the Crew Exploration Vehicle (CEV), a lunar lander, and associated crew and cargo launch vehicles. The transportation architecture is also utilized for the long-duration missions, but an additional surface habitation infrastructure and re-supply systems is required to enable these long-duration stays. The crew size for both short and long stays is 4 crew members [Cul-08]. We can therefore summarize that a minimum of three life support systems are required for a lunar exploration campaign:

- The ***CEV life support system***, which must be considered a ***legacy*** system at this point because a development contract has been awarded and there is a well-established life support system architecture for the CEV. The model of the CEV life support system was based on information provided in [ESAS-05].

- The ***lunar lander life support system*** which is located in the ascent stage. Given that over the course of a representative campaign [Cul-08][NASA-08] the lunar lander is predominantly used for crew transportation to the outpost this was assumed as the driving use case for the lander. No contract for the lunar has been awarded at this point and early design studies are still ongoing; the lunar lander life support system can therefore be considered as a ***future system*** subject to architecture analysis. It was assumed that the lander could sustain 4 crew members for 2 days.

- A ***lunar surface habitat life support system*** designed for long stays of up to 180 days with 4 crew members. The representative lunar campaign in [Cul-08] assumes a cumulative duration on the lunar surface of 1442 days with 4 crew members; a significant portion of this cumulative time would be spent on extravehicular activity (EVA) and in pressurized mobility assets. For the purposes of the analysis presented in this chapter it was assumed that a total of 842 days with 4 crew members was spent in the habitat, leaving 600 days for EVA and roving. This is consistent with the time allocation envisioned in [Yod-07]. The lunar surface habitat is still in the earliest stages of design [KT-08] and can therefore be considered as a ***future system*** subject to architecture analysis.

The life support systems for the EVA suit and for any pressurized mobility asset are not included in the analysis because they cannot be considered true multi-person life support systems and because their design drivers are different due to mobility concerns in addition to propulsive transportation constraints. However, life support system functionality is included in the surface mobility system case study presented in Chapter 5 of this thesis and opportunities for commonality at the part-level with life support systems for multi-person use are considered there.

Missions to NEOs have been proposed both for their scientific value due to the possibility of sample return from primordial bodies of the solar system as well as their preparation value for human Mars missions due to the significant distances achieved from the Earth during the mission (about 10 times lunar distance) which require more autonomous operations that on the lunar surface. NEO mission architectures in the literature have been focused on minimalist missions using only the CEV as primary habitat with 2 crew members on short missions of only 90-120 days duration (which occur relatively infrequently [Lan-07] [Kor-07]). In this study we investigate a NEO mission architecture which features a separate habitat which provides living space and life support for 4 crew members for missions of up to 180 days duration; this significantly increases the number of NEO targets available and hence the mission opportunities in a given time. 4 crew members instead of 2 are also more representative of a human Mars mission which might require 4 - 6 crew members based on requirements for operational skills. It was assumed that a total of 4 missions to a NEO would be carried out prior to the commencement of human Mars missions.

Missions to the surface of Mars are generally considered to be the ultimate achievement in human spaceflight due to the significant transportation and logistics challenges involved. Two main motivations for this mission type are recurring in the literature: the scientific exploration of Mars (including the search for past or present life) and the demonstration of the long-term human habitability of Mars as a precursor activity to establishing a permanent human presence there [DRM-97][DRM-98][Zubrin-91]. A number of transportation and surface systems architectures have been proposed in the literature; all of these involve two long-duration habitats with two main approaches to the allocation of mission segments: the first is to use one habitat for Earth-Mars transit and the Mars surface stay (about 780 days total) and the other for the Earth return trip (either from the surface of Mars or from Mars orbit, about 180 days). The second approach allocates the Earth-Mars and Mars-Earth segments (about 360 days total) to one habitat and the Mars landing and surface stay segment (about 600 days) to the other habitat; this approach requires two rendezvous in Mars orbit: one prior to landing and one following ascent to orbit.

For this study we choose to adopt the latter Mars transit approach because it allows for more explicit calculation of the transportation costs associated with each of the two habitats. We therefore introduce an additional two future use cases into the portfolio: the Mars surface habitat and Earth-Mars-Earth transit habitat life support systems. It is assumed that an initial Mars campaign would involve a total of 5 surface missions (which would correspond to a cumulative campaign duration of about 13 years), each with 6 crew members and each going to a different location. It should be noted that architectures with a rendezvous in Mars orbit following ascent require another crew compartment with a life support system; in accordance with [DRM-97] it is assumed that the Earth entry capsule (i.e. the CEV CM) would be used for this purpose.

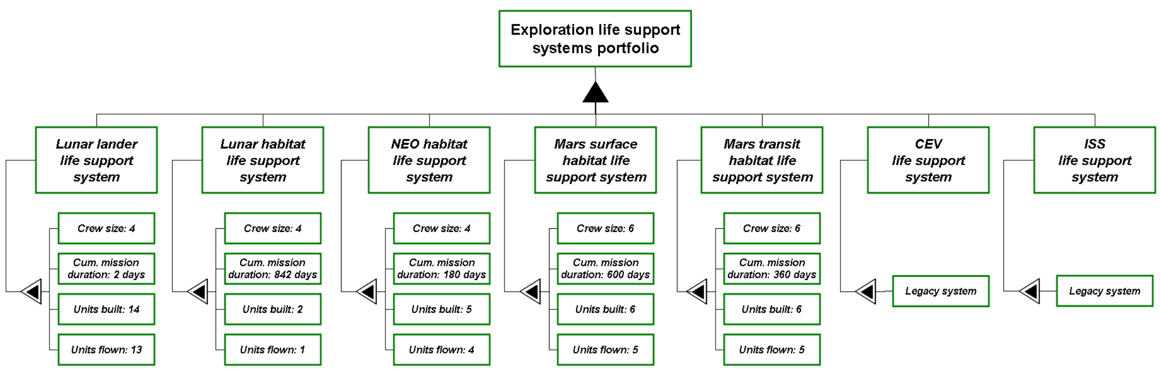


Figure 22: Overview of the exploration life support systems portfolio

The International Space Station (ISS) life support system is considered as another legacy system in addition to the CEV life support system. Other US legacy systems such as the Space Shuttle, Apollo Command and Service Module (CSM), and Skylab space station life support systems could have been considered; however, most of the associated subsystem technologies can be assumed to be included in the designs of the CEV and the ISS. In addition, the CEV (and perhaps also the ISS) will be in service when the 5 future systems in the portfolio are operated, whereas the Space Shuttle, the Apollo CSM, and Skylab will obviously not. In order to reduce the number of systems to be considered for the commonality analysis in Step 3 of the methodology, these systems were therefore not included.

Figure 22 and Table 20 in Appendix II summarize the exploration life support system portfolio use cases, associated requirements, and the number of units produced and flown for each of the five future use cases. This data will serve as input to the architecture analysis carried out in Step 2, described in Section 3.2.

For the purposes of this case study, life support systems are assumed to carry out the following functions:

- Provision, storage, and preparation of food
- Provision and cleaning (if required) of clothing
- Provision of drinking and wash water, management of waste water (sources: wash water, humidity condensate, urine; potentially including recycling)
- Removal of carbon dioxide from the crew compartment atmosphere
- Maintenance of acceptable oxygen partial pressure, provision of breathing oxygen to the crew compartment atmosphere
- Removal of trace contaminants from the crew compartment atmosphere (Trace Contaminant Control = TCC)
- Humidity removal from cabin atmosphere

It is interesting to note that with the exception of trace contaminant control, these functions can all be coupled through the water and oxygen management functions: the content of water in the food affects the amount of water that can be recycled, indirectly impacting oxygen provision function if oxygen is recycled from carbon dioxide. Humidity removal and clothing obviously affect the water management functionality.

Typically, two additional functions are included in the scope of life support systems: provision of buffer gas and associated partial pressure management and provision of hygiene consumables. These two functions were not included in this case study because for the following three reasons: (1) they are completely unrelated to the above functions, (2) only one prevalent alternative for implementing the functionality is available (i.e. no architectural variation occurs), and (3) the life-cycle mass contributions of these functions tend to be small.

Temperature control of the cabin atmosphere is accounted for in the form of a mass overhead based on the heat power that needs to be rejected; a similar approach is taken for the power provision and volume provision functions for the life support systems (see also life support system equivalent mass modeling in Section 3.2).

According to Principle 1 (see Section 2.1), solution-neutral metrics are a precondition for objective architecture analysis. Ideally, one would like to calculate cost, performance, and risk exactly based on the design information at hand. In many cases, however, accurate calculation of cost and risk properties often requires detailed design information that is beyond the scope of an architectural analysis as performed in this case study. A common approach to solve this dilemma has been to carry out iso-performance [WJ-06] and iso-risk analyses (each architectural alternative has approximately the same performance and risk attributes), and to use proximate metrics based on empirical relationships for the estimation of development, unit, spare part, and transportation cost for each of the alternatives. The alternatives can then be ranked with regard to an integrated life-cycle cost and a down-selection of preferred architectures can be carried out. This approach was chosen as the basis of the evaluation of alternatives for this case study.

Performance requirements in the form of mission crew size and cumulative mission duration for the five future portfolio use cases are presented in Figure 22 and Table 20. With regard to risk it is assumed that the parametric designs generated using scaling relationships for different technologies from the literature would all have similar reliability and operational risk characteristics so that they would be identical in a relative sense. Spare parts requirements to maintain operational readiness were included in the analysis. Life-cycle cost for each of the future systems as well as for the entire portfolio is used as cost metric. Life-cycle cost for each of the future portfolio use cases individually is defined as the sum of Design, Development, Test and Evaluation (DDT&E) cost, unit production cost, spare parts production cost, and transportation cost (Equation 7):

$$C_{LC\_Use\_Case} = C_{DDT\&E} + C_{Units} + C_{Spares} + C_{Transportation} \quad \textbf{Equation 7}$$

DDT&E cost is estimated using a parametric relationship between historical manned spacecraft dry mass and DDT&E cost (Equation 8). This relationship was obtained by interpolating data points from the NASA JSC Spacecraft Vehicle Level Cost Model [JSC-07], see Figure 23. Strictly speaking, the cost model applies to entire manned spacecraft systems. It was assumed for this case study that the model could also be used for individual subsystems such as the life support system; for the relative assessment of life-cycle cost that is the objective in this analysis this assumption seems valid because the scaling relationships between system mass and DDT&E / unit cost are preserved.

$$C_{DDT\&E}[FY04\_\$\_Mn] = 20.251 \cdot m_{DDT\&E}^{\ 0.55} \quad \textbf{Equation 8}$$

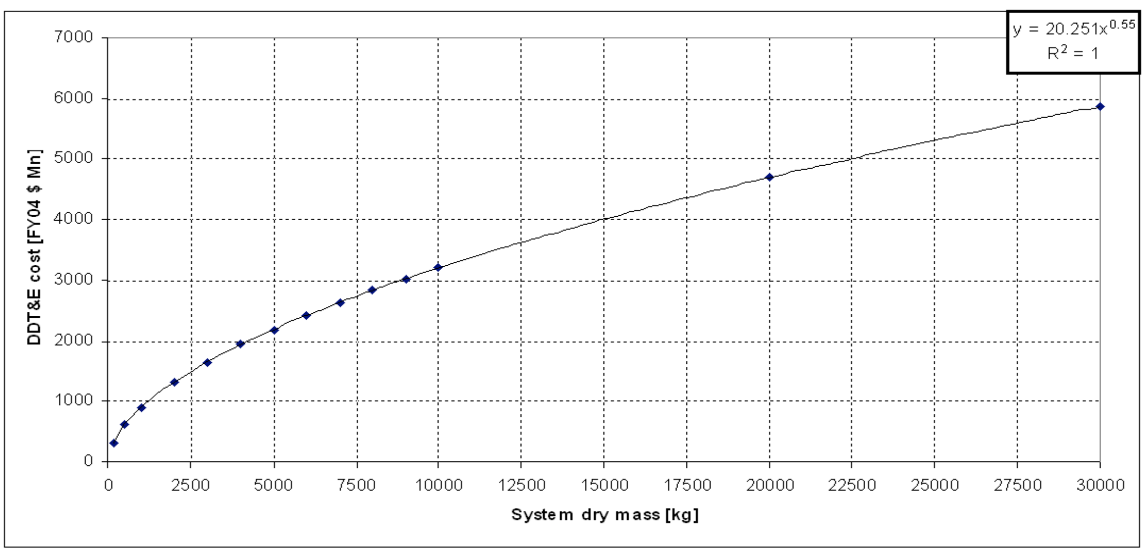


Figure 23: Empirical cost estimation relationship for DDT&E costs of manned spacecraft

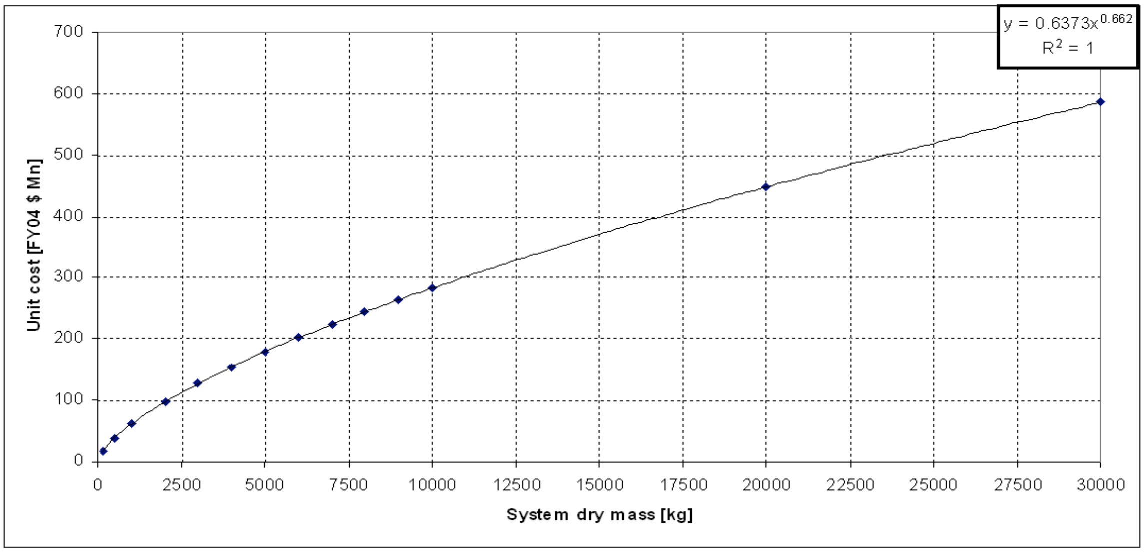


Figure 24: Empirical cost estimation relationship for 1st unit or 1st spare cost of manned spacecraft

The cost of the first unit or first spare part produced is estimated using a parametric relationship between unit or spare part dry mass and unit or spare part cost (see Equation 9). The relationship is also derived from an interpolation of data from the NASA JSC Spacecraft Vehicle Level Cost Model (see Figure 24).

$$C_{1st\_Unit}[FY04\_\$\_Mn] = 0.6373 \cdot m_{Unit}^{\ 0.662} \quad \textbf{Equation 9}$$

The calculation of cumulative unit and spare part cost take into account learning curve effects which lead to a reduction of individual unit or spare part cost as the number of units or spare parts produced increases. The cost of the ***n-th*** unit or spare part produced is shown in Equation 10; ***LR*** is the learning rate parameter which typically has a value of 0.85 for spacecraft [NASA-SP-610S]:

$$\begin{aligned} C_{n-th\_Unit} &= C_{1st\_Unit} \cdot n^{b} \\ b &= \frac{\ln(LR)}{\ln(2)} \end{aligned} \quad \textbf{Equation 10}$$

Cumulative unit or spare parts cost for ***k*** identical units or spare parts for a single use case can be expressed as follows:

$$C_{Units} = C_{1st\_Unit} \cdot \sum_{n=1}^{k} n^{b} \qquad \textbf{Equation 11}$$

In addition to DDT&E, unit, and spare parts cost, transportation cost is an important contribution to life-cycle cost. Transportation cost for each of the five future use cases was estimated based on the unit cost of launch vehicles and in-space transportation elements used in the transportation mode. Detailed descriptions of the transportation / mission mode used and the derivations of the associated transportation cost are provided in Table 21 in Appendix II; it was assumed that all life support systems mass is transported as pressurized cargo. The resulting transportation cost factors are:

- To lunar surface: $f_{Lunar\_surface}$ = 115570 \$ / kg
- To lunar orbit, via surface: f_{Lunar_orbit} = 231140 \$ / kg
- To NEO-Earth return trajectory: $f_{NEO\text{-}Earth\_trajectory}$ = 148300 \$ / kg
- To Mars surface: $f_{Mars\_surface}$ = 134770 \$ / kg
- To Mars-Earth return trajectory: $f_{Mars\text{-}Earth\_trajectory}$ = 302300 \$ / kg

The actual transportation cost is calculated as the product of life-cycle mass to a destination and the associated cost factor (Equation 12):

$$C_{Transportation} = f_{Destination} \cdot m_{Life\text{-}cycle} \qquad \textbf{Equation 12}$$

It should be noted that these are idealized marginal cost factors for continuous scaling which where derived to explicitly include transportation cost in the life-cycle analysis. For the actual implementation of the above missions, transportation cost will no longer be linear because actual transportation systems have fixed capacities; exceeding these capacities would require buying an entire new unit (i.e. transportation cost will increase in steps).

The life-cycle cost of the entire portfolio is the sum of the life-cycle costs of the future portfolio use cases; this includes the cost for all life support systems units produced:

$$C_{LC\_Portfolio} = C_{LC\_Lunar\_Lander} + C_{LC\_Lunar\_Hab} + C_{LC\_NEO\_Hab} + C_{LC\_Mars\_Hab} + C_{LC\_TransitHab}$$

Equation 13

In addition to life-cycle cost, the total number of custom development projects that are required in the portfolio is calculated as a measure of portfolio developmental risk and cost overhead associated with the administration of each project: it is assumed that a lower number of custom development projects in the portfolio potentially leads to lower developmental risk and lower overhead:

$$n_{Portfolio} = n_{Lunar\_Lander} + n_{Lunar\_Hab} + n_{NEO\_Hab} + n_{Mars\_Hab} + n_{TransitHab}$$ **Equation 14**

For portfolios with completely custom systems, it is assumed that each function is implemented through a custom development project. For portfolios with commonality, the number of custom development projects is reduced because fewer custom implementations are required.

It is important to note that the programmatic development and operational risk benefit of having fewer custom implementations for the individual use case internal functions in the portfolio may be canceled out by the increased complexity, developmental risk, and operational risk of the more complex common implementations. The need for a more detailed quantitative study of the net benefit of a reduction of custom development projects in a portfolio is indicated but was beyond the scope of this thesis; see also suggestions for future work in Section 6.4 below.

We have now defined the portfolio use cases, associated requirements, as well as the system and portfolio metrics to be used for the comparative analysis of system architectures and portfolio design solutions. We have accomplished the purpose of Step 1 of the methodology (requirements analysis and metric definition) and are therefore ready to proceed to Step 2, the point design architecture analysis.

3.2 Point Design Architecture Analysis for Portfolio Systems

Step 2 of the methodology is focused on investigating alternative architectures for each of the life support systems associated with future use cases: the lunar lander the lunar surface habitat, the NEO mission habitat, the Mars surface habitat and the Mars transit habitat. The architecture analysis process is discussed in detail below for the lunar surface habitat life support system. First, architectural alternatives are enumerated for the lunar surface habitat. This is achieved using a Morphological Matrix [PB-96] which lists the technology choices available for each function in the life support system. A description of the individual technology choices is provided in Appendix II based on design information published in the literature [Wyd-88] [Eckart-96] [LP-00] [KSC-88] [Nal-07] [San-05]. All technology choices included in the matrix have progressed at minimum to the breadboard level of technology (Technology Readiness Level TRL 4 or 5 [Man-95]) with many of the technologies actually being operationally tested (TRL 9).

Table 2: Morphological Matrix of technology choices for the lunar surface habitat life support system functions; choices within the same row are mutually exclusive

Function	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4	Technology choice 5	Technology choice 6
Food provision	Fully hydrated food	De-hydrated food				
CO2 removal	LiOH	4BMS	Solid amine, pressure-swing			
Oxygen provision	Stored, high-pressure	Stored, cryogenic	Water electrolysis	Electrolysis + Sabatier reactor	Electrolysis + Sabatier + methane pyrolysis	Ilmenite reduction (ISCP)
TCC	Expendable	Partially regenerative				
Clothing	Expendable	Washing machine + dryer				
Humidity removal	CHX + separator	Silica gel, expendable	Solid amine, pressure-swing			
Water management	Stored	Multifiltration	Multifiltration + VCD	Ilmenite reduction (ISCP)		

The enumeration of architectural alternatives for the lunar surface habitat life support system is carried out by choosing one technology alternative per function (row) and proceeding through all combinations in the matrix. Certain combinations may be infeasible due to incompatibilities between technologies; these alternatives are filtered out. For the lunar surface habitat, this enumeration yields a total of 1728 feasible alternatives. Next, we need to evaluate the architectures in order to be able to compare and rank them on a quantitative basis. To that end, we calculate the mass that the implementation of each function requires over the life-cycle, as well as the DDT&E, unit, and spares masses (Equation 15):

$$m_{Lifecycle}[function\_i] = n_{Units\_flown} \cdot n_{Crew} \cdot (m_{Equipment}[function\_i] + m_{Power}[function\_i] +$$

$$+ m_{Thermal}[function\_i] + m_{Volume}[function\_i] + \Delta t \cdot (m_{Consumables}[function\_i] \cdot tare_{Consumable} +$$

$$+ \frac{m_{Spares}[function\_i] \cdot tare_{Spare\_Parts}}{365.25}))$$

Equation 15

The life-cycle mass of each function implementation consists of equipment mass, power systems mass, thermal control system mass, marginal mass associated with the pressurized volume required by the equipment, as well as consumables and spare parts mass and associated tare factors. This approach of calculating life-cycle mass taking into account all mass contributors is sometimes referred to as equivalent mass calculation. A catalog has been created which provides equipment mass, power demand, heat generation, pressurized volume required, and consumables and spare parts needs with associated tare factors for each technology choice in the Morphological Matrix (see Table 22 in Appendix II). The values in the catalog are based on existing designs of various levels of maturity (generally TRL 5 or above).

Using the overheads and tare fractions provided in Table 20 in Appendix II, we can convert power, heat rejection, volume, consumables, and spare parts masses into actual life-cycle mass contributions. Spare parts masses are calculated as 10% of the system equipment mass per year and therefore need to be divided by 365.25 and then multiplied by the cumulative mission duration as well as the number of units flown and the crew size (all equipment scaling factors are given for one person and then scaled up with the crew size) to calculate the life-cycle mass contribution. Consumables mass is given per day and needs to be multiplied with the cumulative duration, crew size, and the number of units flown. All other mass contributions are time-independent and therefore only need to be multiplied with the crew size and the number of units flown. Applying Equation 15 to all 7 function implementations per system, we can calculate the life-cycle mass of each architecture alternative, which can in turn be converted into life-cycle transportation cost using Equation 16:

$$m_{Life\text{-}cycle}[system] = \sum_{i=1}^{7} m_{Life\text{-}cycle}[function\_i] \qquad \textbf{Equation 16}$$

To calculate the other life-cycle cost contributions using Equation 8 and Equation 11, we need to determine the DDT&E, unit, and spare part masses. We do this again for each function individually, using the following relationships:

$$m_{DDT\&E}[function\_i] = n_{Crew} \cdot (m_{Equipment}[function\_i] + m_{Power}[function\_i] +$$

$$+ m_{Thermal}[function\_i] + m_{Volume}[function\_i] + m_{Consumables}[function\_i] +$$

$$+ \frac{\Delta t \cdot m_{Spares}[function\_i]}{365.25 \cdot n_{Spares}})$$

Equation 17

$$m_{Unit}[function\_i] = n_{Crew} \cdot (m_{Equipment}[function\_i] + m_{Power}[function\_i] +$$

$$+ m_{Thermal}[function\_i] + m_{Volume}[function\_i])$$

Equation 18

$$m_{Spare\_part}[function\_i] = \frac{\Delta t \cdot m_{Spares}[function\_i]}{365.25 \cdot n_{Spares}} \qquad \textbf{Equation 19}$$

The mass parameter which serves as input to the DDT&E cost estimation model includes the masses of one set of daily consumables as well as of one set of spare parts (determined by dividing the total spare parts mass by the number of spare parts which his provided in Table 20 in Appendix II). In order to calculate the system-level DDT&E, unit, and spare part masses, we sum over all 7 function implementations:

$$m_{DDT\&E}[system] = \sum_{i=1}^{7} m_{DDT\&E}[function\_i] \qquad \textbf{Equation 20}$$

$$m_{Unit}[system] = \sum_{i=1}^{7} m_{Unit}[function\_i] \qquad \textbf{Equation 21}$$

$$m_{Spare}[system] = \sum_{i=1}^{7} m_{Spare}[function\_i] \qquad \textbf{Equation 22}$$

Now we are in a position to calculate all system metrics introduced in Step 1 and perform a comparative quantitative analysis of architectural alternatives for each of the 5 future life support systems in the portfolio. The enumeration and evaluation of lunar surface habitat life support architecture alternatives was implemented in Java code (source-code provided on the attached thesis CD). Figure 25 shows results of this evaluation for the lunar surface habitat: the sum of DDT&E, unit, and spares cost is plotted for each architectural alternative over the associated life-cycle mass value.

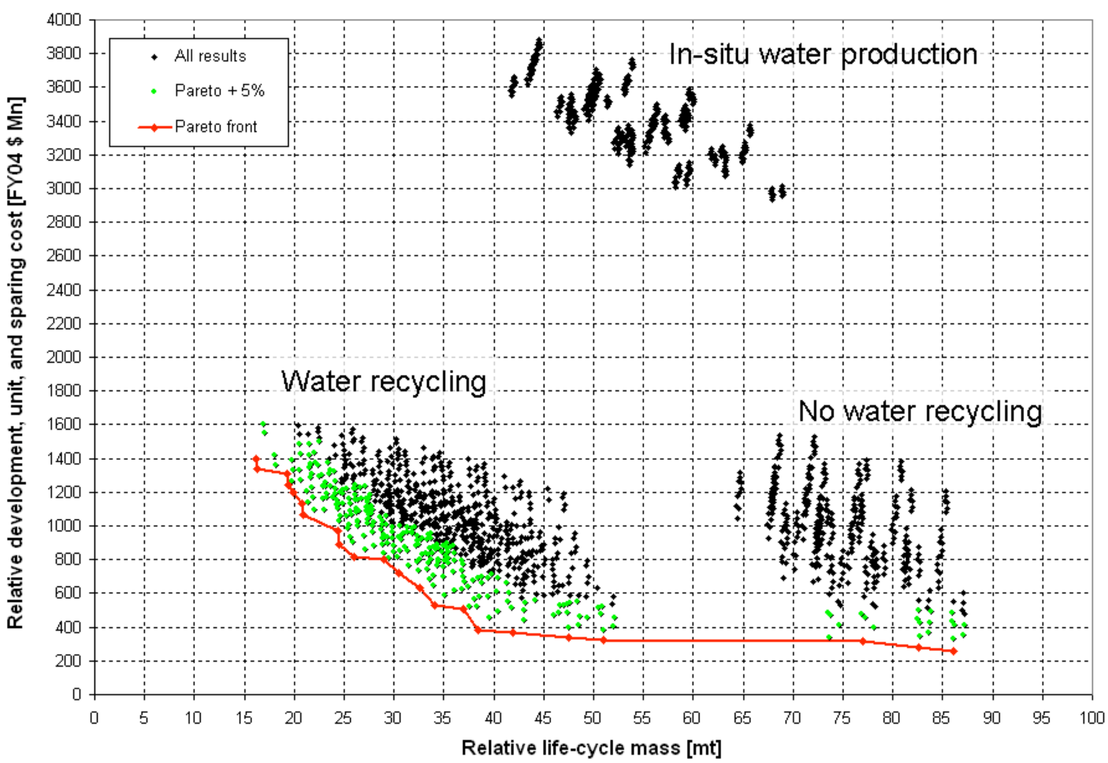


Figure 25: Architecture analysis results for the lunar surface habitat; plotted are relative development, unit, and spare parts cost vs. relative life-cycle mass on the lunar surface

The architecture alternatives fall into three groups: the group on the lower left-hand side consists of architectures which make use of wash water regeneration technology, the group on the lower right-hand side consists of architecture alternatives that do not use wash water regeneration. The group on the top includes all architecture alternatives which utilize in-situ consumables production based on ilmenite reduction for the provision of drinking and wash water to the crew. The development and unit masses for this technology choice (ilmenite reduction for water production with imported hydrogen) are very high, leading to a high DDT&E, unit, and spare parts cost. Due to the need to import hydrogen, the life-cycle mass is not as strongly reduced for these alternatives as it is for the alternatives which recycle water (the lower left-hand group); this makes these alternatives very unattractive. A similar grouping is observed for architectural alternatives of the Mars surface habitat (see Figure 75 in Appendix II) which also requires the import of hydrogen for in-situ water generation. All other use cases in the portfolio do not have the option of utilizing in-situ resource utilization and therefore show different grouping patterns (see Figure 71, Figure 73, Figure 77 in Appendix II).

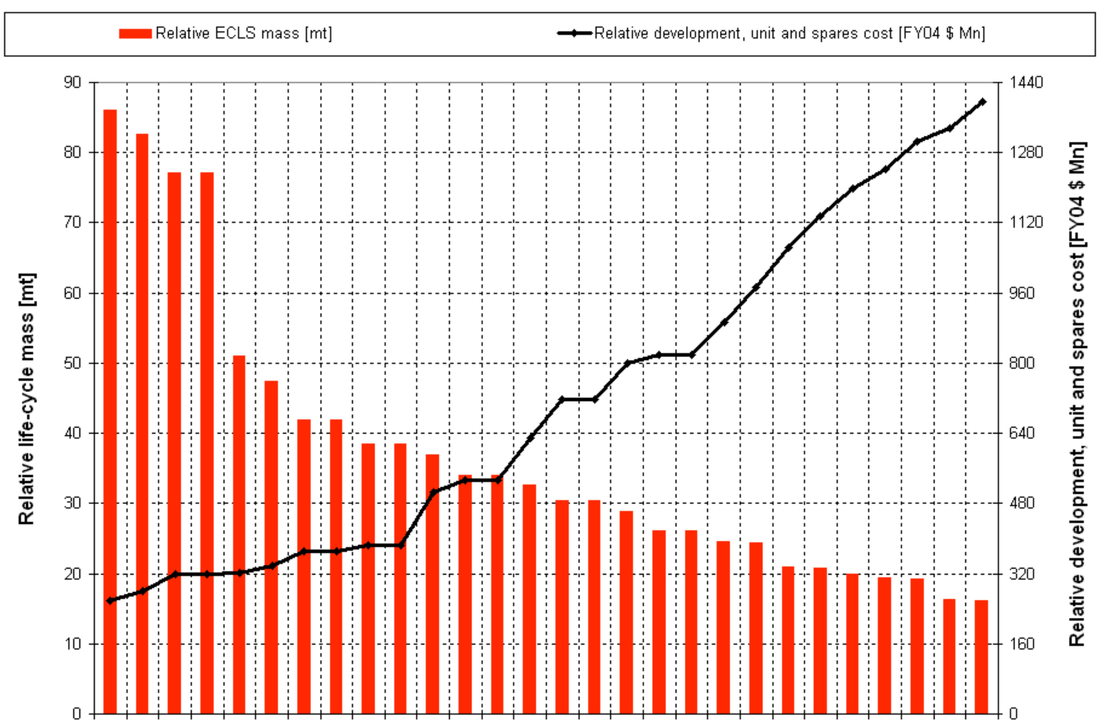


Figure 26: Relative development, unit, and spare parts cost vs. relative life-cycle mass on the lunar surface for architectures on the Pareto front for the lunar surface habitat

The red line in Figure 25 represents the architecture alternatives which are non-dominated, i.e. each of these alternatives is equal or better than all other alternatives with regard to at least one of the two metrics shown (this set of alternatives is sometimes also called the Pareto front). The metric values for this set of non-dominated architectures are shown in more detail in Figure 26: it starts on the left with alternatives which have low DDT&E, unit, and spare parts cost, and high life-cycle mass (these alternatives are based on low-closure technology choices which are cheaper to development and produce, but require significantly more re-supply). The Pareto front then proceeds along alternatives with steadily increasing DDT&E, unit, and spare parts cost and with steadily decreasing life-cycle mass, representing a trend towards more and more closure in the consumables loops. The variation between the metric value extremes is a factor 5 for both DDT&E, unit, and spare parts cost, and life-cycle mass.

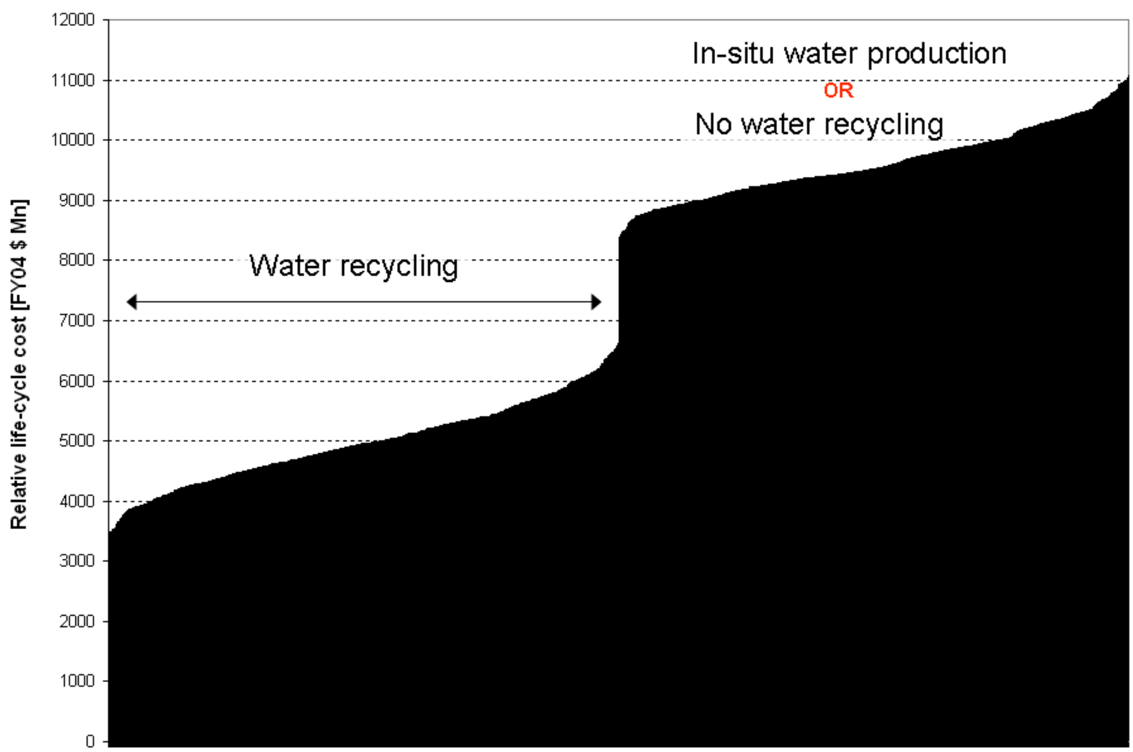


Figure 27: Life-cycle cost ranking of architectural alternatives for the lunar surface habitat life support system

Using Equation 15 and the transportation cost factor for the lunar surface, we now convert life-cycle mass into transportation cost and then calculate the true life-cycle cost for each architecture alternative. Figure 27 shows the resulting ranking of alternatives with regard to life-cycle cost: a significant step-increase in life-cycle cost is apparent about half-way through the set of ranked alternatives; this step-increase represents the transition from the lower left-hand group of architectures in Figure 25 to the top group of alternatives which have significantly higher DDT&E, unit, and spare parts costs and equal or increased transportation cost (i.e. equal or increased life-cycle mass). Figure 27 also makes it apparent that transportation cost is a significant part of life-cycle cost.

We use the ranking to identify preferred alternatives for the lunar surface habitat; Table 3 shows the 7 best-ranked alternatives. It is interesting to note that all preferred alternatives show the same technology choices for the functions of food provision, clothing provision, humidity removal, and water management, and differences between the alternatives exist primarily with regard to the technology choices for the functions carbon dioxide removal, oxygen provision, and trace contaminant control (TCC).

Table 3: Preferred architecture alternatives for the lunar surface habitat life support system

Function	Arch. 1	Arch. 2	Arch. 3	Arch. 4	Arch. 5	Arch.6	Arch. 7
Food provision	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food
CO2 removal	4BMS	4BMS	4BMS	4BMS	4BMS	Solid amine beds	4BMS
Oxygen provision	Ilmenite reduction	Ilmenite reduction	Electrolysis + Sabatier	Stored, hp	Electrolysis	Ilmenite reduction	Electrolysis + Sabatier
TCC	Exp.	Part. regen	Exp.	Exp.	Exp.	Exp.	Part. regen
Clothing	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine
Humidity removal	CHX	CHX	CHX	CHX	CHX	CHX	CHX
Water management	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD

The choice of regenerative technologies such as water recycling, condensing heat exchanger (CHX), or a washing machine is not surprising given the cumulative mission duration of the lunar surface habitat. The choice of water recycling technology leads to a water-rich environment aboard the habitat, obviating the need for additional water supply with food; this is the reason for the choice of de-hydrated food in all cases. Preferred architecture 6 is of particular interest because it represents a major variation in the oxygen provision approach: it utilized solid amine beds for CO_2 and humidity removal, thereby venting the CO_2 over board. Low life-cycle mass and cost can still be achieved because oxygen is produced from ilmenite on the lunar surface, thereby obviating the need for oxygen re-supply. Architecture 6 could potentially enable the reuse of the CEV solid amine CO_2 and humidity removal system design for the lunar surface habitat.

In order to assess the robustness of the ranking of architectural alternatives, a sensitivity analysis was carried out with regard to changes in the cumulative mission duration for the use case. As the life-cycle DDT&E, unit, and spare parts cost does not vary significantly with small (10-20%) increases in cumulative mission duration, the sensitivity of the alternatives can be judged by the change in life-cycle mass (and by proxy the change in life-cycle transportation cost) as a function of cumulative mission duration.

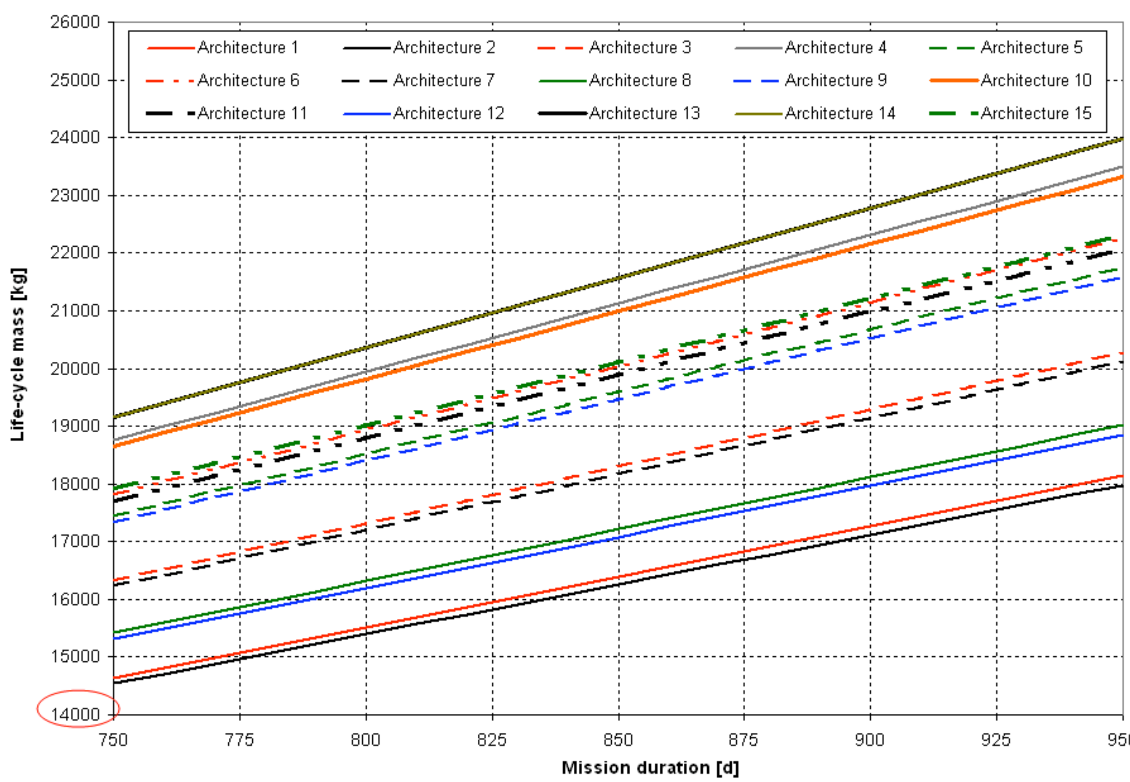


Figure 28: Results from sensitivity analysis with regard to cumulative mission duration for the lunar surface habitat preferred life support system architectures (note the buried zero)

Figure 28 shows the changes in life-cycle mass as a result of varying the cumulative mission duration for the 15 best-ranked architectures (ranking with regard to life-cycle cost). The lines for these architectures do not cross, indicating that the choice of preferred architectures is robust with regard to local (10%) changes in cumulative mission duration.

The analysis of architectural alternatives of the life support systems for the lunar lander, the NEO mission habitat, the Mars surface habitat, and the Mars transit habitat is carried out using the same steps as for the lunar surface habitat. The preferred architecture alternatives for each use case are described below; a comprehensive overview of results is provided in Figure 71 to Figure 78 and Table 23 to Table 26 Appendix II.

The preferred architecture alternatives for the lunar lander (Table 4) show robust technology choices for food provision, trace contaminant control, and clothing (all expendable, as would be expected for the short mission duration). For the other functions, technology choices vary between expendable and regenerative options. Of particular interest are alternatives with solid amine beds for both carbon dioxide and humidity removal; this indicates a potential opportunity for re-using CEV life support hardware.

Table 4: Preferred architecture alternatives for the lunar lander life support system

Function	Arch. 1	Arch. 2	Arch. 3	Arch. 4	Arch. 5	Arch.6	Arch. 7
Food provision	Fully hydrated	Fully hydrated	Fully hydrated	Fully hydrated	Fully hydrated	Fully hydrated	Fully hydrated
CO2 removal	Solid amine, pressure-swing	LiOH	Solid amine, pressure-swing	LiOH	Solid amine, pressure-swing	LiOH	LiOH
Oxygen provision	Stored, high-pressure	Stored, high-pressure	Stored, high-pressure	Stored, high-pressure	Stored, cryogenic	Stored, cryogenic	Stored, high-pressure
TCC	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
Clothing	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
Humidity removal	Solid amine	Silica gel	Solid amine	Silica gel	Solid amine	Silica gel	CHX
Water management	Stored	Stored	Multi-filtration	Multi-filtration	Stored	Stored	Stored

The preferred alternatives for the NEO mission habitat life support system (Table 5) exhibit robust technology choices for food provision, carbon dioxide removal, clothing provision, humidity removal, and water management (regenerative technologies and de-hydrated food due to water regeneration). Major distinctions between the architectures exist only for oxygen provision and trace contaminant control.

The preferred alternatives for the Mars surface habitat life support system exhibit robust technology choices for food provision, carbon dioxide removal, clothing provision, humidity removal, and water management (regenerative in all cases due to the long mission duration, de-hydrated food). Major differences exist for oxygen provision and trace contaminant control.

Table 5: Preferred architecture alternatives for the NEO mission habitat life support system

Function	Arch. 1	Arch. 2	Arch. 3	Arch. 4	Arch. 5	Arch.6	Arch. 7
Food provision	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food
CO2 removal	4BMS	4BMS	4BMS	4BMS	4BMS	4BMS	4BMS
Oxygen provision	Stored hp	Electrolysis	Stored hp	Electrolysis + Sabatier	Cryo	Electrolysis	Stored hp
TCC	Exp.	Exp.	Part. regen.	Exp.	Exp.	Part. regen.	Exp.
Clothing	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine
Humidity removal	CHX	CHX	CHX	CHX	CHX	CHX	CHX
Water management	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD

Table 6: Preferred architecture alternatives for the Mars surface habitat life support system

Function	Arch. 1	Arch. 2	Arch. 3	Arch. 4	Arch. 5	Arch.6	Arch. 7
Food provision	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food
CO2 removal	4BMS	4BMS	4BMS	4BMS	4BMS	4BMS	4BMS
Oxygen provision	Zirconia electrolysis	Zirconia electrolysis	Electrolysis + Sabatier + pyrolysis	Electrolysis + Sabatier + pyrolysis	Electrolysis + Sabatier	Electrolysis + Sabatier	Electrolysis
TCC	Exp.	Part. regen.	Exp.	Part. regen.	Exp.	Part. regen.	Exp.
Clothing	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine
Humidity removal	CHX	CHX	CHX	CHX	CHX	CHX	CHX
Water management	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD

The preferred alternatives for the Mars transit habitat life support system (Table 7) are similar to the alternatives for the NEO mission habitat life support system (Table 5). The major difference is that higher-closure technology choices for oxygen provision are favored due to the longer cumulative mission duration of the transit habitat.

Table 7: Preferred architecture alternatives for the Mars transit habitat life support system

Function	Arch. 1	Arch. 2	Arch. 3	Arch. 4	Arch. 5	Arch.6	Arch. 7
Food provision	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food	Dehydrated food
CO2 removal	4BMS	4BMS	4BMS	4BMS	4BMS	4BMS	4BMS
Oxygen provision	Electrolysis + Sabatier + pyrolysis	Electrolysis + Sabatier + pyrolysis	Electrolysis + Sabatier	Electrolysis + Sabatier	Electrolysis	Electrolysis	Stored hp
TCC	Exp.	Part. regen.	Exp.	Part. regen.	Exp.	Part. regen.	Exp.
Clothing	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine	Washing machine
Humidity removal	CHX	CHX	CHX	CHX	CHX	CHX	CHX
Water management	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD	MF + VCD

Based on the 7 preferred life support system architecture alternatives for each of the 5 future use cases in the portfolio, we can now enumerate $7^5 = 16807$ preferred portfolio design solutions without commonality by combining preferred architecture alternatives for the 5 future use cases. Figure 29 shows the resulting portfolio design solutions with the relative life-cycle transportation cost plotted over relative life-cycle DDT&E, unit, and spare parts cost. A Pareto front of non-dominated portfolio design solutions without commonality can be identified; however, dominated portfolio design solutions without commonality are intentionally considered because once commonality is introduced they may actually outperform the non-dominated portfolios without commonality.

Figure 29 shows the 16807 portfolio design solutions with the total number of development projects required for the future use cases in the portfolio plotted over life-cycle cost including transportation. The total number of development projects is constant at 35 because each of the 5 future use case implementation requires 7 development projects (1 for each function). Life-cycle cost including transportation varies from about 44 billion in FY04 dollars to about 49 billion in FY04 dollars. Note: these numbers may seem high when compared to traditional life support system cost estimates; however, the traditional estimates do not include the transportation cost associated with the life support system and its consumables and spare parts.

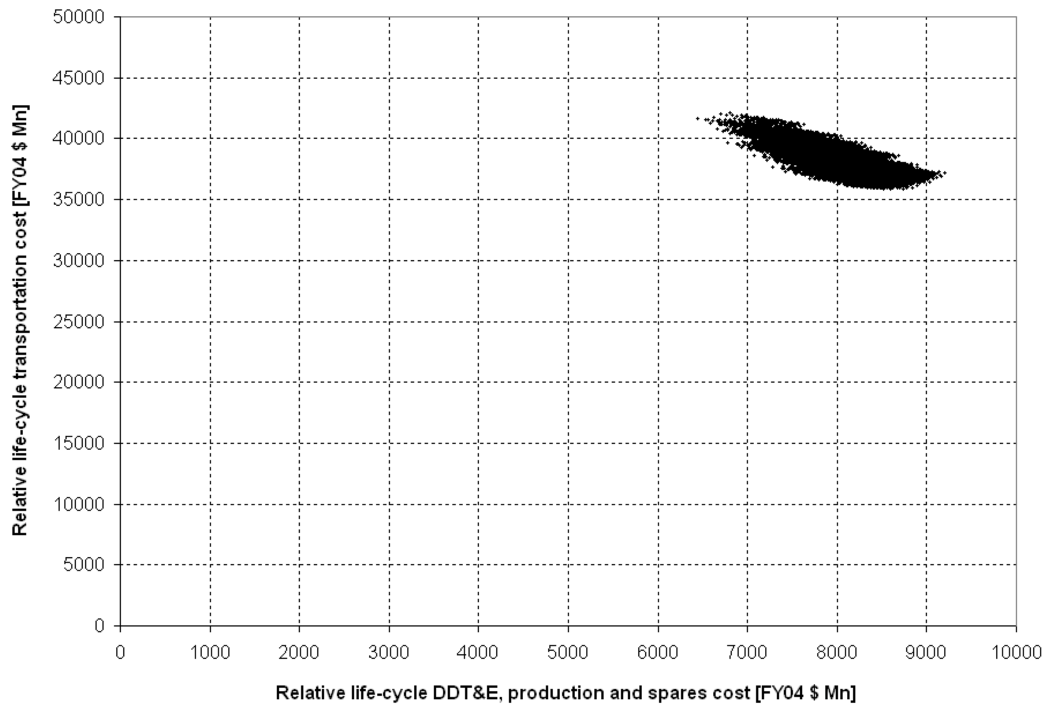


Figure 29: Relative life-cycle transportation cost vs. relative DDT&E, unit, and spare parts cost for the preferred portfolio design solutions without commonality

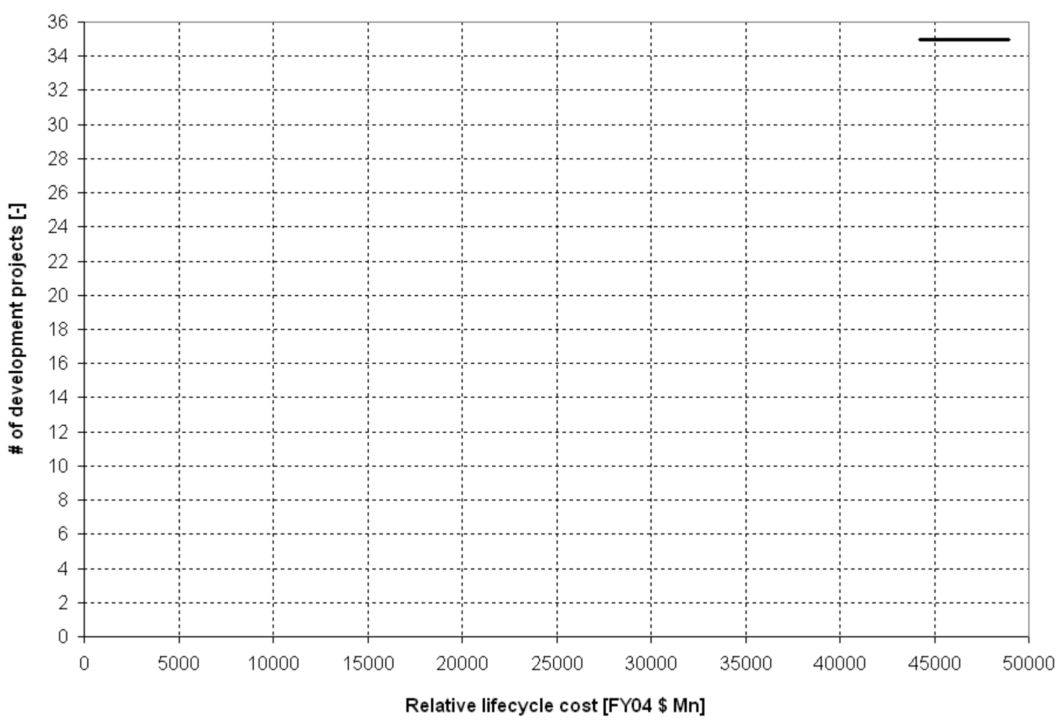


Figure 30: Number of portfolio development projects vs. relative life-cycle cost for the preferred portfolio design solutions without commonality

3.3 Commonality Screening

The next step (Step 3: Commonality Screening) is to identify commonality opportunities within each of the 16807 point design portfolios and calculate a best-case net benefit of commonality for each portfolio design solution. This step transforms each point design portfolio design solution into a portfolio design solution with commonality by choosing the variant with the minimum number of dedicated development projects for each portfolio design solution. The identification of commonality opportunities is achieved by assessing whether the four commonality criteria described in Section 2.2 are fulfilled for all system pairings in a particular portfolio design solution without commonality; the process is then repeated for all other portfolio design solutions without commonality that are the output of the individual system architecture analysis in Step 2. The following is a description of the four commonality criteria customized for the life support systems portfolio design solutions:

- **Criterion 1 (identical internal functionality):** overlap in functionality is ensured by only analyzing commonality opportunities between the same internal function for all system pairings in a portfolio design solution. This corresponds to only considering commonality opportunities between implementations of functions in the same row in the Morphological Matrix.

- **Criterion 2 (identical technology choices):** overlap in technology choices is ensured by only considering commonality if the two systems implement the same internal function with the same technology choice; this corresponds to both systems having the same position in the Morphological Matrix (same row, same column / technology choice).

- **Criterion 3 (similarity in operational environments):** overlap in operational environments is assessed only if Criteria 1 and 2 are fulfilled. A list of operational environments is defined for all portfolio design solutions, and then the number of identical operational environments is assessed for each function (assuming identical technology choices for both systems). This number is then divided by the total number of operating environments for each of the two systems in the pairing; if the quotient is larger than a specific ***operational overlap fraction δ*** then Criterion 3 is fulfilled. The process is repeated for each system pairing inn the portfolio design solution, and then for all the other portfolio design solutions. The operating environments considered for the life support systems portfolio are:

- ***Active operation under high dynamic loads***: this corresponds to the launch and entry phases of a mission. Only the CEV life support system has a requirement for operation in this environment.

- ***Dormant operation under high dynamic loads***: this corresponds to the launch and entry phases of a mission. All life support systems in the portfolio have a requirement for operation under these conditions since all need to be launched into space.

- ***Microgravity operations***: this corresponds to coasting in an orbital or interplanetary trajectory. The lunar lander, CEV, ISS, NEO mission habitat, and Mars transit habitat life support systems have to be able to work in this environment.

- ***Hypogravity operations***: hypogravity is a state with less gravity than on the surface of the Earth, but not microgravity; examples for hypogravity environments include the lunar and Mars surfaces, but also spacecraft environments under major propulsive burn loads. All systems in the portfolio except the ISS life support system have to operate under hypogravity conditions, either on planetary surfaces or during in-space burns.

- ***1-g operations***, such as on the surface of the Earth. Only the CEV life support system has to operate under these conditions (prior to Earth launch, after Earth landing).

- ***Operations in a vacuum environment***: the CEV and lunar lander cabins must be capable of depressurization in order to enable extravehicular activities both for nominal and contingency mission operations.

- **Criterion 4 (similarity in design parameters):** overlap in quantitative design parameters such as equipment mass, throughput (air or water), power consumption and heat rejection needs is assumed to be acceptable for all functions because of the following considerations: for the same technology, the difference between different use cases is whether the equipment is designed around 4 or 6 crew; given that equipment mass is not the most significant cost driver in terms of life-cycle cost. Criterion 4 is therefore assumed to be fulfilled if Criteria 1-3 are fulfilled; the common implementation is designed around the maximum requirements encountered (for example around the 6-crew case).

In order to assess whether Criteria 1-3 are met, the concept description matrix (CDM) / system overlap matrix (SOM) approach introduced in Section 2.2 was used (see Figure 31 for a CDM / SOM template). The left-hand side of the CDM / SOM is a vertical Morphological Matrix for all functions considered in the portfolio. This Morphological Matrix contains the union of all sets of technology choices encountered in the portfolio for each function; that way any architecture in the portfolio can be captured. Along the top of the CDM / SOM (columns) the union of all sets of operational environments that the systems in the portfolio have to operate in is arranged horizontally.

	Operational environment	High-g active (launch and entry)	High-g dormant (launch and entry)	0-gravity	Hypogravity	1-gravity	Vacuum
Function	**Technology**						
Food provision	Fully hydrated						
	De-hydrated						
CO2 removal	LiOH						
	Solid amine						
	4BMS						
O2 provision	Stored, high-pressure						
	Stored, cryogenic						
	Water electrolysis						
	Sabatier reactor						
	Sabatier reactor + methane pyrolysis						
	Ilmenite reduction (Moon)						
	Zirconia electrolysis (Mars)						
TCC	Expendable						
	Partially regenerative						
Clothing	Expendable						
	Washing machine + dryer						
Humidity removal	CHX + separator						
	Solid amine						
	Silica gel						
Water provision	Stored						
	Multifiltration						
	Multifiltration + VCD						
	Ilmenite reduction (Moon)						
	Zirconia electrolysis + fuel cell (Mars)						

Figure 31: Overview of the concept description matrix (CDM) / system overlap matrix (SOM) template for exploration life support systems analysis

In a CDM / SOM that is constructed in this way every architecture concept for each system in the portfolio (legacy and future) can be expressed in standardized form by marking required operations for technology choices with “1”; all other fields in the CDM are “0”. In order to assess the validity of Criteria 1-3, the CDMs of two systems are “overlaid” by adding the entries in both CDMs for each field; this creates the associated SOM. Fields in the SOM for which the sum of entries is equal to “2” indicate overlap. For each function we can now calculate the quotients required by Criterion 3 and compare to the required ***operational overlap fraction δ***. For a visualization of this process, please refer to Figure 19 in Section 2.2.

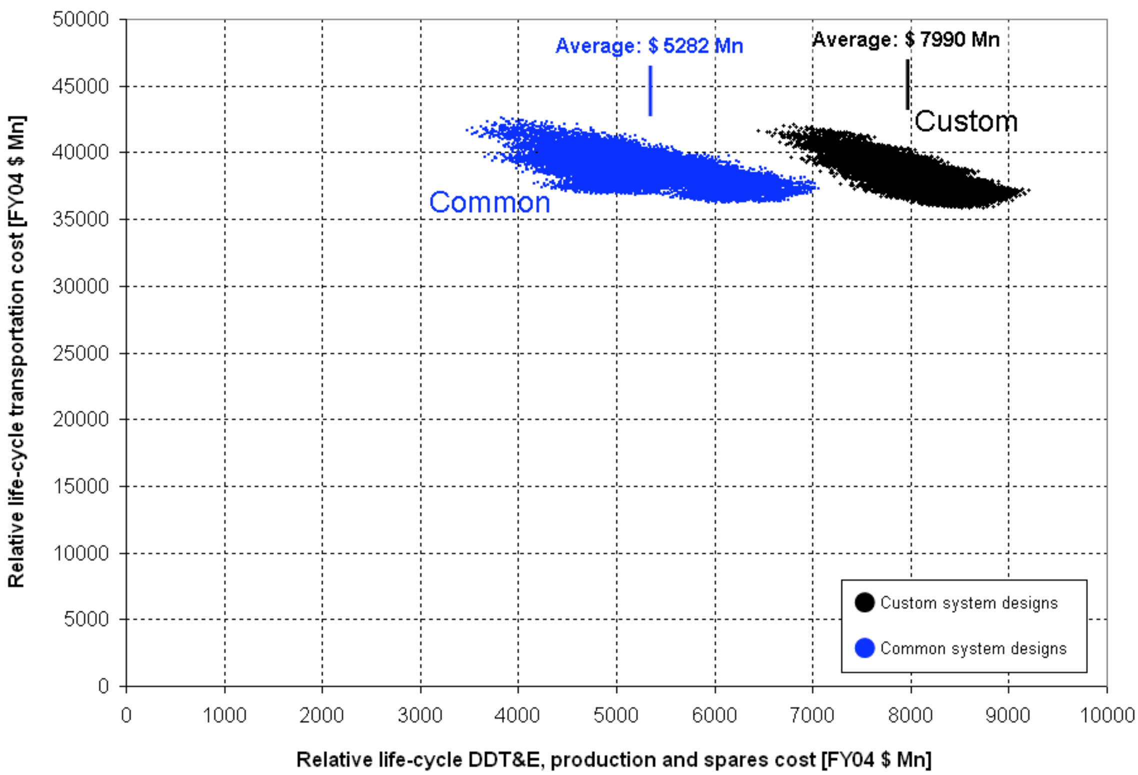


Figure 32: Results of portfolio commonality assessment for δ = 90%; life-cycle transportation cost vs. life-cycle DDT&E, unit, and spare parts cost

This assessment was implemented in Java code for each of the 7 functions separately; the automated implementation is necessary to enable the analysis of 16807 portfolios with 21 pairings of systems each for the 7 systems in the portfolio. The source code for the Java implementations is provided on the attached thesis CD. Figure 32 shows the results for the common portfolio design solutions plotted as relative life-cycle transportation cost vs.

relative DDT&E, unit, and spare parts cost. The threshold δ for Criterion 3 was assumed to be 90%, i.e. the number of common entries per function normalized with the total number entries must be greater or equal 90% for both systems considered (high operational similarity). The blue set of points in Figure 32 represents portfolio design solutions with commonality, the black set those without commonality (see also Figure 29). It is apparent that, in an average sense, commonality leads to a significant decrease in life-cycle DDT&E, unit and spare parts cost due to the reduced number of dedicated designs and learning curve effects, while incurring a modest increase in transportation cost due to the added mass necessitated by over-design.

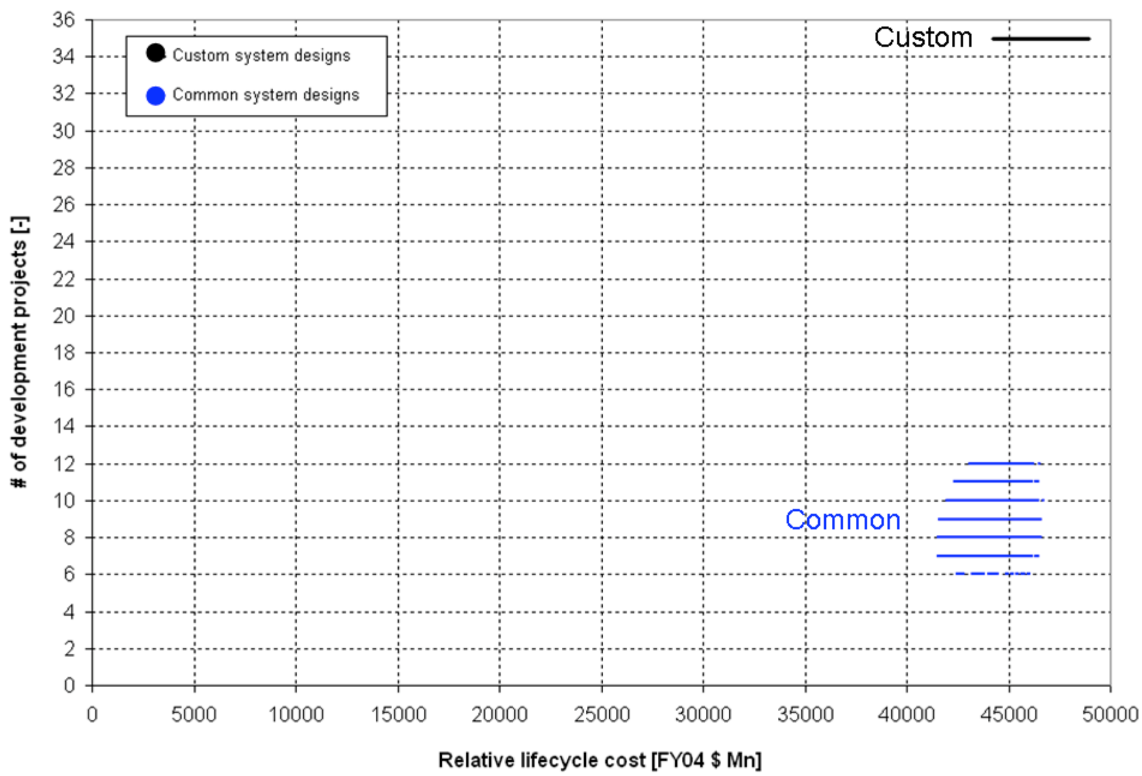


Figure 33: Results of portfolio commonality assessment for δ = 90%; # of development projects vs. portfolio life-cycle cost

Figure 33 provides a perhaps more instructive way of visualizing the overall impact of commonality on the portfolio design solutions: for the assumed threshold value, commonality leads to a net 5-10% reduction in life-cycle cost, but to a 3-fold reduction in the number of development projects required (see Figure 79 and Figure 80 in the Appendix II for a portfolio-by-portfolio view of life-cycle cost and number of development project reductions). This indicates that life-cycle cost reductions may not be the primary driver for and benefit of commonality, but instead the reduction in the number of development projects and the associated developmental risks and cost overheads are a stronger benefit. It is also interesting to note that the portfolio design solutions with minimum life-cycle cost are not the ones with the lowest number of development projects, confirming the empirical insight that commonality itself is neither positive or negative: it is the trade-off between the advantages and disadvantages of a particular commonality opportunity that determine the net benefit to life-cycle cost.

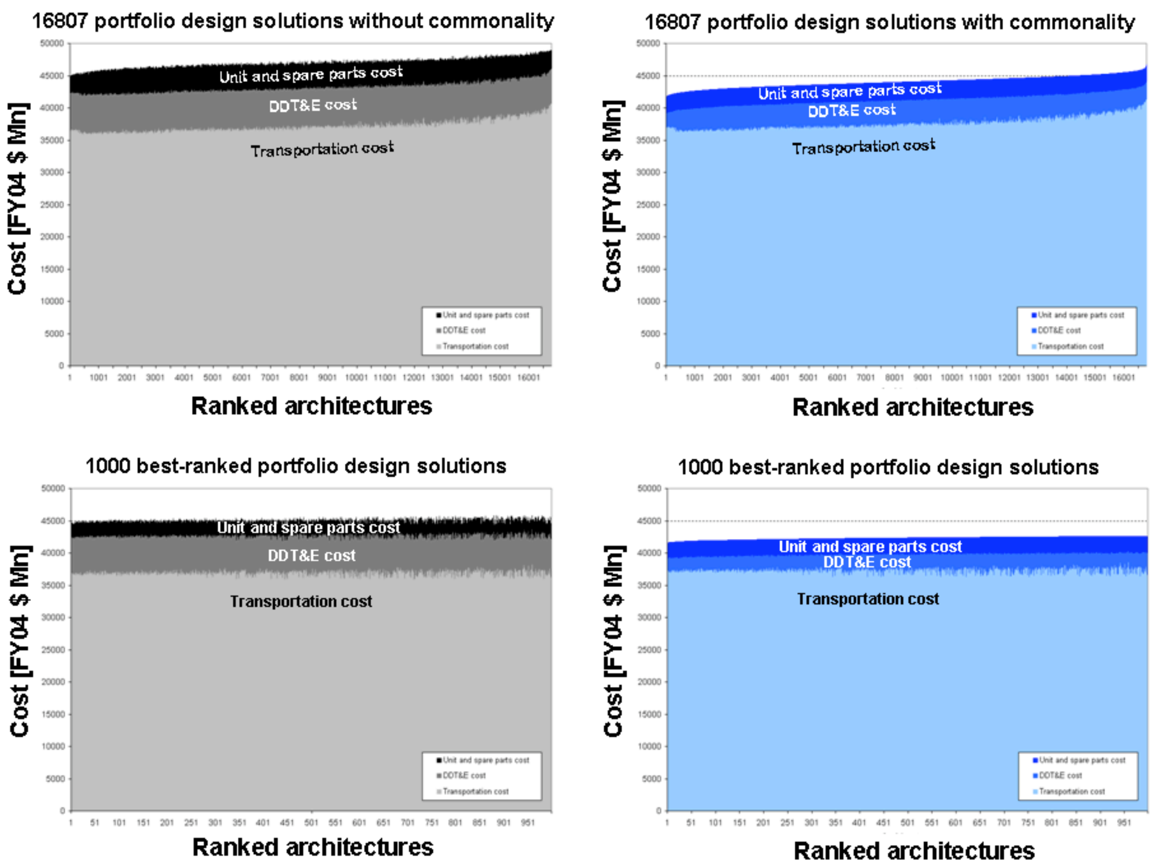


Figure 34: Life-cycle cost breakdown for portfolio design solutions (left-hand side: custom, right-hand side: common); ranking by life-cycle cost for the common portfolios. The top two diagrams show all 16807 portfolio design solutions, while the lower two diagrams only show the 1000 best-ranked portfolio design solutions (ranking with regard to life-cycle cost).

In order to understand the relatively modest benefit in terms of life-cycle cost reduction, it is necessary to understand the cost breakdown of portfolio life-cycle cost. Figure 34 provides breakdowns for both custom and common portfolio design solutions. It is apparent that the majority (about 80%) of life-cycle cost consists of transportation cost, with DDT&E and unit & spare parts cost each being about 10%. As the positive effect of commonality is limited to DDT&E, unit, and spare part costs, whereas life-cycle transportation cost may slightly increase due to commonality, the net effect of commonality has to be limited: even if all of the DDT&E, unit, and spare parts cost could be saved, the net reduction in life-cycle cost would still only be about 20%.

Figure 35 shows the common portfolio design solution with the lowest life-cycle cost among the 16807 alternatives in the form of a clustered design structure matrix (DSM) of life support system functions in the portfolio [DSM-09]: the colored shaded fields across multiple functions indicate opportunities for common design implementations across multiple functions. For this particular portfolio design solution, commonality leads to a portfolio life-cycle cost reduction from FY04 \$ 44440 Mn to \$ 41577 Mn, and to a reduction of the number of custom development projects from 35 to 8.

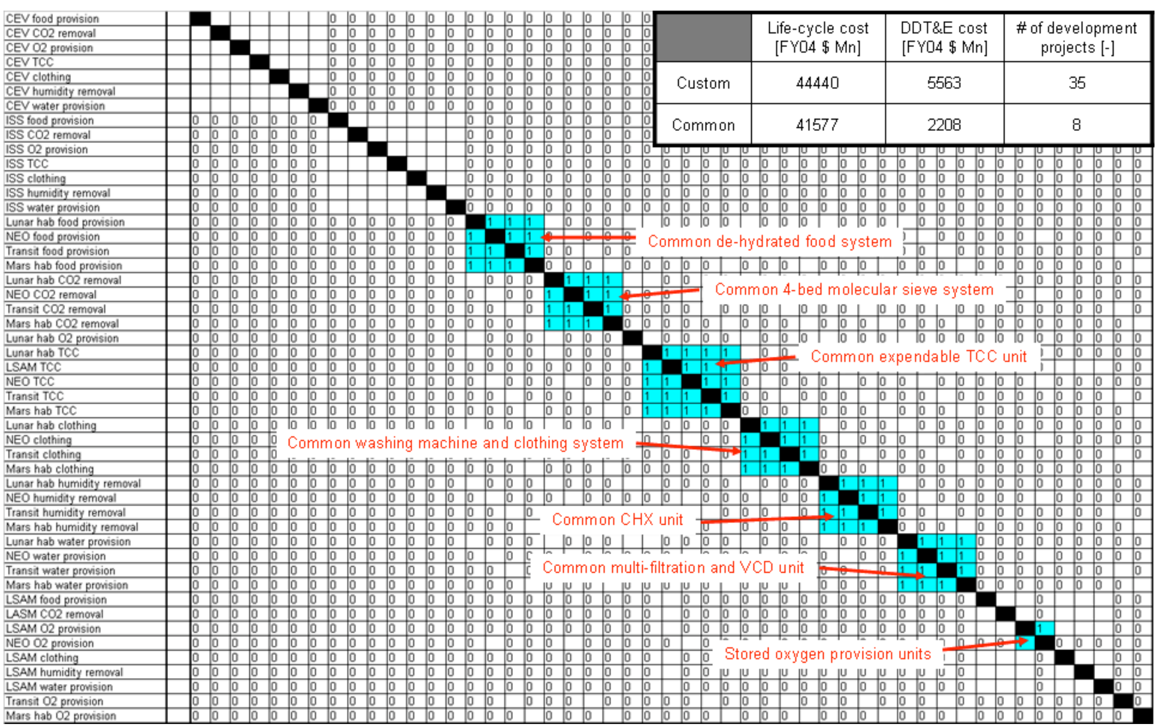


Figure 35: Common portfolio design solution with the lowest life-cycle cost for δ = 90%; shaded clusters indicate commonality opportunities

Commonality opportunities for this portfolio design solution include (see shaded clusters in Figure 35; each cluster represents one opportunity for a common implementation of a specific function across different vehicles):

- The use of a common de-hydrated food system for the lunar surface, NEO mission, Mars surface, and Mars transit habitats
- The use of a common 4-bed molecular sieve (4BMS) design based on the ISS design for the lunar surface, NEO mission, Mars surface, and Mars transit habitats
- The use of a common extendable filter unit for trace contaminant control (TCC)
- The use of a common washing machine and clothing system design for the lunar surface, NEO mission, Mars surface, and Mars transit habitats
- The use of a common water recycling system design based on the ISS design for the lunar surface, NEO mission, Mars surface, and Mars transit habitats

Table 8: Carbon dioxide technology choices for the 20 lowest-life-cycle portfolio design solutions with commonality; identical color indicates identical technology choice

Portfolio	CEV	ISS	Lunar lander	Lunar surface habitat	NEO mission habitat	Mars surface habitat	Mars transit habitat
1	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
2	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
3	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
4	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
5	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
6	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
7	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
8	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
9	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
10	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
11	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
12	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
13	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
14	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
15	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
16	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
17	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
18	Solid amine	4BMS	LiOH	4BMS	4BMS	4BMS	4BMS
19	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS
20	Solid amine	4BMS	Solid amine	4BMS	4BMS	4BMS	4BMS

The best-ranked common portfolio design solution is, of course, not the only one to be considered for input into more detailed design phases; the results shown in Figure 33 and Figure 34 suggest that there are many common portfolio design solutions with similar life-cycle cost and number of development projects. In order to assess the robustness of the commonality opportunities identified for the best-ranked portfolio design solution we investigate what technology choices are favored among the 20 best-ranked (with regard to life-cycle cost) portfolio design solutions. Table 8 shows the technology choices of these 20 portfolios for the carbon dioxide removal function.

It is apparent that the commonality opportunity of using a common 4BMS based on the ISS design is very robust indeed, whereas the reuse of the CEV solid amine system design is less robust with only about half of the portfolios favoring this technology choice for the lunar lander. Table 27 - Table 32 in Appendix II provide corresponding overview of technology choices for the remaining 6 functions (food provision, oxygen provision, TCC, humidity removal, clothing provision, and water management); based on these tables it is possible to identify a number of other robust commonality opportunities: a common clothes washing system, a common de-hydrated food system, a common condensing heat exchanger design, a common water recycling system, as well as a common Sabatier reactor design for CO_2 recycling. This indicates that the majority of the commonality opportunities identified with the best-ranked portfolio design solution are actually robust (at least across the 20 best-ranked portfolio design solutions). It also indicates that variations in technology choices occur primarily in the areas of CO_2 removal, TCC, and oxygen provision for a subset of the systems in the portfolio.

A more detailed discussion and analysis of the portfolio design solutions with commonality is beyond the scope of this thesis; however, the data for the 16807 portfolio design solutions is provided on the attached thesis CD (see also Appendix V).

3.4 Sensitivity Analysis and Selection of Commonality Opportunities for Detailed Design

Criterion 3 requires the definition of a value for the threshold parameter δ for the assessment of the degree of operational overlap in a system pairing. For the analysis presented in Section 3.3, this threshold was assumed to be 90%, i.e. a relatively high overlap in terms of operational environments / requirements is necessary for two systems to be eligible for common implementation.

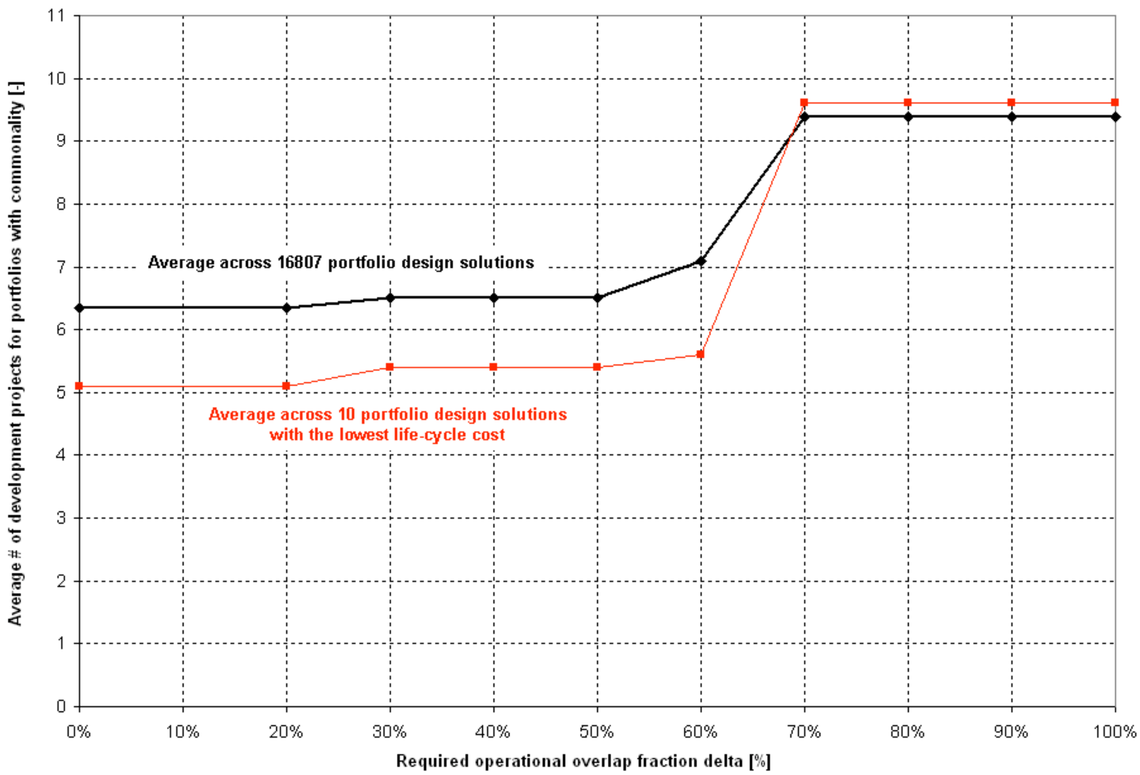


Figure 36: Average number of development projects across the 16807 common portfolio design solutions as a function of the value for the overlap parameter δ

The parameter δ is the major free variable in the commonality screening, and therefore a sensitivity analysis is necessary to assess the impact of changes in the parameter. To that end, the parameter δ is varied from 100% to 0%, and we assess the impact on commonality opportunities by calculating the average number of custom development projects across the 16807 common portfolio design solutions for each case, as well as across the 10 best-ranked (i.e. lowest life-cycle cost) portfolio design solutions. Figure 36 shows the results for this sensitivity analysis; both for the 16807 portfolio design solutions as well as for the 10 best-ranked portfolio design solutions there are three transitions in the level of average custom development projects: one from 70% - 60%, one from 60% - 50%, and one from 30% to 20%.

In order to enable an informed down-selection among the portfolio design solutions with commonality we need to investigate what impact the parameter change has on the portfolio design solutions with commonality. To that end we repeat the comprehensive analysis of commonality opportunities within the 16807 preferred point design portfolios which was previously carried out with $\delta = 90\%$ with a new parameter setting of $\delta = 50\%$; this corresponds to the iteration shown in Figure 14, Section 2.2.

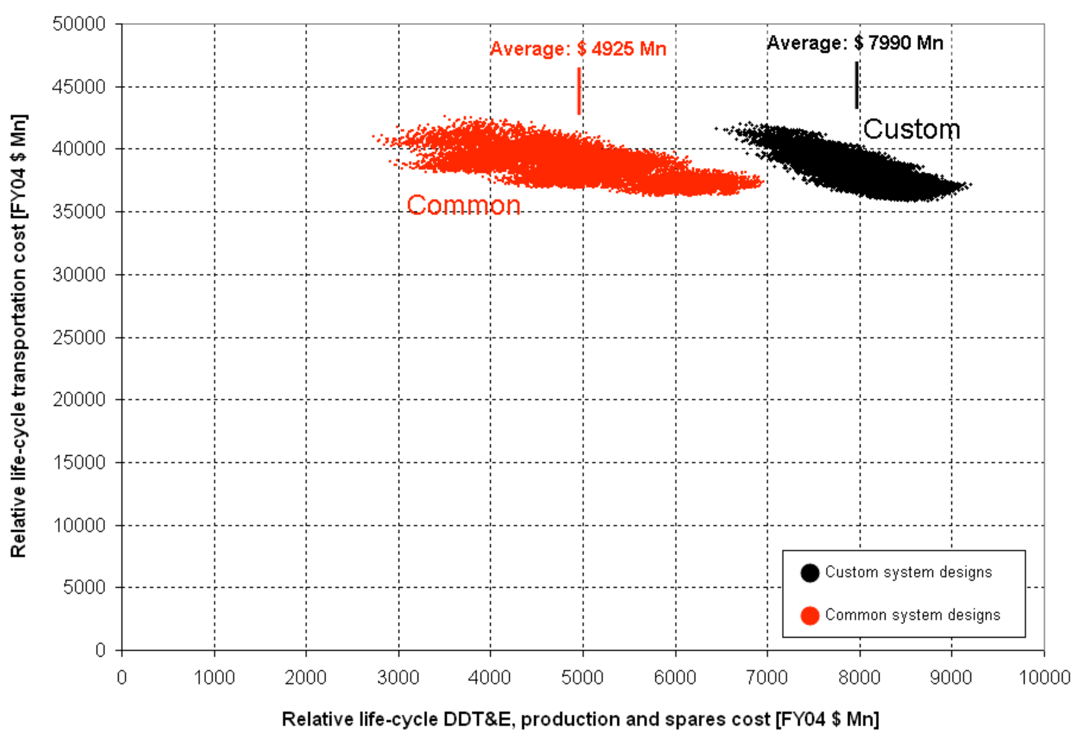


Figure 37: Results of portfolio commonality assessment for $\delta = 50\%$; life-cycle transportation cost vs. life-cycle DDT&E, unit, and spare parts cost

Figure 37 and Figure 38 show the results of this analysis. Requiring a lower overlap of operational requirements leads to an increase in commonality opportunities as evidenced by the lower number of custom development achievable; however, this increase in commonality opportunities does not translate into further reductions of life-cycle cost compared to the δ = 90% case. This is a further indication that commonality does not necessarily result in a life-cycle cost decrease, because over-design may result in more DDT&E, unit, and spares cost for the common design as well as increased transportation costs which may outweigh the savings through commonality.

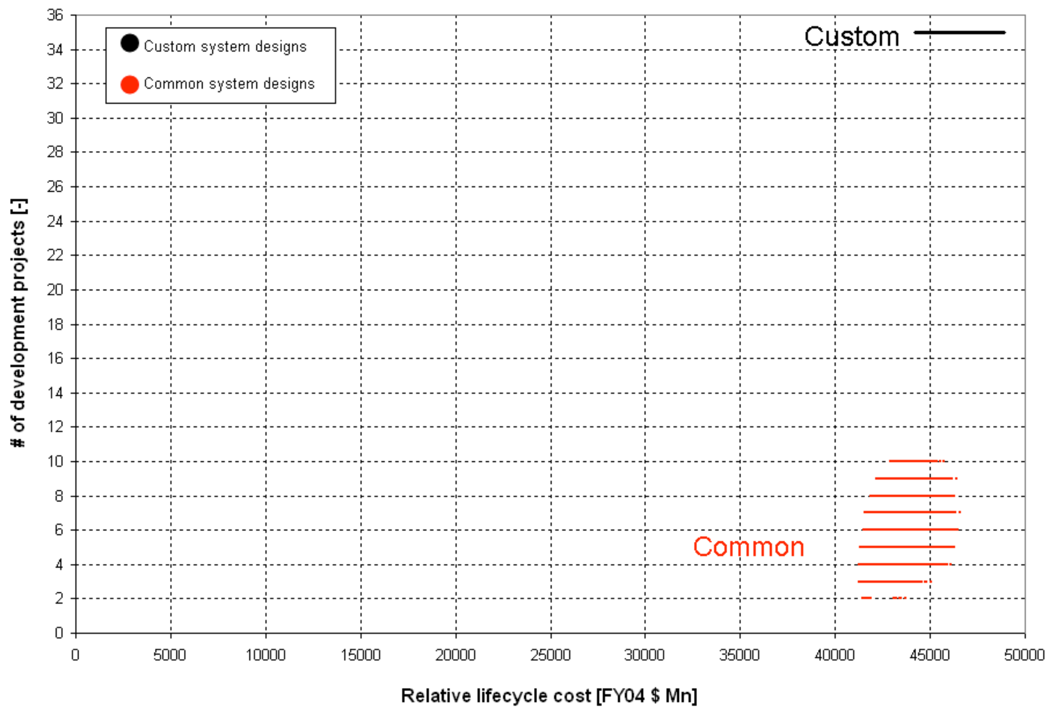


Figure 38: Results of portfolio commonality assessment for δ = 50%; # of development projects vs. portfolio life-cycle cost

Figure 39 shows the commonality opportunities identified for the best-ranked portfolio design solution in the δ = 50% case; as is expected, the relaxed requirement for operational overlap leads to a significant increase in the number of commonality opportunities identified. Only 4 custom implementations of subsystem functions are required in this case, compared to 35 for completely custom portfolio design solutions. The life-cycle cost is reduced from FY04 $ Mn 44440 to FY04 $ Mn 41290. Major additional commonality opportunities identified beyond those described above for the δ = 90% case include:

- A common solid amine system design for carbon dioxide and humidity removal for use on the CEV and on the lunar lander (extensibility of the CEV design)

- A common hydrated food system (MRE-style) for the lunar lander, based on ISS and CEV food system designs

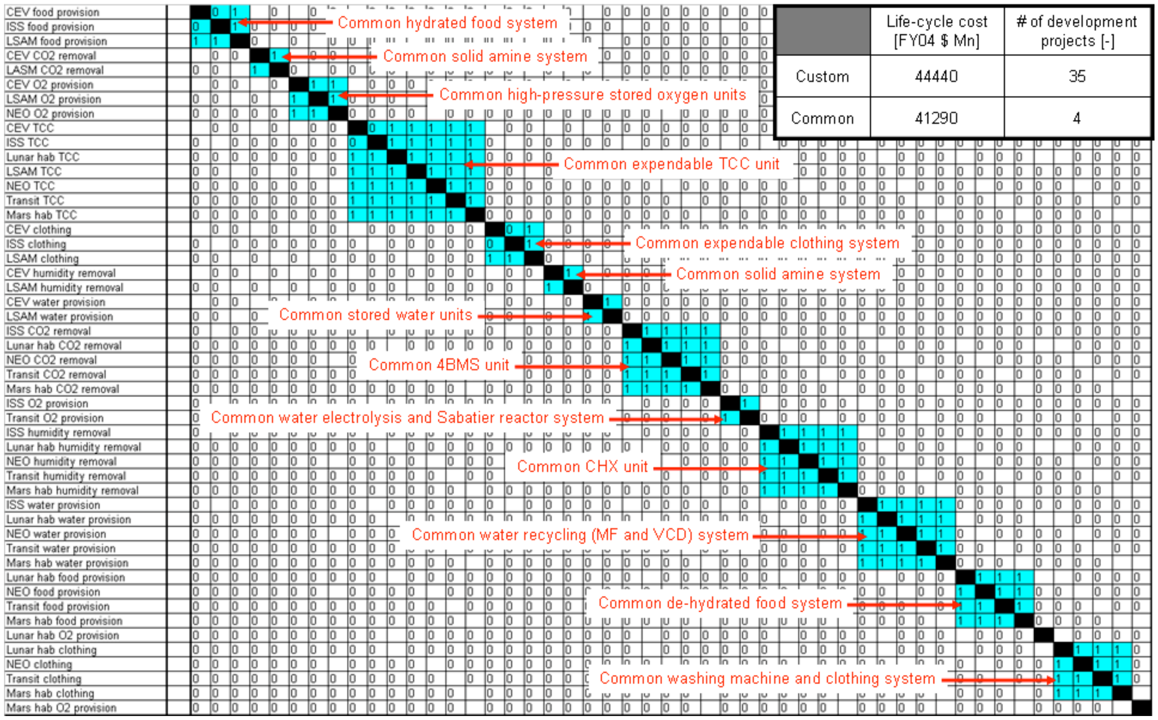


Figure 39: Common portfolio design solution with the lowest life-cycle cost for δ = 50%; shaded clusters indicate commonality opportunities

- Common high-pressure oxygen storage tanks for the CEV, lunar lander, and NEO mission habitat

- A common expendable clothing system for the lunar lander, CEV, and ISS

- A water electrolysis and Sabatier system for oxygen production on the Earth-Mars-Earth transit habitat based on the ISS system design

Other commonality opportunities remain the same but may now include more systems.

Figure 40 provides further insight into the differences in commonality analysis results between the δ = 90% and δ = 50% cases. Shown is the similarity or difference of technology choices for the 50 best-ranked portfolio design solutions function by function and use-case by use-case; each row represents one portfolio. Red fields indicate differences between the technology choices; white fields indicate identical technology choices. It is apparent that for the food provision and clothing provision, there is no difference between the two cases, i.e. the exact same commonality opportunities exist. For the CO_2 removal, humidity removal, and water removal functions, the technology choices for all of the long-duration systems are identical. This indicates that the associated robust commonality opportunities (common 4BMS, common CHX, common water recycling system) identified with δ = 90% are also valid with δ = 50%.

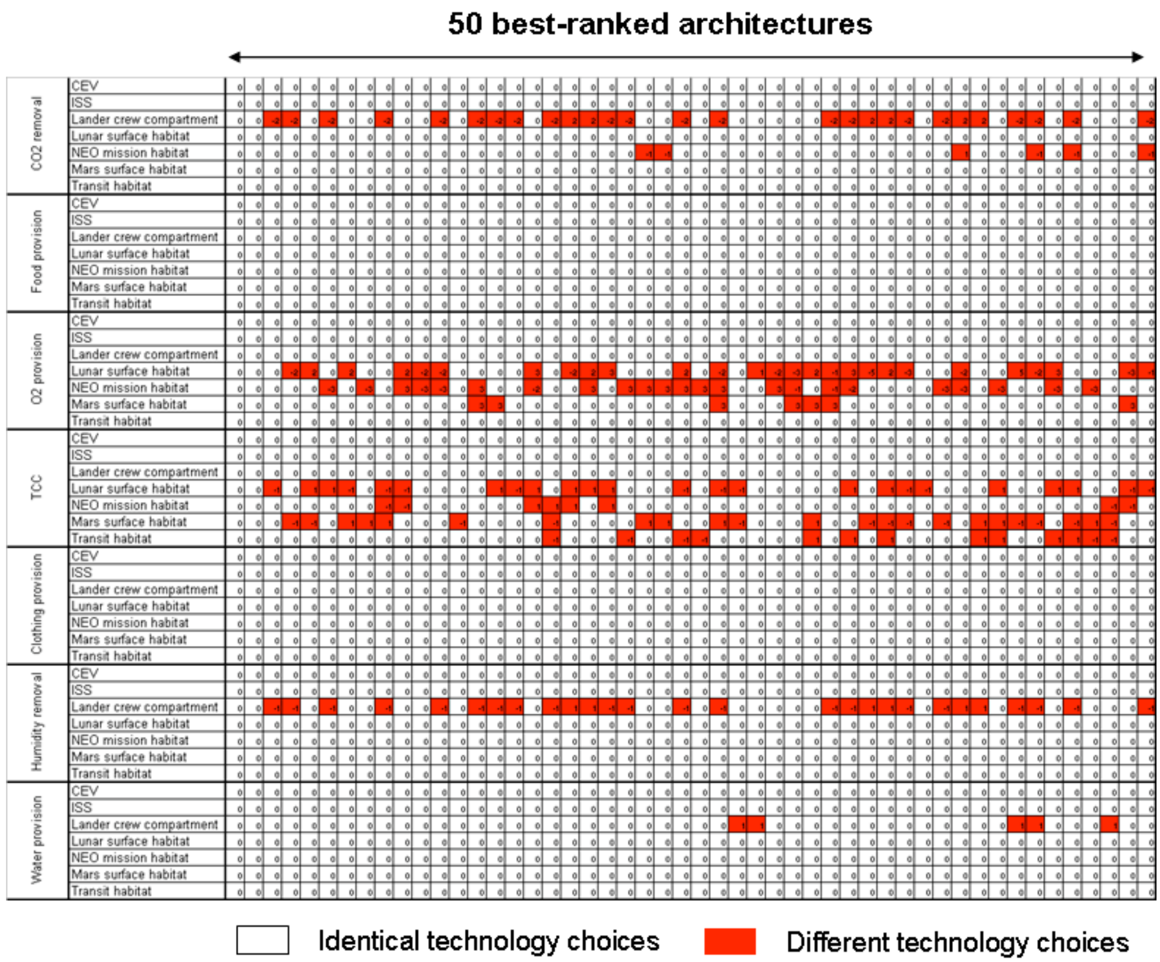


Figure 40: Overlap of technology choices for the 50 best-ranked architectures for values of δ = 90% and δ = 50%; red color indicates different technology choices for the given functionality.

The oxygen provision and trace contaminant removal functions exhibit major differences in technology choices; however the commonality opportunity with regard to the reuse of the ISS Sabatier reactor system design for the Mars transit habitat is also valid with δ =

50%. These results indicate that the use of δ = 90% identified a robust set of commonality opportunities, both with regard to changed in preferred portfolio and with regard to changes in the overlap parameter $\boldsymbol{\delta}$.

After exploring the sensitivity of commonality opportunities to the degree of overlap in operational environments / requirements we are now in a position to make an informed down-selection of design solutions and commonality opportunities for the 7 subsystem functions which should be considered during more detailed design activities. This selection is based on the preferred portfolio design solution for the δ = 50 % case; the rationale for choosing this case is that 50 % overlap in operational environments still constitutes significant operational similarity while leading to the identification of a significantly larger number of commonality opportunities for further consideration. These commonality opportunities are shown in Figure 39. Special consideration should be given to those commonality opportunities which were identified as robust by the analysis presented in Figure 40:

- **CO_2 removal:** a common 4-bed molecular sieve system based on the ISS technology and design for use on all future long-duration systems
- **Food provision:** a common hydrated food system for the CEV, ISS, and lunar lander, based on the ISS food system; and a new common de-hydrated food system for all future long-duration applications
- **Oxygen provision**: common high-pressure stored oxygen units for use on the lunar lander and CEV (and potentially also on the NEO mission habitat – this is a less robust choice); and a water electrolysis and Sabatier system design for the transit habitat derived from the ISS technology and design
- **Trace contaminant control**: common expendable TCC units for all applications based on the ISS technology and design
- **Clothing provision**: common expendable clothing for the CEV and lunar lander based on the ISS clothing system; and a common regenerable clothing system for all future long-duration applications

- **Humidity removal**: a common condensing heat exchanger system for use on all future long-duration habitats based on the ISS technology and design

- **Water provision**: a common regenerative water management system with filtration and distillation units for reclamation of water both from urine, condensate and wash waste water for use on all future long-duration habitats; this design should be based on the ISS technology and design.

While not nearly as robust as the above commonality opportunities, the potential for use of a common carbon dioxide and humidity removal system on the CEV and lunar lander (based on the CEV solid amine system) is sufficiently interesting to be considered in more detailed analysis.

3.5 Life Support System Commonality Summary

Chapter 3 describes an analysis of system architecture alternatives and commonality opportunities for a portfolio of multi-person life support systems for human exploration missions. The analysis is intended as a detailed application case study of the portfolio architecting methodology developed in Section 2.2. The portfolio under consideration includes 7 life support system use cases: five future use cases (lunar lander, lunar surface habitat, NEO mission habitat, Mars surface habitat, and Mars transit habitat), and two legacy use cases (CEV and ISS). The CEV use case is considered a legacy use case because it is already in detailed development. Each use case has one system architecture and system design associated with it.

The analysis proceeds in four steps (see also Figure 14): first, the portfolio use cases are defined in more detail and metrics for quantitative analysis of architecture and portfolio design alternatives are specified. The second step is an enumeration and evaluation of alternative life support system architectures for each of the future use cases based on a Morphological Matrix approach with discrete technology choices for each life support function. Life-cycle cost was used as the primary metric for the selection of preferred architecture alternatives for each use case. Based on these preferred alternatives a set of 16807 preferred portfolio design solutions without commonality was enumerated.

These 16807 portfolio design solutions are then translated into portfolio design solutions with commonality by comprehensive assessment of commonality opportunities on the function-level between each pair of systems in each portfolio. The resulting 16807 portfolio design solutions are then evaluated with regard to the life-cycle cost savings and the reduction in the number of custom development projects required for the portfolio. A number of robust commonality opportunities were identified, among them: extension of ISS technology to all future long-duration habitats in the areas of water recycling, humidity removal, carbon dioxide removal and the reuse of the CEV carbon dioxide and humidity removal system on the lunar lander. Further commonality opportunities include the development of a common de-hydrated food system and the development of a washing system for crew clothing for all future long-duration use cases.

These results demonstrate the effectiveness of the methodology to transform a solution-neutral description of an aerospace systems portfolio into a set of preferred portfolio design solutions with robust commonality opportunities. The portfolio in this case study includes legacy and future systems, enabling the identification of opportunities for both intentional (between future systems) and unintentional commonality (between a legacy and a future system).

4. Case Study 2: Saturn Launch Vehicle Commonality Analysis

This chapter contains a description of the second application case study for the application of the 4-step methodology and the system overlap matrix tool for the analysis of commonality in aerospace systems portfolios developed in this thesis and described in Section 2.2. This is a retrospective case study investigating system architectures and commonality opportunities within the family of Saturn launch vehicles, the rockets used for the Earth orbital and lunar missions of the United States Apollo human spaceflight programs in the 1960s and 1970s [NASA-1975]. The family includes three launch vehicles: the Saturn I, Saturn IB (both for Earth-orbital missions), and the Saturn V used for lunar missions, see Figure 41:

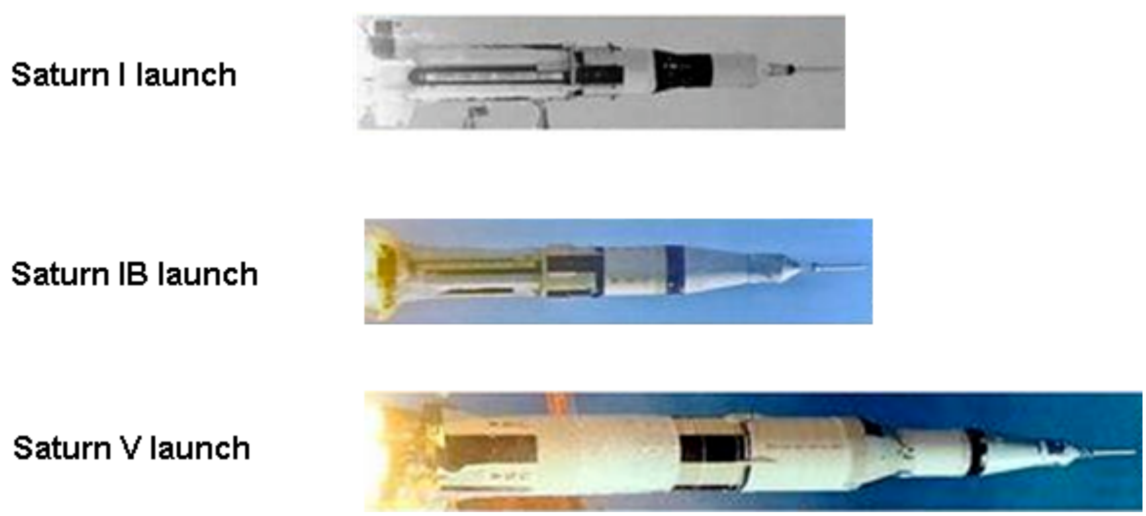


Figure 41: Overview of the Saturn launch vehicles (at launch) [credit NASA]

Retrospective analysis enables a comparison of methodology application results with the design solution that was actually implemented. An analysis of the Saturn family also allows for application of the methodology to a technological domain different from life support: the domain of rocket engines and propulsion stages.

Section 4.1 describes the use cases and functionality included the portfolio as well as the metrics used for comparative analysis of architecture and portfolio design alternatives.

Section 4.2 provides results from a comprehensive analysis of architectural alternatives for the individual use cases considered in the portfolio without taking into account commonality; this is the basis for the selection of preferred architecture alternatives as input to the commonality screening process in Step 3. The commonality screening process transforms a set of portfolio design solutions without commonality (based on the preferred point design architectures from Step 2) into a set of portfolio design solutions with commonality. In Step 4, the sensitivity of portfolio design solutions to changes in the commonality analysis process is carried out in order to assess the robustness of technology choices and commonality opportunities identified in Step 2 and Step 3. This chapter concludes with a summary of results and insights from the application of the methodology to the Saturn launch vehicle family.

4.1 Saturn Launch Vehicle Portfolio Definition

Step 1 of the novel architecting methodology described in Section 2.2 involves defining the portfolio to be analyzed for commonality opportunities in terms of its scope in use cases and associated functionality and defining metrics to be used for relative ranking of use case architecture alternatives and portfolio design solution alternatives. Each of these aspects of the portfolio is discussed in the following subsections.

Portfolio Use Cases

The historical Saturn launch vehicle family was a set of advanced launch vehicles developed initially for US military applications but later adapted towards exclusively civilian use for human spaceflight to Earth orbit and beyond [Cor-75] [Bel-77] [EE-78] [Bil-96]. Initially, a large number of variants of the Saturn launch vehicles were contemplated, including versions using upper stage designs from previous programs such as the Centaur upper stage and Titan II second stage. The Saturn concepts were classified as C1 – C5 based on different first stage and upper stage designs as well as different numbers of engines on the first stage. The Saturn rockets were the first designs with clustered engines, enabling very high lift-off mass and thrust with smaller engines. The Saturn launch vehicle family as implemented included only three vehicle designs; these are the use cases analyzed in this case study (see also Figure 42):

- The Saturn I use case: this vehicle was used in two forms (Block I and Block II), with and without an active upper stage. Four suborbital flights of the Block I vehicle were carried out and 6 of the Block II. Payloads for the orbital test flights included boilerplate models of the Apollo Command & Service Module (CSM). Ten units were built for the 1st stage and 6 units for the upper stage. The payload to Low Earth Orbit was 9000 kg for a delta-v of approximately 9500 m / s.

- The Saturn IB use case: this vehicle was used only in one configuration with a live upper stage. The Saturn IB was used for Apollo CSM and lunar module unmanned test flights, as well as for 5 manned CSM flights: the Apollo 7, Skylab 2, 3, 4, and Apollo Soyuz Test Program missions [NASA-1975] [Bel-77] [EE-78] [Good-00]. 12 units of the entire vehicle were produced. The payload to Low Earth Orbit was 17000 kg for a delta-v of approximately 9500 m / s.

- The Saturn V use case: this vehicle was used to launch the Apollo lunar missions, including the CSM and LM as payloads. A two-stage version of the 3-stage Saturn V was also used to launch the Skylab space station [Bel-77] on mission Skylab 1. 15 units of the entire vehicle were produced. The payload to Low Earth Orbit was 47790 kg for a delta-v of approximately 12259 m / s.

Figure 42 provides a summary of the three use cases with attributes:

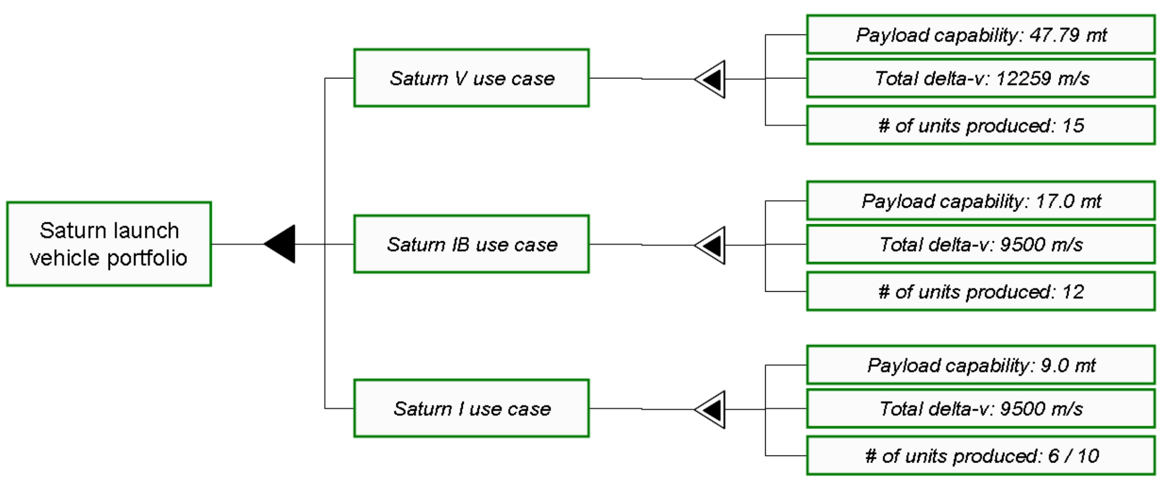


Figure 42: Overview of Saturn launch vehicle portfolio use cases and attributes

Functionality

The functionality of each of the Saturn vehicle propulsion stages was captured in two main functions:

- Provision of thrust to accelerate the vehicle and payload using rocket propulsion
- Provision of propellant storage, load transmission from the engines to the payload of the stage, as well as provision of structural integrity

This breakdown of propulsion stage functionality is commonly used in the literature [LP-00]. For both the engine and fuselage elements, parametric sizing models were used for calculating engine and fuselage mass as a function of engine thrust and fuselage propellant volume. These models are described in more detail in Section 4.2 and in Appendix III.

Metrics

Performance, cost, and risk are the metrics considered in the Saturn portfolio commonality analysis. Given that payload and delta-v capability are held constant for each of the three use cases the analysis must be considered an iso-performance analysis. It is assumed that the parametric models used for sizing fuselage and engine elements, which are based on regression analysis of past designs, provide acceptable reliability and operational risk attributes for the individual elements. Vehicle architectures with different numbers of engines per stage and different numbers of propulsion stages obviously have different reliability attributes if the engine and fuselage elements used have identical reliability characteristics; however, these differences in reliability and the resulting differences in operational risk were not considered in the analysis presented in this chapter.

The following metrics were used to asses the relative cost of vehicle architecture alternatives: DDT&E and unit production cost for engines and fuselages to assess the life-cycle cost of each use case, and vehicle height and vehicle wet mass at launch as proximate metrics for ground processing and operations cost. DDT&E and 1st unit production cost for individual engines and fuselage elements were calculated using dry-mass-based cost estimating relationships derived from NASA Air Force Cost Model (NAFCOM) (Equation 23 and Equation 24) which are publicly accessible [JSC-07]:

$$C_{Engine\_DDT\&E} = 32.264 \cdot m_{Engine}^{0.55}$$
$$C_{Fuselage\_DDT\&E} = 7.9875 \cdot m_{Fuselage}^{0.55}$$
Equation 23

$$C_{Engine\_1st\_unit} = 0.1776 \cdot m_{Engine}^{0.662}$$
$$C_{Fuselage\_1st\_unit} = 0.1898 \cdot m_{Fuselage}^{0.662}$$
Equation 24

The total unit production cost for a rocket engine or fuselage was calculated taking into account learning curve effects with a learning rate ***LR*** of 0.85 [NASA-SP-610S] [JSC-07] (Equation 25):

$$C_{n-th\_Unit} = C_{1st\_Unit} \cdot n^{b}$$
$$b = \frac{\ln(LR)}{\ln(2)}$$
$$C_{Units} = C_{1st\_Unit} \cdot \sum_{n=1}^{k} n^{b}$$
Equation 25

Calculation of vehicle mass and height is based on the mass and volume characteristics of the individual propulsion stages in the vehicle architecture and on payload mass and height, assuming a uniform diameter of 10 m for each propulsion stage in the portfolio. A 10 meter diameter is the maximum diameter that could be supported by the Saturn manufacturing infrastructure. While the actual Saturn launch vehicles had varying diameters for the individual stage designs [NASA-1975] [Bil-96], the assumption of a common diameter for all stages is appropriate for the relative ranking that the vehicle height metric is going to be used for. In addition, the use of the largest possible diameter for each stage design results in the most optimistic vehicle height achievable.

For the relative ranking of portfolio design solutions, portfolio life-cycle cost and the number of custom development projects required for implementation of a specific portfolio design solution were used as metrics for relative ranking of alternatives. Life-cycle cost for a portfolio design solution is defined as the sum of the life-cycle costs for the individual use case architecture alternatives in the portfolio design solution, either with or without commonality.

4.2 Saturn Launch Vehicle Point Design Analyses

Step 2 of the commonality analysis methodology from Section 2.2 is devoted to the analysis of architectural alternatives for each of the use cases in the Saturn portfolio individually, i.e. without consideration for commonality opportunities. The analysis of architectural alternatives involves a comprehensive enumeration of architecture alternatives for each use case based on a set of architecture-level design factors and the subsequent evaluation of these alternatives with regard to the metrics outlined in Section 4.1. This evaluation is the basis for the down selection to a preferred set of architecture alternatives for each use case as input to the commonality screening in Step 3 of the methodology.

Table 9: Morphological Matrix for the Saturn V launch vehicle design analysis

Design factor	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4
# of propulsion stages	3	2		
Thrust generation stage 3 – propellant type	LOX/LH2 (Isp = 421 s)	LOX/Kerosene (Isp = 310)	N2O4/UDMH (Isp = 308)	N/A
Thrust generation stage 3 – # of engines	1	2	5	N/A
Propellant storage stage 3	Common bulkhead tanks	2-tank structure	N/A	
Design delta-v stage 3 [m/s]	4159 for 3-stage case	N/A in 2-stage case		
Thrust generation stage 2 – propellant type	LOX/LH2 (Isp = 421 s)	LOX/Kerosene (Isp = 310)	N2O4/UDMH (Isp = 308)	
Thrust generation stage 2 – # of engines	1	2	5	
Propellant storage stage 2	Common bulkhead tanks	2-tank structure		
Design delta-v stage 2 [m/s]	4700 for 3-stage case	6259 – 8259 in 2-stage case		
Thrust generation stage 1 – propellant type	LOX/Kerosene (Isp = 265)	N2O4/UDMH (Isp = 259)		
Thrust generation stage 1 – # of engines	2	5	8	
Propellant storage stage 1	2-tank structure	Multi-tank structure		
Design delta-v stage 1 [m/s]	3400 for 3-stage case	4000 – 6000 for 2-stage case		

The enumeration of architecture alternatives for each of the use cases in the portfolio utilized a Morphological Matrix [PB-96] which includes all feasible technology choices for the design factors of relevance for the use case. Table 9 shows the Morphological Matrix used for the Saturn V use case. The design factors included are: the number of propulsion stages on the vehicle (either 2 or 3; 1 is not practically feasible), and the technology choices for thrust generation, propellant storage, and propellant type for each of the stages on the vehicle. It should be noted that for 1st stages which would be used at ground-level, liquid hydrogen / liquid oxygen propulsion was not considered because this technology was immature when the Saturn launch vehicle family was being developed. For the same reason, solid propellant options were also not included in the analysis. For the 2-stage architectures 10 different values for the first stage delta-v are considered to vary the relative sizing of the propulsion stages (4000 – 6000 m/s first stage delta-v); this leads to different relative sizes of the 1st and 2nd stages in this case.

By selecting one technology choice from each row, we can systematically enumerate a total of 3997 architecture alternatives for the Saturn V use case, taking into account the constraints that if the number of propulsion stages equals 2, all choices for propulsion stages number 3 must equal "N/A", and that if the number of propulsion stages equals 3, the choices of "N/A" are not selectable.

The propulsion stages are sized in reverse order of usage: the stage carrying the actual vehicle payload is sized first, then the next-lower propulsion stage using both the actual vehicle payload and the higher stage as payload, and so on. For each of these architecture alternatives, the propellant masses of the individual stages were determined using the rocket equation for each stage:

$$m_{\mathrm{Pr}opellant} = \left(m_{Payload} + m_{Fuselage} + n_{Engine} \cdot m_{Engine}\right) \cdot \left(\exp\left(\frac{\Delta v}{g_0 \cdot I_{sp}} \right) - 1 \right) \quad \textbf{Equation 26}$$

The engine dry mass can be estimated using the empirical relationship in Equation 27 adapted from [LP-00]; Equation 28 shows how to calculate the thrust required per engine:

$$m_{Engine} = \frac{\alpha \cdot Thrust_{Engine}}{\left(25.2 \cdot \ln\left(Thrust\right) - 80.7\right) \cdot 9.81} \qquad \textbf{Equation 27}$$

$$Thrust_{Engine} = \left(m_{Payload} + m_{Fuselage} + n_{Engine} \cdot m_{Engine} + m_{\Pr opellant}\right) \cdot g_0 \cdot T / W \qquad \textbf{Equation 28}$$

The mass of the stage fuselage can be estimated using the empirical relationship in Equation 29 which is based on interpolation of data found in [Orl-01]:

$$m_{Fuselage} = \beta \cdot Volume_{\Pr opellants} \cdot \left(\frac{V_{\mathrm{Re}\,f\,erence}}{Volume_{\Pr opellants}}\right)^{0.1623} \qquad \textbf{Equation 29}$$

The propellant volume is calculated using Equation 30:

$$Volume_{\Pr opellants} = \frac{m_{\Pr opellant}}{OTF + 1} \cdot \left(\frac{OTF}{\rho_{Oxidizer}} + \frac{1}{\rho_{Fuel}}\right) \qquad \textbf{Equation 30}$$

The constants α, β, and $V_{Reference}$ as well as the values for *OTF* (the ratio of oxidizer mass to fuel mass required by the engine), I_{sp}. *T/W* (the ratio of the stage thrust force to the weight force of the vehicle at the time of stage ignition), and n_{Engine} in Equations 26 - 30 are determined by the choices in the Morphological Matrix, as is the number of engines. Table 33 in Appendix III provides values for these constants as a function of technology choice. It is apparent that Equations 26 – 30 cannot be solved analytically; an iteration scheme was therefore implemented which initially sets the engine and fuselage masses to zero. The Java source code for the enumeration and evaluation of architecture alternatives for each of the use cases is provided on the attached thesis CD.

Figure 43 and Figure 44 show results from this enumeration and evaluation of architecture alternatives for the Saturn V use case. Results for 2-stage architecture alternatives are shown in red color, and results for 3-stage architecture alternatives in black. 2-stage alternatives generally results in increased vehicle height for similar life-cycle cost; this is understandable given that the significantly higher delta-v per stage well above the value of the exhaust velocity of the engine leads to much larger stage size. For vehicle launch mass, the increase due to choosing a 2-stage design is more pronounced than for vehicle height: the lowest-mass 2-stage alternatives require nearly 50% more launch mass than the lowest-mass 3-stage alternatives for similar life-cycle cost. The increased height and mass of two-stage alternatives would result in increased ground processing cost due to more demanding infrastructure requirements (building height, launch pad foundations, etc.) while not offering any life-cycle cost benefit. In addition, 2-stage designs leave less performance margin for this high-delta-v use case. This makes 2-stage design solutions unattractive for the Saturn V use case.

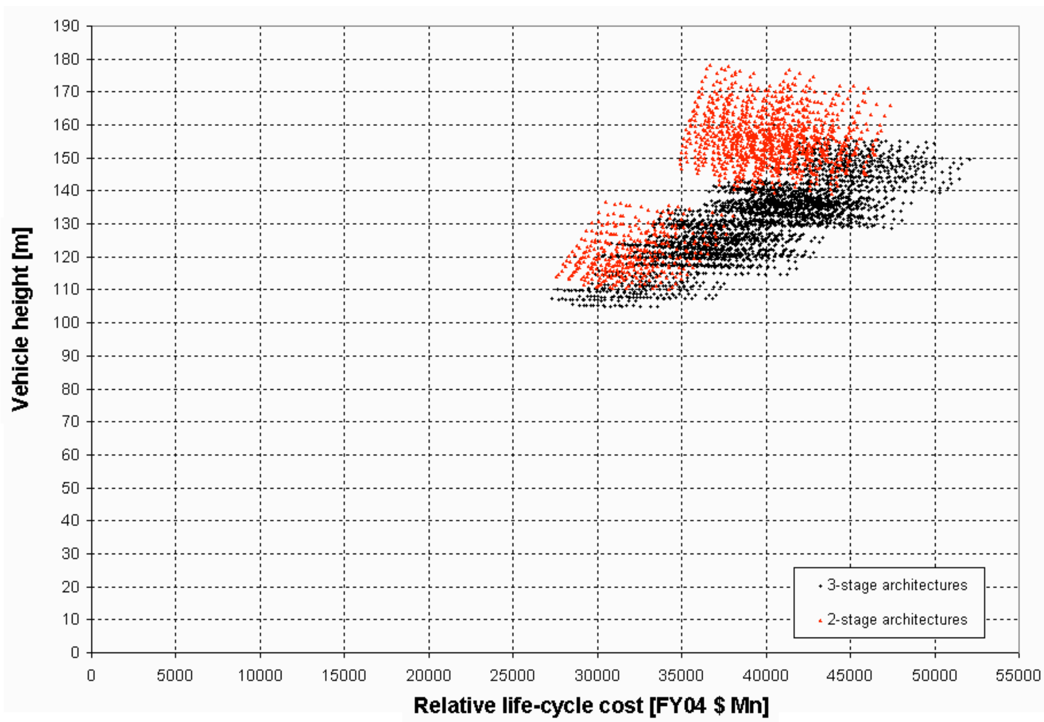


Figure 43: Point design architecture analysis results for the Saturn V use case: vehicle height vs. relative life-cycle cost

The preferred point design solutions for the Saturn V are therefore selected from the 3-stage architecture alternatives based on life-cycle cost ranking. Table 10 provides an overview of the 30 preferred point design architecture alternatives selected for the Saturn V use case ranked by life-cycle cost. The reason for choosing 30 preferred architecture alternatives lies in the limitations of the size of arrays that the Java compiler used for the architecture and commonality analysis source code would accept; ideally as large a number of preferred architecture alternatives as possible should be selected in order to allow for synergistic effects with high net benefit in the portfolio.

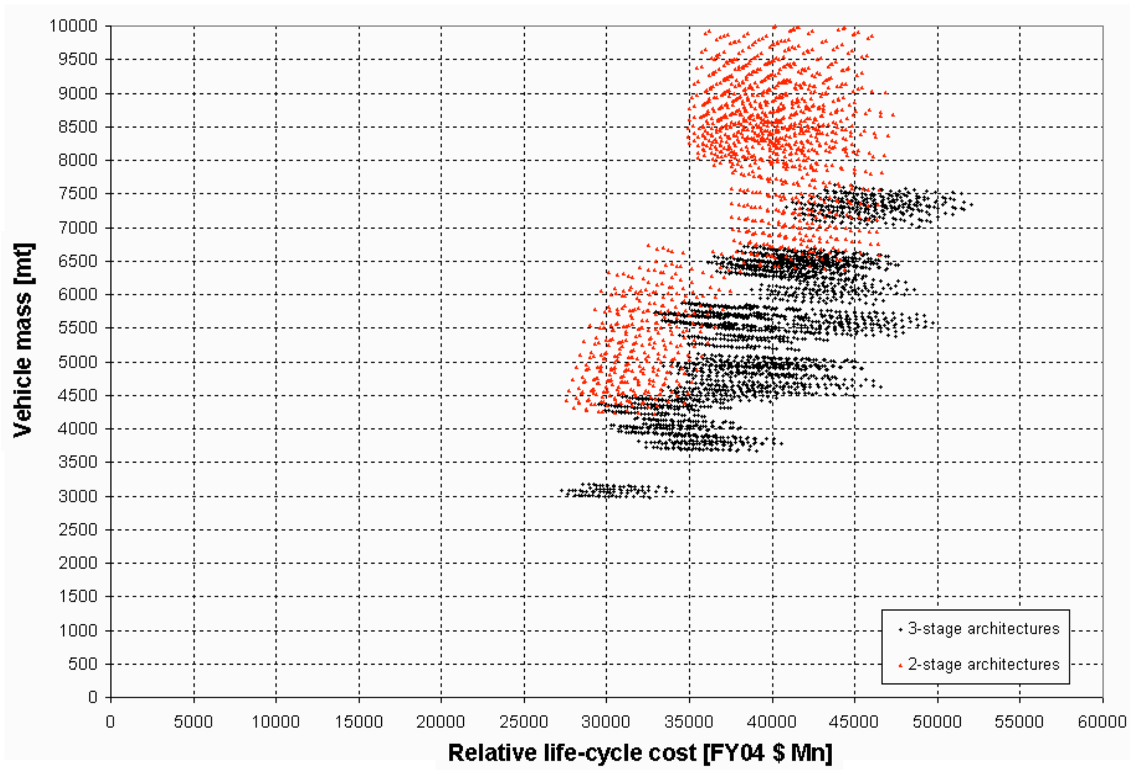


Figure 44: Point design architecture analysis results for the Saturn V use case: vehicle wet mass vs. relative life-cycle cost

Preferred architecture number 5 corresponds to the historical Saturn V design as implemented. From the preferred architectures it is apparent that the choice of propellant type is quite robust: for the third and second stages LOX / LH_2 propellants are preferred, and for the first stage LOX / RP1 propellants. In addition, common bulkhead fuselage designs are preferred for the third stage and the second stage, and 2-tank designs for the first stage. The preferred number of engines is significantly more variable in the set of preferred architectures; this is beneficial for enabling commonality opportunities with regard to engines in the Saturn portfolio.

Table 10: Preferred point design architectures for the Saturn V use case; different colors indicate different technology choices (delta-v values for stages not shown). The historical preferred architecture is marked by the red box.

Preferred architecture	LCC [FY04 $ Mn]	Stage 3			Stage 2			Stage 1		
		Structure	# engines	Propellant	Structure	# engines	Propellant	Structure	# engines	Propellant
1	27647	Common BH	2	LOX/LH2	Common BH	5	LOX/LH2	2-tank	8	LOX/RP1
2	28069	Common BH	1	LOX/LH2	Common BH	5	LOX/LH2	2-tank	8	LOX/RP1
3	28299	Common BH	2	LOX/LH2	Common BH	5	LOX/LH2	2-tank	5	LOX/RP1
4	28475	Common BH	2	LOX/LH2	Common BH	2	LOX/LH2	2-tank	8	LOX/RP1
5	28720	Common BH	1	LOX/LH2	Common BH	5	LOX/LH2	2-tank	5	LOX/RP1
6	28896	Common BH	1	LOX/LH2	Common BH	2	LOX/LH2	2-tank	8	LOX/RP1
7	28961	Common BH	2	LOX/LH2	Common BH	5	LOX/LH2	Multi-tank	8	LOX/RP1
8	29126	Common BH	2	LOX/LH2	Common BH	2	LOX/LH2	2-tank	5	LOX/RP1
9	29381	Common BH	1	LOX/LH2	Common BH	5	LOX/LH2	Multi-tank	8	LOX/RP1
10	29500	Common BH	2	LOX/LH2	Common BH	1	LOX/LH2	2-tank	8	LOX/RP1
11	29546	Common BH	1	LOX/LH2	Common BH	2	LOX/LH2	2-tank	5	LOX/RP1
12	29621	Common BH	2	LOX/LH2	Common BH	5	LOX/LH2	Multi-tank	5	LOX/RP1
13	29786	Common BH	2	LOX/LH2	Common BH	2	LOX/LH2	Multi-tank	8	LOX/RP1
14	29913	Common BH	2	LOX/LH2	Common BH	5	N2O4/UDMH	2-tank	8	LOX/RP1
15	29919	Common BH	1	LOX/LH2	Common BH	1	LOX/LH2	2-tank	8	LOX/RP1
16	30040	Common BH	1	LOX/LH2	Common BH	5	LOX/LH2	Multi-tank	5	LOX/RP1
17	30110	Common BH	2	LOX/LH2	Common BH	5	LOX/RP1	2-tank	8	LOX/RP1
18	30150	Common BH	2	LOX/LH2	Common BH	1	LOX/LH2	2-tank	5	LOX/RP1
19	30205	Common BH	1	LOX/LH2	Common BH	2	LOX/LH2	Multi-tank	8	LOX/RP1
20	30331	Common BH	1	LOX/LH2	Common BH	5	N2O4/UDMH	2-tank	8	LOX/RP1
21	30366	Common BH	2	LOX/LH2	Common BH	5	LOX/LH2	2-tank	2	LOX/RP1
22	30445	Common BH	2	LOX/LH2	Common BH	2	LOX/LH2	Multi-tank	5	LOX/RP1
23	30529	Common BH	1	LOX/LH2	Common BH	5	LOX/RP1	2-tank	8	LOX/RP1
24	30569	Common BH	1	LOX/LH2	Common BH	1	LOX/LH2	2-tank	5	LOX/RP1
25	30687	Common BH	2	LOX/LH2	Common BH	5	N2O4/UDMH	2-tank	5	LOX/RP1
26	30717	Common BH	2	N2O4/UDMH	Common BH	5	LOX/LH2	2-tank	8	LOX/RP1
27	30784	Common BH	1	LOX/LH2	Common BH	5	LOX/LH2	2-tank	2	LOX/RP1
28	30810	Common BH	2	LOX/LH2	Common BH	1	LOX/LH2	Multi-tank	8	LOX/RP1
29	30829	Common BH	2	LOX/RP1	Common BH	5	LOX/LH2	2-tank	8	LOX/RP1
30	30863	Common BH	1	LOX/LH2	Common BH	2	LOX/LH2	Multi-tank	5	LOX/RP1

The use of hypergolic propellants does not reduce life-cycle cost; given their toxicity and the associated special ground processing requirements at the launch pad, hypergolic propellants must therefore be considered unattractive for the Saturn V use case.

An architecture enumeration, evaluation, and selection process identical to that for the Saturn V use case is carried out for the Saturn IB and Saturn I use cases; Figure 81 - Figure 84 and Table 34 - Table 35 in Appendix III show the associated results. For both the Saturn IB and Saturn I use cases, 2-stage vehicle architectures are preferred because 3-stage architectures exhibit somewhat higher life-cycle cost. The 30 preferred point design solutions for these use cases are shown in Table 11 and Table 12 in order of life-cycle cost ranking. Preferred architectures 23, 26, and 28 in Table 11 are similar to the historical Saturn IB vehicle architecture, albeit with varying delta-v allocations to the propulsion stages. Preferred architectures 12, 15, 19, 23 and 27 in Table 12 are similar to the historical Saturn I vehicle architecture, also with varying delta-v allocations to the propulsion stages.

Table 11: Preferred point design architectures for the Saturn IB use case; different colors indicate different technology choices (delta-v values for stages not shown). Historical preferred architectures are marked with red boxes.

Preferred architecture	LCC [FY04 $ Mn]	Stage 2			Stage 1		
		Structure	# engines	Propellant	Structure	# engines	Propellant
1	10637	Common BH	5	LOX/LH2	2-tank	8	LOX/RP-1
2	11145	Common BH	5	LOX/LH2	2-tank	8	LOX/RP-1
3	10932	Common BH	5	LOX/LH2	2-tank	5	LOX/RP-1
4	11475	Common BH	5	LOX/LH2	2-tank	5	LOX/RP-1
5	11095	Common BH	2	LOX/LH2	2-tank	8	LOX/RP-1
6	11479	Common BH	2	LOX/LH2	2-tank	8	LOX/RP-1
7	11102	Common BH	5	LOX/LH2	Multi-tank	8	LOX/RP-1
8	11859	Common BH	5	LOX/LH2	Multi-tank	8	LOX/RP-1
9	11388	Common BH	2	LOX/LH2	2-tank	5	LOX/RP-1
10	11807	Common BH	2	LOX/LH2	2-tank	5	LOX/RP-1
11	11399	Common BH	5	LOX/LH2	Multi-tank	5	LOX/RP-1
12	11764	Common BH	5	LOX/LH2	Multi-tank	5	LOX/RP-1
13	11558	Common BH	2	LOX/LH2	Multi-tank	8	LOX/RP-1
14	12084	Common BH	2	LOX/LH2	Multi-tank	8	LOX/RP-1
15	11853	Common BH	2	LOX/LH2	Multi-tank	5	LOX/RP-1
16	12073	Common BH	2	LOX/LH2	Multi-tank	5	LOX/RP-1
17	11667	Common BH	1	LOX/LH2	2-tank	8	LOX/RP-1
18	11902	Common BH	1	LOX/LH2	2-tank	8	LOX/RP-1
19	11853	Common BH	5	LOX/LH2	2-tank	2	LOX/RP-1
20	12073	Common BH	5	LOX/LH2	2-tank	2	LOX/RP-1
21	11959	Common BH	1	LOX/LH2	2-tank	5	LOX/RP-1
22	12109	Common BH	1	LOX/LH2	2-tank	5	LOX/RP-1
23	12128	Common BH	1	LOX/LH2	Multi-tank	8	LOX/RP-1
24	12144	Common BH	5	LOX/LH2	2-tank	2	LOX/RP-1
25	12144	Common BH	2	LOX/LH2	Multi-tank	5	LOX/RP-1
26	12153	Common BH	1	LOX/LH2	Multi-tank	8	LOX/RP-1
27	12164	Common BH	1	LOX/LH2	2-tank	5	LOX/RP-1
28	12183	Common BH	1	LOX/LH2	Multi-tank	8	LOX/RP-1
29	12189	Common BH	2	LOX/LH2	Multi-tank	8	LOX/RP-1
30	12194	Common BH	5	LOX/LH2	Multi-tank	5	LOX/RP-1

Table 12: Preferred point design architectures for the Saturn I use case; different colors indicate different technology choices (delta-v values for stages not shown). Historical preferred architectures are marked with red boxes.

Preferred architecture	LCC [FY04 $ Mn]	Stage 2			Stage 1		
		Structure	# engines	Propellant	Structure	# engines	Propellant
1	7595	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
2	7629	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
3	7664	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
4	7702	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
5	7743	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
6	7789	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
7	7839	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
8	7850	Common BH	6	LOX/LH2	2-tank	5	LOX/RP-1
9	7885	Common BH	6	LOX/LH2	2-tank	5	LOX/RP-1
10	7895	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
11	7923	Common BH	6	LOX/LH2	2-tank	5	LOX/RP-1
12	7933	Common BH	6	LOX/LH2	Multi-tank	8	LOX/RP-1
13	7957	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
14	7964	Common BH	6	LOX/LH2	2-tank	5	LOX/RP-1
15	7985	Common BH	6	LOX/LH2	Multi-tank	8	LOX/RP-1
16	8009	Common BH	6	LOX/LH2	2-tank	5	LOX/RP-1
17	8026	Common BH	6	LOX/LH2	2-tank	8	LOX/RP-1
18	8037	Common BH	2	LOX/LH2	2-tank	8	LOX/RP-1
19	8038	Common BH	6	LOX/LH2	Multi-tank	8	LOX/RP-1
20	8054	Common BH	2	LOX/LH2	2-tank	8	LOX/RP-1
21	8058	Common BH	6	LOX/LH2	2-tank	5	LOX/RP-1
22	8074	Common BH	2	LOX/LH2	2-tank	8	LOX/RP-1
23	8095	Common BH	6	LOX/LH2	Multi-tank	8	LOX/RP-1
24	8097	Common BH	2	LOX/LH2	2-tank	8	LOX/RP-1
25	8112	Common BH	6	LOX/LH2	2-tank	5	LOX/RP-1
26	8124	Common BH	2	LOX/LH2	2-tank	8	LOX/RP-1
27	8156	Common BH	6	LOX/LH2	Multi-tank	8	LOX/RP-1
28	8156	Common BH	2	LOX/LH2	2-tank	8	LOX/RP-1
29	8172	Common BH	6	LOX/LH2	2-tank	5	LOX/RP-1
30	8189	Common BH	6	LOX/LH2	Multi-tank	5	LOX/RP-1

It is interesting to note that, as for the Saturn V use case, the choice of preferred propellants for the Saturn IB and Saturn I are robust; the choice of the number of engines and the type of fuselage structure is more varied, especially for the Saturn IB use case. As for the Saturn V use case, this variability in the number of engines is beneficial for enabling commonality opportunities.

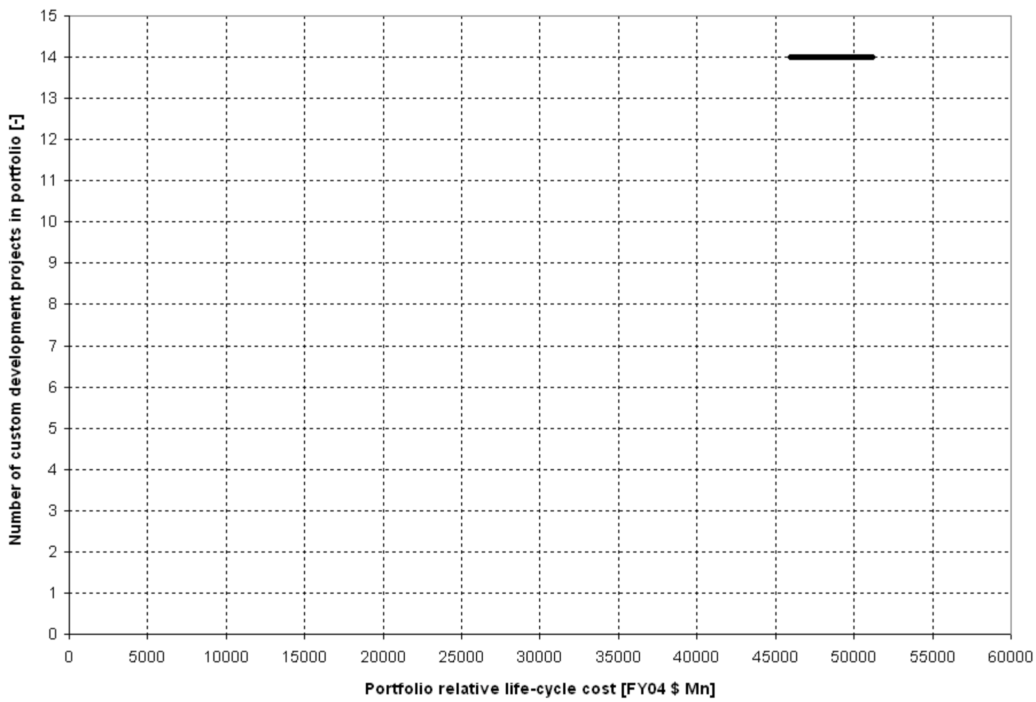


Figure 45: Portfolio design solutions without commonality; the number of custom development projects for engine and fuselage elements is plotted vs. the relative life-cycle cost for each portfolio

Based on the 30 preferred point design architectures for each use case we can enumerate a total of 27000 point design portfolio architectures without commonality; the choice of 30 preferred solutions each was based on processing limits of the Java compiler used for the implementation of the case study. Figure 45 shows the number of custom development projects of these portfolios plotted over the relative life-cycle cost for each of the custom portfolio design solutions. The number of development projects is constant at 14 for all portfolio design solutions: 7 engine developments and 7 fuselage developments, one for each of the three stages in the Saturn V use case, for each of the 2 stages in the Saturn IB use case, and for each of the 2 stages in the Saturn I use case. The

27000 portfolio design solutions serve as input to the commonality screening process (see Section 4.3).

4.3 Saturn Launch Vehicle Family Commonality Screening

Step 3 of the architecting methodology from Section 2.2 is the systematic screening of preferred architecture pairs for commonality opportunities for each of the 27000 portfolio design solutions without commonality. In the case of the Saturn portfolio, all pairs of propulsion stage designs are subjected to the commonality screening, resulting in 21 pairs for the 7 stages in the portfolio for each of the 27000 portfolio design solutions.

For the identification of opportunities for commonality as part of the screening process the four heuristic commonality criteria described in Section 2.2 were used:

- **Criterion 1 (identical internal functionality):** commonality requires identical internal functionality, i.e. commonality can only occur between pairs of engines and pairs of fuselage elements, but not between an engine and fuselage element. This criterion is always satisfied because in the commonality screening process only pairs of engine and fuselage elements are investigated.

- **Criterion 2 (identical technology choices):** commonality requires identical technology choices. For engine elements this means that the same propellant choice is required. For fuselage elements this means that the same propellant choice is required and in addition the same number of engines per stage.

- **Criterion 3 (similarity in operational environments):** commonality requires similarity in operating environments in the sense of ground operations or altitude operations for the propulsion stages. This means that in order to be suitable for commonality, both elements in a pair of engine or fuselage elements must operate either at altitude or at ground-level; this corresponds to a selection of a value of 100 % for the ***operational overlap parameter δ*** (complete operational overlap required).

- **Criterion 4 (similarity in design parameters):** the values of quantitative design parameters must be within a factor ***k (overlap parameter)*** of each other (see Equation 31) in order for two engines or two fuselage element designs to be common; this criterion applies to propellant volume for fuselage elements and to thrust for engine elements.

$$Volume_{System\_1} \cdot \frac{1}{k} < Volume_{System\_2} < Volume_{System\_1} \cdot k$$
$$Thrust_{System\_1} \cdot \frac{1}{k} < Thrust_{System\_2} < Thrust_{System\_1} \cdot k$$

Equation 31

It is interesting to note that this customization of the commonality Criteria is quite different from the customization chosen for the life support systems case study in Chapter 3: for life support systems, the operational overlap fraction δ was the free variable in the commonality screening and the design parameter overlap factor k was not explicitly varied because the modest differences in equipment design parameters were acceptable, whereas in this case study the required operational overlap fraction δ is assumed to be 100 % and the design parameter overlap factor k becomes the free variable for the commonality screening analysis.

Figure 46 shows the transformed portfolio design solutions with commonality based on the application of the 4 above commonality criteria to each of the portfolio design solutions without commonality; the overlap parameter k was set to k = 2.0 for this analysis The introduction of commonality enables significant reductions both in life-cycle cost and in the number of custom propulsion stage fuselage and engine development projects. The minimum number of development projects is down to 7 from 14, and the minimum life-cycle cost moves from just over FY04 $ 45000 Mn to just over $ 35000 Mn. Figure 46 also shows the location of the historical Saturn launch vehicle family as modeled in this case study. Figure 47 shows the life-cycle cost breakdown of the 27000 portfolio design solutions with and without commonality, ranked by life-cycle cost in the common case. In both cases, life-cycle cost consists of approximately equal parts of DDT&E and unit production costs for the propulsion stages. The introduction of commonality results in a reduction in both of these cost components: DDT&E cost is reduced due to the elimination of custom designs for fuselage and engine elements, and unit production cost is reduced to the increased number of units produced for the common elements and the associated learning curve benefits.

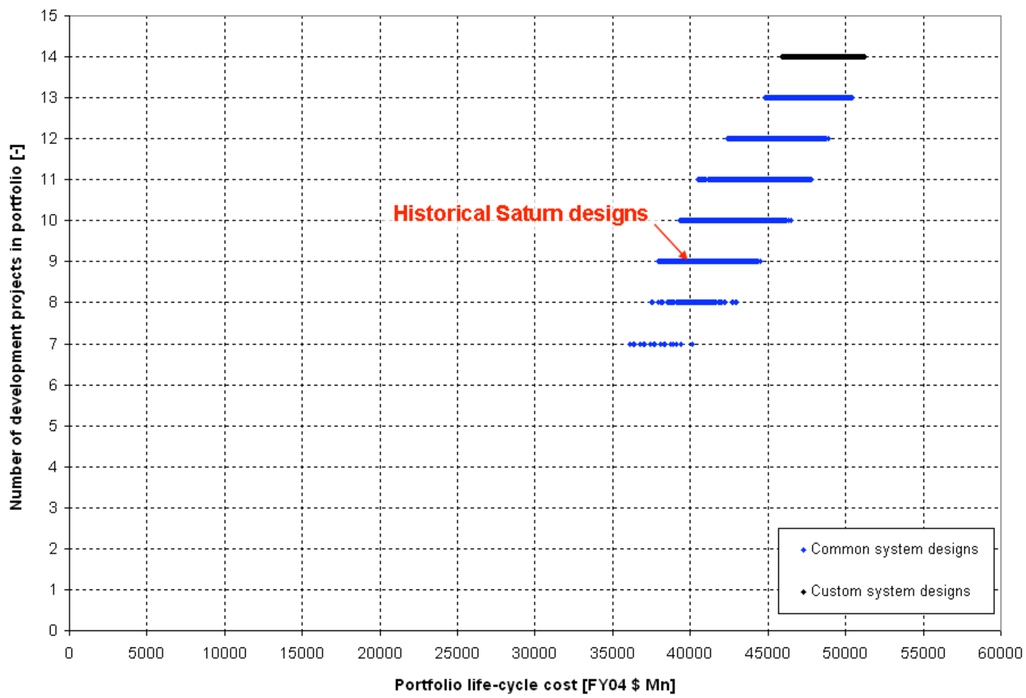


Figure 46: Preferred portfolio design solutions with commonality for the Saturn launch vehicle family: # of development projects vs. portfolio life-cycle cost; k = 2.0

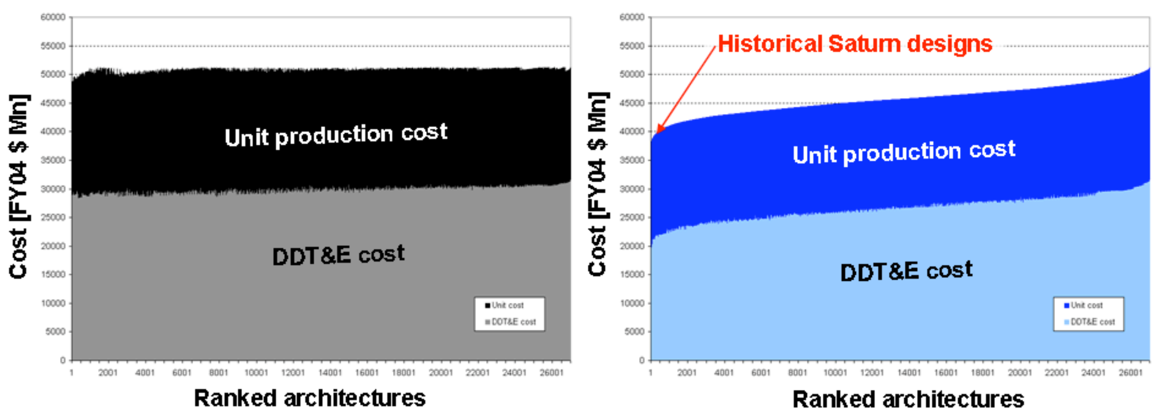


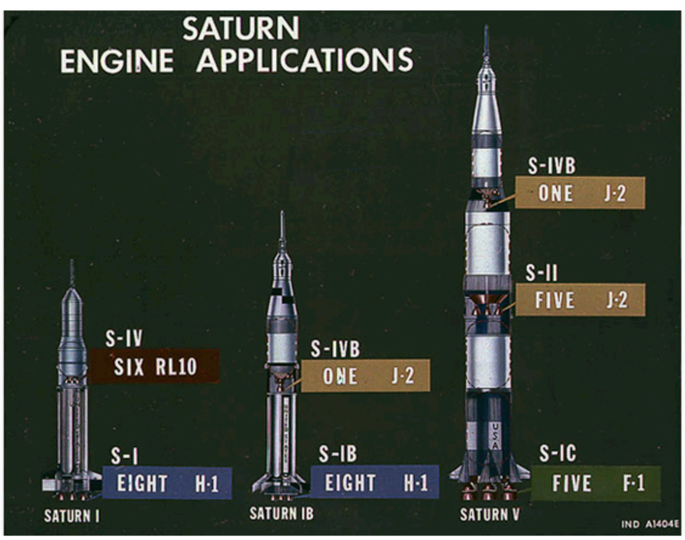
Figure 47: Life-cycle cost breakdown into DDT&E and unit cost for portfolio design solutions without commonality (left-hand side) and with commonality (right-hand side); k = 2.0

Figure 48 shows the commonality scheme implemented in the best-ranked portfolio design solution with commonality (see also Table 13). A common engine design is utilized for the Saturn V third stage and for the Saturn IB and Saturn I second stages, as well as for the Saturn V second stage. In addition, a common fuselage design is employed for the Saturn V third stage and Saturn IB and Saturn I second stages.

Element	Common engine 1	Common engine 2	Common fuselage 1	Common fuselage 2
Saturn V: 3rd stage fuselage			X	
Saturn V: 3rd stage engine	X			
Saturn V: 2nd stage fuselage				
Saturn V: 2nd stage engine	X			
Saturn V: 1st stage fuselage				
Saturn V: 1st stage engine				
Saturn IB: 2nd stage fuselage			X	
Saturn IB: 2nd stage engine	X			
Saturn IB: 1st stage fuselage				X
Saturn IB: 1st stage engine		X		
Saturn I: 2nd stage fuselage				
Saturn I: 2nd stage engine				
Saturn I: 1st stage fuselage				X
Saturn I: 1st stage engine		X		

	Life-cycle cost [FY04 $ Mn]	# of development projects [-]
Custom	46780	14
Common	36124	7

Figure 48: Commonality opportunities for the portfolio design solution with commonality with the lowest life-cycle cost; k = 2.0



- Propulsion stages:
  - S-IV
  - S-IV B
  - S-I
  - S-IC
  - S-II
- Rocket engines:
  - J-2
  - F-1
  - H-1
  - RL-10

Figure 49: Saturn launch vehicle family design solution as implemented in the 1960s

These commonality opportunities correspond to using the S-IVB stage as second stage for the Saturn I, albeit with 2 engines (see Table 13) instead of the single J-2 engine on the S-IVB (see Figure 49). Two further commonality opportunities are implemented: a common first stage engine and fuselage design for the Saturn IB and Saturn I. This is identical to the S-I stage commonality implemented in the historical Saturn portfolio. Together with the use of a common second stage for the Saturn IB and Saturn I this means that the Saturn IB and Saturn I use cases have been merged into a single use case.

In Table 13 the propellant, engine, and fuselage structure choices for the 50 best-ranked portfolio design solutions with commonality are shown; changes in these choices are highlighted by coloring. It is apparent that the preferred technology choices are quite robust among the 50 best-ranked architecture alternatives.

Table 13: Overview of technology choices for the 50 best-ranked (by life-cycle cost) portfolio design solutions with commonality; technology variations highlighted by colors; k = 2.0

Saturn V propellants			Saturn V # of engines			Saturn V stage structures			Saturn IB propellants		Saturn IB # of engines		Saturn IB stage structures		Saturn I propellants		Saturn I # of engines		Saturn I stage structures	
Saturn V propellants			Saturn V # of engines			Saturn V stage structure			Saturn IB prop.		Saturn IB # of eng.		Saturn IB stage struct.		Saturn I prop.		Saturn I # of eng.		Saturn I stage struct.	
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	103	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	103	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	103	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	103	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	103	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	103	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	5	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	5	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	5	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	5	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	5	39	39	103	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	1	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	1	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	1	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	1	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	8	39	39	66	LOX/LH2	LOX/RP1	1	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	5	39	66	LOX/LH2	LOX/RP1	6	5	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	5	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	2	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	5	39	66	LOX/LH2	LOX/RP1	6	5	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	5	39	66	LOX/LH2	LOX/RP1	6	5	39	66
LOX/LH2	LOX/LH2	LOX/RP1	1	5	8	39	39	66	LOX/LH2	LOX/RP1	1	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66
LOX/LH2	LOX/LH2	LOX/RP1	2	5	8	39	39	66	LOX/LH2	LOX/RP1	2	8	39	66	LOX/LH2	LOX/RP1	6	8	39	66

The historical Saturn portfolio design solution and commonality scheme was identified by the commonality screening process, but is not among the 50 best-ranked alternatives (it is number 350) because it required 9 development projects instead of 7 and had a higher life-cycle cost close to $40000 Mn as opposed to $36000 Mn (see also Figure 46). The major difference between the historical Saturn portfolio and the best-ranked portfolio is the custom Saturn I upper stage; the use of a single common engine on the S-IVB instead of 2 engines as for the preferred portfolio design solution can be regarded as a minor difference.

The use of a custom Saturn I upper stage in the historical portfolio can be understood when taking into account the development of the RL-10 engine for the Centaur upper stage (see Figure 49) preceded the Saturn I development (it was in fact a legacy element) [Wade-09], thereby reducing the DDT&E cost associated with it. The motivation for building a custom fuselage for the Saturn I upper stage may have been rooted in the desire to gain design and production experience for high-performance common bulkhead and multi-engine upper stages before the development of the S-IVB and S-II which needed to provide very high structural performance for the low-margin lunar use case.

4.4 Sensitivity Analysis and Selection of Portfolio Design Solutions

The results from commonality screening presented in Section 4.3 are based on a value of k = 2.0 for the overlap parameter associated with Criterion 4. It order to assess the robustness of commonality results, a sensitivity analysis with regard to changes in the value of the overlap parameter k is carried out; k is varied between 1.0 (identical propellant volume and thrust required for commonality) and 3.0.

Figure 50 provides an overview of the variation in the average number of custom development projects required across the 27000 portfolio design solutions as well as across the 10 best-ranked portfolio design solutions as a function of the value of the ***overlap parameter k***. For a parameter value of k = 1.0, no commonality opportunities are identified and the average number of developments remains 14 as in the custom case.

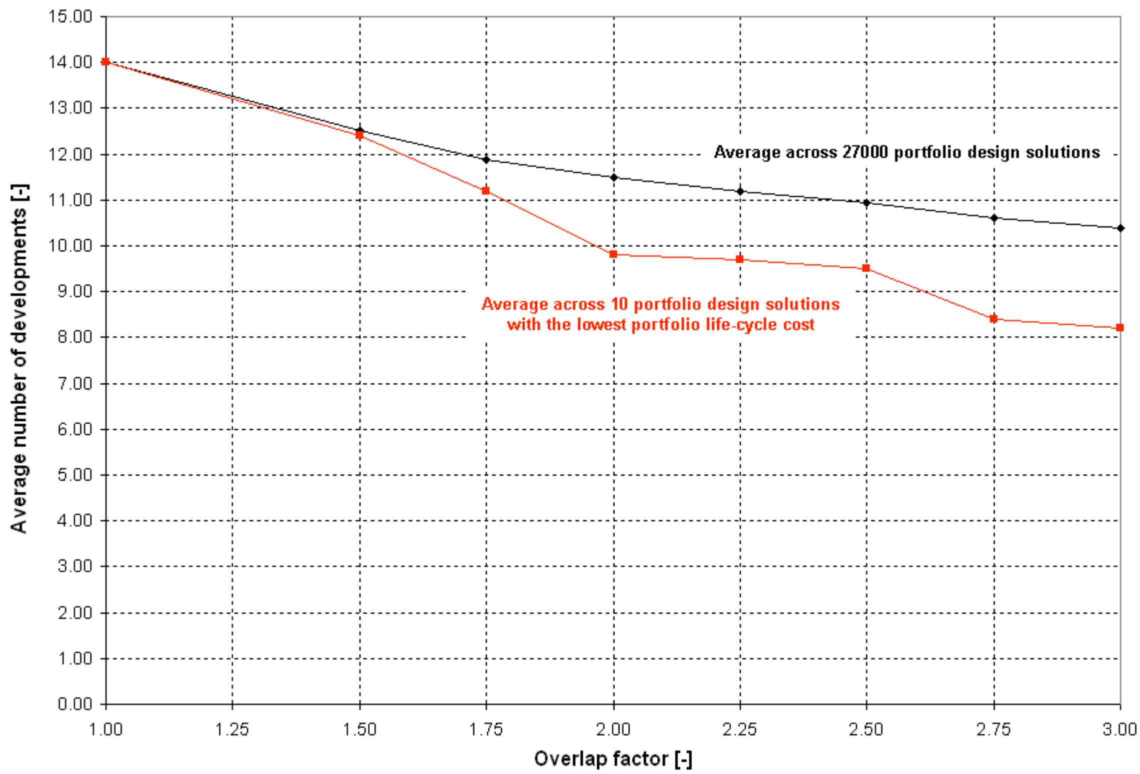


Figure 50: Sensitivity of the average number of development projects for the portfolio design solutions considered in the commonality analysis as a function of the overlap parameter k

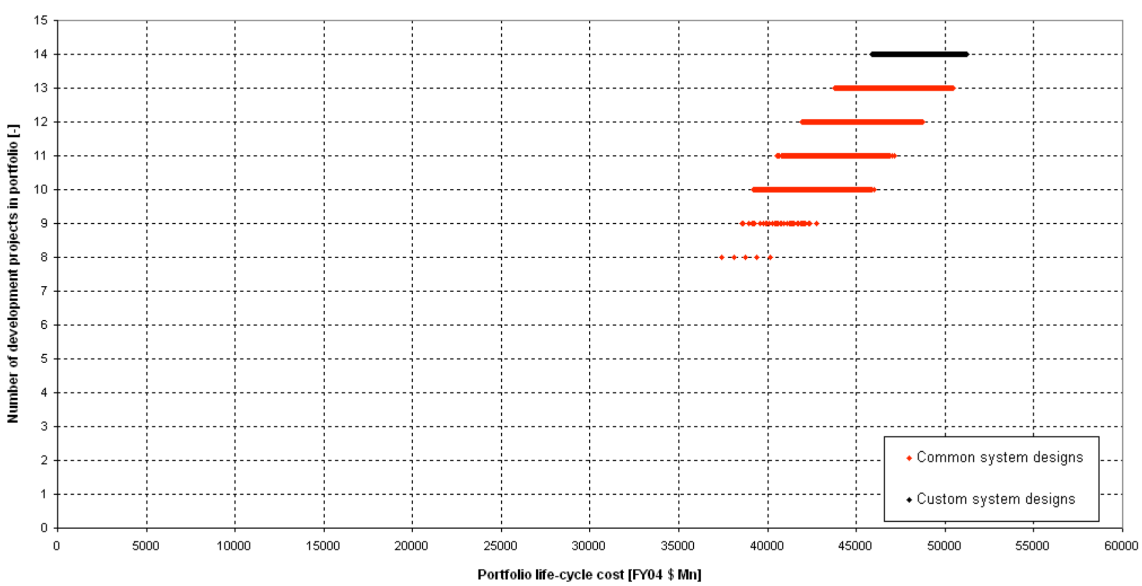


Figure 51: Preferred portfolio design solutions with commonality for the Saturn launch vehicle family: # of development projects vs. portfolio life-cycle cost; k = 1.5

In order to assess the impact of changing k on specific communality opportunities and on life-cycle cost, a variant commonality analysis for a value of k = 1.5 was carried out. Results from this analysis are shown in Figure 51 with the average number of development projects in the portfolio design solutions plotted over relative life-cycle cost. It is apparent that the implementation still results in significant reductions in the number of development projects and life-cycle cost, albeit slightly less pronounced than for the k = 2.0 case. It is interesting note that the commonality screening still identified portfolio design solutions similar to the historical Saturn portfolio design solution (identical technology choices and number of engines, somewhat different stage delta-v allocations); the first of these portfolio design solutions is now number 50 (instead of 350 for k = 2.0).

Table 14: Overlap of technology choices for the 50 best-ranked portfolio design solutions with commonality for overlap parameter values of k = 2.0 and k = 1.5

Saturn V propellants			Saturn V # of engines			Saturn V stage structures			Saturn IB propellants		Saturn IB # of engines		Saturn IB stage structures		Saturn I propellants		Saturn I # of engines		Saturn I stage structures	
0	0	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	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	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	0	0
0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	1
0	0	0	1	0	1	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	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	1
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	1	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	1	0	0	0
0	0	0	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	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	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	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	1	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	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
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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	1	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	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1

We also investigate the similarity in technology choices for the 50 best-ranked portfolio design solutions for k = 1.5 and k = 2.0 (see Table 14, coloring marks differences in technology choices). It is apparent that the preferred propellant choices, as well as the preferred fuselage structure choices are exceptionally robust to changes in the overlap parameter k. Pronounced variations occur for the number of engines for all three use cases; this observation mirrors the results from the architecture analysis in Section 4.2 with regard to variations in the preferred number of engines per stage for the individual use cases themselves.

4.5 Saturn Launch Vehicle Family Case Summary

In this chapter we have discussed the results from the application of the systems architecting and commonality analysis methodology from Section 2.2 to the historical Saturn launch vehicle family. Results from Step 2 of the methodology (point design architecture analysis for each use case) indicate that the architectures implemented for the Saturn I, Saturn IB, and Saturn V vehicles are among the preferred point design architectures identified by the methodology using life-cycle cost ranking as the primary metric. The point design analysis also shows that the propellant choices for the Saturn launch vehicles are robust; the use of hypergolic propellants does not offer any significant performance advantage and therefore is unattractive due to the special handling requirements due to the toxicity of hypergolic propellants. Major variations between preferred point design architectures for all three use cases occur with regard to the number of engines per stage: generally more engines are preferred because of the reduced DDT&E cost of smaller engines and the learning curve benefits from producing an increased number of smaller engines. However, the variability in engine number also indicates that to some degree it is possible to choose an engine number that is the best match for an intended commonality scheme.

Application of the commonality screening process of the methodology (Step 3) results in the identification of the commonality scheme implemented in the Saturn launch vehicle family. However, the commonality analysis also shows that the actual Saturn V vehicle family is not necessarily the best-ranked portfolio design solution with regard to the life-cycle cost model used. The best-ranked portfolio that was found merges the Saturn I and Saturn IB use cases, resulting in a common upper stage design for all three use cases based on a common bulk-head fuselage and two LOX / LH_2 engines. Furthermore, the best-ranked portfolio features 8 engines on the Saturn V first stage, and utilizes a 2-tank fuselage design for the Saturn I and Saturn IB common first stage (instead of a multi-tank design).

These differences in design and technology choices between the historical Saturn vehicles and the best-ranked portfolio design solution are understandable when taking into account legacy hardware available at the beginning of the Saturn program: the RL-10 engine development preceded the Saturn family, and was subsequently used as upper stage engine for the Saturn I. This necessitated a custom upper stage design for the Saturn I, but a common bulk-head upper fuselage design was chosen to gain design experience for the higher-performance Saturn IB and Saturn V upper stage. In addition, the 6-engine Saturn I upper stage provided design experience for the common-bulkhead multi-engine second stage of the Saturn V vehicle (the so called S-II stage). The choice of a multi-tank fuselage for the common Saturn I and Saturn IB first stage design is understandable when taking into account that Redstone missile tooling could be reused to manufacture the individual tanks. While the methodology indicates that the best-ranked portfolio design solution would have 10% lower life-cycle cost than the historical Saturn portfolio, the historical context suggests that the reuse of legacy elements (such as the RL-10 engine and the Redstone tooling) could have reduced this life-cycle cost difference to an acceptable level.

A sensitivity analysis for the overlap parameter used in the commonality analysis process suggests that further relaxation of the commonality requirements beyond a value of $k = 2.0$ does not result in significant further reductions in the number of custom development projects required in the portfolio nor in significant further reductions in life-cycle cost. Only the choice of the number of engines per stage shows significant sensitivity to changes in the overlap parameter. The best-ranked portfolio design solutions with commonality achieve a 50% reduction in the number of custom development projects required and approximately a 23% reduction in life-cycle cost when compared to the corresponding portfolio design solutions without commonality.

This second case study demonstrates the applicability of the systems architecting and commonality analysis methodology to a second domain (space transportation / propulsion systems) and to a historical portfolio for which the design solution that what implemented is known. The historical portfolio design solution is found, but so are a number of portfolio design solutions which outperform the historical solution in the context of the analysis assumptions. The choice of the historical design solution can be understood when taking into account the historical context of the portfolio. The Saturn case study further demonstrates the flexibility of the methodology to analyze a portfolio where the systems used in the commonality screening in Step 3 (the individual propulsion stages) are actually elements of the use cases analyzed in Step 2 (the entire launch vehicles consisting of multiple stages). The case study employs the same 4 generic commonality criteria from Section 2.2 as the life support systems case study in Chapter 3; however, the criteria are customized in a different way: Criteria 1 and 2 are identical, Criterion 3 is implemented with an operational overlap fraction of δ = 100 %, and the overlap parameter k for design parameter overlap becomes the major free variable. This demonstrates the flexibility of the architecting methodology to accommodate portfolios with significantly different functional and operational attributes.

5. Case Study 3: Planetary Surface Mobility System Commonality Analysis

This chapter contains the third applications case study for the systems architecting and commonality analysis methodology described in Section 2.2 above. Chapter 3 provides the first application case study in the area of exploration life-support systems for multi-person habitats, including both future systems and legacy systems. Chapter 4 is devoted to a retrospective analysis of architectures and commonality opportunities for the 1960s Saturn launch vehicle family; because of its retrospective character this case study can also serve as a kind of benchmark for the methodology itself. The third case study described in this chapter is devoted to commonality opportunities between future pressurized surface mobility systems for planetary exploration, applying the architecting methodology to a complete aerospace system with life support, power, and mobility functionality.

Surface mobility systems provide a crucial supporting function to human planetary exploration by enabling access to regions of the planetary surface beyond the immediate vicinity of the mission landing site. The added value of a surface mobility system was impressively demonstrated by the use of the Lunar Roving Vehicle (LRV) during the Apollo 15, 16, and 17 missions where it quadrupled the area accessible to the crew and led to a significant increase in the variety of geological regions that the crew could visit [Cor-75] [NASA-1975]. Unpressurized mobility systems such as the Apollo LRV are limited in range and radius by the constraint that the entire surface traverse needs to take place within the duration of a single extravehicular activity (EVA). Given current EVA durations of about 8 hours and average surface driving speeds of 5-10 km/h in unknown terrain, distances greater than 40 km from the landing site are therefore difficult to achieve with an unpressurized surface mobility system.

Future exploration missions to the Moon and Mars are envisioned to include cumulative surface stays 600 days at a single surface site [DRM-97] [DRM-98] [Zubrin-91]; the exploration targets of interest within a 40 km radius from the surface site will be quickly exhausted during stays of this length. This indicates the need for surface mobility systems providing a pressurized habitable environment for the crew to eliminate the constraint imposed by EVA length, enabling multi-day traverses. It is therefore safe to say that effective surface exploration for future lunar and Mars mission will have to include some kind of pressurized surface mobility system. A variety of design and operations studies in the area of pressurized mobility have been carried out since the Apollo era; Figure 52 provides an overview of selected design concepts [Ben-66] [JG-93] [DRM-97] [Yod-07].

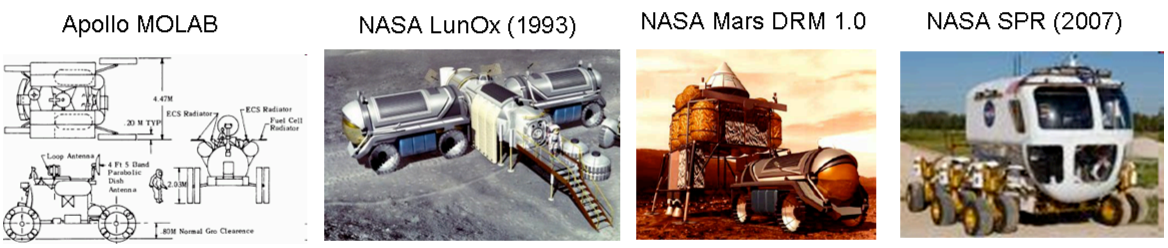

Figure 52: Overview of past and present pressurized planetary surface mobility system concepts

Commonality between pressurized surface mobility systems for both lunar and Mars exploration could offer important benefits with regard to reducing life-cycle cost (through design reuse and learning curve effects) as well as reducing operational risk through reuse of proven equipment and systems as well as operational procedures on the surface of Mars. This chapter investigates opportunities for commonality between lunar and Mars surface pressurized mobility systems using the 4-step methodology described in Section 2.2. Section 5.1 corresponds to Step 1, the definition of the aerospace systems portfolio in terms of use cases and functionality as well as the metrics to be used for comparative analysis between design alternatives. Section 5.2 provides an analysis of point designs for both lunar and Mars pressurized mobility system architectures without consideration for commonality between the two systems (Step 2 of the methodology). In Section 5.3 we investigate opportunities for commonality between the preferred architecture alternatives for lunar and Mars pressurized surface mobility systems, yielding a set of portfolio design solutions with commonality (Step 3 of the methodology). In Section 5.4 a sensitivity analysis with regard to commonality analysis assumptions is carried out, leading to the robust selection of portfolio design solutions with commonality. Section 5.5 provides a summary of the surface mobility case study results and insights.

5.1 Surface Mobility Portfolio Definition

Mission Scope

In the foreseeable future, human spaceflight will venture to only two planetary destinations in the solar system where surface mobility systems are required: the lunar surface and the Martian surface. The surfaces of Mercury as well as of the moons of the outer planets must be considered inaccessible for the foreseeable future due to excessive energy requirements for reaching them and due to other environmental concerns (thermal input, ionizing radiation). The surfaces of Venus and the gas giants are practically inaccessible for humans due to atmospheric conditions, and the very low surface gravity of NEOs, main-belt asteroids, and the moons of Mars do not require surface mobility in the sense of roving vehicles. The portfolio therefore includes only two use cases:

- Use case 1: use of pressurized surface mobility systems on the surface of the Moon, primarily for surface traverses from a polar outpost or base [Yod-07].

- Use case 2: use of pressurized surface mobility systems on the surface of Mars. In accordance with the life support systems study in Chapter 3, we will assume that the Mars exploration campaign consists of 5 conjunction class missions [DRM-97] to different sites which are globally distributed.

There are two major considerations that need to be taken into account when deriving requirements for these two use cases: crew safety in contingency situations and the actual capabilities that expected energy storage technologies can provide. For the Apollo LRV operations, the loss of the LRV driving capability at distance from the lunar module would have required the crew to walk back to the lunar module; the distance from the lunar module achievable was therefore constrained by the amount of consumables available to the crew for a walk-back scenario. The use of two (or more) independent vehicles, each capable of transporting the entire crew on traverse in a contingency scenario eliminates the walk-back constraints in favor of a drive-back constraint; this approach is adopted for the case study. In accordance with the case study presented in Chapter 3, the crew size for lunar exploration is assumed to be 4 crew members and 6 for

Mars surface missions. Given that crew members should never be alone in a pressurized habitat (except for their space suit, of course), the 2-vehicle approach necessitates that all 4 crew members are present on traverse; this is identical to the way surface operations are currently being envisioned by NASA [Yod-07]. For Mars, three options exist: (1) the entire crew is on traverse and two vehicles are used, resulting in 3 crew members per vehicle; (2) the entire crew is on traverse and 3 vehicles are used, resulting in 2 crew members per vehicles; (3) only 4 crew members are on traverse at a given time, and 2 vehicles are used. Given that for a Mars surface mission there is no anytime abort option as well as no re-supply option for critical maintenance parts, it is reasonable to assume that it would be desirable to have a minimum of 2 crew members at the Mars base in order to carry out repairs and maintenance on EVA while the other 4 crew members are on the exploration traverse. Option (3) was therefore adopted for Mars surface missions, resulting in the same number of vehicles and crew size per vehicles as for the lunar operations.

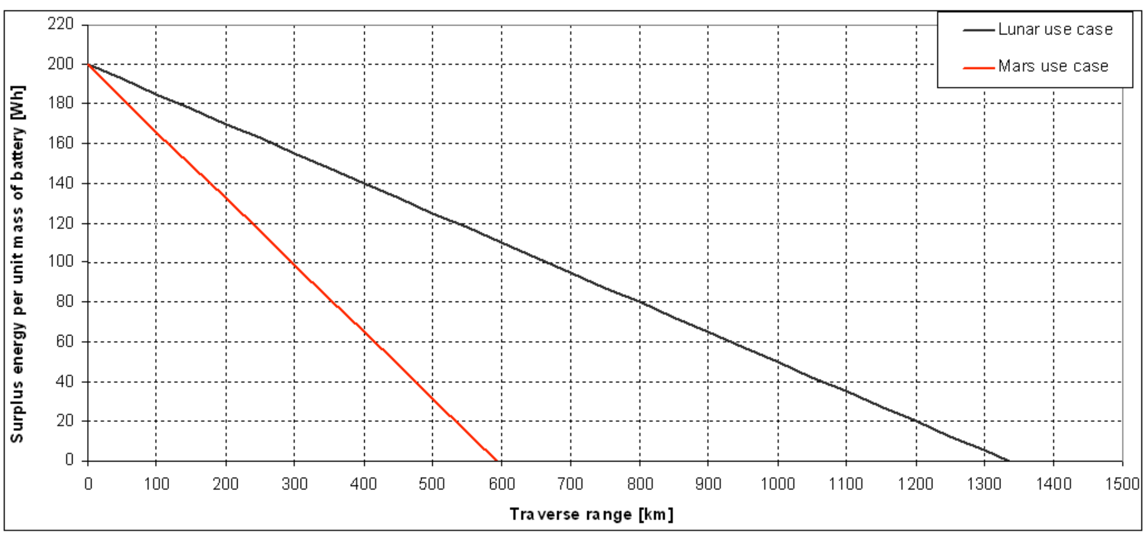

Figure 53: Surplus energy per unit mass of battery as a function of traverse range; values shown are for a 200 Wh/kg Li-Ion battery

In order to set range requirement for the lunar and Mars use cases it is necessary to understand the pertinent technology limitations of energy storage systems in case no power generation is available on traverse: the energy storage system needs to be able to at minimum power its own mobility for the traverse range (for feasible designs it obviously also needs to provide surplus energy). For the purposes of this analysis we assume that the energy storage system with the lowest energy density is a future Li-Ion battery with an energy density of 200 Wh / kg [Yod-07] (the currently achievable energy density is about 150 Wh / kg). We further assume that the specific mobility energies required for roving movement along the lunar and Mars surfaces are 0.15 Wh / kg / km [LP-00] and 0.3375 Wh / kg / km; this difference is based the higher surface gravity on Mars. We can now calculate the surplus energy per unit battery mass as a function of traverse range; results are shown in Figure 53. Based on this analysis we choose a traverse range of 1000 km for the lunar use case and of 500 km for the Mars use case; this allows for future Li-Ion batteries to be used, albeit with low surplus energies over the course of the traverse.

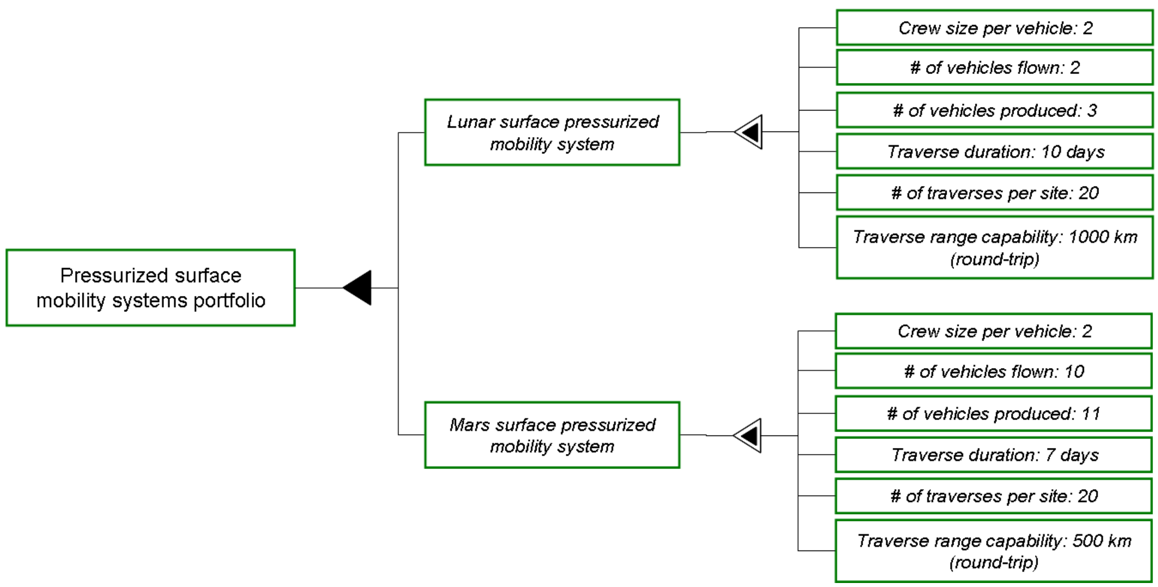

Figure 54: Overview of the pressurized surface mobility system portfolio

The duration of the traverse is another important solution-neutral requirement for the design of surface mobility systems because it determines the amount of consumables that must be carried and the energy that must be provided for habitation and associated activities. Assuming that the crew does not spend more than 10 hours driving per day, we can use the range requirements to provide a lower bound: 10 days for the lunar case, and 5 days for the Mars case. The actual traverse durations chosen were 10 days for the lunar case, and 7 days for the Mars case. It was assumed that of the 1442 days of cumulative lunar surface stay (see assumptions in Chapter 3) 200 days would be allocated to surface exploration traverses, leading to 20 10-day excursions on the lunar surface. The same number of excursions was assumed for Mars surface missions, i.e. 140 out of the 600 days on the Martian surface [DRM-97] were allocated to surface exploration traverses. Figure 54 and Table 36 in Appendix IV provide a summary of the portfolio use cases and associated requirements:

Functionality Scope

All subsystem functions of the pressurized surface mobility systems are modeled, but only the following functions different technology options were investigated and included in the commonality analysis:

- Carbon dioxide removal from the crew cabin atmosphere
- Humidity removal from the crew cabin atmosphere
- Energy storage for mobility and habitation
- Optional power generation on traverse when the rover is standing on traverse
- Mobility provision and ground interfacing: the functionality provided by the chassis, suspension, wheels and integrated drive units

All other functions are modeled with only one technology choice and are not subject to commonality analysis.

Metrics

Performance, operational risk, and cost (including developmental risk) are considered as metrics for this case study. Performance is captured by the traverse requirements discussed above: traverse duration, crew size on traverse, traverse range capability, and science payload mass on the vehicle (assumed to be 500 kg for both the lunar and Mars use case). As these requirements are solution-neutral and do not vary amongst lunar or Mars design alternatives performance is considered by way of an iso-performance analysis.

With regard to operational risk, a similar iso-risk approach was taken: we have already discussed above the need for two independent vehicles on traverse which eliminates walk-back constraints and always provides the crew on traverse with a redundant way back to base (assuming that both vehicles would not be lost at the same time). With regard to vehicle component reliability, we assume that the parametric scaling relationships from the literature used for determining vehicle properties are based on the same reliability requirements; the analysis can therefore be considered to be an iso-reliability analysis as well.

Three types of cost were considered: (1) design, development, test, and evaluation (DDT&E) cost, (2) unit cost, and (3) transportation cost for vehicles and consumables to lunar and Mars surface locations. The life-cycle cost for a use case consists of the sum of these three costs (Equation 30) and the life-cycle cost for the portfolio is the sum of the life-cycle costs for the lunar and Mars use cases (Equation 32):

$$C_{Lif\,ecycle\_lunar} = C_{Lunar\_DDT\&E} + C_{Lunar\_units} + C_{Lunar\_transportation} \quad \textbf{Equation 32}$$

$$C_{Lif\,ecycle\_Portf\,olio} = C_{Lif\,ecycle\_lunar} + C_{Lif\,ecycle\_Mars} \quad \textbf{Equation 33}$$

DDT&E (Equation 34) and 1st unit (Equation 35) costs are estimated separately for the crew compartment and for the chassis and drive elements of the pressurized mobility system using empirical cost-estimating relationships based on element dry mass [JSC-07]:

$$\begin{aligned} C_{CrewCab\_DDT\&E} &= 20.251 \cdot m_{CrewCab}^{\;0.55} \\ C_{Chassis\_DDT\&E} &= 20.251 \cdot m_{Chassis}^{\;0.55} \end{aligned} \quad \textbf{Equation 34}$$

$$\begin{aligned} C_{CrewCab\_1st\_unit} &= 0.6373 \cdot m_{CrewCab}^{\;0.662} \\ C_{Chassis\_1st\_unit} &= 0.6373 \cdot m_{Chassis}^{\;0.662} \end{aligned} \quad \textbf{Equation 35}$$

In order to calculate the total unit cost for a use case, learning curve effects with a learning rate ***LR*** of 0.85 [NASA-SP-610S] are taken into account for the production of the total number of vehicles for each use case (3 for the lunar use case, 11 for the Mars use case), see Equation 36:

$$C_{n-th\_Unit} = C_{1st\_Unit} \cdot n^b$$
$$b = \frac{\ln(LR)}{\ln(2)} \qquad \textbf{Equation 36}$$
$$C_{Units} = C_{1st\_Unit} \cdot \sum_{n=1}^{k} n^b$$

Transportation cost is estimated using constant multipliers for the mass delivered to the lunar and Mars surfaces; the values for the multipliers are (see Table 21 in Appendix II):

- Lunar surface transportation cost: 115570 $ / kg
- Mars surface transportation cost: 134770 $ / kg

The mass transported to the lunar and Mars surface consists of the cumulative number of vehicles flown for each use case (2 for the lunar case, 10 for Mars), and the life-cycle consumables mass (and associated tare mass) transported to each surface (Equation 37):

$$m_{Transportation\_lunar} = n_{Vehicles} \cdot \left(m_{Vehicle} + m_{Consumables\_lif\,ecycle}\right) \qquad \textbf{Equation 37}$$

In addition to life-cycle cost, the number of custom development projects in the portfolio is also used as a metric. Only development projects related to the five functions considered in the commonality analysis are included (see function listing above). It should be noted that point design portfolios do not necessarily all have the same number of development projects as some system designs include supplementary power generation systems and others do not. The number of development projects in the point design portfolios can therefore vary between 8 and 10.

5.2 Surface Mobility Point Design Architecture Analysis

Step 2 of the architecting methodology is the comprehensive analysis of the space of architecture alternatives for each of the use cases in the portfolio without consideration for commonality between the use cases (see also Figure 14). This is accomplished by enumerating architecture alternatives for each use case and subsequently evaluating these alternatives with regard to the metrics defined in Step 1.

Table 15: Morphological Matrix of functions and technology choices for the lunar pressurized rover; note: only functions which are included in the commonality analysis are shown

Function	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4
CO_2 removal	Lithium hydroxide (LiOH)	4-bed molecular sieve	Metal oxide canisters (MetOx)	Solid amine beds, pressure swing
Humidity removal	Silica gel	CHX	Solid amine beds, pressure swing	
Energy storage	Li-Ion batteries (energy density: 200 Wh/kg)	Regenerative fuel cells (energy density: 700 Wh/kg)		
Supplementary power generation	Tracking solar arrays (20% efficiency)	Stirling RTG	None	
Ground interfacing and propulsion	4 wheel chassis	6 wheel chassis		

The enumeration is accomplished using a Morphological Matrix (see Table 15) that lists the possible technology choices for the 5 different functions considered in the analysis. By choosing one technology option from each row we can combinatorially enumerate architecture alternatives, in this case for the lunar pressurized surface mobility system. The individual technologies in the Morphological Matrix are described in more detail in Appendix IV and Table 36. The full enumeration of combinations in the Morphological Matrix would yield 144 architecture alternatives for the lunar pressurized rover. However, not all of these combinations are feasible due to logical and operational constraints. An example for such a logical constraint would be: if solid amine beds are used for carbon dioxide removal, then the choice for humidity removal can only be solid amine beds or CHX. Incorporating these constraints, the enumeration yielded 96 feasible architecture alternatives for the lunar pressurized mobility system and 72 feasible alternatives for the Mars pressurized mobility system.

Next we need to evaluate the alternatives for each use case with regard to life-cycle cost in order to be able to rank the alternatives and select preferred alternatives. To that end we need to calculate the DDT&E, unit, and transportation cost components for each use case. This requires the calculation of vehicle DDT&E, unit, and consumables masses (see Equations 38 - 44) for use in Equations 32 - 37 from Section 5.1:

$$m_{CrewCab\_DDT\&E} = m_{CrewCab\_Unit} = m_{Structure\_crewcab} + m_{CO2\_removal} + m_{Humidity\_removal} + m_{Avionics\_Comm} + m_{Thermal\_control} + m_{Supplementary\_power\_generation}$$

Equation 38

$$m_{Chassis\_DDT\&E} = m_{Chassis\_unit} = m_{Energy\_storage} + m_{Chassis\_Wheels\_Drives}$$

Equation 39

$$m_{Consumables\_Lifecycle} = n_{Traverses} \cdot \Delta t_{Traverse} \cdot n_{Crew} \cdot \left(m_{Water\_Cons.} + m_{Oxygen\_Cons.} + m_{Food\_Cons.} + m_{Humidity\_Removal\_Cons.} + m_{CO2\_Removal\_Cons.}\right)$$

Equation 40

The mass of the energy storage system is calculated based on the choice of energy storage technology and on the energy required on traverse $E_{Traverse\_Energy}$, which is in turn a function of vehicle mass, traverse range $R_{Traverse\_Range}$, specific mobility energy ε, power consumption for subsystems other than the drive system $P_{Habitation}$, and supplementary power generation $P_{Supplementary}$:

$$m_{Energy\_Storage} = \frac{E_{Traverse\_Energy}}{D_{Energy\_Density\_Storage}}$$

Equation 41

$$E_{Traverse\_Energy} = m_{Vehicle\_Loaded} \cdot \varepsilon \cdot R_{Traverse\_Range} + \Delta t_{Traverse} \cdot \left(P_{Habitation} - \gamma_{Duty\_Cycle} \cdot P_{Supplementary}\right)$$

Equation 42

The vehicle loaded mass is calculated as the sum of the vehicle component masses and the mass of the crew, the science payload, and the mass of the consumables required on traverse, see Equation 43:

$$m_{Vehicle\_Loaded} = m_{Structure\_crewcab} + m_{CO2\_removal} + m_{Humidity\_removal} + m_{Avionics\_Comm} + m_{Thermal\_control} + m_{Supplementary\_power\_generation} + m_{Science\_Payload} + m_{Crew} + m_{Energy\_Storage} + m_{Chassis\_Wheels\_Drive} + \Delta t_{Traverse} \cdot n_{Crew} \cdot \left(m_{Water\_Cons.} + m_{Oxygen\_Cons.} + m_{Food\_Cons.} + m_{Humidity\_Removal\_Cons.} + m_{CO2\_Removal\_Cons.}\right)$$

Equation 43

The subsystem masses for the avionics & communications and for the structures subsystems are set at constant values for the lunar and Mars use cases (100 kg and 1000 kg, respectively). The masses associated with carbon dioxide and humidity removal equipment are based on the different technology choices outlined in the Morphological Matrix above; scaling values for the different technology choices as well as for all daily consumables requirements are provided in Table 36 in Appendix IV along with reference citations. The thermal control system mass is estimated based on the habitation power (see Equation 44 below) and a constant overhead of 20 W of heat rejection per kg of thermal control system mass; this value holds for both the lunar and Mars surface environments based on an analysis performed by Chase Cooper of the Massachusetts Institute of Technology [Cooper-08] and is in accordance with active thermal; control system designs for lunar surface systems proposed in the literature [Boe-92] [SICSA-93]. The science payload mass is set at 500 kg for both the lunar and Mars use cases; this mass also corresponds to the mass of 2 crew members with lunar surface extravehicular activity gear (about 200 kg per crew member), allowing for substituting science payload with extra crew members in an emergency without changing overall vehicle mass.

The energy storage system mass is estimated based on Equation 41; given the circular relationship between the energy required on traverse and the vehicle loaded mass, iterative solution of the set of equations starting with an energy storage system mass of zero is required. The supplementary power system mass is set at a fixed value, corresponding to a fixed power generating capability. Values for supplementary power generating capabilities as well as for the associated duty cycles are provide in Table 36 in Appendix IV.

The mass of the propulsion system itself (including chassis, drives, and wheels) was calculated using the "Pressurized Surface Vehicle (PSV)" model created at the Massachusetts Institute of Technology by Afreen Siddiqi and Seungbum Hong [CER-05] [SW-09] [Bair-06]. The model requires a number of inputs such as vehicle payload mass, range, number of wheels, etc., and calculates the drive, wheel, and chassis component masses as well as wheel motor torque, taking into account the actual wheel – surface interaction on the lunar and Mars surface. The PSV model has been benchmarked against the Apollo LRV design and shows accuracy that is appropriate for a system-level design effort as in this case study [CER-05].

The power required for systems other than propulsion consists of the power required for the avionics and communications systems (constant at 500 W in this analysis) and for carbon dioxide and humidity removal (varying dependent on technology choice), see Equation 44:

$$P_{Habitation} = P_{CO2\_removal} + P_{Humidity\_removal} + P_{Avionics\_Comm} \qquad \textbf{Equation 44}$$

The mathematical models for the lunar and Mars pressurized surface mobility systems were implemented in spreadsheets with individual tabs for variants of certain architectures (see attached thesis CD with original models). Given the limited size of the architecture space for this case study, the spreadsheet approach proved sufficiently flexible to allow for fast analysis of ~100 architecture alternatives for each use case.

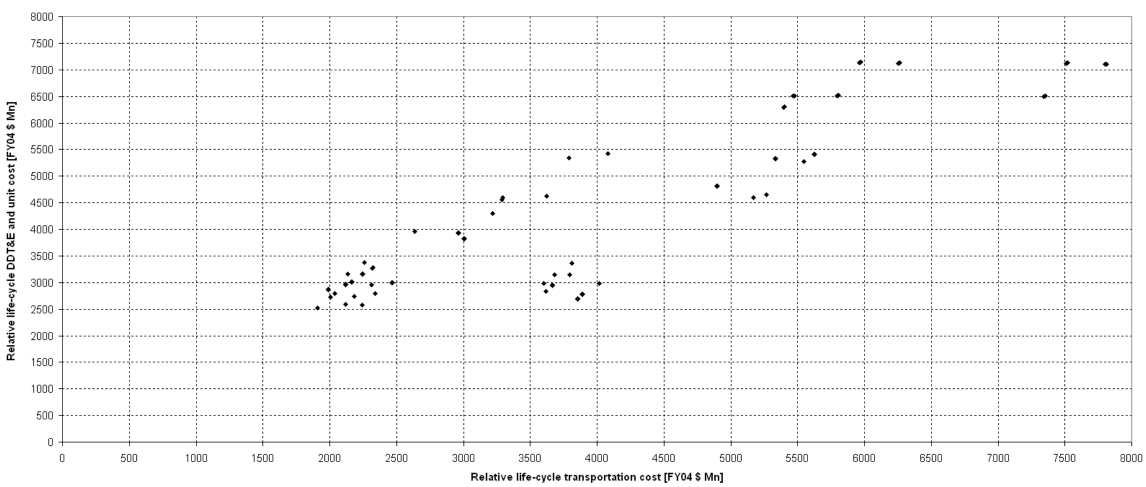

Figure 55: Lunar pressurized rover architecture analysis results: sum of life-cycle DDT&E and unit costs vs. life-cycle transportation cost

Figure 55 and Figure 56 show the results of this evaluation for the 96 lunar pressurized mobility system alternatives. Clearly distinguishable is a group of about 30 architectures which are low both in DDT&E and unit as well as in transportation cost, leading to lower life-cycle cost. It is interesting to note that for the lunar use case DDT&E and transportation cost clearly dominate unit cost; this is due to the small number of vehicles produced (only 3 vehicles total in the program, see Figure 54).

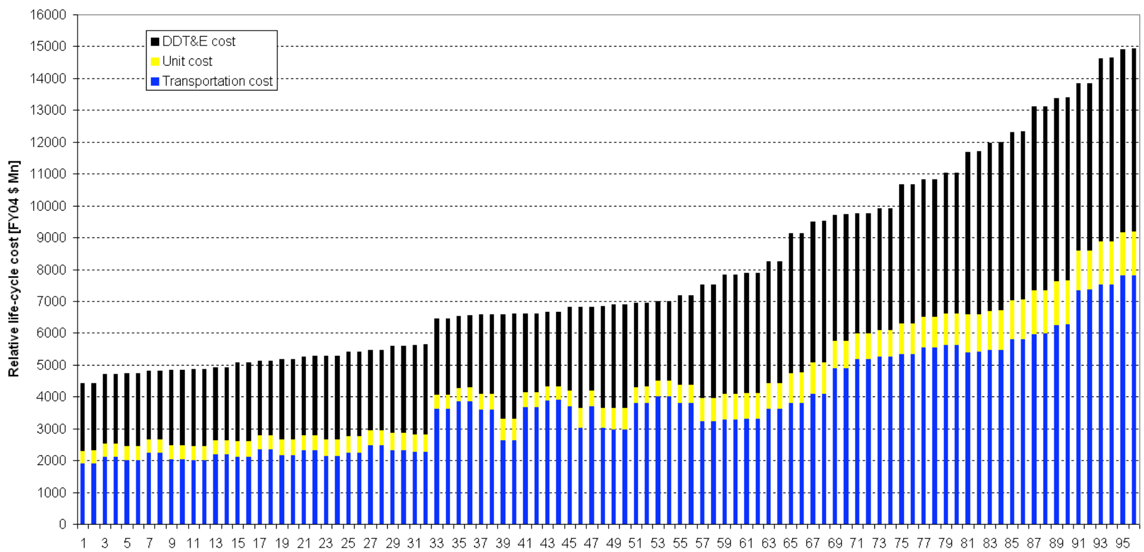

Figure 56: Lunar pressurized rover architecture analysis results: life-cycle cost ranking

Table 16: 40 lowest-ranked alternatives with regard to life-cycle cost for the lunar use case; different colors highlight different technology choices

Alternative	Life-cycle cost [FY04 $ Mn]	Carbon dioxide removal	Humidity removal	Energy storage	Supplementary power generation	Chassis type (# of wheels)
1	4427	SA	CHX	RFC	Solar	6
2	4433	SA	CHX	RFC	Solar	4
3	4707	SA	SA	RFC	Solar	6
4	4712	SA	SA	RFC	Solar	4
5	4733	4BMS	CHX	RFC	Solar	6
6	4738	4BMS	CHX	RFC	Solar	4
7	4820	LiOH	CHX	RFC	Solar	6
8	4825	LiOH	CHX	RFC	Solar	4
9	4832	SA	CHX	RFC	Stirling RTG	6
10	4837	SA	CHX	RFC	Stirling RTG	4
11	4855	MetOx	CHX	RFC	Solar	6
12	4860	MetOx	CHX	RFC	Solar	4
13	4922	SA	SA	RFC	Stirling RTG	6
14	4927	SA	SA	RFC	Stirling RTG	4
15	5078	4BMS	CHX	RFC	Stirling RTG	6
16	5082	4BMS	CHX	RFC	Stirling RTG	4
17	5129	LiOH	CHX	RFC	Stirling RTG	6
18	5133	LiOH	CHX	RFC	Stirling RTG	4
19	5170	SA	CHX	RFC	None	6
20	5173	SA	CHX	RFC	None	4
21	5264	SA	SA	RFC	None	6
22	5268	SA	SA	RFC	None	4
23	5285	MetOx	CHX	RFC	Stirling RTG	6
24	5289	MetOx	CHX	RFC	Stirling RTG	4
25	5400	4BMS	CHX	RFC	None	6
26	5403	4BMS	CHX	RFC	None	4
27	5464	LiOH	CHX	RFC	None	6
28	5468	LiOH	CHX	RFC	None	4
29	5590	SA	CHX	Li-Ion	Solar	6
30	5601	SA	CHX	Li-Ion	Solar	4
31	5632	MetOx	CHX	RFC	None	6
32	5635	MetOx	CHX	RFC	None	4
33	6449	4BMS	Silica gel	RFC	Solar	6
34	6454	4BMS	Silica gel	RFC	Solar	4
35	6543	LiOH	Silica gel	RFC	Solar	6
36	6547	LiOH	Silica gel	RFC	Solar	4
37	6581	MetOx	Silica gel	RFC	Solar	6
38	6586	MetOx	Silica gel	RFC	Solar	4
39	6590	MetOx	CHX	Li-Ion	Solar	6
40	6596	MetOx	CHX	Li-Ion	Solar	4

In order to include a diverse set of architectures, the 40 lowest-ranked alternatives with regard to life-cycle cost were chosen as input for the commonality screening process in Step 3 (see Table 16). These preferred architectures show broad variations of technology choices for all functions except energy storage (regenerative fuel cells are preferred). The number of wheels for the chassis design is clearly not a distinguishing factor given that 4- and 6-wheel versions are included for all other technology choices. Supplementary power generation could be based on solar arrays or Stirling RTGs, or could even be eliminated altogether without strongly impacting life-cycle cost. For humidity removal the use of a condensing heat exchanger dominates, but the use of solid amine beds is possible as is even the use of expendable silica gel. For carbon dioxide removal all technology choices can lead to low life-cycle cost, indicating the potential for accommodating any choice made for the Mars mobility system to increase commonality.

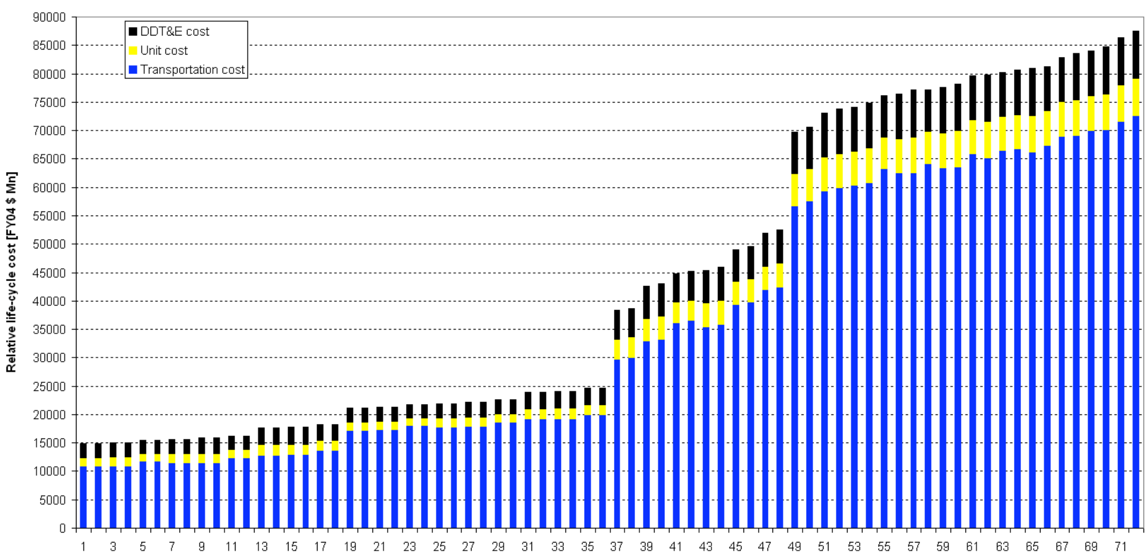

Figure 57: Mars pressurized rover architecture analysis results: life-cycle cost ranking

An identical enumeration and evaluation of architecture alternatives was carried out for the Mars surface pressurized mobility system; results are presented in Figure 57 and Table 17 as well as in Figure 87 in Appendix IV (Table 37 in Appendix IV also provides the Morphological Matrix used for the enumeration of Mars architecture alternatives). It is interesting to note that the cost structure for the Mars use case is different from that of the lunar use case: an increased number of units (11 over the life-cycle) produced leads to a higher unit cost contribution relative to DDT&E cost; however, both of these costs are dominated by transportation cost which constitutes more than 70% of the life-cycle cost for all alternatives considered.

Table 17: 40 lowest-ranked alternatives with regard to life-cycle cost for the Mars use case; different colors highlight different technology choices

Alternative	Life-cycle cost [FY04 $ Mn]	Carbon dioxide removal	Humidity removal	Energy storage	Supplementary power generation	Chassis type (# of wheels)
1	14813	4BMS	CHX	RFC	RTG	6
2	14814	4BMS	CHX	RFC	RTG	4
3	15021	MetOx	CHX	RFC	RTG	6
4	15022	MetOx	CHX	RFC	RTG	4
5	15452	LiOH	CHX	RFC	RTG	6
6	15455	LiOH	CHX	RFC	RTG	4
7	15613	4BMS	CHX	RFC	None	4
8	15614	4BMS	CHX	RFC	None	6
9	15848	MetOx	CHX	RFC	None	4
10	15850	MetOx	CHX	RFC	None	6
11	16263	LiOH	CHX	RFC	None	6
12	16264	LiOH	CHX	RFC	None	4
13	17603	4BMS	CHX	RFC	Solar	4
14	17609	4BMS	CHX	RFC	Solar	6
15	17796	MetOx	CHX	RFC	Solar	4
16	17804	MetOx	CHX	RFC	Solar	6
17	18269	LiOH	CHX	RFC	Solar	4
18	18274	LiOH	CHX	RFC	Solar	6
19	21133	4BMS	Silica gel	RFC	RTG	6
20	21133	4BMS	Silica gel	RFC	RTG	4
21	21342	MetOx	Silica gel	RFC	RTG	4
22	21343	MetOx	Silica gel	RFC	RTG	6
23	21772	LiOH	Silica gel	RFC	RTG	6
24	21774	LiOH	Silica gel	RFC	RTG	4
25	21928	4BMS	Silica gel	RFC	None	4
26	21930	4BMS	Silica gel	RFC	None	6
27	22166	MetOx	Silica gel	RFC	None	4
28	22169	MetOx	Silica gel	RFC	None	6
29	22579	LiOH	Silica gel	RFC	None	4
30	22579	LiOH	Silica gel	RFC	None	6
31	23923	4BMS	Silica gel	RFC	Solar	4
32	23930	4BMS	Silica gel	RFC	Solar	6
33	24117	MetOx	Silica gel	RFC	Solar	4
34	24125	MetOx	Silica gel	RFC	Solar	6
35	24589	LiOH	Silica gel	RFC	Solar	4
36	24594	LiOH	Silica gel	RFC	Solar	6
37	38329	LiOH	CHX	Li-Ion	RTG	4
38	38725	LiOH	CHX	Li-Ion	RTG	6
39	42570	MetOx	CHX	Li-Ion	RTG	4

As for the lunar use case, the 40 architecture alternatives ranked best with regard to life-cycle cost were chosen as input for the commonality screening process in Step 3. These preferred Mars architecture alternatives are shown in Table 17. Regenerative fuel cell energy storage is preferred, as is the use of a condensing heat exchanger. For Mars, the use of Stirling RTGs is preferred over solar arrays; this is due to the lower insolation available on the surface of Mars. As for the lunar use case, the chassis type is not a major distinguisher for life-cycle cost. All feasible carbon dioxide removal technologies are among the low-lifecycle-cost alternatives, indicating an opportunity for accommodating a common implementation for this function.

Based on the 40 preferred architectures for each use case, a total of 1600 portfolio design solutions without commonality can be enumerated. The life-cycle properties of these point design portfolio are shown in Figure 58 and Figure 59:

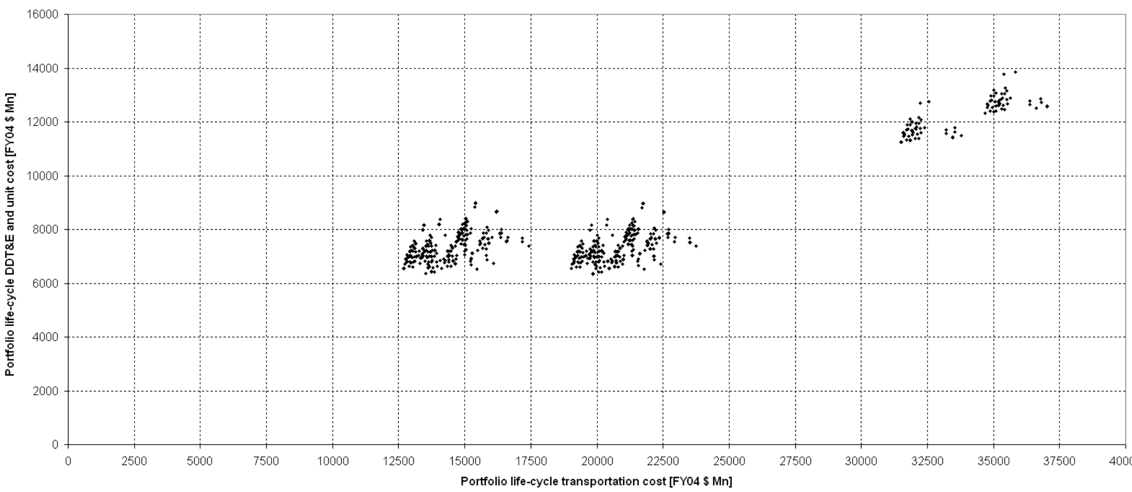

Figure 58: Point design portfolio design solutions: sum of life-cycle DDT&E and unit costs vs. life-cycle transportation cost

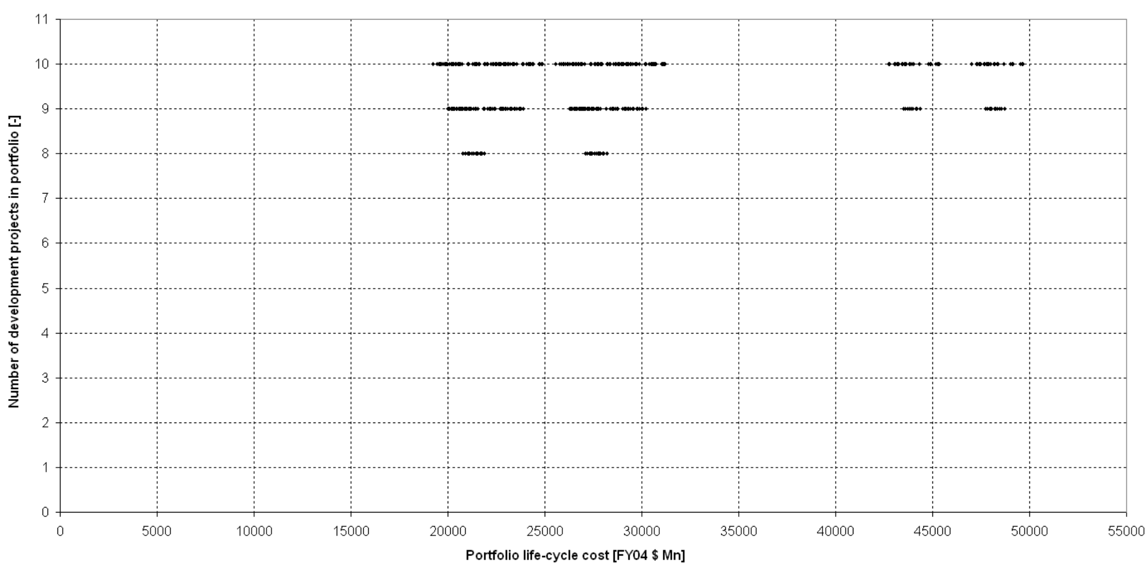

Figure 59: Point design portfolio design solutions: number of portfolio development projects vs. life-cycle cost

It is apparent that the point design portfolios fall into 4 groups distinguished by the energy storage technology used. The two groups with lower life-cycle cost are based on regenerative fuel cell energy storage for the Mars use case with the lunar use case either using RFC or Li-Ion batteries. The two groups with higher life-cycle cost are based on Li-Ion battery technology for energy storage in the Mars use case with the lunar use case either using RFC or Li-Ion batteries. Portfolio transportation cost dominates portfolio DDT&E and unit cost. As pointed out in Section 5.1, the number of custom development projects varies between 8 and 10 depending on the use of supplementary power generation systems.

5.3 Surface Mobility Commonality Screening

The next step in the methodology (Step 3) is the screening of portfolio design solutions for commonality opportunities and evaluating the net benefit of these commonality opportunities. As for the life support systems and Saturn launch vehicle case studies in Chapters 3 and 4, the same 4 generic heuristic commonality criteria from Section 2.2 are employed for the surface mobility systems case study. The following is an overview of the customized versions of these criteria:

- **Criterion 1 (identical functionality):** identical internal functions are required for a common design implementation; this applies to the five internal mobility systems functions considered in the commonality analysis: only implementations of the same internal function are considered for commonality.

- **Criterion 2 (identical technology choices):** in order for two functional implementations to be common, they must use the same technology choice. This corresponds to having the same entry in the Morphological Matrix.

- **Criterion 3 (similarity in operational environments)**: similarity in the operational environments (and associated requirements) is required for a common implementation of an internal function. As both planetary surface mobility systems operate in very similar environments (dusty surface, hypogravity), we can assume that the operational environments are identical insofar as they impact the 5 internal functions considered in the commonality analysis; this corresponds to an operational overlap of 100 % (i.e. if the required ***operational overlap fraction***

δ was 100 %, it could be satisfied). Note: in areas where the operational environments differ (such as thermal control, mission operations, etc.) custom subsystems design solutions for both systems are assumed.

- **Criterion 4:** in order for two functional implementations to be common, their design parameter values (such as stored energy, mass, torque, etc.) must be similar; this corresponds to satisfying the condition expressed in Equation 45. The design parameter ***overlap factor k*** is in this case study the free variable to be set by the system architect; it is subject to sensitivity analysis in Step 4 of the methodology (discussed in Section 5.4).

$$Parameter_{System\_1} \cdot \frac{1}{k} < Parameter_{System\_2} < Parameter_{System\_1} \cdot k \qquad \textbf{Equation 45}$$

The following specific design parameters were used for assessing whether Criterion 4 was satisfied for commonality opportunities between the five functions considered:

- Carbon dioxide removal function: subsystem equipment mass
- Humidity removal function: subsystem equipment mass
- Energy storage function: subsystem equipment mass, corresponding to the energy storage capability of the vehicle
- Supplementary power generation function: subsystem equipment mass
- Ground interfacing and propulsion function: chassis payload gravitational force and torque capability

Figure 60 and Figure 61 show results for the commonality analysis for a setting of k = 2.0 for the overlap parameter in Criterion 4. The implementation of commonality opportunities results overall in a noticeable decrease in DDT&E and unit cost, and in a slight increase in transportation cost. The overall decrease in life-cycle cost is modest; however, the decrease in the number of development projects from 8-10 down to 5-7 is significant (see also Figure 88 and Figure 89 in Appendix IV for rankings with regard to life-cycle cost and the number of custom development projects in the portfolio).

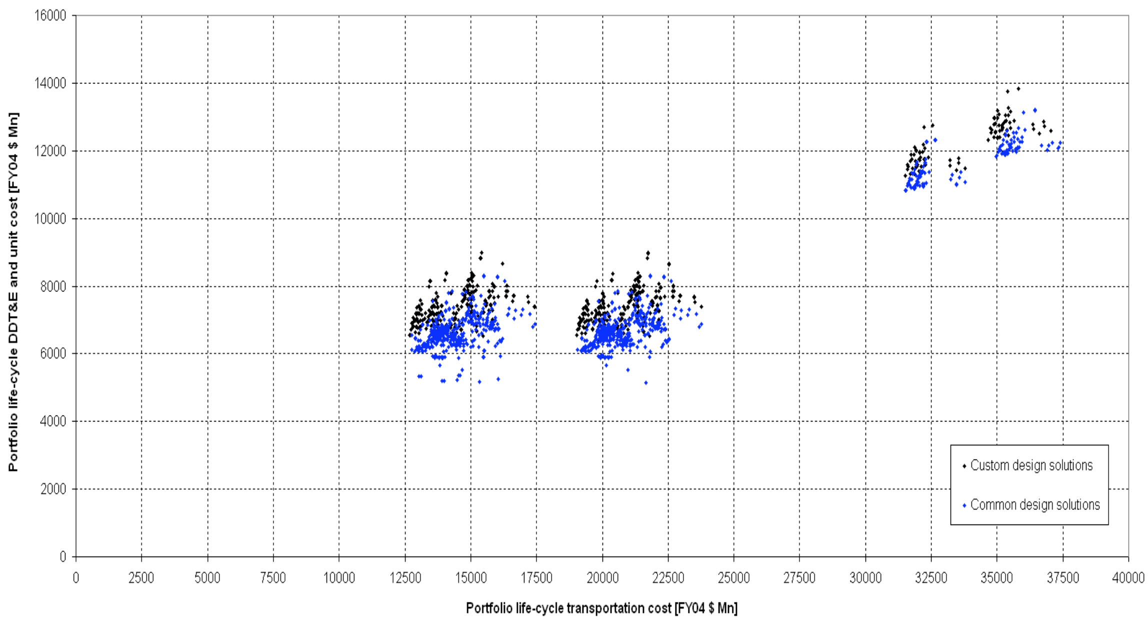

Figure 60: Common portfolio design solutions (k = 2.0): sum of life-cycle DDT&E and unit costs vs. life-cycle transportation cost

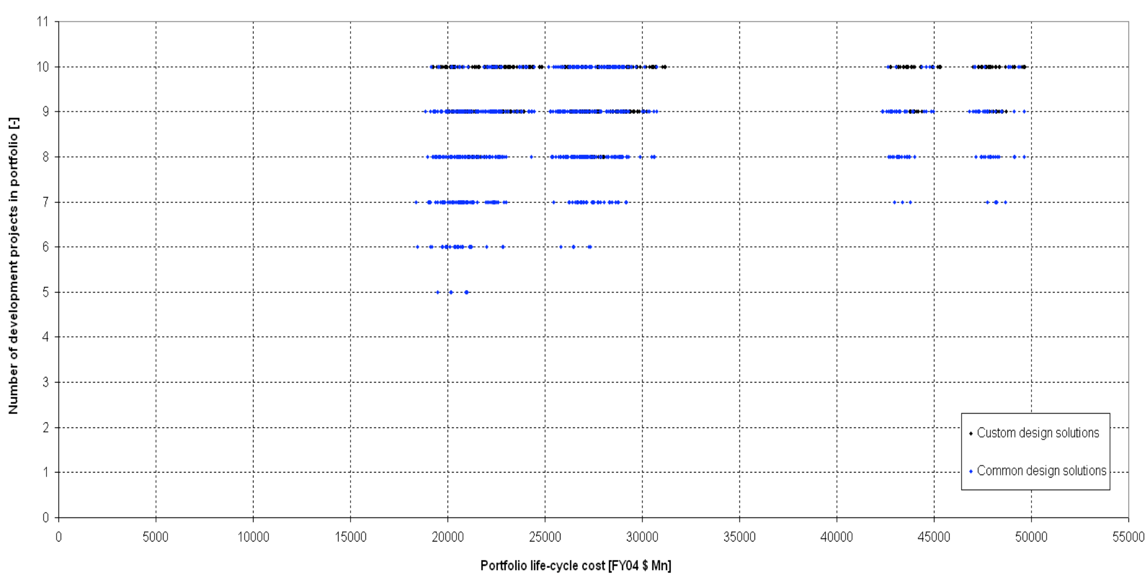

Figure 61: Common portfolio design solutions (k = 2.0): number of portfolio development projects vs. life-cycle cost

Table 18: Overview of the life-cycle cost properties and technology choices for the 40 best-ranked portfolio design solutions with commonality. Same color indicates identical technology choice for a given function. Coloring indicates commonality opportunity for a given function.

Lifecycle cost common [FY04 $ Mn]	Lifecycle cost custom [FY04 $ Mn]	# common [-]	# custom [-]	Carbon dioxide removal lunar	Carbon dioxide removal Mars	Carbon dioxide removal common?	Humidity removal lunar	Humidity removal Mars	Humidity removal common?	Energy storage lunar	Energy storage Mars	Energy storage common?	Power lunar	Power Mars	Power common ?	Chassis lunar	Chassis Mars	Chassis common ?
18358	20104	7	10	MetOx	4BMS	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	4	1
18460	20098	6	10	MetOx	4BMS	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	1	6	6	1
18858	19242	9	10	SA	4BMS	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	6	4	0
18862	19246	9	10	SA	4BMS	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	4	6	0
18864	19247	9	10	SA	4BMS	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	4	4	0
18955	19650	8	10	SA	4BMS	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	6	0
18957	19651	8	10	SA	4BMS	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	4	0
18995	19895	7	10	4BMS	4BMS	1	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	6	0
18996	19896	7	10	4BMS	4BMS	1	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	4	0
19031	19545	7	10	4BMS	4BMS	1	CHX	CHX	1	RFC	RFC	1	Solar	RTG	0	6	6	0
19033	19547	7	10	4BMS	4BMS	1	CHX	CHX	1	RFC	RFC	1	Solar	RTG	0	6	4	0
19035	19550	7	10	4BMS	4BMS	1	CHX	CHX	1	RFC	RFC	1	Solar	RTG	0	4	6	0
19036	19552	7	10	4BMS	4BMS	1	CHX	CHX	1	RFC	RFC	1	Solar	RTG	0	4	4	0
19085	19645	7	10	SA	4BMS	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	1	6	6	0
19087	19647	7	10	SA	4BMS	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	1	6	4	0
19100	20744	7	10	MetOx	LiOH	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	4	1
19111	19740	9	10	SA	4BMS	0	SA	CHX	0	RFC	RFC	1	RTG	RTG	0	4	6	0
19112	19741	9	10	SA	4BMS	0	SA	CHX	0	RFC	RFC	1	RTG	RTG	0	4	4	0
19115	19890	6	10	4BMS	4BMS	1	CHX	CHX	1	RFC	RFC	1	RTG	RTG	1	6	6	0
19117	19892	6	10	4BMS	4BMS	1	CHX	CHX	1	RFC	RFC	1	RTG	RTG	1	6	4	0
19142	19519	10	10	SA	4BMS	0	SA	CHX	0	RFC	RFC	0	Solar	RTG	0	6	6	0
19143	19521	10	10	SA	4BMS	0	SA	CHX	0	RFC	RFC	0	Solar	RTG	0	6	4	0
19147	19525	10	10	SA	4BMS	0	SA	CHX	0	RFC	RFC	0	Solar	RTG	0	4	6	0
19149	19526	10	10	SA	4BMS	0	SA	CHX	0	RFC	RFC	0	Solar	RTG	0	4	4	0
19194	20737	6	10	MetOx	LiOH	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	1	6	6	1
19241	19946	8	10	LiOH	4BMS	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	6	0
19242	19948	8	10	LiOH	4BMS	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	4	0
19244	19735	8	10	SA	4BMS	0	SA	CHX	0	RFC	RFC	1	RTG	RTG	1	6	6	0
19245	19737	8	10	SA	4BMS	0	SA	CHX	0	RFC	RFC	1	RTG	RTG	1	6	4	0
19247	19633	9	10	LiOH	4BMS	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	6	6	0
19248	19634	9	10	LiOH	4BMS	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	6	4	0
19252	19638	9	10	LiOH	4BMS	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	4	6	0
19253	19449	9	10	SA	MetOx	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	6	6	0
19253	19449	9	10	SA	MetOx	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	6	4	0
19254	19640	9	10	LiOH	4BMS	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	4	4	0
19258	19454	9	10	SA	MetOx	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	4	6	0
19258	19455	9	10	SA	MetOx	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	4	4	0
19291	19240	9	10	SA	4BMS	0	CHX	CHX	1	RFC	RFC	0	Solar	RTG	0	6	6	0
19326	19858	8	10	SA	MetOx	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	6	0
19326	19859	8	10	SA	MetOx	0	CHX	CHX	1	RFC	RFC	1	RTG	RTG	0	4	4	0

Table 18 shows the life-cycle properties and the technology choices for the 40 best-ranked portfolio design solutions (with regard to life-cycle cost) with commonality. Robust commonality opportunities exist for the humidity removal (common CHX) and energy storage (common RFC energy storage) functions; these commonality opportunities are implemented for the majority of the 40 best-ranked portfolio design solutions as well as for the best-ranked solution itself. For supplementary power generation, there is an opportunity for using a common Stirling RTG system; however, it is not selected for the majority of the best-ranked portfolios. Given the potential benefit to the lunar and Mars base infrastructure of using Stirling RTG power sources (provision of steady power during eclipse and dust storms without an additional mass penalty to the outposts) we consider this commonality opportunity significant. A similar argument can be made for commonality of the lunar and Mars chassis and drive systems: while the majority of best-ranked portfolio design solutions do not make use of this commonality opportunity, it further reduces the number of custom development projects for the portfolio and leads to a modest reduction of life-cycle cost.

For carbon dioxide removal there exists the opportunity to use a common design based on 4BMS technology; however, this is not the best-ranked choice. Given that the use of solid amine bed technology for the lunar pressurized mobility system may open up commonality opportunities with the CEV, lunar lander, and lunar EVA suit (see life support systems case study results in Chapter 3), this indicates the need for a higher-level trade between commonality focused on lunar exploration or commonality between the lunar and Mars exploration programs. This trade analysis is beyond the scope of this case study and this thesis.

5.4 Surface Mobility Sensitivity Analysis and Selection of Portfolio Design Solutions with Commonality

As mentioned above, the overlap parameter ***k*** for Criterion 4 is the free variable in the commonality screening and is set by the system architect. In order to gain an understanding of the impact of changing ***k***, we carry out an analysis of the sensitivity of the average number of custom development projects in the set of 1600 portfolio design solutions with commonality to changes in the value of ***k***; in addition, the sensitivity of the number of development projects across the 10 best-ranked portfolio design solutions is also explored. Figure 62 shows the results from this sensitivity analysis: for the average of the 1600 portfolio design solutions, there is a marked change in slope between ***k*** = 3.0 and ***k*** = 3.5, indicating a change in the marginal rate of increase in commonality opportunities.

The sensitivity results for the 10 best-ranked portfolio design solutions show a less straight-forward behaviour: after decreasing somewhat, the average number of development projects goes up again for k = 2.5 - 3, then decreases for k = 3.5 and k = 4.0 and then goes up again. This behavior can be explained when taking into consideration that in the screening analysis in Step 3 of the methodology commonality opportunities have to be implemented if they are feasible according to the 4 heuristic commonality criteria, regardless of the economic impact. As certain commonality opportunities have the potential to result in a net increase of life-cycle cost (i.e. the economic penalties due to increased unit production and transportation cost may outweigh the DDT&E cost savings), maximum commonality (i.e. a minimum number of custom development projects) does not always have to be the portfolio design solution with the lowest life-cycle cost. In Figure 62 we can see the negative effect of enforcing commonality on life-cycle cost.

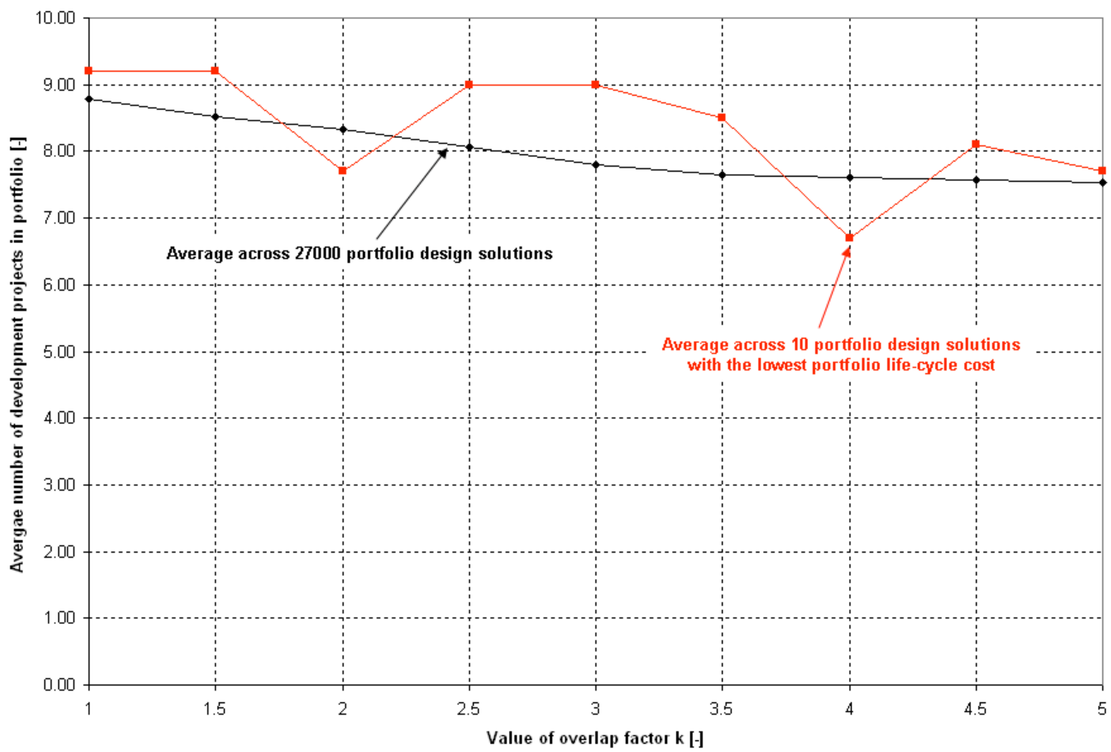

Figure 62: Changes in the average number of custom development projects across the 1600 portfolio design solutions with commonality as a function of the value of the overlap parameter k. Shown is the average number of development projects across all 1600 portfolio design solutions (black line) as well as the average number of development projects across the 10 best-ranked portfolio design solutions.

In order to assess the impact of relaxing the overlap parameter on life-cycle cost and on the number of custom development projects in the portfolio for the best-ranked design solutions we carry out a commonality screening with an overlap parameter of $k = 4.0$ (corresponding to the second minimum of custom development projects for the 10 best-ranked portfolio design solutions). Figure 63 shows the revised results for portfolio life-cycle cost and number of custom development projects based on this analysis. Additional commonality opportunities are identified, leading to a further reduction of the number of custom development projects to a minimum of 4, as well as to a modest further reduction in life-cycle cost (see also Figure 61).

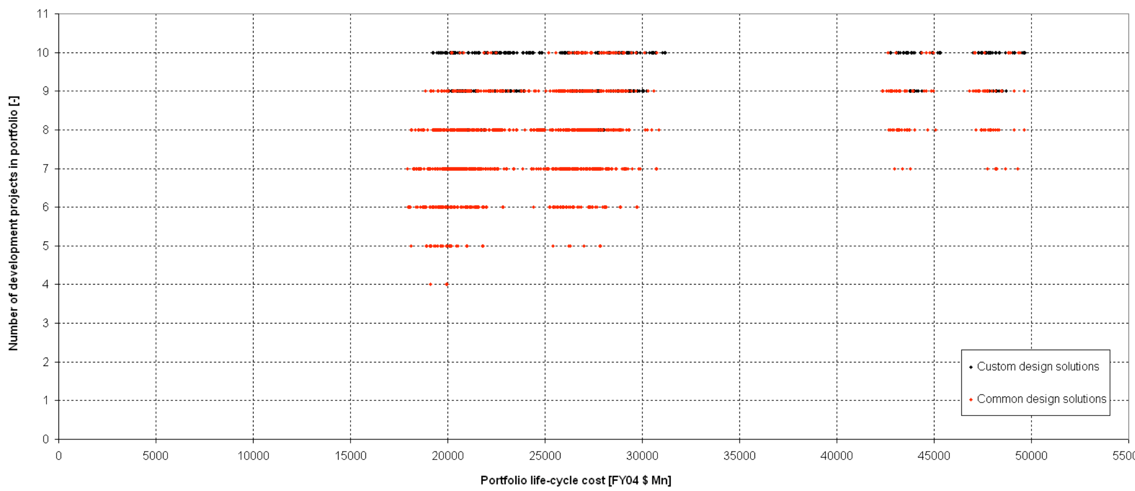

Figure 63: Common portfolio design solutions (k = 4.0): number of portfolio development projects vs. life-cycle cost

Table 19 shows the impact of changing the overlap parameter ***k*** on the technology choices for the 40 best-ranked portfolio design solutions in both commonality analyses. Red color indicates differences in technology choice for a given function, use case, and rank of the portfolio design solution. It is evident that no changes occur with regard to the choice of energy storage technology (no red entries). For the humidity removal function and the supplementary power generation function no changes occur for the Mars use case, but changes do occur for the lunar use case. However, for the best-ranked portfolio design solutions these two functions have identical technology choices (and hence identical commonality opportunities). For the ground interfacing and propulsion functions both use cases have major differences in technology choices; however, the best-ranked portfolio design solutions have identical technology choices for the Moon and Mars. The carbon dioxide removal function shows significant differences in technology choices between the two commonality analyses, although individual portfolio design solutions feature identical technology choices.

Table 19: Overlap of technology choices for commonality analyses based on k = 2.0 and k = 4.0 for the 40 best-ranked portfolio design solutions in each case. For each function and use case red color indicates differences in technology choice between the two analyses.

Carbon dioxide removal lunar	Carbon dioxide removal Mars	Humidity removal lunar	Humidity removal Mars	Energy storage lunar	Energy storage Mars	Power lunar	Power Mars	Chassis lunar	Chassis Mars
1	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	1	1
1	0	0	0	0	0	0	0	0	1
1	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	1	0	1	1
1	0	0	0	0	0	0	0	1	0
0	0	1	0	0	0	0	0	0	0
1	0	1	0	0	0	1	0	1	0
1	0	1	0	0	0	1	0	0	0
1	0	0	0	0	0	1	0	1	1
1	0	1	0	0	0	1	0	0	1
1	0	0	0	0	0	0	0	1	0
1	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	1	1
0	0	0	0	0	0	1	0	1	0
1	1	0	0	0	0	0	0	1	1
1	0	1	0	0	0	0	0	0	1
1	0	1	0	0	0	1	0	1	1
1	0	0	0	0	0	1	0	1	1
0	1	0	0	0	0	1	0	0	1
1	1	1	0	0	0	0	0	1	1
1	0	1	0	0	0	1	0	0	1
0	1	1	0	0	0	1	0	1	0
0	1	0	0	0	0	1	0	0	0
1	0	0	0	0	0	0	0	1	1
1	1	1	0	0	0	1	0	1	0
1	1	1	0	0	0	1	0	0	0
0	1	1	0	0	0	1	0	0	0
0	1	1	0	0	0	1	0	1	0
1	1	0	0	0	0	1	0	1	1
1	1	0	0	0	0	0	0	0	1
1	1	0	0	0	0	0	0	0	1
1	0	0	0	0	0	1	0	1	1
0	1	0	0	0	0	1	0	0	1
1	1	1	0	0	0	1	0	1	1
0	1	1	0	0	0	1	0	0	1
1	0	0	0	0	0	0	0	1	1
1	1	0	0	0	0	0	0	1	1
0	1	1	0	0	0	1	0	1	0
0	1	1	0	0	0	1	0	0	0

The results indicate that commonality opportunities with regard to humidity removal, energy storage, and supplementary power generation are relatively insensitive to changes in the overlap parameter value, whereas the carbon dioxide removal and ground interfacing & propulsion functions are more strongly affected by changes in the overlap parameter value ***k***.

Given that the increase of the design parameter overlap factor k from 2.0 to 4.0 did not results in significantly more commonality opportunities or significant further life-cycle cost reductions, the best-ranked portfolio design solution for the k = 2.0 case was chosen as the reference for input to more detailed design analysis. Robust commonality opportunities for this portfolio design solution and the k = 2.0 case are (see Table 18):

- The use of a common condensing heat exchanger unit for reclamation of condensate water for recycling at the surface habitat.
- Use of regenerative fuel cells for energy storage on the vehicle.

Less robust but still interesting commonality opportunities for the best-ranked portfolio design solutions in the $k = 2.0$ case include:

- The use of a common 4-bed molecular sieve system, in particular if power generation on traverse is used on both the lunar and Mars vehicles.
- The use of a common mobile radioisotope power source with dynamic conversion (using the Stirling process) for power generation on traverse
- The use of a common 4-wheel or 6-wheel chassis and drive train

5.5 Surface Mobility Case Study: Summary and Conclusion

This chapter provides a discussion of the third application case study for the systems architecting and commonality analysis methodology developed in Section 2.2. The subject of this application is planetary surface mobility systems for human exploration, specifically pressurized mobility systems for multi-day excursions. Two use cases are considered in the analysis: a lunar surface pressurized mobility system and a Mars surface pressurized mobility systems; other destinations either do not require pressurized surface mobility systems or are inaccessible for the foreseeable future of human spaceflight.

First, a comprehensive analysis of point design architecture alternatives without considerations for commonality between them is carried out for each of the use cases. The results from this analysis indicate that for both use cases the ~30 best-ranked alternatives with regard to life-cycle cost show only a modest variation in life-cycle cost. This indicates that a degree of freedom exists for choosing the pair of alternatives which provides the best commonality opportunities. For both use cases, alternatives which provide supplementary power generation on traverse are preferred, as is regenerative fuel cell energy storage. The number of wheels is not a significant distinguishing factor, as is the specific choice of carbon dioxide removal technology. For the humidity removal function, regenerative technologies are preferred.

For both use cases, the 40 point design alternatives best-ranked with regard to life-cycle cost were included in the commonality screening process in Step 3, yielding 1600 portfolio design solutions with and without commonality. The analysis indicates robust commonality opportunities exist for energy storage (using regenerative fuel cells), for supplementary power generation (using Stirling RTG), humidity removal (using CHX), for the chassis (both 4 and 6 wheel versions). For carbon dioxide removal, there is more variability between the preferred technology and commonality choices (regenerative in both cases): a common implementation is possible using 4BMS technology; alternatively custom units can be utilized based on 4BMS for Mars and SA or MetOx for the Moon.

The significance of this third case study with regard to the systems architecting and commonality methodology is that it shows the applicability of the methodology to a portfolio in yet another domain (ground vehicles and power generation and energy storage) with different portfolio-level attributes. Not all internal functions in the surface mobility portfolio need to be implemented: the supplementary power generation function for recharging energy storage on traverse is optional, which leads to a range values for the number of custom development projects even for point design portfolios. As for the Saturn launch vehicle case study described in Chapter 4, a comparison of the operational environments (heuristic commonality Criterion 3) does not yield a sufficient basis for an overlap analysis because the operational conditions and environments are too similar for the lunar and Mars surface mobility systems as far as the internal functions in the commonality analysis are concerned. This leads to the use of subsystem design and performance attributes as the basis for a continuous overlap analysis (heuristic commonality Criterion 4), much as for the Saturn case study in Chapter 4. However, methodologically speaking there are two major differences to the Saturn family analysis: (1) as only two use cases are included in the portfolio, a much larger number of preferred portfolio alternatives can be selected per use case (40 vs. 7 in the life support analysis in Chapter 3 and 30 for the Saturn case study). (2) The analysis was implemented in Excel spreadsheet models as opposed to Java code, demonstrating that the methodology and heuristic SOM tool are independent of the specific software tool used for the implementation. This enables the system architect to choose the software tool which is best suited to the complexity of the portfolio to be analyzed.

6. Conclusion

6.1 Thesis Summary

This thesis developed a framework for the systems architecting of aerospace systems portfolios with commonality. In response to the general research objective, the framework is capable of transforming a solution-neutral description of an aerospace systems portfolio and its constituent systems into portfolio design solutions which are technically and operationally feasible, are suitable as input for more detailed design phases, are located within close proximity to the overall portfolio Pareto front with regard to the portfolio metrics, and include an explicit scheme for the utilization of technology and design commonality. Required for this transformation is a systems architect who carries out the analysis as well as engineering domain knowledge, as required for example for the parametric design of life support systems. The framework is intended to provide a repeatable way of carrying out this transformation, i.e. different system architects with the same domain knowledge at their disposal should arrive at similar answers with regard to the portfolio design solutions. The framework is applicable during the earliest stages of portfolio and systems design, often called the systems architecting phase, and therefore provides a way of explicitly considering commonality when the leverage to decrease the disadvantages of commonality and capitalize on its advantages is greatest.

The framework consists of a set of generally applicable systems architecting principles as well as a concrete 4-step methodology (see Figure 64). The principles were synthesized from the literature as well as from systems architecting experience acquired by the author over several years of working on NASA's new human spaceflight architecture. The principles provide both guidance for systems architecting without commonality, as well as for aerospace systems commonality itself. The methodology represents a 2-stage commonality analysis process: the first stage, corresponding to Steps 1 and 2 of the methodology, is concerned with identifying preferred architectures for each of the systems in the portfolio individually (no consideration for commonality, point design solutions). This is achieved through a definition of portfolio scope (use cases and functionality) and metrics in Step 1, and through the enumeration and evaluation of architecture alternatives for each use case individually in Step 2, leading to the selection of preferred architecture alternatives for each use case. In the second stage, corresponding to Steps 3 and 4 of the methodology, a comprehensive screening of commonality opportunities among the preferred point design solutions in the portfolio is carried out based on heuristic commonality criteria (Step 3). In Step 4 involves a sensitivity analysis of portfolio design solutions with regard to changes in the heuristics and the subsequent selection of preferred portfolio design solutions with commonality.

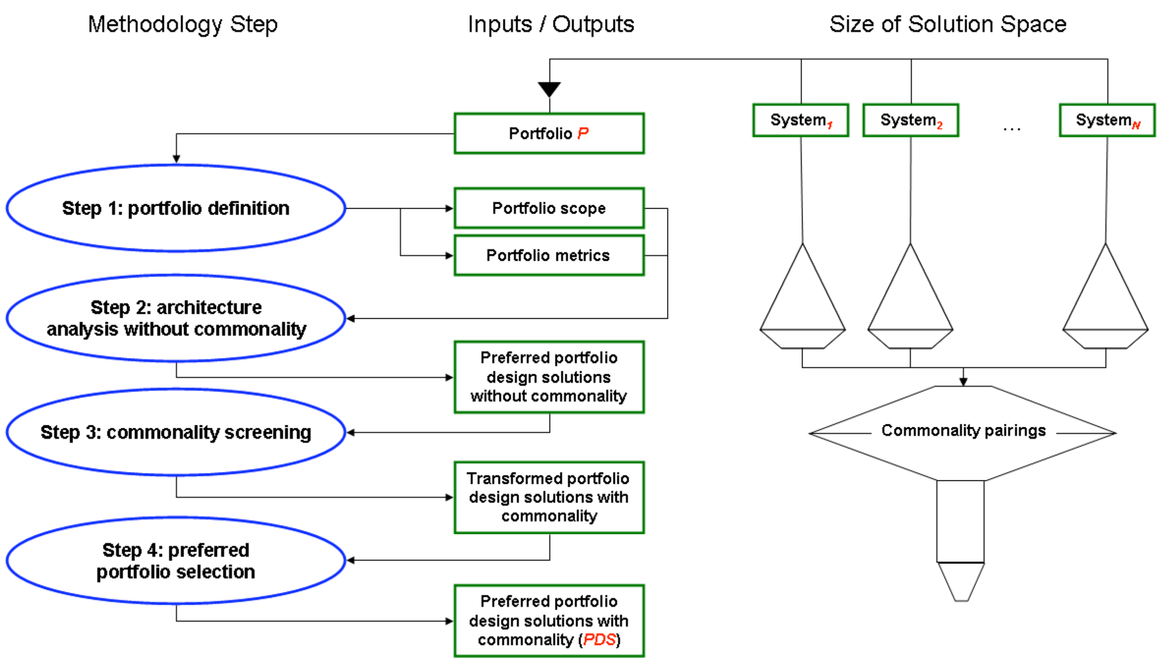

Figure 64: 4-step portfolio architecting methodology (see Section 2.2 for a detailed description)

A heuristic approach, called system overlap matrix (SOM), was developed for the assessment of the potential for commonality based on overlap of functional requirements, associated technology choices, as well as operational requirements. Similarity in quantitative design specifications can be required as an additional commonality constraint. The algorithmic implementation of the system overlap matrix allows for automated screening of a large number of portfolio design solutions with regard to commonality opportunities.

The framework was applied to three systems architecting case studies in different areas of human spaceflight and astronautics:

- A case study in life support system commonality for future multi-person exploration missions, such as lunar surface exploration, missions to NEOs, as well as Mars surface missions.
- A retrospective case study revisiting the Saturn launch vehicle family of the 1960s, including the Saturn I, Saturn IB, and Saturn V launch vehicles.
- A case study on commonality between future lunar and Mars pressurized surface mobility systems for human exploration.

The life support system case study considered 5 possible future use cases: life support for a lunar lander, a lunar surface habitat, a NEO mission habitat, a Mars surface habitat, and for an interplanetary transfer habitat to be used as part of a human Mars mission. In addition, the CEV and ISS life support systems were considered as legacy systems for which an architecture and associated technologies have already been selected. For each of the 5 future systems, an architecture analysis was carried out with regard to different combinations of physicochemical life support technologies, and preferred architectures were selected based on relative life-cycle cost rankings. For the 16807 portfolio design solutions considered in the commonality screening, robust commonality opportunities were identified using the SOM approach in the following areas: water management, food provision, clothing provision, carbon dioxide removal, and humidity removal. Specific commonality opportunities are described in detail in Section 6.2. The ultimate validation for the analysis would, of course, be a comparison to the life support systems which will be chosen for the actual designs to fly on the above-mentioned missions. However, comparison with previous work on exploration life support systems suggests that the case study results are in accordance with past results [DRM-97]. This first case study demonstrates that the systems architecting and commonality analysis methodology developed in this thesis can be applied to complex subsystems in the chemical and mechanical engineering domains.

The Saturn case study investigated 2- and 3-stage launch vehicle architectures with a variety of structural design options and propellant choices for each of the three systems in the family: the Saturn I, Saturn IB, and Saturn V launch vehicles. Preferred architectures were selected based on relative life-cycle cost rankings, as well as on considerations for vehicle height and wet mass which served as proxies for ground processing infrastructure cost. Interestingly, the preferred architectures for each vehicle differed predominantly in the choice of structural design for the propulsion stages and in the number of engines used per stage; major variations in propellant choice were not observed. For the set of 27000 point design portfolios enumerated based on the preferred architectures a comprehensive analysis of commonality opportunities was carried out using the SOM approach. The portfolio design solution implemented with the actual Saturn launch vehicle family was identified during the commonality screening. However, common portfolio design solutions with superior life-cycle cost were found which merged the Saturn I and Saturn IB use cases and used more engines on the upper stage and on the Saturn V first stage. These portfolio design solutions achieve a 10% lower life-cycle cost and require only 7 instead of 9 custom development projects when compared to the historical Saturn portfolio design solution. The selection of the historical solution in spite of its "non-optimality" can be understood when taking into account legacy engines and fuselage tooling at the beginning of the Saturn program. This second case study demonstrates that the systems architecting and commonality analysis methodology developed in this thesis can be applied to space launch and propulsion systems.

The third cast study investigated architecture alternatives and commonality opportunities for lunar and Mars pressurized surface mobility systems for human exploration. Robust preferred point design architectures for both use cases were identified using life-cycle cost ranking. It is interesting to note that the 30 lowest-ranked alternatives for both use cases show only modest variations in life-cycle cost, indicating the opportunity to select an optimal pairing of alternatives based on commonality potential. A total of 1600 portfolio design solutions were investigated in the commonality screening process, based on 40 preferred point design alternatives for each of the lunar and Mars use cases. Robust commonality opportunities were identified for humidity removal, energy storage, supplementary power generation, and for the chassis. Specific commonality opportunities are described in more detail in Section 6.2. The commonality opportunities and technology choices identified are in agreement with previous design analyses in the field of pressurized surface mobility [DRM-97] [Yod-07]. This third case study demonstrates that the systems architecting and commonality analysis methodology developed in this thesis can be applied to integrated aerospace systems featuring a diverse set of internal functions.

The successful application of the methodology to this diverse set of case studies (including one case with explicit consideration for legacy elements) demonstrates broad relevance of the methodology to the analysis of portfolio design problems in the field of aerospace systems.

6.2 Aerospace Systems Portfolio Commonality: Key Findings

The application of the methodology to the three case studies described in Chapters 3, 4, and 5 yielded a number of important findings and conclusions with regard to specific commonality opportunities in future systems and with regard to the general field of aerospace systems commonality. Findings with regard to specific robust commonality opportunities of interest for future aerospace systems include:

- A ***common water recycling system*** intended for use in all future long-duration habitat applications based on multi-filtration and vapor compression and distillation technology. Different crew sizes could be accommodated by different duty cycles for the system. The US water recycling system currently in use on the ISS could provide the design basis for this common water recycling system.

- A ***common carbon dioxide and moisture removal system*** based on 4BMS and CHX technology for all future long-duration habitats (including Mars surface), adapted or extended from the ISS design. Different crew sizes could be accommodated by different cycle times for the carbon dioxide and moisture removal beds.

- A ***common food system*** based primarily on de-hydrated food for all future long-duration habitats. De-hydrated food is desirable because the use of water recycling from wash water, condensate, and feces results in water surplus in the habitat. Metabolic water production provides sufficient addition water to completely close the water loop in the habitat. Food systems scale with crew size and can therefore accommodate any crew size.

- A ***common cleaning system for clothing*** for use in all future long-duration habitats. This system would also include the crew clothing itself, potentially based on existing clothing items from the shuttle and ISS programs. It should be noted that for the longer-duration missions (lunar surface, Mars), stored clothing will still be required given that the clothes wear out with use and need to be replaced after a certain duration of use.

- The ***reuse of the CEV carbon dioxide and humidity removal system design*** on the Altair lunar lander ascent stage. The short mission duration of the Altair ascent stage allows for loss of CO_2 and water to vacuum, enabling virtually unaltered reuse of the CEV design.

- A ***common regenerative fuel cell energy storage system*** for use on lunar and Mars pressurized rovers. The exact size of the storage capability for water, hydrogen, and oxygen may differ between the lunar and Mars implementations, but the same components (tanks, valves, etc.) could be used, including electrolyzers and fuel cells.

- A ***common supplementary power generation system*** for power production on traverse for lunar and Mars pressurized mobility systems. The system would be based on Stirling RTG units with optional solar power for lunar applications. An added benefit of this common traverse power generation system would be that it could be used for base power generation during eclipse and also during dust storms on Mars.

- A ***common surface mobility chassis and drive system*** for lunar and Mars use, based either on a 4- or 6-wheel design. This commonality opportunity was identified based on matching payload and torque capabilities for the lunar and Mars use cases. The selection of the number of wheels should be based on considerations for terrain accessibility.

General findings with regard to aerospace systems commonality and associated analysis methodologies include:

- In a scenario which includes both human lunar and human Mars exploration programs, the implementation of commonality opportunities between lunar and Mars programs can prevent the implementation of commonality opportunities in the lunar program itself and vice versa. This indicates that there is a need to clearly define the objective and the scope of the implementation of commonality in the exploration enterprise: is it the improvement of life-cycle properties for each program individually, or is it the improvement of the overall life-cycle properties of the exploration enterprise?

- Cost reduction, both in terms of life-cycle and development cost, is not necessarily always the strongest motivation for portfolio-level commonality. While all three case studies show that commonality can lead to appreciable cost savings (10 % or more over the life-cycle within the accuracy of the models used and dependent on the specific portfolio), the reduction in the number of major development projects over the lifecycle of the portfolio is potentially more pronounced (on the order of 50 % or more in the case studies in this thesis, dependent on the specific portfolio). As each custom development project in a program carries a fixed cost overhead, this may lead to an additional cost benefit that has not been captured by the mass-based life-cycle cost models used in the analysis.

- The reduction of the number of major projects that need to be carried out potentially leads to a reduction of developmental risk and to an increase in operational experience with the common element designs which may lead to reduced operational risk. This is of particular interest for space applications where the cumulative number of units and operations tends to be small (in some cases only one unit and mission), and each additional unit produced and operated provides a significant opportunity to accumulate operational experience with the associated design. It should be noted, however, that if the number of development projects becomes too small there may be additional programmatic risk introduced due to the increased impact of developmental difficulties.

- The systems architecting framework developed in this thesis can be used not only to identify individual preferred portfolio design solutions with commonality, but can also to identify robust commonality opportunities across many different portfolio design solutions. The framework can therefore not only provide input for more detailed design phases, but can also serve to identify the areas where more detailed architecture-level analysis may be beneficial. In addition, the assessment of commonality opportunity robustness provides insight into the opportunity cost associated with individual common design and technology choices. This property of the methodology demonstrates the value of comprehensive investigation of the space of architectural alternatives (Principle 3).

- Four distinct heuristic criteria for the assessment of the technical and operational feasibility of commonality opportunities between two system designs were identified and implemented in the case studies: [Criterion 1] identity in internal functionality, [Criterion 2] identity in technology choices (Criteria 1 and 2 correspond to identical entries in the Morphological Matrix), [Criterion 3] similarity in the operational environments for both systems as measured by operational overlap fractions greater or equal to a threshold fraction δ, and [Criterion 4] similarity in quantitative design parameters as measured by design parameter values within a factor k of each other. These four criteria need to be considered for each case study, although their customization will differ for different portfolios. The required values for the operational overlap parameter δ and the design parameter overlap fraction k are in general arbitrary choices and therefore need to be subject to sensitivity analysis. In many cases (such as in all three case studies presented in this thesis), analysis of the differences in operational environments or the differences in design parameters may results in a simplification of Criteria 3 and 4: if the operational environments are nearly identical, then Criterion 3 can be assumed to be fulfilled in all cases and does not explicitly be assessed (see the Saturn and surface mobility system case studies in Chapters 4 and 5), and if the differences in design parameters are insignificant with regard to their impact on the portfolio metrics, then design parameter overlap can be assumed to be acceptable in all cases (see the life support systems case study in Chapter 3).

- For exploration payloads, such as habitats and surface mobility systems, there is a tendency that portfolio-level improvements in development and unit cost due to commonality may be reduced or outweighed by increased transportation cost due to the increased equipment and spare parts mass needs. This indicates that analysis of commonality with metrics of development and unit cost on the one hand and life-cycle mass on the other hand is not sufficient to identify truly advantageous commonality opportunity; an integrated assessment of portfolio life-cycle cost including transportation cost is required.

- For “high-volume” aerospace systems such as launch vehicle propulsion stages and in particular rocket engines, commonality has a significant impact on portfolio unit cost over the life-cycle because of learning curve effects. This leads to a different “commonality dynamic” than for payloads such as life support systems and surface mobility systems.

6.3 Thesis Contributions

The work presented in this thesis is aimed at closing a gap in the capability of frameworks available for the architecting of aerospace systems portfolios with commonality. This thesis provides the following four specific contributions to the field:

- **The synthesis of a set of principles for the architecting of aerospace systems portfolios.** In systems architecting theory, principles are used to provide guidance to the systems architect that is generally valid and unchanging over time. Nine principles were developed which address the systems architecting of individual systems as well as commonality in aerospace systems and ways for identifying opportunities for commonality. Most notable among the principles are the observation that comprehensive analysis of architectural alternatives is the basis for informed selection of good architectures and the definition of an integrated set of commonality types forming a hierarchy which can be exploited in the search for commonality opportunities. It is important to emphasize that it is the synthesis of this set of principles that the author claims as a contribution, not the derivation of the individual principles themselves: while some of the principles are based exclusively on work by the author, others are built upon work described in the literature.

- **The development of a novel methodology for the architecting of aerospace systems portfolios with commonality.** The methodology transforms a solution-neutral description of an aerospace systems portfolio into a set of portfolio design solutions which are technically and operationally feasible, suitable as input to more detailed design activities, are located within proximity to the Pareto front with regard to the portfolio metrics, and provide an explicit scheme for the utilization of commonality within the portfolio. While generic applicability of the methodology has not been proven, application to three diverse case studies suggests broad applicability within the field of astronautics. Repeatability of results using the methodology has also not been proven; however, possible sources of perturbations that can lead to changes in results have been identified, enabling a better understanding of the limitations of repeatability. The methodology developed can therefore be regarded as an implementation of the process described in the general research objective in Chapter 1.

- **The development of a heuristic approach to the automated identification of commonality opportunities using the system overlap matrix (SOM) within Step 3 of the methodology.** The intellectual basis for the heuristic approach is the observation that if two systems have identical internal functionality, associated technology choices, and operational requirements, then identical designs would be chosen for both systems. The observation is extended into the postulate that if two systems have identical internal functionality and associated technology choices as well as ***significant overlap*** in operational requirements (the exact level of overlap required can be varied for sensitivity analysis), then an opportunity for a common design implementation for both systems exists. The SOM approach allows for the calculation of a normalized overlap fraction for both systems in question for each system function. The tool was initially implemented in Excel, and later on in the Java code used for comprehensive pair-wise commonality screening as part of the three case studies presented in this thesis.

- **Application of the novel architecting methodology to case studies of commonality opportunities in three diverse aerospace systems portfolios.** Two of the case studies were concerned with portfolios of systems that have yet to be developed (exploration life support systems and planetary surface mobility systems), and the remaining case study was dedicated to a review of commonality opportunities in the Saturn launch vehicle family used in the Apollo program. Each of the case studies produced a set of preferred portfolio design solutions with commonality that showed improved portfolio metric values compared to custom portfolio design solutions. The Saturn launch vehicle case study found the portfolio design solution chosen for the actual launch vehicle family, thereby validating the capability of the methodology to find historical portfolio design solutions. The three case studies are also intended as tutorials for future application of the methodology to other aerospace systems portfolios.

Based on the above contributions, we can consider the specific research objectives defined in Chapter 1 as achieved.

6.4 Opportunities for Future Work

The work documented in this thesis represents an initial foray into the field of architecting aerospace systems portfolios with commonality. A number of opportunities for follow-on work to further develop the thesis framework have been identified:

- The **further application of the framework** to architecture and commonality studies for portfolios of complex systems. These systems do not necessarily have to be aerospace systems only: experience with the three case studies described this thesis suggests that the methodology is applicable to general sets of complex systems that satisfy the basic requirements of portfolios (relationship between the portfolio systems and a central authority or organization in control of design of all systems in the portfolio). These further case studies will provide additional insight into the strengths and weaknesses of the methodology and into its generic applicability and its repeatability with regard to results. Application of the methodology will yield new information regarding preferred system architectures and commonality opportunities for portfolios that have not been previously studied, thereby adding value to major new development programs. One example, among many, for future application of the framework could be in the area of propulsion system architectures for all-electric and hybrid ground vehicles.

- The **development of additional systems architecting principles**: further application of the methodology will yield new insight that can be used to derive guidance for systems architecting and commonality in a wide variety of complex system portfolios. In order to make this guidance usable to future system architects, it should be captured in the form of systems architecting principles which can be added to the set that was synthesized in this thesis.

- The **development of higher-fidelity cost models** that capture aspects of portfolio and lifecycle cost that traditional dry-mass-based cost estimating relationships do not capture. Examples for cost factors which are not included would be administrative overhead for development projects and operations cost. In addition, it would be desirable to consider the distinction between fixed recurring cost for having the capability to produce or operate a system and the marginal recurring cost for actually producing or operating a unit of the system. Fixed recurring costs tend to accumulate linearly with time, whereas marginal recurring costs accumulative linearly with the number of units produced or operated. Commonality can have a significant beneficial effect on portfolio life-cycle cost through removal of fixed recurring cost lines; current cost models do not allow for explicit analysis of this effect.

- The **development of quantitative proximate metrics capturing the benefits and penalties of commonality types other than design commonality**, such as functional, operational, architectural, and technology commonality (see Chapter 2). Currently, qualitative discussion of benefits and penalties of these are the only basis to judge the merits of these commonality types; clearly, a more rigorous approach is necessary in order to obtain a better understanding of the relevance and impact of these commonality types. This should also include a further exploration of the significance of the second type of commonality hierarchy identified in Principle 7 between the commonality types of system reuse, varying functionality, and implementation commonality.

- **Integration of the custom architecture and commonality analysis codes into a single software application**. The current implementation of the methodology features individual Java codes for the architecture analysis for each system in the portfolio as well as for the commonality analysis for each function; this leads to a significant need for manual data management which proved to be among the most time-consuming tasks when applying the methodology to a case study. An integrated software providing both the architecture and commonality analysis capabilities could largely eliminate any manual data management needs, allowing the system architect to concentrate on the tasks which ***require*** manual input and manipulation (such as the definition of portfolio scope and metrics as well as the input of problem-specific knowledge). This integrated software tool could be implemented as a stand-alone application or as an add-on to wide-spread computing tools such as Excel.

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Appendices

This section includes appendices which provide supplementary information that was not presented in the main body of the thesis. There are four appendices:

- Appendix I provides descriptions of additional historical aerospace systems portfolios not included in the discussion in Chapter 1.
- Appendix II provides results for the architecture analysis of life support systems for exploration missions not shown in Chapter 3.
- Appendix III provides results for the architecture analysis of the Saturn I and Saturn IB launch vehicle use cases not shown in Chapter 4.
- Appendix IV provides results for the architecture analysis of planetary surface mobility systems for human exploration missions not shown in Chapter 5.
- Appendix V provides a description of the contents of the data CD attached to this thesis.

Appendix I: Historical Aerospace Systems Portfolio Examples

Appendix I provides descriptions of additional historical aerospace systems portfolio examples based on the portfolio concept developed in Chapter 1.

The International Space Station

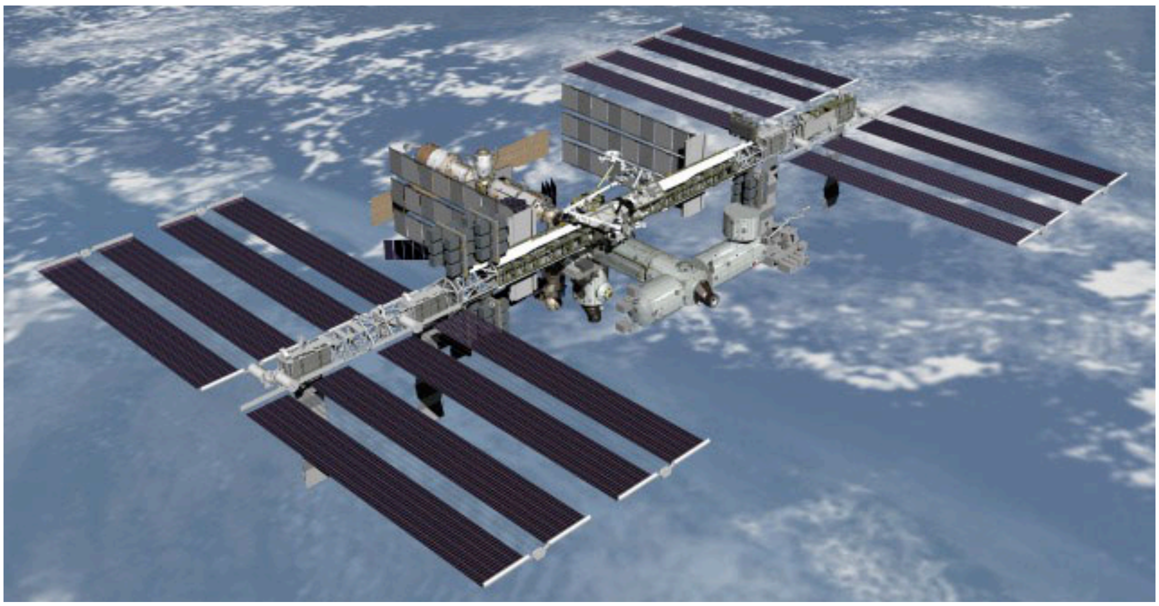

Figure 65: Overview of the elements of the ISS in its assembly complete configuration

The International Space Station (ISS) is a complex assembly of a variety of modules, both pressurized and unpressurized, provided by different nations, including Russia, the US, Europe, and Japan (see Figure 65) [ME-99]. Each of these modules is a complex system in itself, consisting of many interrelated subsystems which together perform a higher-level function that the individual subsystems could not provide [NASA-98]. While different nations provide different parts of the ISS portfolio, they coordinate their actions both in terms of design and operations in a joint committee which can be regarded as the single controlling entity for the ISS portfolio. The ISS can therefore be viewed as a portfolio of space systems.

The ISS is a hybrid aerospace systems portfolio: while individual elements provide similar or identical externally delivered functionality (for example the laboratory modules), overall different externally delivered functionalities are present in the portfolio.

For the US orbital segment of the ISS, commonality was explicitly taken into account during the initial design phase [Quinn-08].

The Soviet Salyut Civilian Space Stations

Starting in 1971, the Soviet Union launched a string of civilian space stations and carried out stays of increasing duration aboard them using the Soyuz spacecraft to transport crew from the Earth to the station and back [Me-99] [Good-01]. These stations were: Salyut-1, Salyut-4, Salyut-6, and Salyut-7 (see Figure 66). Salyut-1 and Salyut-4 had only one docking port and were therefore not capable of being re-supplied [Ivan-08] [Har-96]; these stations had to be abandoned when their store of consumables was exhausted.

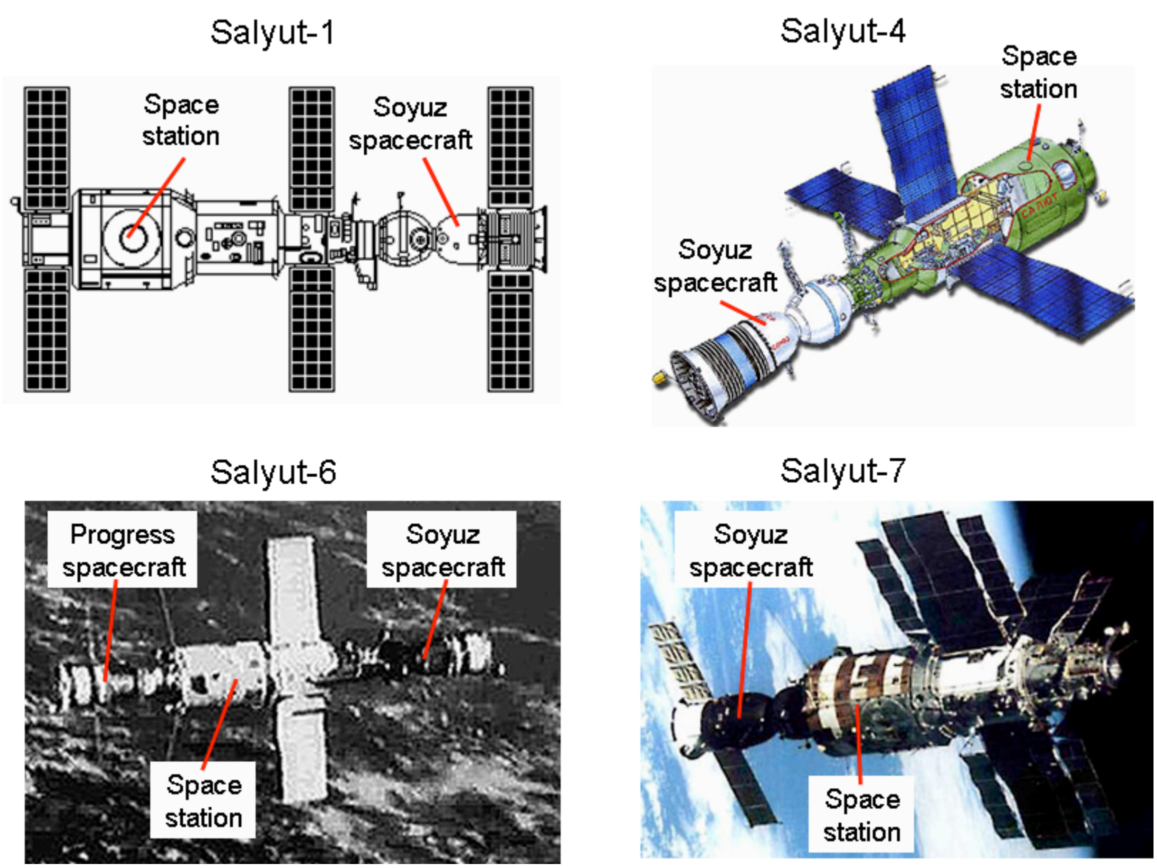

Figure 66: Overview of the Soviet Salyut civilian space stations

Salyut-6 and Salyut-7 were outfitted with two docking ports, thereby enabling re-supply of the space station with consumables using the Progress spacecraft as well as overlapping visits by two different crews [NSSDC-08] [Por-95]. Using these space stations, continuous presence in space was achieved for the first time.

Each of the Salyut space stations is a complex system with many interrelated functions working together to enable a higher-level function. The Salyut space stations were all developed by the same Soviet design bureau and were launched and operated by the same organization. The set of civilian Salyut space stations can therefore be considered an aerospace systems portfolio. The Salyut space stations all have similar externally delivered functionality (provision of long-duration crewed stays, Earth observation, etc.). It is interesting to note that the Salyut space stations represent the evolution of a design concept: each new station built upon an existing design but added new design features (such as the second docking port); commonality was therefore explicitly considered and utilized in the design and operations of the Salyut portfolio.

The Atlas V Launch Vehicle Family

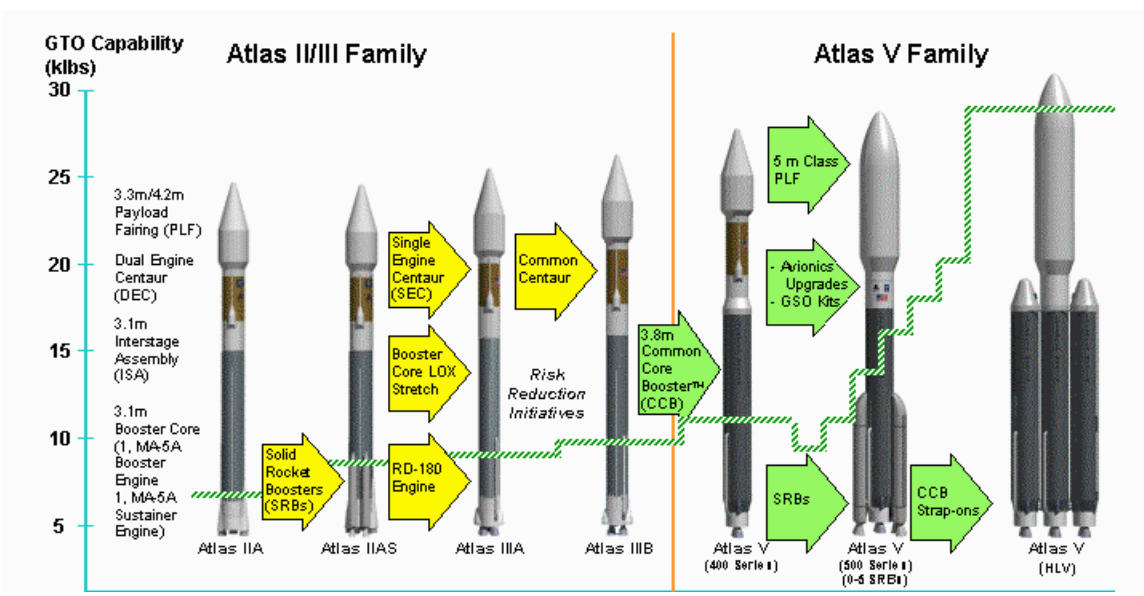

Figure 67: Overview of the Atlas V launch vehicle family

The Atlas V launch vehicle family is very similar to the Delta IV launch vehicle family: a common core booster stage and the Centaur upper stage are the fundamental common building blocks of the family [ILS-99]. These building blocks can be used alone, or in conjunction with solid strap-on rockets or with two additional booster cores attached for large LEO payload capability ("Atlas V heavy", see Figure 67). The common booster core and the Centaur upper stage are highly-integrated, complex technical systems. The Atlas V portfolio is controlled by the company United Launch Alliance (as is the Delta IV portfolio).

The Ares Launch Vehicle Family

The implementation of the Vision for Space Exploration announced in January 2004 requires the development of new space systems, including new crew and cargo launch vehicles. NASA defined the future launch vehicle architecture in their 2005 Exploration Systems Architecture Study (ESAS) [ESAS-05]. Two launch vehicles were initially introduced: a crew launch vehicle based on a single solid rocket booster and a LOX / LH2 upper stage (the so-called Ares I) and a cargo launch vehicle in the 100 mt LEO payload class based on 2 solid rocket boosters strapped to a multi-engine LOX/LH2 core stage and a LOX/LH2 upper stage (the so-called Ares V). In addition, a hybrid variant of these launch vehicles was introduced later, the Ares IV (see Figure 68): this vehicle would make use of the solid rocket boosters and core of the Ares V, but would use the Ares I upper stage. This way, missions beyond LEO such as lunar flyby and orbit, as well as NEO missions could be carried out prior to the development of the Ares V upper stage [Kor-07] [Lan-07].

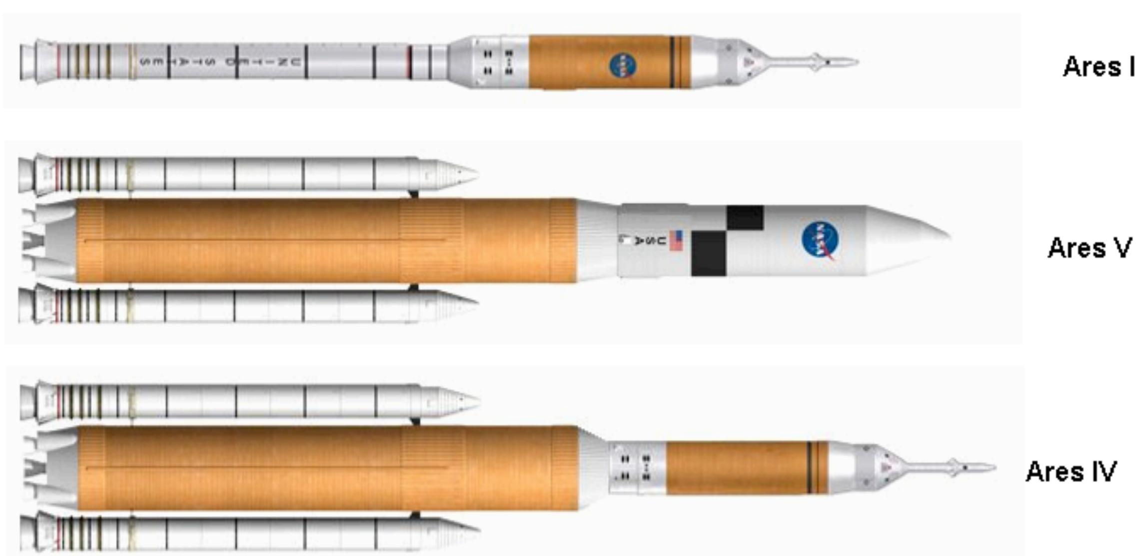

Figure 68: Overview of the Ares launch vehicle family

The Ares launch vehicle family is a set of complex technical systems which have identical externally delivered functionality (delivery of payloads to LEO). They are controlled by NASA: design and development is managed by the Exploration Systems Mission Directorate (ESMD), launch operations will be managed by the Space Operations Mission Directorate (SOMD). The Ares family therefore qualifies as an aerospace systems portfolio. Commonality within the portfolio, as well as with legacy elements such as the space shuttle and the Saturn V (for the J-2X engine) was explicitly considered during the architecting of the Ares family.

The Boeing 737 Commercial Aircraft Family

Figure 69: Overview of the Boeing 737 commercial aircraft family

The 737 commercial aircraft family is very similar to the Airbus 320 aircraft family: the original aircraft design has been extended by adding or removing barrel sections from the fuselage while retaining the original wing and cockpit designs (see Figure 69). This way, the payload – range characteristics were optimized for different use cases, resulting in more economical aircraft operations for the airlines while retaining common pilot certification for all aircraft in the family. Each aircraft clearly is a complex system; the different aircraft have identical externally delivered functionality. The design and production of all aircraft is controlled by Boeing [Boe-08].

The Joint Strike Fighter Aircraft Family

The Joint Strike Fighter Program is the result of merging a variety of projects in the US military concerned with developing a common fighter aircraft for the Air Force, Marine Corps, and Navy [USAF-09]. This goal resulted in the design of three different variants (see Figure 70), driven mainly by different take-off and landing requirements: the Air Force primarily utilizes regular runways and can therefore afford conventional horizontal take-off and landing. The Navy plans to utilize the aircraft on carriers and therefore requires very high-thrust for take-off on a catapult and carrier landing capability (hook). The Marine Corps will launch the aircraft from landing ships and therefore requires short take-off and vertical landing capability, much like the Harrier aircraft that are currently being used [Clan-96].

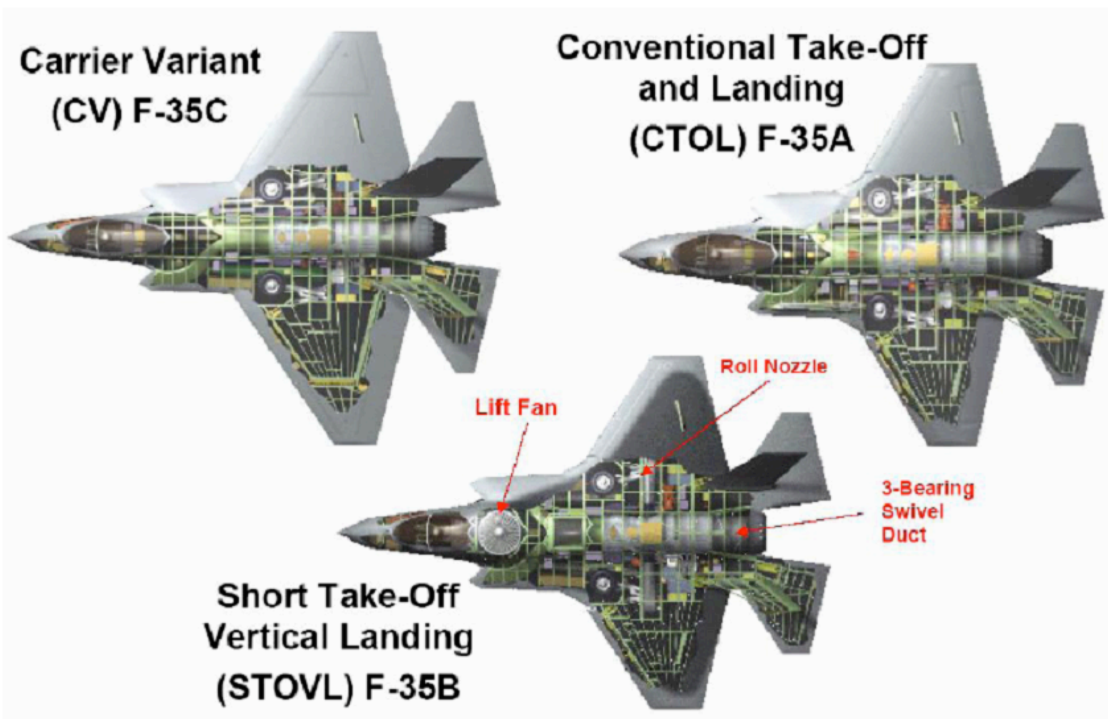

Figure 70: Overview of the Joint Strike Fighter (JSF) aircraft variants

While the three designs have diverged significantly from the concept originally envisioned, a significant degree of commonality still remains [Boas-08]. Given that all three variants are being developed by the same company, the Joint Strike Fighter Family can be considered an aerospace systems portfolio.

Appendix II: Supplementary Material for the Exploration Life Support System Case Study

Appendix II provides additional material on assumptions and results for the human exploration life support systems case study not shown in Chapter 3.

Table 20 provides an overview of mission requirements as well as important parameters used in the life support system architecture analysis. The parameters are largely related to overhead for power consumption, heat rejection, and pressurized volume required for equipment associated with life support, as well as for mass overheads associated with storage vessels for solid, or fluid consumables (sometimes also called "tare" overhead or "tare" factor).

Table 20: Summary of requirements and attributes of the 5 future life support portfolio use cases

System	LSAM	Lunar habitat	Neo mission habitat	Mars surface habitat	Mars transit habitat
Description of functionality	Crew transport to and from lunar surface	Support of long-duration missions on lunar surface	Support of crew during a visit to a NEO	Support of long-duration stays on the surface of Mars	Support of the crew in transit to and from Mars
# of crew [-]	4	4	4	6	6
Duration [d]	2	842	180	600	360
# of units built (flown)	14 (13)	2 (1)	5 (4)	6 (5)	6 (5)
Power overhead [W/kg]	4	10	25	12	9
Heat rejection overhead [W/kg]	20	20	20	20	20
Volume overhead [kg/m^3]	45	45	45	45	45
Pressurized tare multiplier [-]	1.8	1.8	1.8	1.8	1.8
Water storage tare factor [-]	1.1	1.1	1.1	1.1	1.1
High-pressure gas storage tare [-]	1.9	1.9	1.9	1.9	1.9
Cryogenic oxygen tare [-]	2.25	2.25	2.25	2.25	2.25
Cryogenic hydrogen tare [-]	4.27	4.27	4.27	4.27	4.27
Transportation cost [$ Mn / kg]	0.11557	0.11557	0.14830	0.13477	0.30230

Table 21 shows the derivation of the transportation cost factors used in the life support systems analysis (Chapter 3) and the surface mobility analysis (Chapter 5). Each transportation cost factor is derived based on a specific operations concept for the mission; these concepts as well as associated references are also provided in the table. The transportation cost factors are intended as first-order model for estimating the relative impact of transportation cost; for a more detailed assessment of transportation cost the quantized nature of transportation capability would have to be taken into account.

Table 21: Derivation of transportation cost factors

Destination	Lunar surface	Mars surface	NEO-Earth trajectory	Mars-Earth trajectory
Payload mass	14600	40000	10568	17263
TEI stage dry mass [kg]	-	-	3757	9456
TEI stage unit cost [FY04 $ Mn]	-	-	70	111
# of TEI stages [-]	-	-	1	1
Lander dry mass [kg]	10000	10000	-	-
Lander unit cost [FY04 $ Mn]	283	283	-	-
# of lander units [-]	1	1	-	-
Aeroshell dry mass [kg]	-	35000	-	35000
Aeroshell unit cost [FY04 $ Mn]	-	649	-	649
# of aeroshell units [-]	-	1	-	1
Deep space propulsion stage dry mass [kg]	-	-	6648	-
Deep space propulsion stage unit cost [FY04 $ Mn]	-	-	93	-
# of deep space propulsion stages [-]	-	-	1	-
TMI stage dry mass [kg]	-	11500	-	11500
TMI stage unit cost [FY04 $ Mn]	-	123	-	123
# of TMI stages [-]	-	2	-	2
Ares V unit cost [FY04 $ Mn]	1404	1404	1404	1404
# of Ares V launchers [-]	1	3	1	3
Total unit cost [FY04 $ Mn]	1687	5391	1567	5219
Payload-normalized cost [FY04 $ Mn / kg]	0.11557	0.13477	0.14830	0.30230
Description of transportation concept	Use of a single Ares V and a lander stage to deliver 14600 kg of payload to the lunar surface.	Use of 3 Ares V launches to place 2 TMI stages and one aeroshell with lander into LEO; TMI stages and aeroshell are connected for injection towards Mars.	A single Ares V is used to inject a stack comprised of a habitat, CEV CM, and two propulsion stages towards a NEO; the two propulsion stages are used for capture at the NEO and for injection towards Earth at the end of the mission. For increased mass margin, an approach with 2 Ares Vs and 4 propulsion stages could be used.	Same as for Mars surface except the aeroshell contains a propulsion stage for trans-Earth injection instead of a Mars surface lander
References	[ESAS-05], [NASA-08]	[HGMC-08]	Calculations by the author	[HGMC-08], [WHC-05]

Table 22 provides a list of scaling values for all the life support technology choices included in the life support analysis. For each technology choice, the equipment mass, power, heat rejection, and pressurized volume required are provided, as are yearly spare parts and daily consumables masses with associated tare factors (all for a single crew member). It is important to note that for the water provision function technology choices, the maximum scaling values are provided for completeness; as water demand drops due to recycling the consumables values decline, as do the equipment, power, and heat values in the case of ISRU on the Moon or Mars (Ilmenite reduction or Zirconia electrolysis). See source code on the attached thesis CD for additional information.

Table 22: Scaling information for life support system technology choices

Technology choice	Equipment [kg/p]	Power [W/p]	Heat rejection [W/p]	Pressurized volume [m3/p]	Spare parts [kg/p/a]	Spare parts tare factor [-]	Consumables [kg/p/d]	Consumables tare factor [-]	Comments	References
Food provision function										
Fully hydrated food	0	0	0	0	0	-	2.3	1.8	MRE-style meals	[LP-00]
De-hydrated food	15 kg / crew	0	0	0.0135 m3 / crew	0	-	0.83	1.8	Sink required	[LP-00], [Wyd-88]
Carbon dioxide removal function										
LiOH canisters	0	0	0	0	0	-	1.75	1.8	Reaction produces water which can be recycled	[LP-00]
4-bed molecular sieve	30	300	300	0.15	3	1.8	0	-	Complete condensate recovery for recycling	[LP-00]
Pressure-swing solid amine beds	23.5 / crew	0.7	0.7	0.5 m3 / crew	2.35	1.8	0	-	Only partial (~50%) recovery of condensate possible	[Nal-07]
Oxygen provision function										
Stored oxygen, high-pressure	0	0	0	0	0	-	0.84	1.9	Similar to oxygen storage on space suits	[LP-00]
Stored oxygen, cryogenic storage	0	100	100	0	0	-	0.84	2.25	Derived from space shuttle on-board cryogenic oxygen tanks	[KSC-88]
Water electrolysis	35	350	100	0.03	3.5	1.8	0.945	1.1	Direct connection to water recycling technology choices	[LP-00]
Water electrolysis + Sabatier reactor	75.1	387	277	0.15	7.51	1.8	0.52	1.1	Direct connection to water recycling technology choices	[LP-00]
Electrolysis + Sabatier + CH4 pyrolysis	137.2	564	454	0.25	14	1.8	0.1	1.1	Direct connection to water recycling technology choices	[LP-00]
Ilmenite reduction (lunar surface)	31	625	625	0	3.1	1.8	0.01	4.27	-	Based on [San-05]
Zirconia electrolysis of carbon dioxide (on Mars)	33.6	1000	1000	0.5	3.36	1.8	0	-	-	[DRM-97]
Trace contaminant control function										
Completely expendable filters	0	0	0	0	0	-	0.1	1.8	-	Estimate by author
Partially regenerative system	20	50	50	0.15	2	1.8	0.05	1.8	Some expendable filters still required	[LP-00], estimate
Clothing provision function										
Expendable clothing	0	0	0	0	0	-	2	1.8	Conservative estimate	[LP-00], estimate
Washing machine + expendable clothing	160 / crew	100	100	2 / crew	16	1.8	0.55	1.8	Reduces expendable clothing demand	[LP-00], estimate
Humidity removal function										
Condensing Heat Exchanger (CHX)	10	100	100	0.2	1	1.8	0	-	-	[KSC-88], estimate
Silica gel, expendable	0	0	0	0	0	-	4.4	1.8	-	Estimate by author
Pressure-swing solid amine beds	23.5 / crew	0.7	0.7	0.5 m3 / crew	2.35	1.8	0	-	Synergy possible with carbon dioxide removal function	[Nal-07]
Water provision function										
Stored water	0	0	0	0	0	-	14.42	1.1	Exact amount of comsumables is dependent on the technology choices for food, oxygen, and clothing provision as well as carbon dioxide removal functions	[LP-00]
Multifiltration	10	40	40	0.04	1	1.8	Reduced	1.1	Exact amount of comsumables is dependent on the technology choices for food, oxygen, and clothing provision as well as carbon dioxide removal functions	[LP-00]
Multifiltration and vapor compression distillation	35	70	70	0.14	3.5	1.8	Reduced	1.1	Exact amount of comsumables is dependent on the technology choices for food, oxygen, and clothing provision as well as carbon dioxide removal functions	[LP-00]
Ilmenite reduction and fuel cell (lunar surface)	468	9510	9510	0	46.8	1.8	1.6	4.27	Maximum values shown, actual values depende on the technology choices for food, oxygen, and clothing provision as well as carbon dioxide removal functions	Based on [San-05]
Zirconia electrolysis and fuel cell (Mars surface)	512	15253	15253	6.4	51.2	1.8	1.6	4.27	Maximum values shown, actual values depende on the technology choices for food, oxygen, and clothing provision as well as carbon dioxide removal functions	[DRM-97]

Table 23: Morphological Matrix for the lunar lander life support system

Function	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4	Technology choice 5	Technology choice 6
Food provision	Fully hydrated food	De-hydrated food				
CO2 removal	LiOH	4BMS	Solid amine, pressure-swing			
Oxygen provision	Stored, high-pressure	Stored, cryogenic	Water electrolysis	Electrolysis + Sabatier reactor	Electrolysis + Sabatier + methane pyrolysis	
TCC	Expendable	Partially regenerative				
Clothing	Expendable	Washing machine + dryer				
Humidity removal	CHX + separator	Silica gel, expendable	Solid amine, pressure-swing			
Water management	Stored	Multifiltration	Multifiltration + VCD			

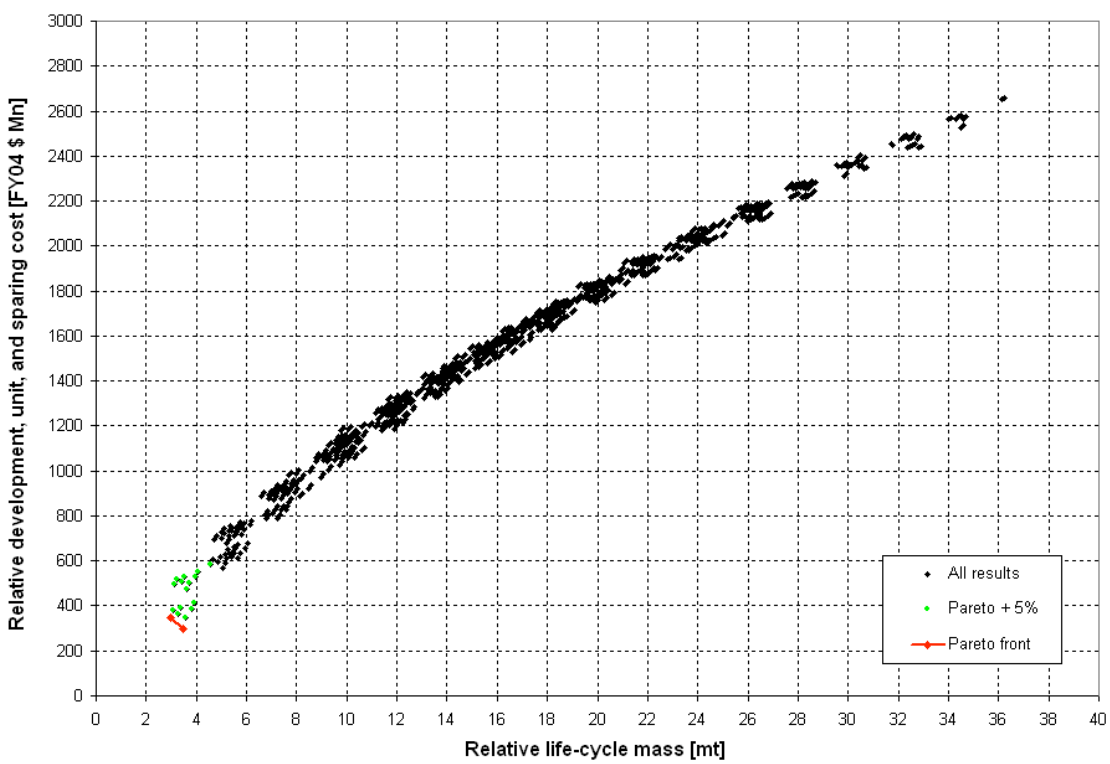

Figure 71: Results of lunar lander architecture evaluation; relative life-cycle DDT&E, unit and spares cost plotted over relative life-cycle mass

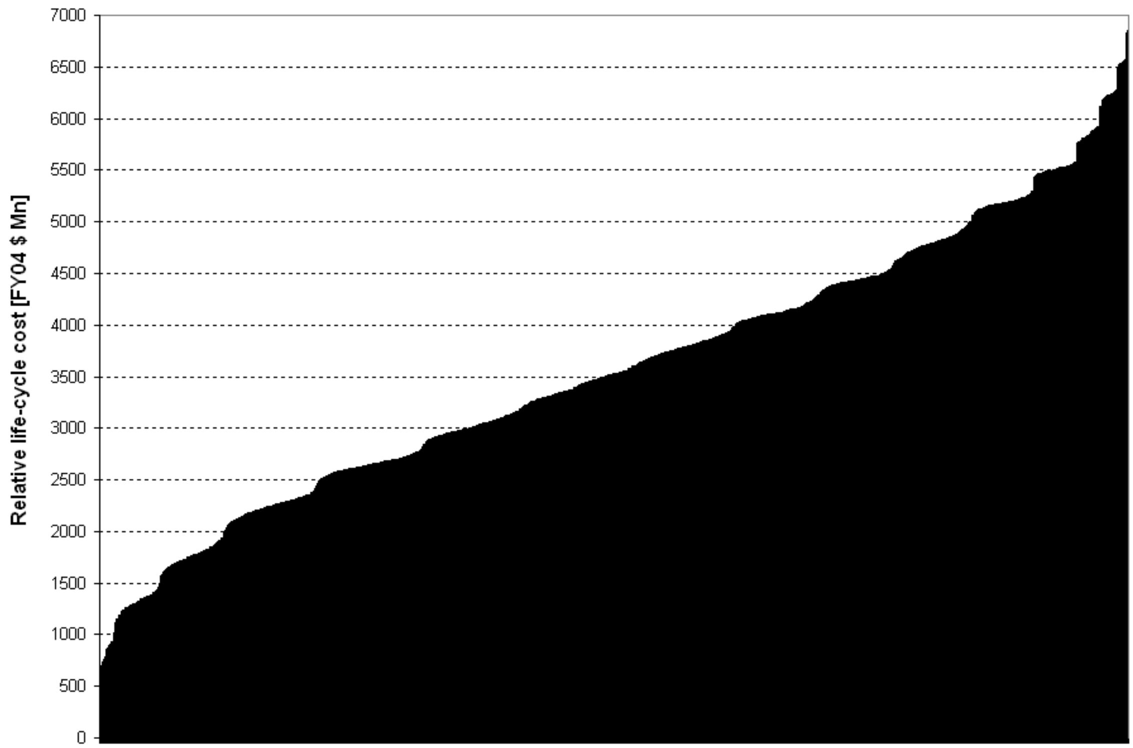

Figure 72: Lunar lander life support system architecture alternatives: life-cycle cost ranking

Table 24: Morphological Matrix for the NEO mission habitat life support system

Function	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4	Technology choice 5	Technology choice 6
Food provision	Fully hydrated food	De-hydrated food				
CO2 removal	LiOH	4BMS	Solid amine, pressure-swing			
Oxygen provision	Stored, high-pressure	Stored, cryogenic	Water electrolysis	Electrolysis + Sabatier reactor	Electrolysis + Sabatier + methane pyrolysis	Ilmenite reduction (ISCP)
TCC	Expendable	Partially regenerative				
Clothing	Expendable	Washing machine + dryer				
Humidity removal	CHX + separator	Silica gel, expendable	Solid amine, pressure-swing			
Water management	Stored	Multifiltration	Multifiltration + VCD	Ilmenite reduction (ISCP)		

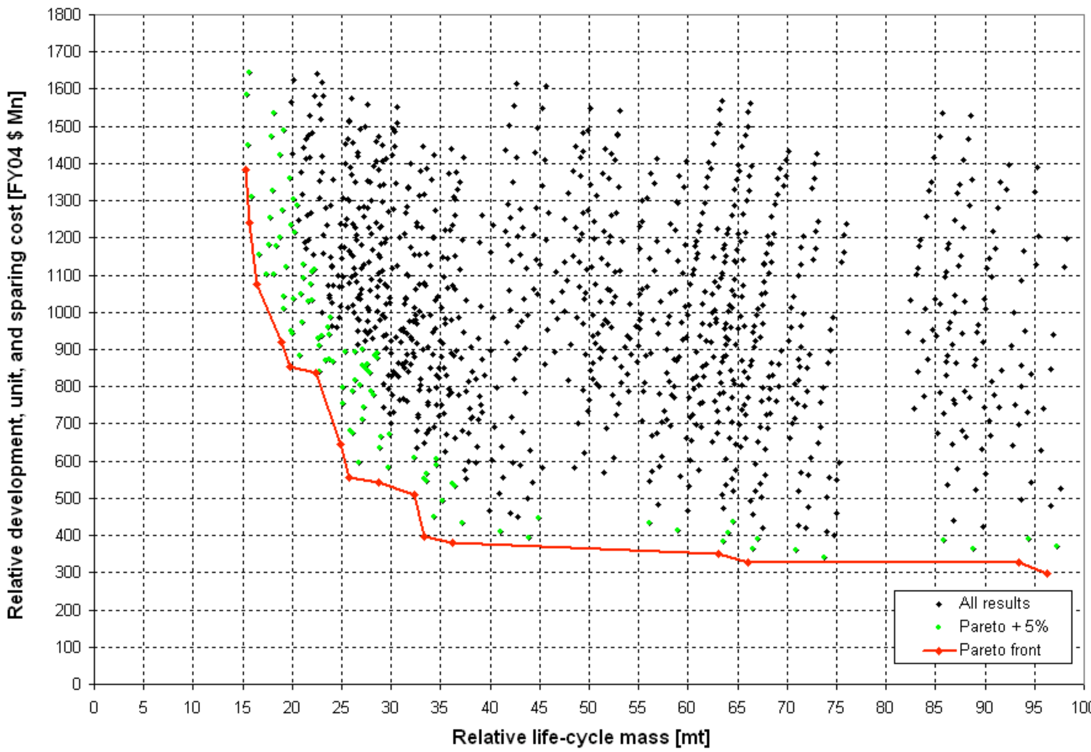

Figure 73: Results of NEO mission habitat architecture evaluation; relative life-cycle DDT&E, unit and spares cost plotted over relative life-cycle mass

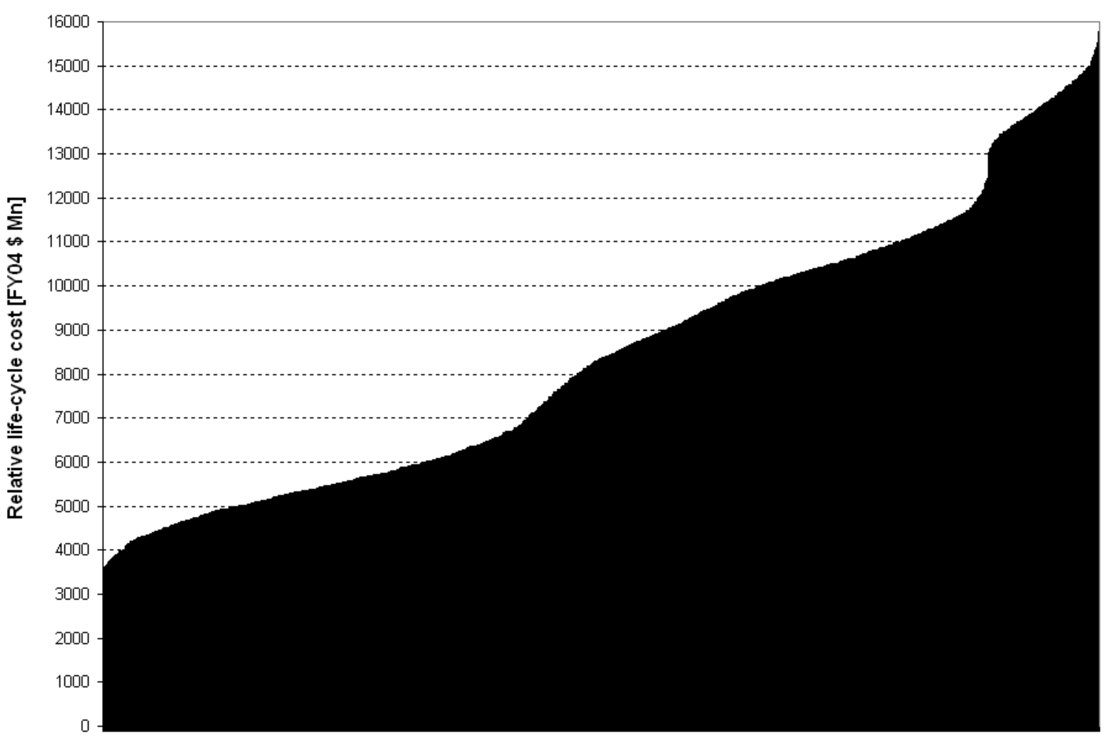

Figure 74: NEO mission habitat life support system architecture alternatives: life-cycle cost ranking

Table 25: Morphological Matrix for the Mars surface habitat life support system

Function	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4	Technology choice 5	Technology choice 6
Food provision	Fully hydrated food	De-hydrated food				
CO2 removal	LiOH	4BMS				
Oxygen provision	Stored, high-pressure	Stored, cryogenic	Water electrolysis	Electrolysis + Sabatier reactor	Electrolysis + Sabatier + methane pyrolysis	Zirconia electrolysis
TCC	Expendable	Partially regenerative				
Clothing	Expendable	Washing machine + dryer				
Humidity removal	CHX + separator	Silica gel, expendable				
Water management	Stored	Multifiltration	Multifiltration + VCD	Zirconia electrolysis + fuel cell		

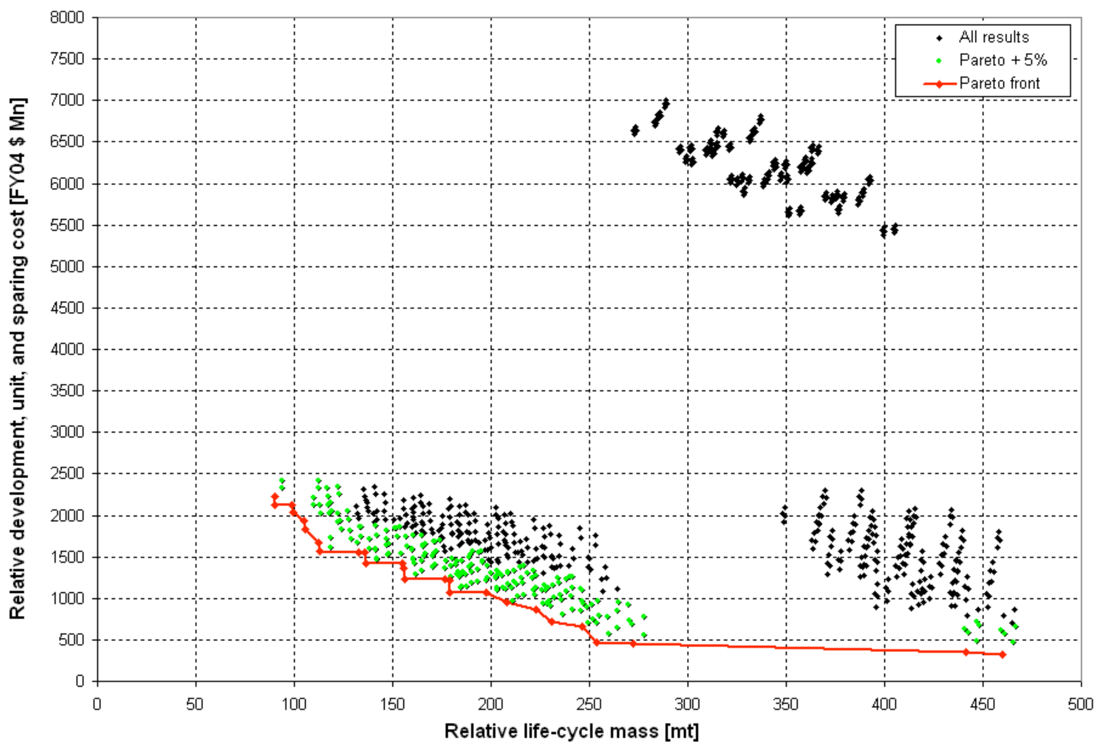

Figure 75: Results of Mars surface habitat architecture evaluation; relative life-cycle DDT&E, unit and spares cost plotted over relative life-cycle mass

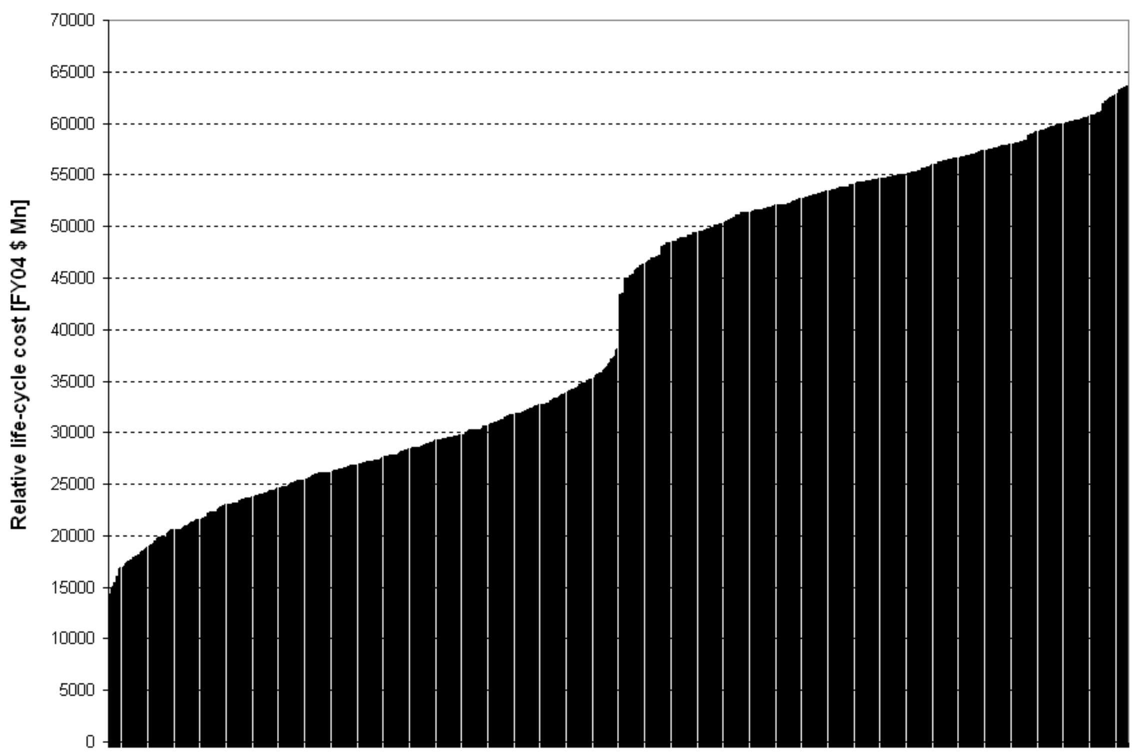

Figure 76: Mars surface habitat life support system architecture alternatives: life-cycle cost ranking

Table 26: Morphological Matrix for the Mars transit habitat life support system

Function	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4	Technology choice 5	Technology choice 6
Food provision	Fully hydrated food	De-hydrated food				
CO2 removal	LiOH	4BMS	Solid amine, pressure-swing			
Oxygen provision	Stored, high-pressure	Stored, cryogenic	Water electrolysis	Electrolysis + Sabatier reactor	Electrolysis + Sabatier + methane pyrolysis	
TCC	Expendable	Partially regenerative				
Clothing	Expendable	Washing machine + dryer				
Humidity removal	CHX + separator	Silica gel, expendable	Solid amine, pressure-swing			
Water management	Stored	Multifiltration	Multifiltration + VCD			

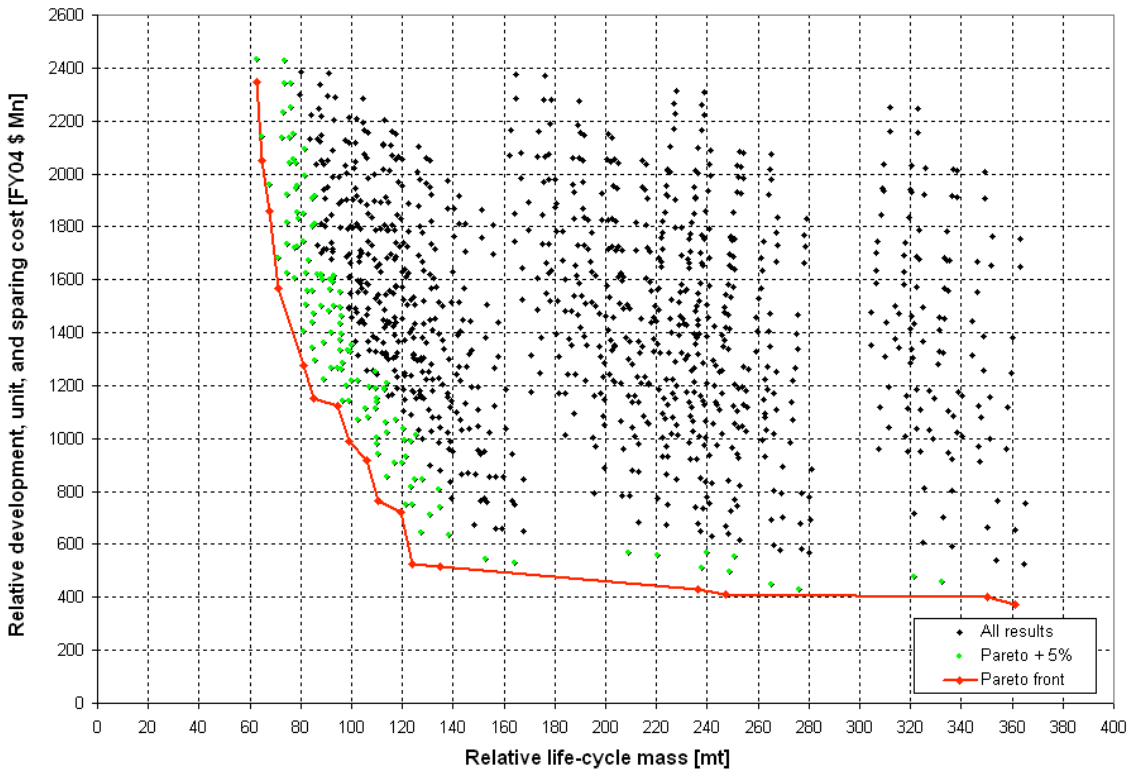

Figure 77: Results of Mars transit habitat architecture evaluation; relative life-cycle DDT&E, unit and spares cost plotted over relative life-cycle mass

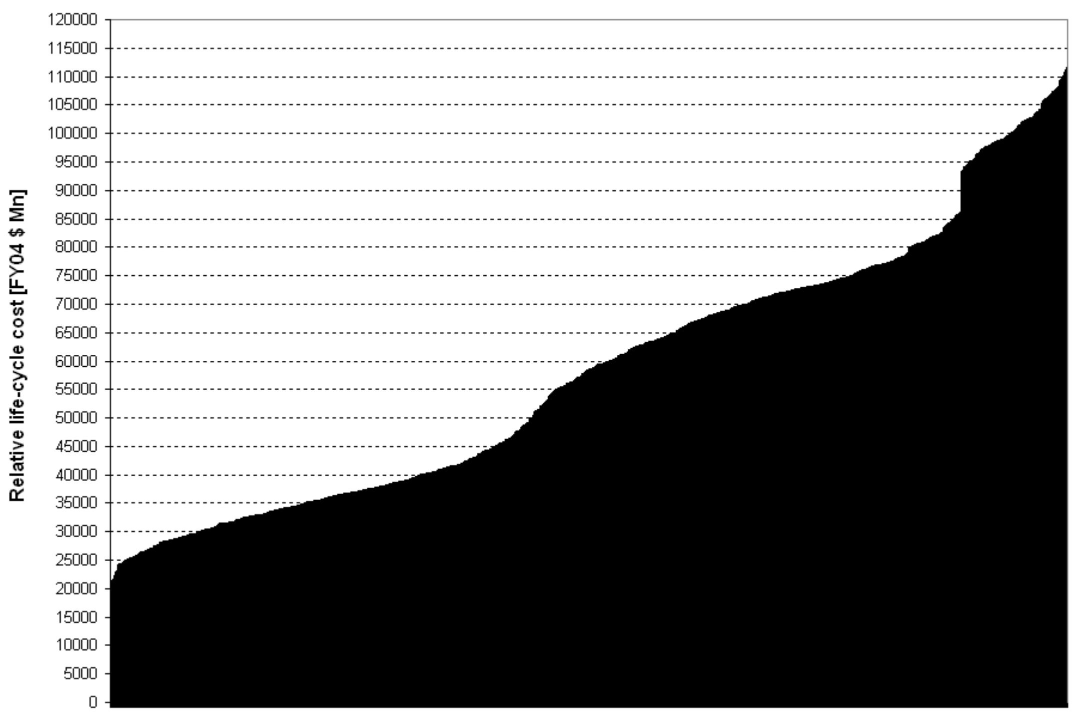

Figure 78: Mars transit habitat life support system architecture alternatives: life-cycle cost ranking

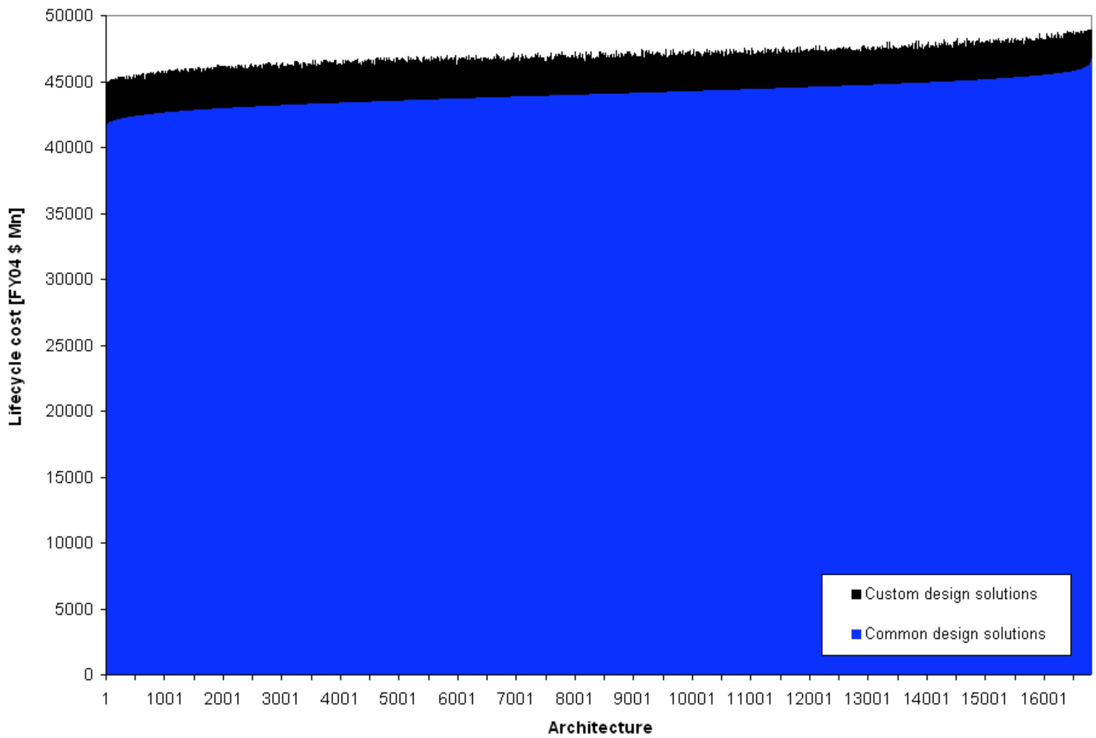

Figure 79: Life-cycle cost reduction through commonality, δ = 90%

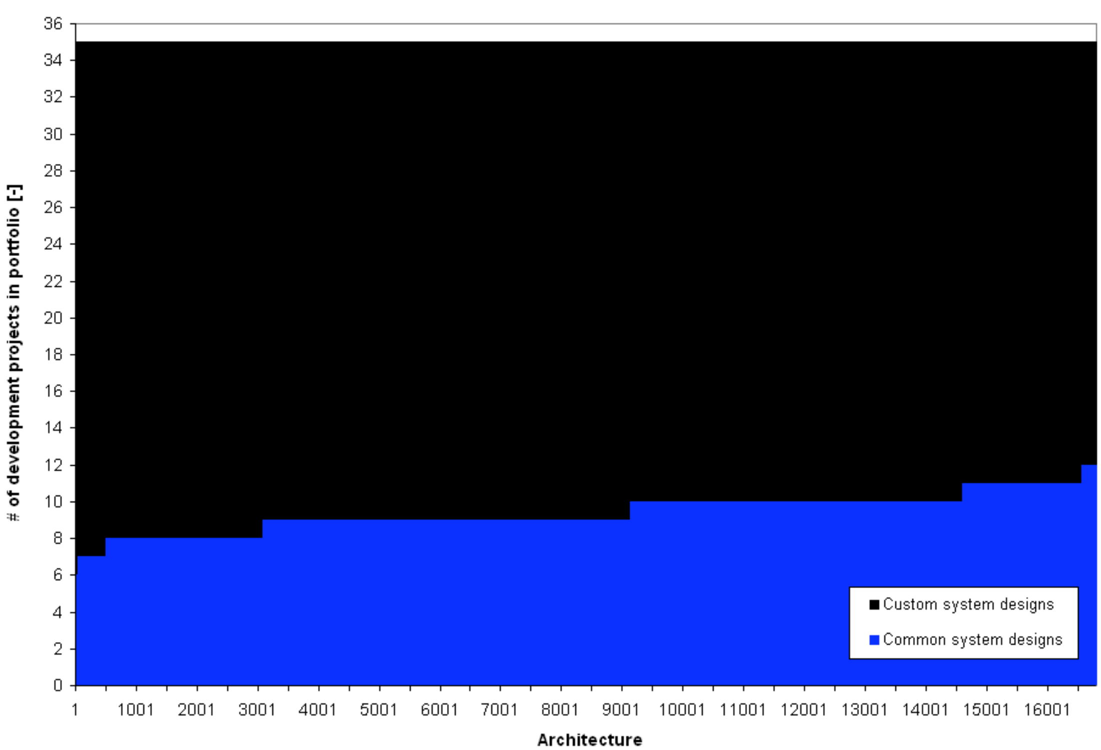

Figure 80: Reduction in development projects through commonality, δ = 90%

Table 27: Food provision technology choices for the 20 lowest-life-cycle portfolio design solutions with commonality

Portfolio	CEV	ISS	Lunar lander	Lunar surface habitat	NEO mission habitat	Mars surface habitat	Mars transit habitat
1	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
2	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
3	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
4	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
5	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
6	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
7	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
8	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
9	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
10	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
11	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
12	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
13	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
14	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
15	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
16	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
17	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
18	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
19	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated
20	Fully hydrated	Fully hydrated	Fully hydrated	De-hydrated	De-hydrated	De-hydrated	De-hydrated

Table 28: Oxygen provision technology choices for the 20 lowest-life-cycle portfolio design solutions with commonality

Portfolio	CEV	ISS	Lunar lander	Lunar surface habitat	NEO mission habitat	Mars surface habitat	Mars transit habitat
1	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Stored, hp	Zirconia electr.	Sabatier
2	Stored, hp	Sabatier	Stored, hp	Sabatier	Stored, hp	Zirconia electr.	Sabatier
3	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Stored, hp	Zirconia electr.	Sabatier
4	Stored, hp	Sabatier	Stored, hp	Sabatier	Stored, hp	Zirconia electr.	Sabatier
5	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Stored, hp	Zirconia electr.	Sabatier
6	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Stored, hp	Zirconia electr.	Sabatier
7	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Stored, hp	Zirconia electr.	Sabatier
8	Stored, hp	Sabatier	Stored, hp	Sabatier	Stored, hp	Zirconia electr.	Sabatier
9	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Stored, hp	Zirconia electr.	Sabatier
10	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Sabatier	Zirconia electr.	Sabatier
11	Stored, hp	Sabatier	Stored, hp	Sabatier	Stored, hp	Zirconia electr.	Sabatier
12	Stored, hp	Sabatier	Stored, hp	Sabatier	Stored, hp	Zirconia electr.	Sabatier
13	Stored, hp	Sabatier	Stored, hp	Sabatier	Sabatier	Zirconia electr.	Sabatier
14	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Sabatier	Zirconia electr.	Sabatier
15	Stored, hp	Sabatier	Stored, hp	Sabatier	Stored, hp	Zirconia electr.	Sabatier
16	Stored, hp	Sabatier	Stored, hp	Sabatier	Sabatier	Zirconia electr.	Sabatier
17	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Stored, hp	Zirconia electr.	Sabatier
18	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Stored, hp	Zirconia electr.	Sabatier
19	Stored, hp	Sabatier	Stored, hp	Sabatier	Stored, hp	Zirconia electr.	Sabatier
20	Stored, hp	Sabatier	Stored, hp	Ilmenite red.	Sabatier	Zirconia electr.	Sabatier

Table 29: Trace contaminant control technology choices for the 20 lowest-life-cycle portfolio design solutions with commonality

Portfolio	CEV	ISS	Lunar lander	Lunar surface habitat	NEO mission habitat	Mars surface habitat	Mars transit habitat
1	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
2	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
3	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
4	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
5	Expendable	Expendable	Expendable	Regenerative	Expendable	Expendable	Expendable
6	Expendable	Expendable	Expendable	Regenerative	Expendable	Expendable	Expendable
7	Expendable	Expendable	Expendable	Expendable	Expendable	Regenerative	Expendable
8	Expendable	Expendable	Expendable	Expendable	Expendable	Regenerative	Expendable
9	Expendable	Expendable	Expendable	Expendable	Expendable	Regenerative	Expendable
10	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
11	Expendable	Expendable	Expendable	Regenerative	Expendable	Expendable	Expendable
12	Expendable	Expendable	Expendable	Expendable	Expendable	Regenerative	Expendable
13	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
14	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
15	Expendable	Expendable	Expendable	Regenerative	Expendable	Expendable	Expendable
16	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable	Expendable
17	Expendable	Expendable	Expendable	Regenerative	Regenerative	Expendable	Expendable
18	Expendable	Expendable	Expendable	Regenerative	Regenerative	Expendable	Expendable
19	Expendable	Expendable	Expendable	Regenerative	Regenerative	Expendable	Expendable
20	Expendable	Expendable	Expendable	Regenerative	Expendable	Expendable	Expendable

Table 30: Clothing provision technology choices for the 20 lowest-life-cycle portfolio design solutions with commonality

Portfolio	CEV	ISS	Lunar lander	Lunar surface habitat	NEO mission habitat	Mars surface habitat	Mars transit habitat
1	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
2	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
3	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
4	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
5	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
6	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
7	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
8	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
9	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
10	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
11	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
12	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
13	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
14	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
15	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
16	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
17	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
18	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
19	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing
20	Expendable	Expendable	Expendable	Washing	Washing	Washing	Washing

Table 31: Humidity removal technology choices for the 20 lowest-life-cycle portfolio design solutions with commonality

Portfolio	CEV	ISS	Lunar lander	Lunar surface habitat	NEO mission habitat	Mars surface habitat	Mars transit habitat
1	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
2	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
3	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
4	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
5	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
6	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
7	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
8	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
9	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
10	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
11	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
12	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
13	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
14	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
15	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
16	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
17	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
18	Solid amine	CHX	Silica gel	CHX	CHX	CHX	CHX
19	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX
20	Solid amine	CHX	Solid amine	CHX	CHX	CHX	CHX

Table 32: Water management technology choices for the 20 lowest-life-cycle portfolio design solutions with commonality

Portfolio	CEV	ISS	Lunar lander	Lunar surface habitat	NEO mission habitat	Mars surface habitat	Mars transit habitat
1	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
2	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
3	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
4	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
5	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
6	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
7	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
8	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
9	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
10	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
11	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
12	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
13	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
14	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
15	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
16	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
17	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
18	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
19	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD
20	Stored	MF + VCD	Stored	MF + VCD	MF + VCD	MF + VCD	MF + VCD

Appendix III: Supplementary Material for the Saturn Launch Vehicle Family Case Study

Appendix III provides additional material on assumptions and results for the Saturn launch vehicle family case study not shown in Chapter 4.

Table 33: Design parameters for the modeling of engines and propulsion stage fuselages

Function: thrust generation					
Propellant combination	Isp altitude [s]	Isp sea level [s]	OTF [-]	Density oxidizer [kg/m3]	Density fuel [kg/m3]
LOX / LH2	421	N/A	5.5	1141	70.8
LOX / RP1	310	265	2.27	1141	817
N2O4 / UDMH	308	259	1.6	1434	870
Function: propellant storage					
Fuselge design	Constant beta [kg/m3]		Reference volume [m3]		
Common bulkhead design	39.409		310		
2-tank design	65.522		2110		
Multi-tank design	103.234		359		
Thrust parameters					
Parameter	Stage 1	Stage 2		Stage 3	
T/W [-]	1.17	1.17		1.17	
Constant alpha [-]	1	0.8		0.6	

Table 34: Morphological Matrix of technology choices for the Saturn IB use case

Function	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4
# of propulsion stages	3	2		
Thrust generation stage 3 – propellant type	LOX/LH2 (Isp = 421 s)	LOX/Kerosene (Isp = 310)	N2O4/UDMH (Isp = 308)	N/A
Thrust generation stage 3 – # of engines	1	2	5	N/A
Propellant storage stage 3	Common bulkhead tanks	2-tank structure	N/A	
Thrust generation stage 2 – propellant type	LOX/LH2 (Isp = 421 s)	LOX/Kerosene (Isp = 310)	N2O4/UDMH (Isp = 308)	
Thrust generation stage 2 – # of engines	1	2	5	
Propellant storage stage 2	Common bulkhead tanks	2-tank structure		
Thrust generation stage 1 – propellant type	LOX/Kerosene (Isp = 265)	N2O4/UDMH (Isp = 259)		
Thrust generation stage 1 – # of engines	2	5	8	
Propellant storage stage 1	2-tank structure	Multi-tank structure		

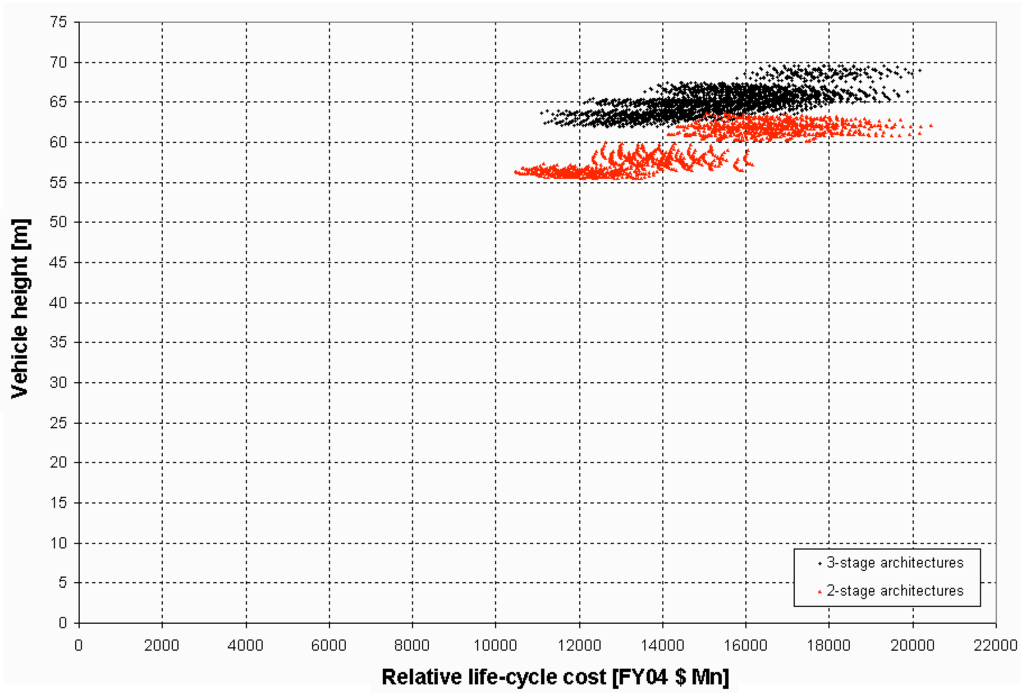

Figure 81: Point design architecture analysis results for the Saturn IB use case: vehicle height vs. relative life-cycle cost

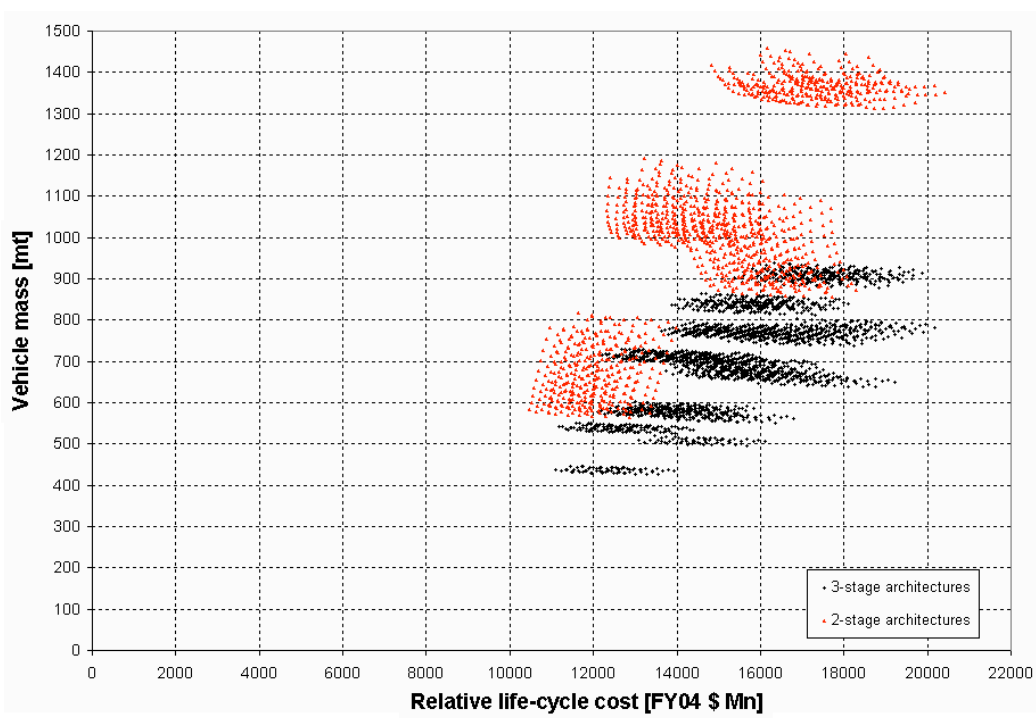

Figure 82: Point design architecture analysis results for the Saturn IB use case: vehicle wet mass vs. relative life-cycle cost

Table 35: Morphological Matrix of technology choices for the Saturn I use case

Function	Technology choice 1	Technology choice 2	Technology choice 3	Technology choice 4
# of propulsion stages	3	2		
Thrust generation stage 3 – propellant type	LOX/LH2 (Isp = 421 s)	LOX/Kerosene (Isp = 310)	N2O4/UDMH (Isp = 308)	N/A
Thrust generation stage 3 – # of engines	1	2	6	N/A
Propellant storage stage 3	Common bulkhead tanks	2-tank structure	N/A	
Thrust generation stage 2 – propellant type	LOX/LH2 (Isp = 421 s)	LOX/Kerosene (Isp = 310)	N2O4/UDMH (Isp = 308)	
Thrust generation stage 2 – # of engines	1	2	5 / 6	
Propellant storage stage 2	Common bulkhead tanks	2-tank structure		
Thrust generation stage 1 – propellant type	LOX/Kerosene (Isp = 265)	N2O4/UDMH (Isp = 259)		
Thrust generation stage 1 – # of engines	2	5	8	
Propellant storage stage 1	2-tank structure	Multi-tank structure		

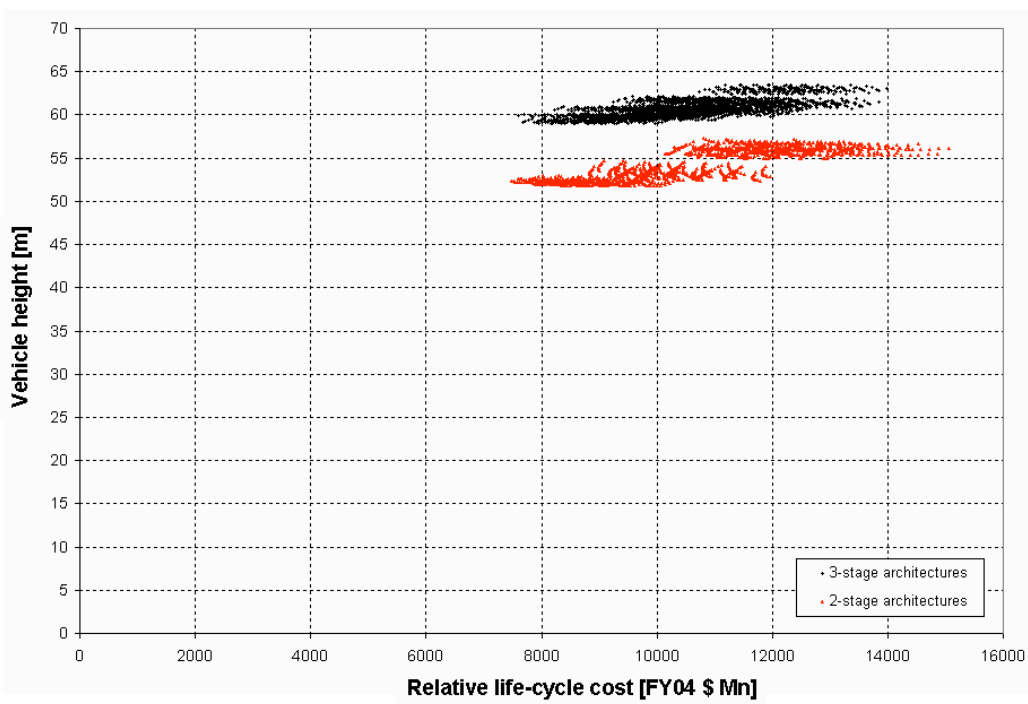

Figure 83: Point design architecture analysis results for the Saturn I use case: vehicle height vs. relative life-cycle cost

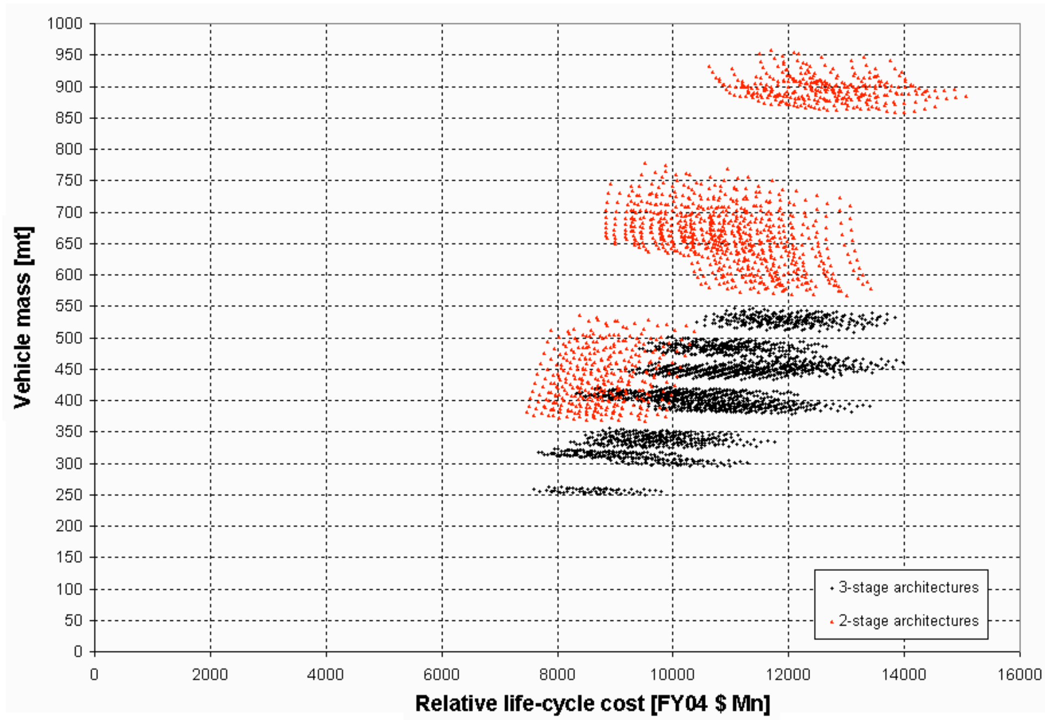

Figure 84: Point design architecture analysis results for the Saturn I use case: vehicle wet mass vs. relative life-cycle cost

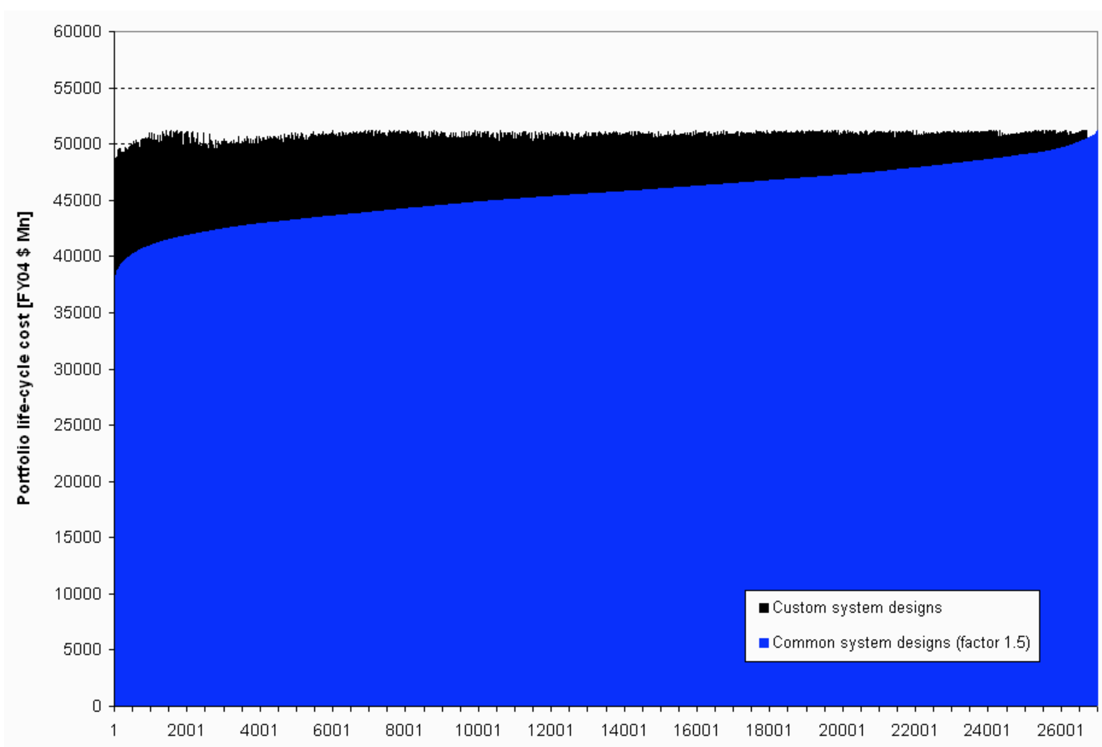

Figure 85: Ranking of portfolio design solutions with commonality by life-cycle cost for an overlap parameter value of k = 2.0; black lines show portfolio design solutions without commonality

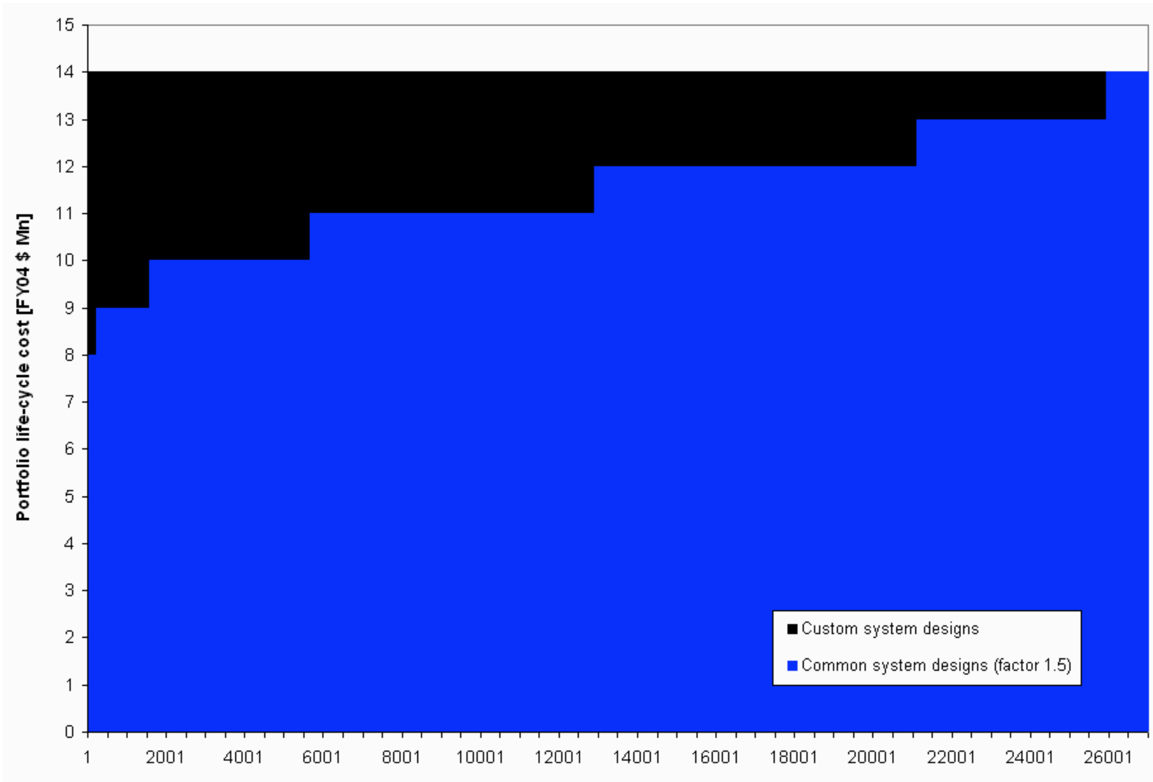

Figure 86: Ranking of portfolio design solutions with commonality by # of developments for an overlap parameter value of k = 2.0; black lines show portfolio design solutions without commonality

Appendix IV: Supplementary Material for the Planetary Surface Mobility Case Study

Appendix IV provides additional material on assumptions and results for the pressurized planetary surface mobility systems case study not shown in Chapter 5.

Table 36: Summary of requirements and parameters for the surface mobility case study

Supplementary power generation						
Use Case	**Technology**	**Power level [W]**	**Mass [kg]**	**Duty cycle [-]**		**Reference, comment**
Moon	RTG	2000	267	100%		[SPSR-05] [SW-07]
Moon	Solar	3500	63	50%		[CHHC-08]
Mars	RTG	3000	400	100%		[SPSR-05] [SW-07]
Mars	Solar	10000	907	8%		[CHHC-08]
Supplementary power generation						
Technology		**Energy density [Wh/kg]**				**Reference, comment**
Li-Ion battery		200				[Yod-07]
Regenerative fuel cell		700				[Burke-03]
Fixed consumables						
Consumable		**Value [kg/p/d]**		**Tare factor [-]**		**Reference, comment**
Food		2.3		1.8		[LP-00]
Oxygen		0.84		1.9		[LP-00]
Water		5		1.2		Estimate based on [LP-00], 3 l drinking water, 2 l hygiene water
Carbon dioxide removal						
Technology	**Equipment [kg/p]**	**Power [W/p]**	**Heat [W/p]**	**Re-supply [kg/p/d]**	**Tare factor [-]**	**Reference, comment**
LiOH	0	5	5	1.75	1.8	[LP-00], Includes 5 W fan power
4-bed molecular sieve	30	300	300	0.00	1.8	[LP-00], Allows for complete capture of condensate for recycling
Solid amine beds	11.75	5.7	5.7	0.00	1.8	[Nal-07] , Includes 5 W fan power
Metal oxide canisters	300	5	5	0.00	1.8	[HAM-09] Allows for capture of CO2 and recycling of CO2 at outpost
Humidity removal						
Technology	**Equipment [kg/p]**	**Power [W/p]**	**Heat [W/p]**	**Re-supply [kg/p/d]**	**Tare factor [-]**	**Reference, comment**
Silica gel	0	0	0	7.90	1.8	Completely expendable, author estimate
Condensing heat exchanger (CHX)	10	100	100	0.00	1.8	Estimate based on [KSC-88], Allows for 50% condensate capture for recycling
Solid amine beds	11.75	5.7	5.7	0.00	1.8	[Nal-07] , Opportunity for synergy with CO2 removal system

Table 37: Morphological Matrix of functions and technology choices for the Mars pressurized rover; note: only functions which are included in the commonality analysis are shown

Function	Technology choice 1	Technology choice 2	Technology choice 3
CO_2 removal	Lithium hydroxide (LiOH)	4-bed molecular sieve	Metal oxide canisters (MetOx)
Humidity removal	Silica gel	CHX	
Energy storage	Li-Ion batteries (energy density: 200 Wh/kg)	Regenerative fuel cells (energy density: 700 Wh/kg)	
Supplementary power generation	Tracking solar arrays (20% efficiency)	Stirling RTG	None
Ground interfacing and propulsion	4 wheel chassis	6 wheel chassis	

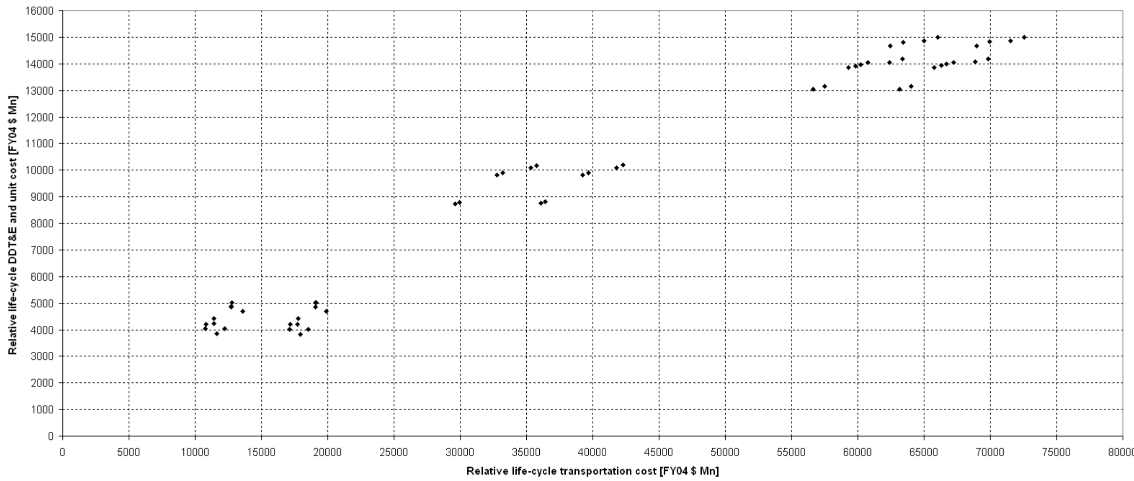

Figure 87: Mars pressurized rover architecture analysis results: sum of life-cycle DDT&E and unit costs vs. life-cycle transportation cost

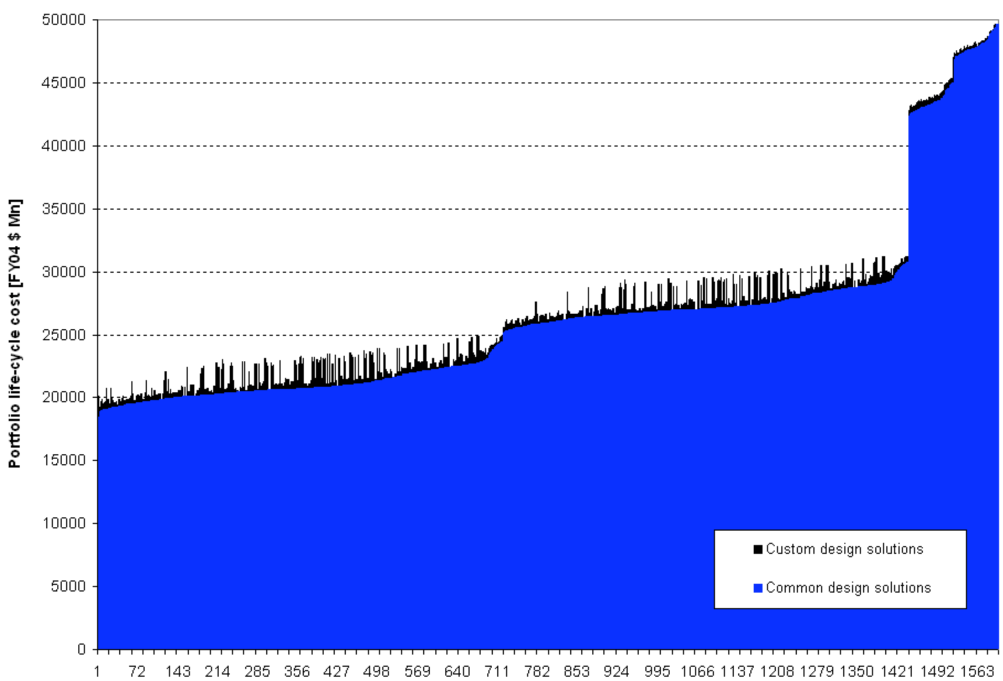

Figure 88: Portfolio design solutions with commonality ranked by life-cycle cost for k = 2.0; portfolio design solutions without commonality shown in the background

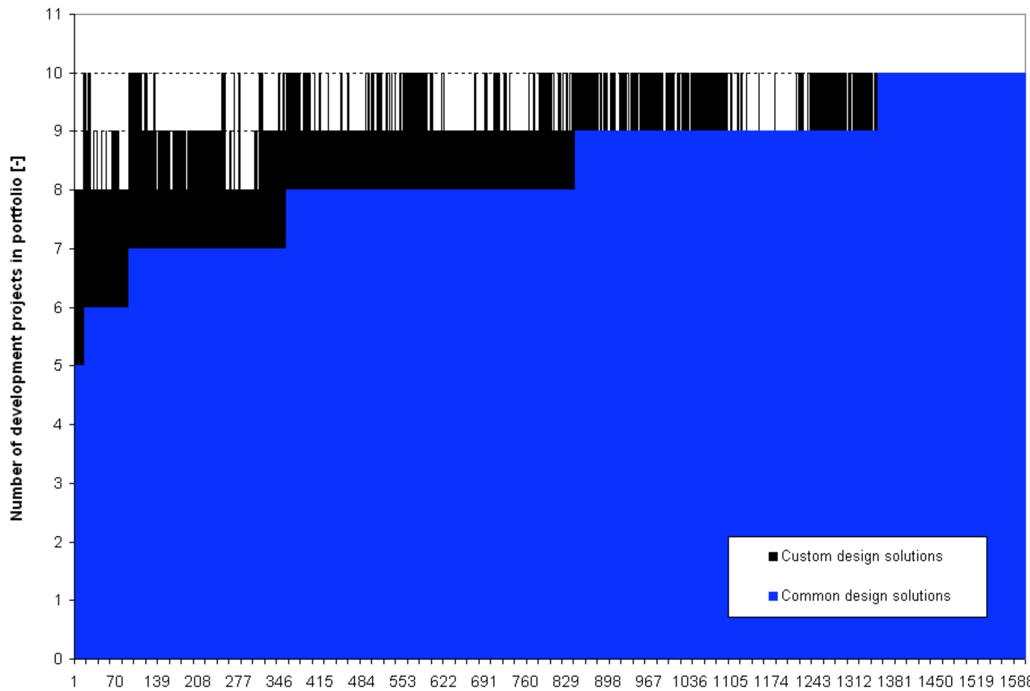

Figure 89: Portfolio design solutions with commonality ranked by the number of custom development projects for k = 2.0; portfolio design solutions without commonality shown in the background

Appendix V: Overview of Thesis CD Contents

The CD attached to this thesis contains the source code and results for all of the case studies, as well as an electronic version of the full text of this dissertation.

The following is an annotated folder structure for the CD:

- ***Dissertation text***: this folder contains a file with the full text of the thesis as well as the thesis defense presentation
- ***Case study 1 – life support systems***: this folder contains the source code and results from the case study on exploration life support systems for multi-person habitats and crew compartments. The following subfolders are included:
    - ***Case study 1 – step 1:*** contains slides summarizing the portfolio use cases, functionality scope, and metrics
    - ***Case study 1 – step 2:*** contains slides with reference data on life support systems modeling as well as subfolders on each future use case considered which provide the Java source code for and the results (spreadsheets) from the analysis of architecture alternatives for this use case:
        - ***Lunar lander***
            - ***Architecture analysis source code***
            - ***Architecture analysis results***
        - ***Lunar surface habitat***
            - ***Architecture analysis source code***
            - ***Architecture analysis results***
        - ***NEO mission habitat***
            - ***Architecture analysis source code***

- ***Architecture analysis results***

- ***Mars surface habitat***

  - ***Architecture analysis source code***

  - ***Architecture analysis results***

- ***Earth-Mars-Earth transit habitat***

  - ***Architecture analysis source code***

  - ***Architecture analysis results***

- ***Case study 1 – step 3:*** contains the source code for and results from the commonality overlap screening process. The Java source code and results (in spreadsheet form) for different overlap parameter values are provided in custom subfolders which are designated according to the required overlap fraction δ:

  - ***Operational overlap 1.0 required***

    - ***Java source code***

    - ***Commonality overlap screening results***

  - ***Operational overlap 0.9 required***

    - ***Java source code***

    - ***Commonality overlap screening results***

  - ***Operational overlap 0.8 required***

    - ***Java source code***

    - ***Commonality overlap screening results***

- ***Operational overlap 0.7 required***
    - ***Java source code***
    - ***Commonality overlap screening results***
- ***Operational overlap 0.6 required***
    - ***Java source code***
    - ***Commonality overlap screening results***
- ***Operational overlap 0.5 required***
    - ***Java source code***
    - ***Commonality overlap screening results***
- ***Operational overlap 0.4 required***
    - ***Java source code***
    - ***Commonality overlap screening results***
- ***Operational overlap 0.3 required***
    - ***Java source code***
    - ***Commonality overlap screening results***
- ***Operational overlap 0.2 required***
    - ***Java source code***
    - ***Commonality overlap screening results***
- ***Operational overlap 0.0 required***
    - ***Java source code***

        - ***Commonality overlap screening results***

  - ***Case study 1 – step 4:*** contains spreadsheets documenting the results of the overlap sensitivity analysis as well as slides which summarize interesting commonality opportunities for detailed study

- ***Case study 2 – Saturn launch vehicle family***:

  - ***Case study 2 – step 1:*** contains slides summarizing the portfolio use cases, functionality scope, and metrics

  - ***Case study 2 – step 2:*** contains slides with reference data on rocket engine and fuselage modeling as well as subfolders on each use case considered which provide the Java source code for and the results (spreadsheets) from the analysis of architecture alternatives for this use case:

    - ***Saturn V***

      - ***Architecture analysis source code***

      - ***Architecture analysis results***

    - ***Saturn IB***

      - ***Architecture analysis source code***

      - ***Architecture analysis results***

    - ***Saturn I***

      - ***Architecture analysis source code***

      - ***Architecture analysis results***

  - ***Case study 2 – step 3:*** contains the source code for and results from the commonality overlap screening process. The Java source code and results (in spreadsheet form) for different overlap parameter values are provided in custom subfolders which are designated according to the required value of the overlap parameter k for design parameter overlap:

- ***Overlap parameter k = 1.0***
  - ***Java source code***
  - ***Commonality overlap screening results***
- ***Overlap parameter k = 1.5***
  - ***Java source code***
  - ***Commonality overlap screening results***
- ***Overlap parameter k = 1.75***
  - ***Java source code***
  - ***Commonality overlap screening results***
- ***Overlap parameter k = 2.0***
  - ***Java source code***
  - ***Commonality overlap screening results***
- ***Overlap parameter k = 2.25***
  - ***Java source code***
  - ***Commonality overlap screening results***
- ***Overlap parameter k = 2.5***
  - ***Java source code***
  - ***Commonality overlap screening results***

        - ***Overlap parameter k = 2.75***
            - ***Java source code***
            - ***Commonality overlap screening results***
        - ***Overlap parameter k = 3.0***
            - ***Java source code***
            - ***Commonality overlap screening results***
    - ***Case study 2 – step 4:*** contains spreadsheets documenting the results of the overlap sensitivity analysis as well as slides which summarize interesting commonality opportunities for detailed study

- ***Case study 3 – planetary surface mobility systems***:
    - ***Case study 3 – step 1:*** contains slides summarizing the portfolio use cases, functionality scope, and metrics
    - ***Case study 3 – step 2:*** contains subfolders with spreadsheets for the lunar and Mars use cases. The spreadsheets provide the models used for the sizing of surface mobility systems and also document the architecture analysis results.
        - ***Lunar pressurized surface mobility system***
        - ***Mars pressurized surface mobility system***
    - ***Case study 3 – step 3:*** contains subfolders with analysis models and results for the commonality screening process based on design parameter overlap. Models and results for a given design parameter overlap value k are provided in a single spreadsheet. The subfolders are designated by the design parameter overlap value k.
        - ***Overlap parameter k = 1.0***

- ***Overlap parameter k = 1.5***
- ***Overlap parameter k = 2.0***
- ***Overlap parameter k = 2.5***
- ***Overlap parameter k = 3.0***
- ***Overlap parameter k = 3.5***
- ***Overlap parameter k = 4.0***
- ***Overlap parameter k = 4.5***
- ***Overlap parameter k = 5.0***

- ***Case study 3 – step 4:*** contains spreadsheets documenting the results of the overlap sensitivity analysis as well as slides which summarize interesting commonality opportunities for detailed study.

The contents of Appendix V are also provided in the file README.pdf on the CD. Please direct any remaining questions to the author's email address: wilfried.hofstetter@gmail.com