Chapter 2
Approaches and Methods

Abstract Space architecture as a discipline is relatively new, but it fills a gap between the engineering approach to design habitats and other space facilities for humans, and the complexity of human factors oriented design—including personal psychology, creativity, and non-work related activities. In order to successfully fill that gap, space architecture needs to be taught academically. This chapter talks about known and potential approaches and methods, drawing examples from current space architecture programs and classes, and representative projects. The authors consider that space architecture approaches to design and planning are important to be introduced to students who are coming from the diverse backgrounds of engineering and architecture. Other disciplines may benefit as well.

2.1 Introduction and Chapter Structure

This chapter addresses architectural and engineering approaches in educational practices. The two can be quite different and cause confusion. This chapter aims to enable students, faculty members, and other interested parties to acknowledge different approaches and therefore to help them better integrate their knowledge in interdisciplinary spaceflight related design and planning processes. A guest statement at the end of the chapter from Brand Griffin[1] talks about key positions of space architecture as a discipline.

Many universities around the world offer aerospace engineering undergraduate and graduate programs, but only a few relate to the field of Space Architecture.[2] This chapter presents examples of educational practices illustrated with student projects from European and American academic institutions that offer space architecture as a mainstream or major component in their curriculum.

[1]Advanced Concepts Office at NASA's Marshall Space Flight Center, Space Architect.
[2]A selection of schools and universities offering courses on Space Architecture are listed in the Appendix.

S. Häuplik-Meusburger and O. Bannova, *Space Architecture Education for Engineers and Architects*, Space and Society,
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The chapter concludes with a guest statement from Brent Sherwood[3] where he talks about Space Architecture Education—Site, Program, and Meaning.

2.2 Future Tasks and Upcoming Challenges

Unlike early space missions, future spacecraft design concepts will not be based mainly upon engineering and structural requirements (cf. Brown 2002). Humans in future long-duration spaceflight and exploration endeavors will be assigned vital roles in the system. Therefore human needs and requirements must be addressed in overall mission architecture and spacecraft design. Human factors need to be taken into account at every stage of the design process—considering people to be more than an 'element' of the system but its modifier and innovator. Today's students and future spacecraft designers need to be prepared for the challenge of planning human missions and designing appropriate artifacts.

Table 2.1 illustrates that design considerations for many mission aspects change significantly in relation to missions' lengths and destinations. It is evident, that all mission aspects have influences on the design and vice versa:

- The longer and more isolated the mission, the more important will be the qualitative design of the habitat, including layout and integration of its structures, systems, and utilities.
- The longer and farther away from Earth, the more sustainable the habitat has to be and the more facilities will be needed for personalized activities, etc.

The importance of integration of human factors and other human-related aspects into the design process has been recognized by institutional parties.

The US Department of Transportation states the following concerning the modernization of the National Airspace System (NAS): "*The integration of human factors into the development and procurement of … new systems is vital to the success of the future NAS. Although the Human Factors Design Guide* (HFDG 1996) *has been available for a number of years and provided vital information, it did not have the weight and impact of a design standard. Instead, the Military Standard* (MIL-STD 1989) *was commonly cited in Federal Aviation Administration (FAA) system specifications.*" (Ahlstrom et al. 2003, pp. 1–1)

Although the statement above refers to current Federal Aviation Administration FAA practices (Wagner et al. 1996, pp.1-1–1-3), an analogy can be drawn for current space systems' and facilities' design approaches with more weight given to human factors and human activities-oriented design. Broader understanding of human-related physical and psychological impacts on design solutions and understanding how design can be used for mitigation purposes are critical for success of future exploration missions.

[3]Strategic Planning & Project Formulation, NASA Jet Propulsion Laboratory, Space Architect.

Table 2.1 Comparison of mission aspects and design considerations of short missions (orbital) and long missions (Moon and Mars)

Missions aspects	Short missions (e.g. Orbital)	Medium missions (e.g. Lunar)	Long-term missions (e.g. to Mars)	Change of design considerations
Duration (months)	<6	6–12	>12	Habitat mass and volume
Distance to Earth (km)	300–400	350–400 K	60–400 M	Logistics mass and volume, increase of sustainability
Crew size	3–6	4≤	6≤	Size of habitat and logistics modules, privacy and social space
Degree of isolation and social monotony	Low to high	High	Very high	Interior design including privacy and social space (territorial issues)
Crew autonomy level	Low	Medium	Very high	Interior design with a certain flexibility to adjust to the crew needs
Emergency evacuation	Yes	Limited	No	Mission architecture and base/vehicle configuration
Availability of mission support				Mission architecture and habitat design, communication technology
Outside monitoring	Yes	Yes	Very limited	
Two-way communications	Yes	Yes	Very constrained	
Email up/down link	Yes	Yes	Yes	
Internet access	Yes	Yes	No	
Entertainment	Yes	Yes	Yes	
Re-supply	Yes	Very limited	No	
Visitors	Yes	No	No	
Earth visibility	Yes	Yes	No	Viewports

Modified from the source: Kanas and Manzey (2003)

When aiming to create an optimized design that is compatible with mission goals, technological, scientific, design, and human factors requirements, there is added complexity because of interdisciplinary design processes. Designing a crew habitat for outer space, surface of Mars, or any other extra-terrestrial body is one of the biggest challenges for space architects and engineers. Interdisciplinary communication is vital for successful and efficient design and interactions between all parties involved in design and planning activities.

Difficulties in understanding each other can arise between professions. Often disciplines and practices use different terminology and acronyms identifying

Table 2.2 Engineering and architectural approaches throughout processes

Task	Engineering approach	Architectural approach
Problem definition	Product-oriented	Process-oriented
Approach	Linear (analysis) start at the beginning of the process	Nonlinear and iterative (synthesis), start at critical points, then adjust
Workflow	Workflow from the start to the end, done with numbers (quantitative methodology)	Workflow anywhere in the project, done with models (qualitative methodology)
Solution	There is one ideal solution, most decisions are quantifiable	There are many solutions, some decisions are quantifiable

Adapted from Table 2.10 by Brand N. Griffin

entities, objects, and functions. Even the meaning of 'design' differs between engineers and architects.[4] That can create confusion and misunderstanding which may lead to significant design flaws and errors affecting overall planning and mission success. Table 2.2 shows examples of how different tasks can be understood by architects and engineers. In general: ways of identifying a problem, perceiving it, and finding design solutions can be quite different (cf. Cross 1993).

2.3 Educational Practices

Different disciplines have different approaches for finding a solution. Although there are no canonical definitions of space-architecture and aerospace engineering practices, they have different educational approaches and often different tasks assigned. The same can be observed in other disciplines such as medicine, industrial design, and physical sciences, etc. This chapter discusses engineering and architectural approaches in order to achieve better integration of space architecture subjects into both curricula.[5]

2.3.1 The Engineering Approach to Habitation Design

> An engineer starts his design from a problem, i.e. from ignorance as non-knowledge. This corresponds to a question and indicates a direction towards an aim. Therefore the engineer needs knowledge concerning means as a functional compliance for an aim, knowledge of

[4]Major terms that are used throughout this book are listed in the Appendix, in the Glossary section of the Appendix.

[5]Note: The authors highly recommend the inclusion of interdisciplinary team-oriented working processes at the university level.

> how to gain and to use such a means, knowledge concerning values behind the aim, and knowledge of how to modify the aim in the light of values, if necessary. (Michelfelder et al. 2013, p. 3)

Several specialized disciplines share an engineering approach. Two branches of aerospace engineering deal with a craft's design and all the components required for its successful implementation: aeronautical engineering concerns aircraft design for operations in Earth atmosphere; astronautical engineering relates to vehicles operating in space and on celestial bodies; others include civil, industrial, and maritime engineering.

Historically, space mission and craft design is based on an engineering approach that is called Systems Engineering. The International Council on Systems Engineering (INCOSE) defines it as follows:

> **Systems Engineering** is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. …Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. (INCOSE 2015[6])

A goal of a system, as a group of elements that interact with each other, is to achieve specific common goals and to make the overall functionality better than the result of each element acting individually. According to Maier and Rechtin (2000, p. 8), "*systems are collections of different things which together produce results unachievable by the elements alone.*" Each system has its boundaries that separate it from the surrounding environment or from other systems. Elements and units inside the system are its basic components and if two or more of them have relationships they can be combined into sets based on the character of those relationships and become a subsystem of the main system. The description of a system as a whole leads to the three most important common characteristics that are present in all systems: *organization, generalization, and integration* (Chang 2011 p. 13).

2.3.1.1 Engineering Classes

Aerospace engineering students have to understand at least the principles of mathematics, physics, science, and engineering in order to design, construct, and test various types of aircraft and spacecraft. Engineering classes are focused on learning about systems, subsystems, elements, and parts. Students understand connections between them in order to perform a particular function for which those systems or units are designed. The engineering approach, illustrated in Fig. 2.1 uses

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[6]INCOSE—International Council on System Engineering. http://www.incose.org/AboutSE/WhatIsSE.

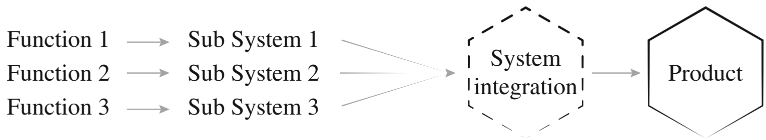

Fig. 2.1 Example of a common engineering design approach

system and sub-system requirements as constraints for the system. Each function is determined by a trade-off process. The organizational stage includes function determination and prerequisites. It is followed by generalized requirements, and the integration stage usually becomes a part of the process in professional system engineering practice. System engineering is dealing with a system as a whole and connects the traditional engineering disciplines. It also includes the evolutionary process of maturity levels (David 2013; Kossiakoff et al. 2011; Kesseler and Guenov 2010).

A drawback of this approach may be the neglected human factor if it is treated as only an equal system element. The International Space Station is an example of an engineering design approach. Important human factors and habitability elements have either been discarded in an early stage (eg. crew module) or have been added lately to the station (eg. personal crewquarters).

2.3.2 The Architectural Approach

> As a professional discipline, architecture spans the arts, engineering, and the sciences. Students must have an understanding of the arts and humanities, as well as a basic technical understanding of structures and construction. Skills in communication, both visual and verbal, are essential. While knowledge and skills must be developed, design is ultimately a process of critical thinking, analysis, and creative activity. The best way to face the global challenges of the 21st century is with a well-rounded education that establishes a foundation for lifelong learning.
>
> (ACSA [Goals] 2015[7])

The architectural discipline is multidisciplinary by its nature. It builds upon a basic understanding of engineering, esthetics, and social sciences. The level of such understanding depends on the complexity of the design problems and proposed architectural solutions. Architectural understanding of a design process includes problem examination, synthesis, and innovative pursuit. Developing skills in communication—both visual and verbal, is an essential part of architectural educational practice.

[7]ACSA—Association of Collegiate Schools of Architecture. http://www.acsa-arch.org/about/about-acsa.

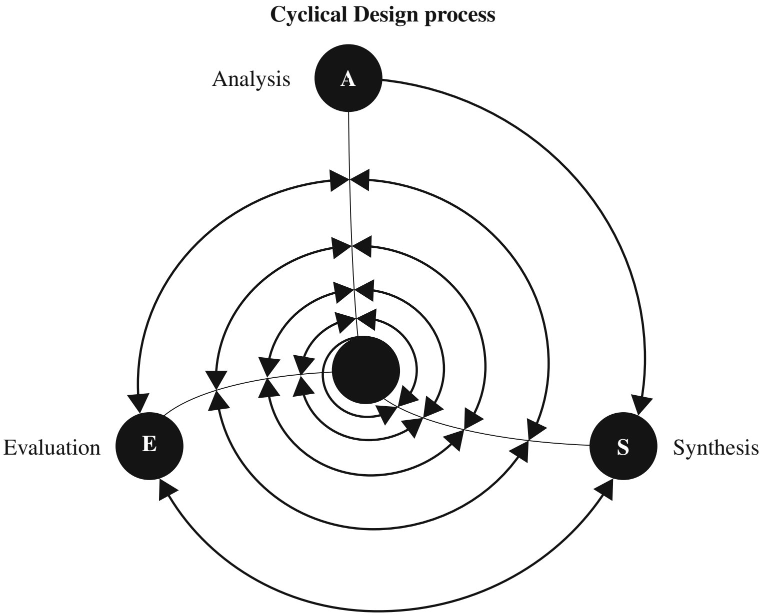

Fig. 2.2 Cyclical design process (original model by Donna P. Duerk, adapted by the authors)

2.3.2.1 Architectural and Design Studios

The architectural studio approach is based on a project-oriented strategy where students have to be creative in identifying required information and knowledge, analyzing it, and synthesizing the results into a final architectural design. The architectural approach to project development is basically non-linear and based on the synthesis of multiple disciplines.

Cycles of design process will evolve through time and levels of development. Figure 2.2 shows a diagram of a cyclical design process. "The design process is often seen as a serendipitous, cyclical process covering much ground at ever-increasing levels of detail at each sweep." (Duerk 1993, p. 10)

Brand Griffin also refers to a model for spiral evolution in his guest statement in Sect. 4.6, which originally comes from software engineering.[8] In terms of Space Architecture, it corresponds to the idea that at every design level all elements are considered, roughly at the beginning and more detailed at a later stage.

"Design is a cyclical process in which the designer or the design organization iterates a sequence of conception, representation, and evaluation until arriving at a satisfactory solution". (Cohen 1996, p. 2)

[8]The original spiral model was developed by the software engineer Barry Boehm in 1986. Since then a number of variations do exist. (Boehm Barry. 1986. A Spiral Model of Software Development and Enhancement.)

Architectural training teaches students to operate at all scales from the "overall picture" down to the smallest details; to provide directive intention—not just analysis—to design opportunities, to address the relationship between human behavior and the built environment, and to interact with many diverse fields and disciplines throughout the project lifecycle.

2.3.3 The Space Architecture Approach

> Engineers think architects make things prettier, difficult to build, and more expensive. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect. (Griffin 2014, p. 2)

The space architecture approach combines engineering thinking with criteria related to habitability and human factors, such as considered in architecture and industrial design, plus including other disciplines such medicine and science.

During a space architecture studio, students advance and complete their individual projects for manned systems and habitat facilities aimed at optimizing human safety, performance, and comfort under extreme and confined conditions of space habitation.

When introducing architecture students to a design studio in Space Architecture, Marc M. Cohen states that "…. *it is always a challenge to orient them to the unique and peculiar characteristics of designing human habitation in vacuum and reduced gravity regimes. Typically, the faculty presents a broad overview of the Space Architecture discipline, and to introduce the students to leading concepts and accomplishments. The challenge is a difficult one, given the shortness of time for a quarter or semester, and the variety of the students' backgrounds, with some stronger or weaker in engineering, human factors, materials science, and physics. Also, the students often start from differing levels of professional preparation and training, so it is inevitable that each one interprets the information differently and takes an individual and often idiosyncratic approach.*" (Häuplik-Meusburger and Lu 2012, p. 4)

Depending upon the overall topic (manned systems design, space structures and applications, lunar and planetary exploration, and terrestrial analogues) students usually start with extended research of relevant topics that include mission architecture, human factors, ergonomic influences, extreme environments, constraints and influences, and psycho-social factors. They will attain a good understanding of the system and associated structures through design, research, and analysis of specific projects. Certain creativity and the development of 'out-of-the-box options' can be helpful at the beginning.

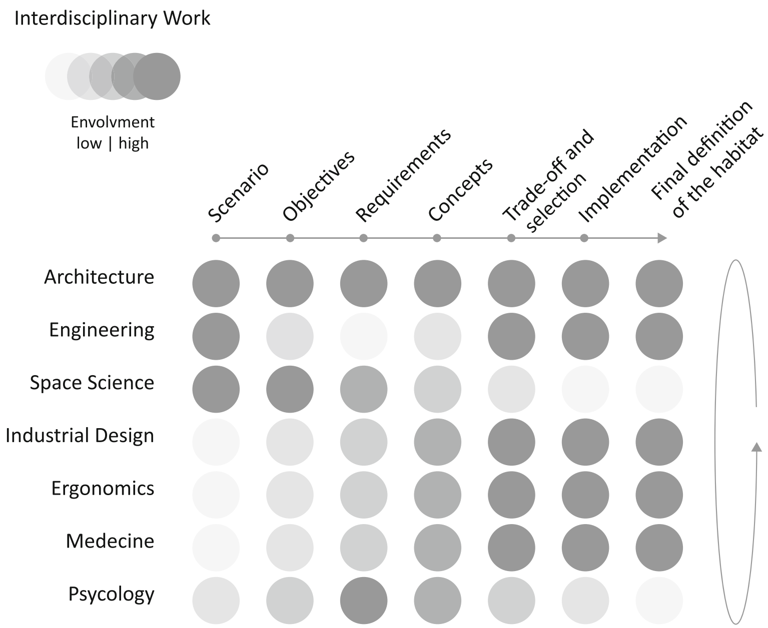

Fig. 2.3 Scheme of a disciplines relationships synthesized approach diagram

The design process is interdisciplinary (Fig. 2.3) and also related to:

- Systems' and elements' Technology Readiness Levels (TRLs) and Habitability Readiness Levels (HRLs)
- Availability of resources (physical and intellectual)
- Timeframe
- Societal and political support
- Economic and environmental impacts. (Testing and feedback)

Interrelationships between design stages with involvement of different disciplines should be established throughout the design and production development (Fig. 2.4).

Many diagrams (e.g. 2.1 and 2.2) address similar reciprocal design processes but depict it from different perspectives: the spiral process reflects an architectural synthetically enhanced approach and is based on system engineering process. The multi-linear diagram reflects engineering and architectural team efforts in pursuing integrated design solutions. There are many more variations of these models and other ways of representation exist.

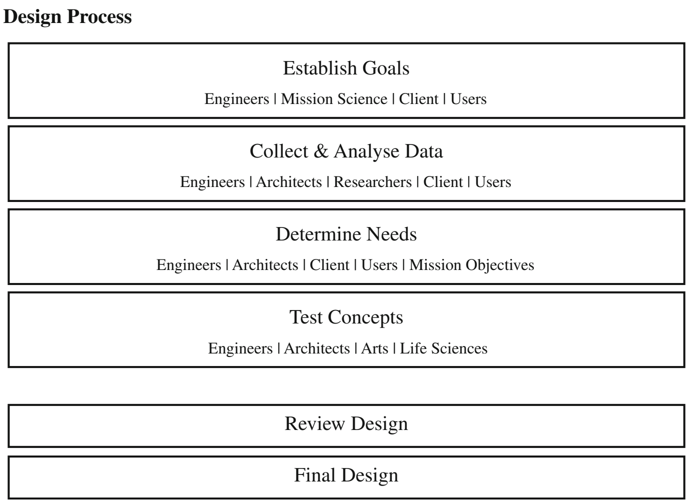

Fig. 2.4 Design process diagram (position paper on the role of space architecture, IAA 2013, p. 3)

2.4 Educational Examples

Although there is still a need for an appropriate educational approach to enumerate space architectural objectives in related disciplines, recent examples of academic courses, programs, and workshops show the benefits of integration to expand the potential of future space exploration mission planning and spacecraft and structures design.

2.4.1 Master of Science in Space Architecture Program (SICSA,[9] University of Houston)

MS-Space Architecture degree at the University of Houston was accredited by the Texas Higher Education Coordinating Board in 2003 after the first class of NASA professionals conducted their studies at the Sasakawa International Center for Space Architecture in 2001–2002 academic year (Table 2.3).

SICSA's central mission is to plan and implement programs that will advance peaceful and beneficial uses of space and space technology on Earth and beyond. Many of these activities address extreme terrestrial environments. The center offers two types of MS-Space Architecture curriculum, one for full-time students

[9]Sasakawa International Center for Space Architecture, Cullen College of Engineering, University of Houston, Houston, Texas, USA.

Table 2.3 Program/course summary 'SICSA Master of Science in Space Architecture Program'

University/Host	SICSA
Length/Disciplines	Three semesters (full-time students), architecture and engineering students; five semesters (part-time industrial students)
Curriculum	Consistent with degree plan and program syllabi
Special features	Regular program

(3 semesters) and another for part-time local industry employees (5 semesters). Students with various degrees and backgrounds work on projects in teams or individually. All projects are related to current trends in the industry and national space exploration programs. Projects also include government and corporate aerospace organizations grants and proposals (Fig. 2.5).

Curriculum includes: project oriented studio classes, seminars, special problems—elective classes and invited lectures. Seminar classes provide students with basic knowledge about man-systems integration, mission planning and analysis, and spacecraft and habitat design (Fig. 2.6).

During the course, students learn the theory, requirements, and design concepts for spacecraft and habitat design. Topics of focus include human factors, ergonomic influences, extreme environments constrains/influences, and psycho-social factors. The goal of the program for students is to attain a good understanding of these structures and systems through design, research, and analysis of specific projects. Projects topics include: manned systems design, space structures and applications, and Mars and Moon exploration (Bannova and Bell 2011).

During the class, students perform detailed investigations and conduct individual research on manned space systems aimed at optimizing human safety, performance

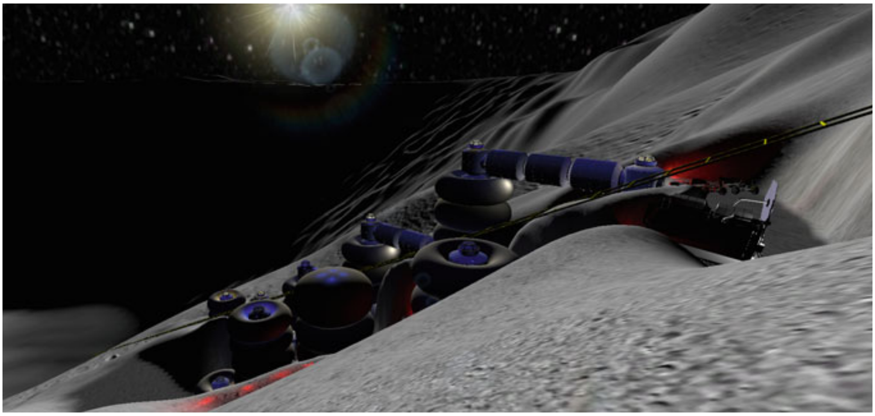

Fig. 2.5 Sustainable Moon settlement for 80 people; Project developed for Houston Museum of Natural Science's Planetarium by graduate students Thomas Hockenberry, Stacy Henze, Nima Cheraghpour (2012 MS-SA student project)

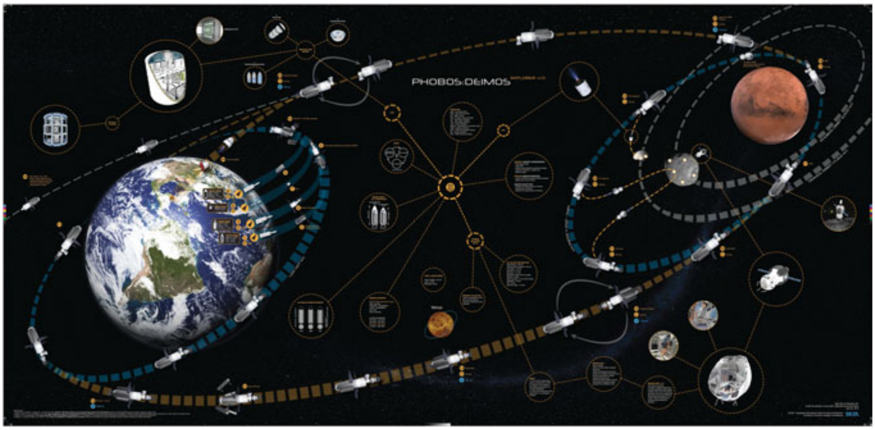

Fig. 2.6 Phobos/Deimos Mission Architecture by graduate students Nejc Trost and Abhishek Jain. (2013 MS-SA student project)

and comfort under extreme conditions. Habitability and human factors lessons from extreme environment analogs on Earth and previous space missions are examined and analyzed.

2.4.1.1 NASA Grants and Cooperation with Industry

In September 2008, the NASA Explorations Systems Mission Directive (ESMD) awarded contracts to Boeing, ILC-Dover and the University of Maryland to conduct concept study investigations to develop requirement definitions and planning for a "Minimum Functionality Habitation Element" (MFHE) lunar habitat. The primary study purpose was to conceptualize the smallest module possible that was capable of providing barest living and work essentials for initial short-term lunar missions with virtually no emergency contingencies other than basic radiation protection countermeasures. Although NASA would never actually fly such a facility, the central intent was to examine lowest operable volumetric, mass, consumable, and equipment system functionalities to establish a foundation baseline upon which more acceptable capabilities and accommodations can then be added. Means to achieve such expanded growth features were then to be conceptualized as a secondary priority. All work was to be completed within a six-month period (Fig. 2.7).

SICSA was a member of two of the study teams, one headed by Boeing, and the other by ILC-Dover. The Boeing team involved several major corporate participants. Members included Hamilton Sunstrand, Harris, Honeywell, ILC-Dover, Oceaneering Space Systems, Orion, and the United Space Alliance. The ILC-Dover team was much smaller, with only SICSA and Hamilton Sunstrand as additional members.

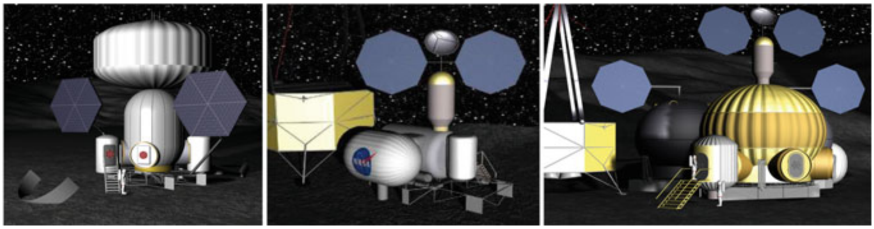

Fig. 2.7 Boeing team and ILC Dover team MFHE evolutionary growth approach proposal. (SICSA project 2009)

Table 2.4 MFHE given guidelines

Crew accommodations	Operations
The MFHE should initially support a crew of four for 28 days plus an additional 30-day contingency exception	Crew missions will be scheduled at 6-month intervals based upon a reference 4.0.0 mission campaign (Fig. 2.8)
Later expanded capacity should provide for continuous 4-person 180-day stays, with surges of an additional 4 people during crew changes	The MFHE will be landed pressurized at a polar location, and will remain on the lander for approximately 2 years prior to occupancy following offloading by a Tri-ATHLETE
Scientific workstations should be incorporated (e.g. a geosciences glove box)	EVA operations for surface exploration and maintenance will occur approximately every other day

NASA established functional support requirements to guide the study, but provided some latitude for contractors to "push back" on those they wished to challenge with logical alternatives. The original guidelines described in Table 2.4.

Students worked on two alternative habitat configuration concepts and expansion scenarios that originated with highly constrained mass/volume features consistent with earliest operational accommodations. The schemes incorporated means to commence operations while placed upon landers, to off-load the modules to the surface using a special lander-integrated crane, and to subsequently increase functional capacities using soft augmentations and additive element growth. Comprehensive team study results were presented to NASA in February, 2009, and have been publicly released to all interested parties. The final reports are available online (Bienhoff 2009; Lin 2009).

Figure 2.8 depicts comparison diagram of NASA mission campaign 4.0 outline and SICSA's mission proposal with use of designed surface elements that offer advantage of minimizing number of launches and overall mission costs.

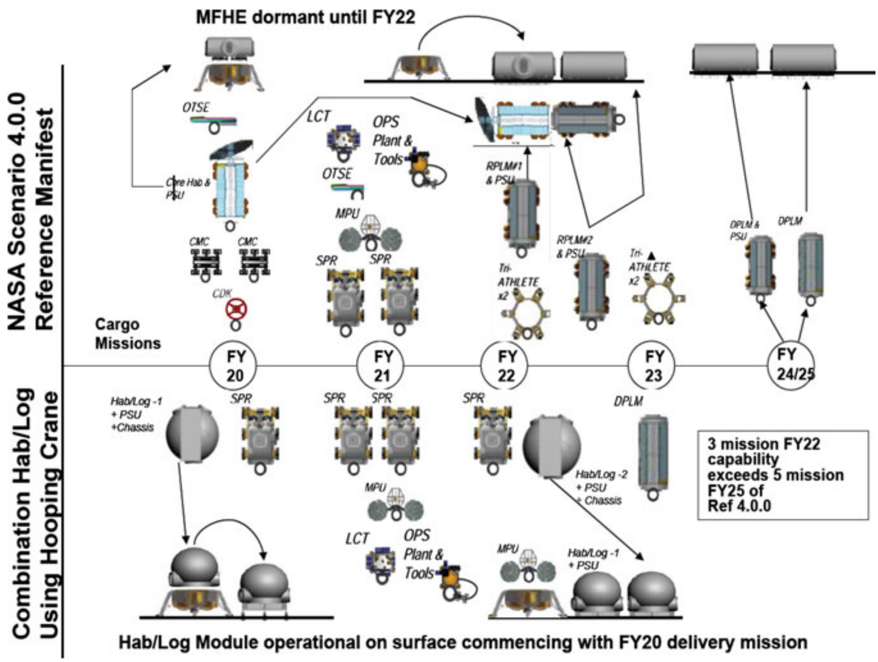

Fig. 2.8 Comparison SICSA's MFHE campaign proposal with NASA mission campaign 4.0

2.4.2 Destination Moon Design Studio (TU Vienna, Vienna University of Technology)

The design studio, 'Destination Moon', took part in the frame of the Master of Architecture program at the Vienna University of Technology (TU Vienna) in 2012. The TU Vienna is one of a few universities worldwide that offers courses in Space Architecture (see Appendix: Hints for Students). In 2012, 25 students took part in the semester program (March–June) and worked on their vision of a future research base on the Moon. All projects have been published and are available online for further research (Häuplik-Meusburger and Lu 2012) (Table 2.5).

In the first phase of the studio a settlement strategy, based on a hypothetical scenario, was developed by the students. The emphasis of the second phase of the studio was on the design and implementation of a lunar research station. Particularly relevant was the mind shift of conventional architectural design challenges required by a change of perspective. As most of the students had no previous knowledge in the field of Space Architecture, this course was accompanied by theme-specific lectures and workshops with space experts.[10]

[10]Studio directed by: Dr. Häuplik-Meusburger Sandra and DI Lu San-Hwan; External project evaluation: Dr. Marc M. Cohen; Students: Abele M., Badzak M., Benesch O., Czech M.,

Table 2.5 Program summary 'Space Architecture Classes at the Vienna University of Technology'

University/Host	Vienna University of Technology (TU Vienna)
Length/Disciplines	A course is one semester (full-time and part-time students), architecture students, guest students from other faculties (engineering)
Curriculum	Part of the Master of Architecture program
Special features	Periodic program Accompanied by a vast space lecture series
HRL	3 (internal configuration, functional definition and allocation, use of reduced scale models)

2.4.2.1 Evaluation Criteria for Student Projects

In order to assess how well the students developed solutions, two kinds of reviews were provided: an internal one in the sense of a traditional studio review and an external one from the perspective of the larger world of human spaceflight. Space Architect Marc M. Cohen was invited to assess the feasibility of the projects in the professional practice of Space Architecture. Based on the design brief by the studio directors, Cohen developed the criteria for evaluation. There were three broad domains of evaluation: Concept, Representation, and Space Architecture Features. This method can be used as an example and adapted for other design studios and projects.

The domain **Concept** encompassed the ideas that the students brought to their projects. Evaluation themes for Concept are listed in Table 2.6.

Figure 2.9 shows a visualization of the student project titled 'Twist', which was evaluated highly in the Concept category. The project 'Twist' creates a linear array of units that begins at the upper edge of a crater wall and follows the slope down towards the center. The form of these habitation units derives from the structure, which consist of a spiral spring. The crew will deploy this spiral inside the inflatable, giving it a form that provides volumes of varying shapes and sizes that can accommodate the living and working environment functions. The spiral will initially be flexible but its foam filling will harden into a rigid shape. This project got a good score in the domain Concept. Areas that need further attention include the construction of the spiral to be further articulated, particularly the outer inflatable layer that would be filled with foam that solidifies (Häuplik-Meusburger 2012, p. 115).

Representation covered the way students presented their ideas as a metric to skill and craft. Evaluation themes for Representation of the Design Concept are

(Footnote 10 continued)

Demirtas T., Galonja D., Hengl K., Heshmatpour C., Khouni A., Klaus J., Kolaritsch A., Krljes D., Küpeli B., Lang E., Lazarova Y., Lukacs D., Milchram T., Mörtl C., Mulic A., Nagy P., Nanu A., Pluch K., Rossetti V., Shi Y., Siedler D., Stefan K., Steinschifter M.; Invited Space Experts: M. Aguzzi, W. Balogh, W. Bein, M. Cohen, S. Fairburn, N. Frischauf, B. Foing, M. Gitsch, G. Grömer, M. Hajek, J. Huber, Kabru, O. Lamborelle, R. Peldszus, T. Rousek, D. Schubert, M. Schultes, U. Schmitzer, G. Thiele, F. Viehböck, A. Vogler.

Table 2.6 Evaluation themes for the criteria CONCEPT for the design studio 'Destination Moon' (Marc M. Cohen)

CONCEPT: definitions of descriptive criteria	
Evaluation themes	Explanation
Analogy, including Backstory	The use of analogy is a time-honored and widespread practice in architecture. Some students use analogy, but that is not a requirement in any sense. However it can add a story line and a degree of richness to the narrative
Formal concept	Developing such a concept as a discrete physical and visual form is an essential step in architecture
Imported philosophy	It has become fashionable in recent decades to start an architecture project from a philosophical—instead of a formal—parti (Point of Departure). Although the use of imported and possibly irrelevant philosophy sometimes provokes controversy, the recording here addresses only whether it is present in the project
Structural concept	Because Space Architecture occurs in the extreme environment of vacuum and reduced or microgravity, the structure must not only support conventional live and dead loads, but also the pneumatic pressure of the atmosphere
Geometric construct	As part of the structural concept or the formal concept, a geometric concomitant often becomes a prominent organizing principle
Science of physics concept	Some Space Architecture concepts invoke innovative applications of science, most often physics, in developing a habitat project. However, often as much peril can accrue to the project as benefit unless the architect brings a solid grasp of the science to the effort

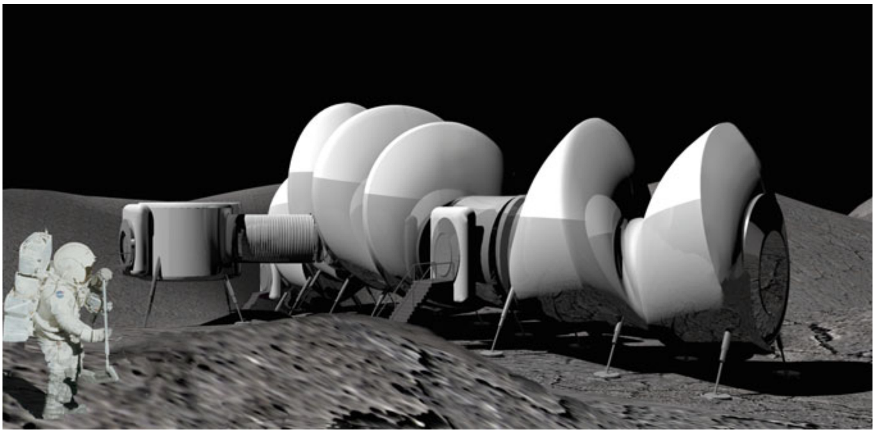

Fig. 2.9 Rendering of the project Twist by Daniela Siedler, Vienna University of Technology, Institute for Architecture and Design, Design Studio Destination Moon 2012 (TU Vienna, HB2, Siedler)

Table 2.7 Evaluation themes for the criteria REPRESENTATION for the design studio 'Destination Moon' (Marc M. Cohen)

REPRESENTATION of the design concept	
Sub themes	Explanation
Storyboard/Preliminary sketches/study model	The early steps in the creative process serve as a tremendously important viewport into the architect's design process, and can offer strong first order predictions of how well the project direction will turn out. The point in this criteria is not whether the architect went through these steps or not, but only whether she or he uses them in the review presentation to explain and illuminate the final project
Functional diagram or matrix	Mature and serious architectural design usually demands a symbolic representation of the relationship between functional areas or spaces. This representation can take the form of a table, a matrix, or a diagram that explains the decisions about adjacency, separation, parallel elements, and other supra-design features that shape the entire project, such as the modularization of living quarters, working areas, or agriculture
Adjacency matrix	An adjacency matrix is a special case of a functional matrix that explicates the importance of connecting or separating individual spaces
Site planning	The base or habitat sits on or under the surface of the extra-terrestrial body. Where the project intersects the surface, the need arises to elaborate that intersection and the relationship between the habitat and the surrounding terrain
Architectural plan	The plan drawing acts as the heart of an architectural project and probably the most time-honored representation of a building. It provides the shorthand for everything else in the project
Architectural building section and elevations	The buildings section and elevation articulates the plan's realization in three dimensions
Architectural 3D CAD	Computer Aided Design (CAD) has become the standard means of representation in most architectural projects
Structural detail or other detail	Because Space Architecture projects are often innovative, the architects often need to explain how they will make their structural concept or other feature feasible and realizable. The detail conveys understanding of the craft of building
Scale model	Presenting a project with a 3D scale model helps the reviewer and the public understand the concept. Scale models are particularly helpful for people who are not trained design professionals and so may encounter difficulty in visualizing a 3D concept from 2D drawing
Working scale model	Where a Space Architecture project involves changes in form or structure as part of installation, deployment, or inflation, a working model offers significant help to demonstrate the concept

listed in Table 2.7. The architect of the project 'Luna Monte' presented her concept with a storyboard, at least partially hand drawn, that was extremely helpful in expressing both the architectural concept and the beginnings of a concept of

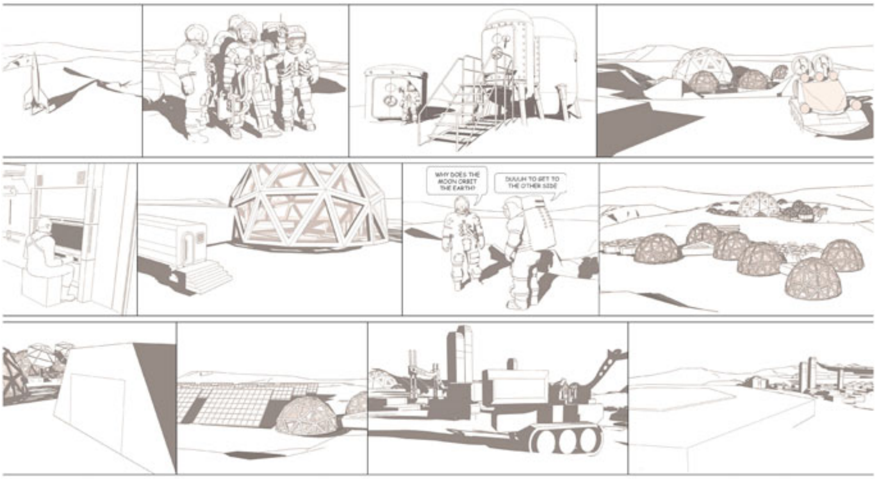

Fig. 2.10 Clipping of the storyboard for the project Luna Monte by Aida Mulic, VUT Vienna, Institute for Architecture and Design, Design Studio Destination Moon 2012 (TU Vienna, HB2, Mulic)

operations. The architect provides a complete functional diagram drawn at a habitable house/human scale. The project conveyed the functional relationships (Häuplik-Meusburger 2012, p. 89) (Fig. 2.10).

The domain **Space Architecture Features** encompassed the specific knowledge that the students gained and applied in the studio. Evaluation themes for Space Architecture Features are listed in Table 2.8.

The 'Balloon in a bowl' habitat, featured in Fig. 2.11 consists of a deployable, hexagonal plan inflatable. It has an inner deployable/ expandable framework. The functional modules include the Habitat, Greenhouses, and Regolith Processing. The Resistance/Residence pursues a philosophy of "environmental adaptation". The concept for an integrated inflatable and rigid structure that all deploys together is quite clever and the model explains it very well (Häuplik-Meusburger 2012, p. 105).

2.4.3 MASH—Deployable Emergency Shelter Study (TU Vienna, Vienna University of Technology)

In 2013, the design studios at the TU Vienna challenged the students to develop, build, and simulate an emergency shelter for Mars. The design brief requested an additional crew support element, with regards to potential EVA/science activities to be performed on Mars and related safety issues. The primary feature had to be a

Table 2.8 Evaluation themes for the criteria REPRESENTATION for the design studio 'Destination Moon' (Marc M. Cohen)

SPACE ARCHITECTURE ELEMENTS	
Sub themes	Explanation
Multiple access	Multiple accesses reflect a design that provides two or more means of entry to important areas, rooms, or spaces. There are many functional and safety reasons for why multiple accesses can be an asset
Dual remote egress	Two or more remotely separated exits from a given room or volume is a hallmark of the earliest life safety and fire codes on Earth. It deserves equal or greater attention in a space habitat
Multiple circulation loops	A circulation loop refers to a means of perambulating or translating around a space habitat or base. Multiple routes or loops would be beneficial for flexible and varying uses
Public space	In a space habitat with five to six or more crewmembers, there will be common living, gathering, and circulation areas in addition to shared workspaces. Common living spaces include the wardroom, galley, exercise, and entertainment areas
Vertical circulation	Nearly all the projects incorporate high ceilings or multiple levels in the habitat. [in the studio] The ways in which the crew can access these parts of the total volume serves as an important functional element
Private quarters	Providing a private living space and sleep quarter stands as one of the most widely recognized requirements since Raymond Loewy's design for the Skylab sleep quarters
Work or lab area	Most crewmembers will go to the space habitat or base to work, doing engineering, research, science, or technology development. They will need suitable accommodations to perform these tasks
Plant Growth Area	Self-sufficiency in food will emerge as a vital capability to sustain human space settlements. In addition, the partial G environment presents opportunities for agricultural research
Life support	Life support is a sine qua non of a space habitat. The issue for the studio Destination Moon is the extent to which the architects recognize the role of life support and make some accommodation or indications for it
Surface mobility	The ability to travel safely and in relative comfort over distances on the lunar surface
Use of robotics	Autonomous, robotic, and teleoperated systems are already becoming ubiquitous in the space exploration environment. Surely these capabilities will act as an integrated element of the Destination Moon base
EVA access airlock	Travel on foot to explore and work will remain essential for nearly all EVA activities on the Moon. Therefore the space habitat should include some type of airlock provisions

portable and deployable shelter that can be employed in the event of an emergency requiring immediate action and where return to the base/rover is not possible in time (Table 2.9).

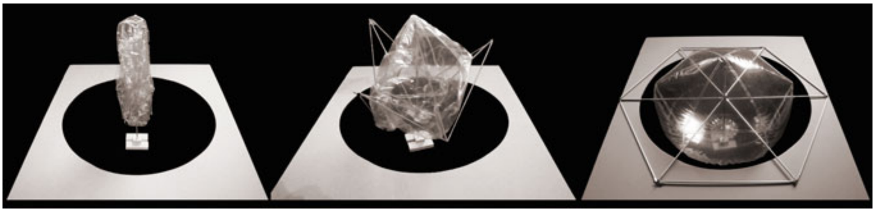

Fig. 2.11 Scale model showing the deployment process of the lunar base project Resistance/Residence undercover by Stefan Kristoffer, VUT Vienna, Institute for Architecture and Design, Design Studio Destination Moon 2012 (TU Vienna, HB2, Kristoffer)

Table 2.9 Program summary 'Space Architecture Classes at the Vienna University of Technology' (TU Vienna)

University/Host	Vienna University of Technology (TU Vienna)
Length/Disciplines	A course is one semester (full-time and part-time students), architecture students, guest students from other faculties (engineering)
Curriculum	PART of the Master of Architecture program
Special features	Periodic program Building of a prototype and Mars Field Simulation
HRL 4–5	4–5 (full scale, low fidelity mockup evaluations), human testing and occupancy evaluations

Following the selection of prospective emergency scenarios and the definition of design criteria, a series of preliminary designs for an emergency shelter was developed within the HB2 academic design studio. A 1:1 prototype was built and tested during the Morocco Mars Analog Field Simulation in February 2013 as part of an operational evaluation of this deployable and portable multipurpose shelter. All design projects and the eventual prototypes have been published and are available online for further research (Häuplik-Meusburger et al. 2013).

2.4.3.1 Prototyping and Field Simulation

The team at the TU Vienna chose a design-orientated approach along with a literature research of the state of the art and potential applications. Students were asked to work on emergency scenarios likely to happen on Mars and to develop the design criteria for the first models.

Based on the res[C]ue concept, a full scale prototype was developed and built.

In total, three prototypes were developed and tested. The second prototype was tested with the suit tester during a Dress Rehearsal Meeting in Innsbruck. The third mock-up was then tested during a field simulation in the Sahara, dealing with the three pre-defined contingency scenarios (Fig. 2.12).

Fig. 2.12 Superposition of several images: Students simulate procedure of selected emergency scenarios to get a feeling for spatial and functional requirements at the Vienna University of Technology, Institute for Architecture and Design, Design Studio Destination Moon 2012 (TU Vienna, HB2)

Between the 1st and 28th of February 2013, the Austrian Space Forum (OEWF) conducted an integrated Mars analogue field simulation in the northern Sahara near Erfoud, Morocco in the framework of the PolAres programme (Groemer et al. 2014). The emergency deployable shelter was among the experiments preparing for future human Mars missions, conducted by a small field crew. The emergency scenarios were tested by the student team and the OEWF analogue astronauts during the analogue simulation mission (Fig. 2.13).

The prototype was made to fit a number of human activities based on the most likely emergency scenarios during an EVA on Mars. Three selected emergency scenarios were tested during the simulation:

Deployment procedure

During the field tests, the handling was successfully demonstrated for the full deployment circle:

- Handling and transportation of the mock-up in packed state and transportation
- Deployment of the structure, including opening the package and inflating the floor membrane
- Deployment of the structure under different topological conditions
- Retraction of the Shelter and performance of the pneumatic system

Fig. 2.13 The Mars Deployable Shelter during the simulation at the Morocco Mars Analog Field Simulation in 2013; TU Vienna, Institute for Architecture and Design, HB2, Design Studio Deployable Emergency Shelter for MARS, 2013 (*Photo* OewF, Zanella-Kux)

Ergonomic usability and its adaptability

The ergonomic usability and its adaptability were evaluated for the following criteria:

- Interaction between the proposed structure and its users (handling and activities in the shelter)
- Off-nominal situations to test the flexibility of the prototype
- Ergonomic and spatial suitability to actions and
- Individual perception of comfort in relation to these activities

The evaluation was based upon a comparison between the shelter deployment behavior under controlled (laboratory) conditions versus the deployment in the field (to account for the influence of dust), as well as a subjective assessment of the developers, the on-site team including the analog astronauts and a post-mission inspection of the wear-and-tear patterns of the hardware. The evaluation demonstrated the expected good functionality of the mock-up. The deployment (pop up) worked as expected and took less than 1 min. Opening (unzipping) the shelter was tested a number of times. Some difficulties were detected due to the small size of the zip pull tabs. Additional ribbons were then connected to the pull tabs allowing easier use with the space suit gloves. The deployment on a slope and rocky surface worked well.

The prototype was designed to allow functional adaptability including the adoption of the sitting and lying positions for the astronauts. The change between the two positions is achieved through air shifting between two supporting pneumatic cushions, one in front and one in the back of the shelter. The change between the two positions was tested with two astronauts inside the shelter. The mechanism worked well and efficiently. The analogue astronauts reported that sitting in the shelter was very comfortable and allowed them to fully relax. The measurements of the astronauts CO_2 levels (carried out by the ÖWF) support this finding. The sitting height was sufficient. The position of the arm-supports could be increased by 5–10 cm. The ergonomic usability in the lying position, however, was not sufficient. The problem was that the life support system on the back and the antenna did not allow the analogue astronauts to lean back, leading to discomfort.

2.5 Guest Statement: The Role of the Space Architect—Part 1 (Brand N. Griffin)

2.5.1 Architectural Versus Engineering Approach

Engineers think architects make things prettier, difficult to build, and more expensive. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect. This is not an identity problem, but an asset more like being ambidextrous rather than schizophrenic. Table 2.10 provides some insight into the different approaches of engineers and architects.

The tendency to classify personal attributes leads to the assumption that they are complementary or mutually exclusive. Thus, one is either engineer or artist; not both. Most authors writing about system architecture are engineers yet they acknowledge that the role requires a combination of deductive (engineer) and inductive (architect) reasoning.

Because space flight started and remains within the engineering domain, space architects have had to masquerade as system engineers or configurators (engineering for vehicle designer). Engineering managers suspect there must be a role for architects but do not know where to place them within their organization. Part of the problem is the job title. This description uses "space architect" which can easily

Table 2.10 Engineers and architects approach problems differently

Engineering approach	Architectural approach
There is a single, ideal solution	There are many solutions
I must start at the beginning of the process	Start anywhere, then adjust
A good process will yield a good solution	Inspiration before process
Most decisions are quantifiable	Some decisions are quantifiable
You can't do that	Why not?

include system architect, space system architect, configurator, subject matter expert, and sometimes systems engineer. MIT professor Crawley (2007, p. 1) offers the following comprehensive definition for system architecture: “the embodiment of concept, and the allocation of physical/informational functions to elements of form, and definition of interfaces among the elements and with the surrounding context.” It is no wonder space architects have not found a home in the engineering organization.

There is no single job title for the “space architects” scattered across international government and private organizations. Practicing space architects currently contribute to mission planning, vehicle integration, habitat design, and human factors, but are particularly attracted to the areas of design integration and concept development.

2.5.2 Waterfall

In his book **Systems Architecting**, Eberhardt Rechtin (an engineer intrigued with architectural problem solving) addresses the role of the architect within the organization. His model has less to do with the individual professions and more about establishing functional connections within an organization. He begins describing different phases of program development using a waterfall (Fig. 2.14). This logical progression defines a sequence of major programmatic steps moving from need and resource to adaptation. Because the conventional waterfall does not accurately represent today’s complex systems, he provides further definition in an expanded waterfall (Fig. 2.15) adding a box for the architect and showing organizational relationships (Maier and Rechtin 2000).

What is clear by this diagram is that the architect must not only have a comprehensive view of the product and process, but must be directly connected to key decisions from beginning to end. Dr. Rechtin believes that the system architect “is not a generalist, but rather a systems-oriented specialist” (Rechtin 1991, p. 141). Furthermore, regarding the architects role, he states that “… architecting is working *for* a client and *with* a builder” (p. 36) Then he upsets the applecart by saying, “… engineering is working *with* an architect and *for* a builder. (p. 8)” Within aerospace, this relationship is disruptive, but it is consistent with the fundamental nature of “architecting” because the architect must be well positioned within the organization to be effective. In other words, you cannot “architect” from below. Considering the nature of the work and role in the organization, it is logical that the number of architects is small compared to the number of engineers. In fact, along with others, Frederick P. Brooks and Robert Spinrad believe that the greatest architectures are the product of a single architect or at least a very small, carefully structured team (Rechtin 1991, p. 47). Rechtin reinforces, “If [...] the single mind is the essence of architectural integrity, then ‘the disciplined team’ is the essence of engineering integrity.” (1991, p. 4)

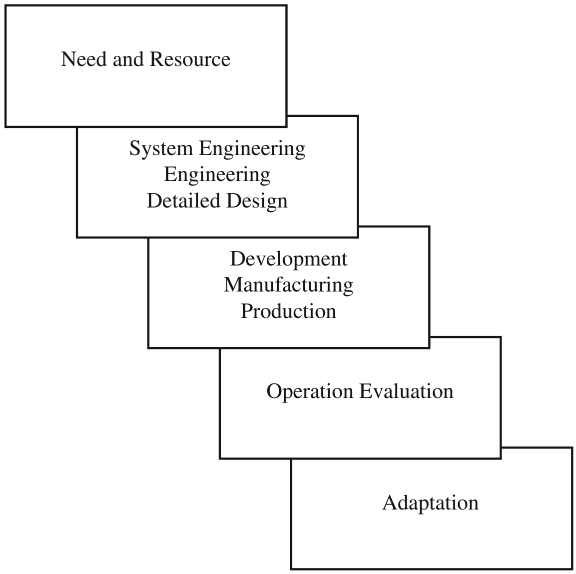

Fig. 2.14 Waterfall of major programmatic steps (Griffin B., redrawn by the Authors, based on Eberhardt Rechtin)

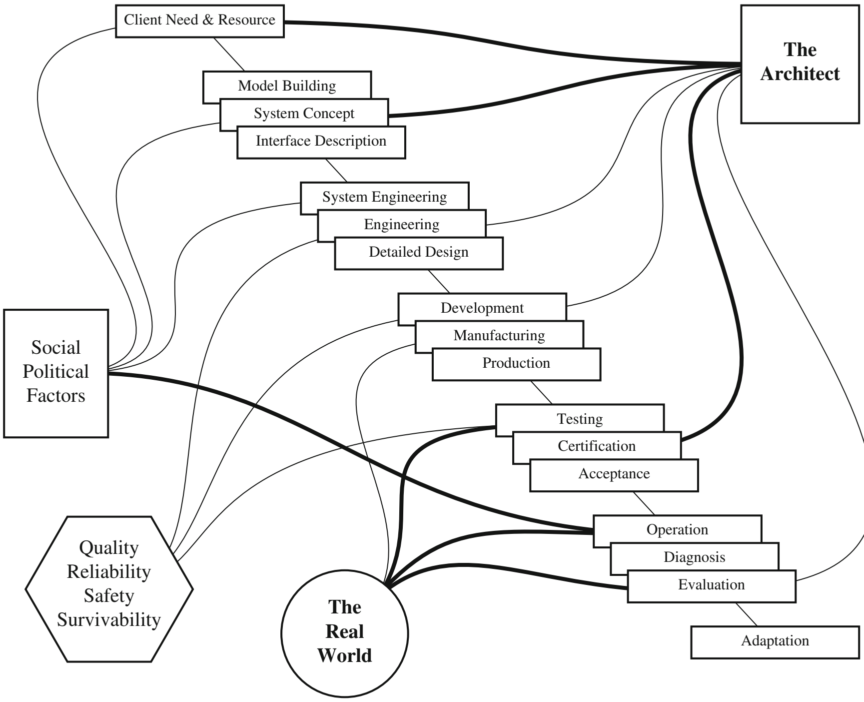

Fig. 2.15 The architect's role in the expanded waterfall (Griffin B., redrawn by the Authors, based on Maier and Rechtin 2000, p. 37)

Regarding roles, there is little purpose to debate the jurisdictional question of just how much system engineering is done by the architects (not much because there are not that many architects) or how much system architecture is done by the typical systems engineer (not much-too many cooks spoil the soup). Overlap is essential-this interface looks fuzzy from either side. The serious mistake is to leave a gap.

2.5.3 Heuristics

Why all the fuss? Just design it, get management buy-in, build it, and then send it to the launch site. This approach is partially correct, but to make a point, it over simplifies each step. In reality, the process for building complex systems relies on many decisions-making techniques, some logical, some heuristic and others a product of management decree.

Georgia Tech's, Tom McDermont states "system architecting differs from system engineering in that it relies more on heuristic reasoning and less on the use of analytics." (2011, p. 26) A similar, yet more forceful assertion is made in **Systems Architecting**. Heuristics, or experienced based reasoning, is characterized as essential to architectural problem solving. Rechtin says, "…architects have insights, lessons learned, rules of thumb and the like that consciously or unconsciously are brought to bear on complex problems." (1991, p. 43)

Heuristics are not new. Three commonly cited examples of heuristics are: (1) Murphy's Law, if anything can go wrong it will, (2) the acronym KISS or Keep It Simple, Stupid; and (3) Occam's Razor: The simplest solution is usually the correct one.

With regard to space architecture, von Tiesenhausen, one of the von Braun German "rocket scientists" who worked on the Apollo Program says, "*If you want to have a maximum effect on the design of a new engineering system, learn to draw. Engineers always wind up designing the vehicle to look like the initial artist's concept*." (Akin's Laws of Spacecraft Design, 30) Furthermore, there are many applicable heuristics in **Systems Architecting** with others collected in personal lists of "laws."

2.6 Guest Statement: Space Architecture Education—Site, Program, and Meaning (Brent Sherwood)

In 2002, the Millennium Charter (SATC 2002) crafted at the 1st International Space Architecture Symposium defined space architecture as "the theory and practice of designing and building habitable environments in outer space," by analogy with terrestrial architecture.

Space architects hunger to tackle the near-existential problem of fashioning "offworld" environments—places off Earth where the native conditions we find are quickly lethal, but in which human civilization could nonetheless someday survive, root, grow, and thrive. We are motivated by the long view that, no matter what else befalls us or what we bring upon ourselves, somehow humans inevitably must lead Earth life out into the universe.

Nothing builders have faced in the most recent ten millennia of human history—recorded in artifacts—exactly prepares us for this new challenge. In just the past half-century humans have ventured into a place where there is no weight or night, touched the Moon, and established a research outpost that skims above Earth's atmosphere. What of the next half-century?

Off Earth, we find a combination of conditions unlike any encountered before by living things: absence of weight; unfiltered, unending sunlight; cold so deep it liquefies air; lethal radiation streaming from solar storms and dying stars; distances too vast to allow direct conversation; and alien landscapes stranger than we might dare imagine.

Architects always start with Site, Program, and Meaning: the "where," "what," and "why" of a building project. But for space architecture, what are these things?

First questions about Site might be about slope, ground consistency, view-lines, and sunlight at some particular place on the lunar surface. Or, following Mars discoveries, we might think about how to keep perchlorate-laden dust from infiltrating an airlock, or about the planetary-protection implications of subsurface ice, or about engineering a scheme to access the ancient southern highlands (which we cannot yet do). However, we shall see that "typical" site topics are all second-order issues. Space is vast, and many more inner solar system destinations will be accessible to humans in this century than just the surfaces of the Moon and Mars. As space architects, we must be prepared to define and solve challenges for all the places people might go, and for what they might be doing there.

So the next issue is the architectural Program. At first, it might seem obvious: keep the "soft pink thing inside" alive (as fighter-jet engineers used to say), but far away from Earth, and for as long as it takes to land, explore, and get back to Earth. This model of an architectural program—which later we will call *Explore*—is, however, only one of four very different programs for what humans might be doing in space in this century. *Explore* is the vision promoted by government space agencies today, but as space architects we must be prepared for other models, too. What happens once exploring is done? Do we move on, or *Settle*…or retreat? How would the architecture of a settlement be different from that of an exploration outpost? And what about the vision several of today's entrepreneurs have, to make space flight accessible to ordinary people? Leisure travelers need a different kind of *Experience*, in different numbers and with quite different amenities than do highly trained, right-stuff mission crews. And finally, what about the architectural needs of technical teams in space who would support these activities, or who would construct and sustain other types of industrial mega-projects to *Exploit* the unique properties and resources we find in space? What are the space architecture implications of the four Programs?

Finally, one of the modern distinctions of today's architects is that as a community of practice, we continuously ask "why." We do not simply design solutions for programs given; we challenge underlying purpose and contextual issues to find and then express Meaning in what we design (Sherwood 2012, pp. 600–609). The built environment speaks, both presently and down through time, by embodying the aspirations and values of both builders and clients. For architecture in space, what are these aspirations? What should they be?

2.6.1 Site

We should think beyond the limited typical view of "destinations" for human space flight. We are fortunate that the universe presents us with two large worlds—the Moon and Mars—that people could explore in this century. Naturally we are drawn to these destinations because they are planet-sized and we, after all, evolved on a planet. But they are only two among myriad potential Sites where space architecture could be important. Ironically, they are also the hardest among all these destinations to reach. Space architects should understand the full range of potential destinations, because design requirements vary significantly across them.

Figure 2.16 is a conceptual map of the "human-accessible" solar system, ranging from near-Earth space out to the surface of Mars. The obvious, traditional

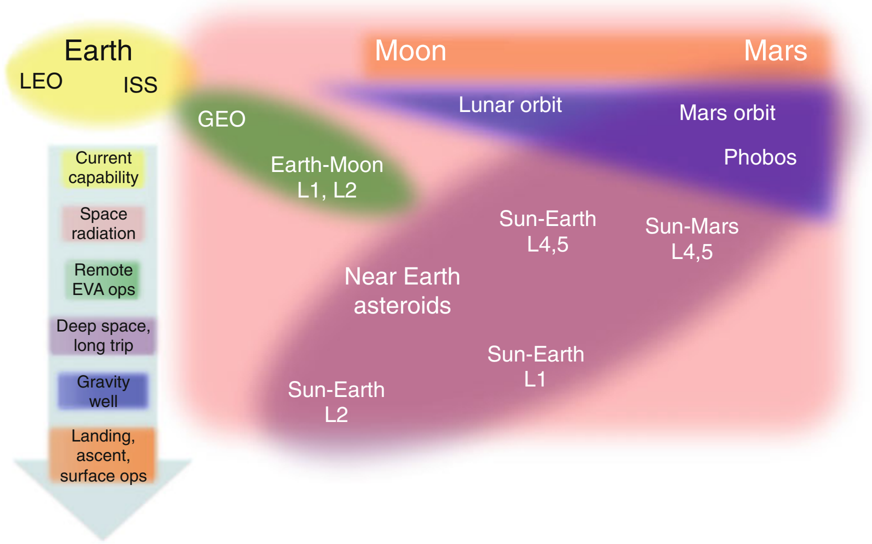

Fig. 2.16 In the foreseeable future, humans could live and work in diverse locations throughout the inner solar system—not only on the Moon or Mars. Each Site poses unique architectural challenges and opportunities (Sherwood)

destinations are across the top. The color key shows additive challenges that must be met, in increasing order of need as we move out from Earth.

Current space flight capability is in the yellow zone: low Earth orbits (LEO) that include the International Space Station. In the 1970s we could get to and from the Moon's surface, but today we cannot, and all human space flight is constrained to the yellow zone. The first challenge beyond LEO is radiation: every destination in the large pink rectangle is bathed in it: (1) transiting the van Allen belts of electrons and protons trapped by Earth's magnetic field; (2) large, episodic fluxes of energetic protons emitted by unpredictable solar storms; (3) galactic cosmic radiation fluence, comprising heavy atomic nuclei and protons accelerated to relativistic speeds by stellar explosions. On Earth's surface, inside the geomagnetosphere and beneath atmosphere, we are shielded from all this, but space voyagers will require shielding technology and biomedical mitigation. Risk tolerance during the Apollo program exceeded today's standards; astronauts flew unshielded, and one of the largest solar flares occurred on August 2, 1972, between Apollo 16 and 17.

Next, consider the green oval containing nearby destinations. GEO comprises geosynchronous orbits, a set of close-to-equatorial orbits centered on a definitive, circular equatorial orbit with 35,786 km altitude. At this special destination, orbital velocity matches Earth's rotation, so satellites "hang in the sky" as viewed from Earth. These orbits are already industrialized for telecommunications and for persistent remote sensing of Earth. The remaining undeveloped major use would be collection, conversion, and transmission to Earth of solar energy for electrical power (more on this below).

The two-body Earth-Moon system also has five Lagrange points, where the inertia of a satellite's orbital motion is in balance with the gravitational fields of both bodies. These special destinations allow spacecraft to maintain position with respect to both Earth and Moon with very little propulsive expenditure. Of the five points, EM-L1 (between Earth and Moon, 85 % of the way to the Moon) and EM-L2 (64,700 km beyond the Moon's Farside) are particularly useful. EM-L1, a gravitational high ground, could be a staging node for routine travel to and from the Moon and other destinations throughout the solar system. At EM-L2, a large "halo orbit" has the benefit of being able to see both Earth and the lunar Farside simultaneously, providing a continuous, real-time telecommunication link between them. In addition to radiation mitigation, the "price of entry" for practical human operations throughout the green zone would be the capacity for extravehicular activity (EVA), especially for maintenance or large-scale construction operations in GEO, or depot operations at EM-L1.

In 1974, Gerard K. O'Neill's concept team postulated that EM-L4 and L5 would become prime locations for space settlements, constructing power stations for GEO. Industrial-scale amounts of lunar resources would be launched to L4 and L5 from lunar mining colonies by electromagnetic catapults. The L5 Society took its name and inspiration from this destination.

The diagonal purple oval zone includes many useful destinations that, while not more challenging to reach than the EM points from an "energetic" (propulsion) standpoint, are all much farther away. All in deep space, they impose long trip times that pose diverse additional challenges for human space flight, as yet undemonstrated: long-duration, deep-space life support, medical care, psychological factors, and operational sustainability.

By far the largest class of destinations in the purple zone is NEOs (Near Earth Objects), asteroids and extinct comets in solar orbits similar to Earth's. There are well over 10,000 NEOs known so far, including about 1000 that are bigger than 1 km, of which almost 200 are classified as Potentially Hazardous Objects (PHO) that could cause large-scale destruction if they hit Earth. NEO orbits continually evolve due to complex perturbations, so PHO orbits are continually monitored and analytically propagated into the future to assess probability of impact. No means have yet been tested to deflect or disrupt such an impending impactor. Potential human activities at NEOs include scientific and geotechnical exploration, disruption experiments, relocation, resource extraction, and eventual settlement.

Other destinations in the purple zone include the five Lagrange points of the two-body Sun-Earth system (Fig. 2.17). SE-L1, between the Sun and Earth, offers a unique vantage point both for monitoring solar wind emissions just before they reach Earth, and for continuously, synoptically observing Earth's entire day-lit hemisphere. SE-L3 allows continuous robotic monitoring of the side of the sun that we cannot see from Earth. SE-L2 is a preferred location for in-space telescopes due to its benign environment, constant distance from Earth, and geometry: to a spacecraft there, both the sun (for power) and Earth (for data relay) are on the same side of the sky all the time. The James Webb Space Telescope is designed for operation at SE-L2. JWST's baseline operations scenario does not include human intervention, but servicing might be planned for future telescopes once human missions reach out into deep space. No human has yet been as far from Earth as SE-L2 (1.5 million km away, four times as far as the Moon).

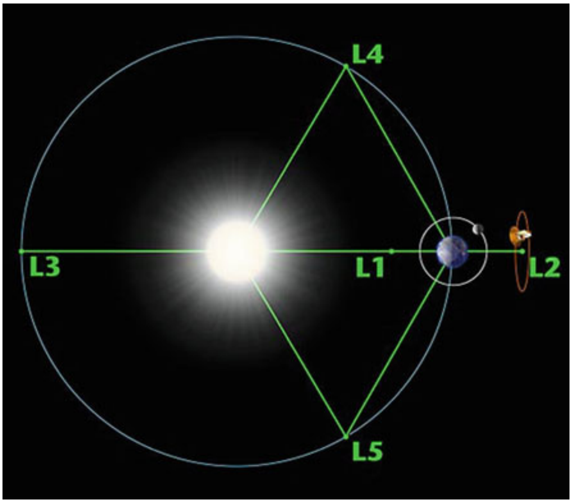

Fig. 2.17 Diagram of all five Earth-Sun lagrange points (NASA)

SE-L4 and SE-L5 are potentially key destinations for an industrial space flight future. These are the “stable” Lagrange points in the Sun-Earth system, 60° ahead of and behind Earth in its orbit (thus, 1 AU from Earth or 150 million km, 100× more distant than SE-L2; a radio signal takes more than eight minutes to travel from Earth to these destinations). Because they are dynamically similar to the Sun-Jupiter L4 and L5 points, where we know that more than 6000 Trojan asteroids orbit, they may harbor asteroids. But because they are in the day-lit sky as viewed from Earth, detecting asteroids with terrestrial telescopes is quite challenging. So far, only a single Earth Trojan asteroid has been discovered (in a highly inclined orbit). But if there are many more, they could comprise a key material resource for in-space use. These places remain among the most promising sites to host human settlements in the distant future.

Mars also has Trojan asteroids, despite its small size; seven have been discovered so far. Just as the moons of Mars can inform our understanding of the dynamical history of solar system formation, the composition of the Mars Trojans likely holds similar clues. From the standpoint of human exploration, they are comparable to voyages to the vicinity of Mars but may represent key stepping stones for increasingly challenging missions on the path to Mars, as they are not deep inside Mars’ own gravity well.

The blue triangle encompasses destinations that require large propulsion stages to get into and back out of planetary gravity wells: orbits around the Moon and Mars; and Phobos and Deimos, the two moons of Mars. Albeit deep in the lunar gravity well, low lunar orbit (LLO) can be a superior staging location for some system architectures, particularly those that use oxygen propellant mined from the Moon. Phobos is particularly interesting: scientifically because of its anomalously low bulk density and record of solar system dynamical evolution, and operationally both as a source of volatiles, and as an orbital base for teleoperating robots on Mars (it rotates synchronously, with Stickney crater always facing Mars).

Finally, the orange bar at the top contains the destinations most commonly talked about: the surface of the Moon and the surface of Mars. Getting humans to and from these destinations requires all the advanced capabilities of the other destination classes (radiation protection, EVA operations, reliability without Earth intervention, large propulsion stages), but also a significant list of additional, expensive capabilities: planetary descent and soft landing, extensive surface operations of multiple types, and planetary ascent and rendezvous. Mars has enough gravity to make landing and ascent a challenge, but barely enough atmosphere to help slow down. While landing robots on Mars may seem almost commonplace today, landing human systems weighing over ten tons would require dramatic implementation of multiple technologies not yet demonstrated. Landing on the Moon must be done using only propulsion, so large descent stages are required. Indeed, the “orange bar” destinations that govern so much of our conversation about future human space flight are the hardest to get to and from, among all the destinations shown.

While not indicated by this map, it is conceivable that after gaining experience with long-duration, even permanent, deep-space flight, humans could venture throughout the Main Asteroid Belt, a vast region of the inner solar system, ranging from about 2–3.3 AU (twice as far from the sun as Mars), that contains hundreds of thousands of asteroids and the icy dwarf planet Ceres. Sunlight in the outer Main Belt is only one tenth as strong as at Earth, but would be sufficient, along with the vast material resources found there, to eventually support a huge human population.

The inner solar system is truly a rich place, full of diverse types of destinations, conditions, and resources. Space architects need to realize that human space flight futures are not limited to just the Moon and Mars, or a specious choice between them. However, without the gravity caused by planetary-scale mass, the other destinations on the map and in the Main Belt are microgravity or milligravity environments. Human habitability exceeding ISS-type mission durations (everywhere beyond cis-lunar space) will depend on effective, sustained deconditioning countermeasures, possibly including rotating artificial gravity. Most of these destinations are too far away for real-time conversations with Earth to occur; one-way signal delays range from minutes to hours. The unique environmental and operational characteristics of specific Sites must be calculated and understood up front.

2.6.2 Program

Given the possible Sites, we can consider the range of architectural Programs for human space flight. All the purposeful activities ever envisioned for human space flight aim principally at one of four objectives:

- Explore
- Exploit
- Experience
- Settle

Table 2.11 contrasts these objectives, focusing for each on its most definitive specific activity (Option), how we might justify it in a few words (Purpose), a simple conceptual template for what each means to our culture (societal Myth it embodies), some unique Needs beyond just time and budget, its Yield after several decades, and finally the actual spacefaring population that it would create by mid-century. The four objectives are not interchangeable. Each measures success using different criteria, each hinges on different investment priorities, and each creates a different future. The differences matter greatly because we cannot really develop all four at once.[11] Even if combined coherently, the resources of all existing global and private space programs would be insufficient to create all four

[11]Further Reading: Sherwood, Brent. 2012. Technology Investment Agendas to Expand Human Space Futures, Proceedings of the AIAA Space 2012 Conference and Exposition (Pasadena), American Institute of Aeronautics and Astronautics (Reston), 2012, AIAA 2012-5131.

futures simultaneously. A choice to pursue one objective cannot avoid deferring progress toward the others, so it is vital that our society be clear about which one we want the most, or first.

2.6.3 Explore

By mid-century, a small team of intrepid humans could stand on Mars. This tiny planet (total surface area about equal to Earth's land area) has fired humanity's imagination for millennia and physically lured us for centuries.

We know its atmosphere is unbreathable, almost two hundred times thinner than Earth's. And we know that while it was once an ocean world, it is now as cold and dry as Antarctica. Still, Mars is the "least inhospitable" ready-made world within our reach. It has polar caps and night frost, wind-driven weather, and Grand Canyon-like landscapes. Plate tectonics never started there. And, far smaller than Earth, it cooled so fast that its magnetic field died billions of years ago, allowing the solar wind to strip its atmosphere and send it into a permanent, desiccated deep freeze. But flowing and standing liquid water once hosted clement conditions; did life ever arise there?

Today, we use robots for scientific exploration of the amazingly diverse remote places throughout our solar system. Back in 1961, just as the first human-launch experiments occurred, President Kennedy connected human space flight to exploration by selecting the "Moonshot" (from among a menu of barely feasible options) as a highly visible yet peaceful project to demonstrate US technological superiority over the Soviet Union.

Ever since Apollo succeeded, exploration has become the de facto raison d'etre for human space flight by space agencies around the world, even though "using people to explore planets" was not actually Apollo's core purpose. This linkage between human space flight and exploration is so strong that it is commonly taken as an equivalence: in some discussions, the astounding feat of continuous operation of an international research laboratory in Earth orbit is derided as "going nowhere, in circles."

Severe technical challenges limit direct or extensive exploration by humans of the Moon, near-Earth asteroids, the moons of Mars, and Mars itself. About ninety times farther than the Moon (as measured in travel days), Mars is cast as the prize: the "horizon goal" and "ultimate destination." Mars is the most distant surface we could reach by mid-century. This explains why, if to *Explore* is our core objective, the Moon cannot compete with Mars—it is neither novel nor distant enough. Hence Table 2.11 defines "Explore Mars" as the best proxy for the broader exploration imperative. Is the societal myth of Lewis and Clark, intrepid explorers of a new continent, as strong elsewhere as in the US? NASA's international partners tend to favor incremental steps, which feeds persistent debate about "exploring" the Moon first.

The space architecture challenge centers around sustaining, and maximizing the hour-by-hour productivity, of a small team of highly trained experts very far from

Table 2.11 Four distinct options capture the range of possible goals for human space flight

Option	Purpose	Myth	Needs (+$\$10^{11}$ over 40 year)	Yields	2050 space population
Explore Mars	Extend direct human experience as far as possible	Hero (Lewis and Clark)	Public commitment sustained over several decades	Cultural achievement: setting foot on Mars	Six international civil servants
Settle the Moon	Establish humanity as a two-planet species	Pioneer (Heinlein)	Routine heavy traffic to lunar surface Use of lunar resources	"Living off the land" in space	10^3 citizens raising families off-world
Accelerate space passenger travel	Create new travel-related industries	Jet set (Branson)	"Four 9s" reliable launch and entry	Highly reliable, reusable space vehicles 1-h intercontinental travel	10^3 crew $+10^5$ citizens in LEO every year
Enable space solar power for Earth	Prepare for post-petroleum age with minimal disruption	Green	Public–private and inter-agency partnerships	Energy-abundant future Economical heavy-lift launch	10^2 skilled workers in GEO

Each transforms unique investments into a unique vision of the future by mid-century (Sherwood 2011; reformatted by the Authors)

any physical help. For such professionals on such a mission, what configuration and amenities are optimal? How can we make an environment safe from natural hazards for several years? What role could the architecture play in managing, or avoiding altogether, spaceflight deconditioning? Which technologies and equipment can control the air, water, temperature, and consumables, and be maintained for such a long voyage; and how should they be integrated into the architecture? What is the relationship between habitats for deep space, for landing and ascent, for planetary surface operations, and for mobility?

The necessary investments to land people on Mars are daunting: advanced in-space propulsion, space vehicles weighing tens of tons that decelerate to a soft landing within seconds (with humans inside), extraction of propellant and breathing oxygen from the tenuous Mars atmosphere, machinery and medical means to survive three years away from Earth, isolation of human biology from the Mars environment, and many others—even small fission reactors. Most of these "stretch" technologies would yield uncountable spinoff benefits we cannot foresee today, as space flight has always done. And at the project's culmination, billions of Earthlings would pause in their quotidian concerns, awed by live video of the "first Martians."

As hard as it is to estimate the cost and date of achieving this milestone, it is impossible to anticipate its impact on humanity's existential sense of self and destiny. We also do not know whether the commitment needed to get that first small crew on Mars can be sustained over the decades of development, tests, and setbacks it would take. Nonetheless, *Explore* is the objective our space agencies are currently aiming for.

2.6.4 Exploit

Imagine a world where electricity comes from the sky, rather than from burning fossil fuels; a world where precious metals, mined on the Moon and harvested from captured asteroids, are imported from space in vast quantities. Space is almost inconceivably empty. But paradoxically it holds resources that can enable a human future without limit. Today we use various Earth orbits only for observation, telecommunications, astronomy, and research. But by mid-century, space could also provide both energy and materials for Earth at industrial scale. Exploiting these resources would almost inevitably then pull humanity naturally out into the solar system.

Space material resources are diverse. The Moon has concentrations of “rare Earth elements” essential for high-tech products ranging from smartphone screens to the magnets in wind-turbine generators. It also contains recoverable amounts of ^{3}He, a rare isotope of helium that could fuel hypothetical fusion power reactors. And a very small fraction of asteroids are almost solid metal: iron and nickel alloyed with platinum-group metals vital for electronics and chemical manufacturing. Nudging the orbits of just a few of the thousands of NEOs could bring such resources close enough to harvest, forever changing industrial economics.

Enabling industrial-scale exploitation of space material resources would require many investments—in high-power space systems, large-capacity electric and electromagnetic propulsion, autonomous extraction and processing technologies—far beyond the means of today’s space entrepreneurs but suitable for government development. How important might it become to some nations to assure access to unlimited amounts of strategic materials?

The most startling space resource weighs nothing at all: photons. In high Earth orbit, sunlight is about forty percent stronger than on the surface, and the sun never sets. The fundamental technologies to convert sunlight into electricity; transmit microwaves to Earth with phased-array antennas; then collect it with dipole-antenna arrays over farmland to convert the power back into electricity for the terrestrial power grid, are all well understood. The geosynchronous orbit, already industrialized for telecommunications and remote sensing, could be developed further into an inexhaustible source of clean electrical power, for “export” anywhere on the globe independent of night, weather, or local conditions, and without blighting the landscape or damaging wildlife or the environment (Fig. 2.18).

This would be “macro-engineering” to be sure. Only a vast enterprise could supply a meaningful fraction of Earth’s energy appetite: complex transnational public-private partnerships, funding a steady stream of heavy-lift cargo launches,

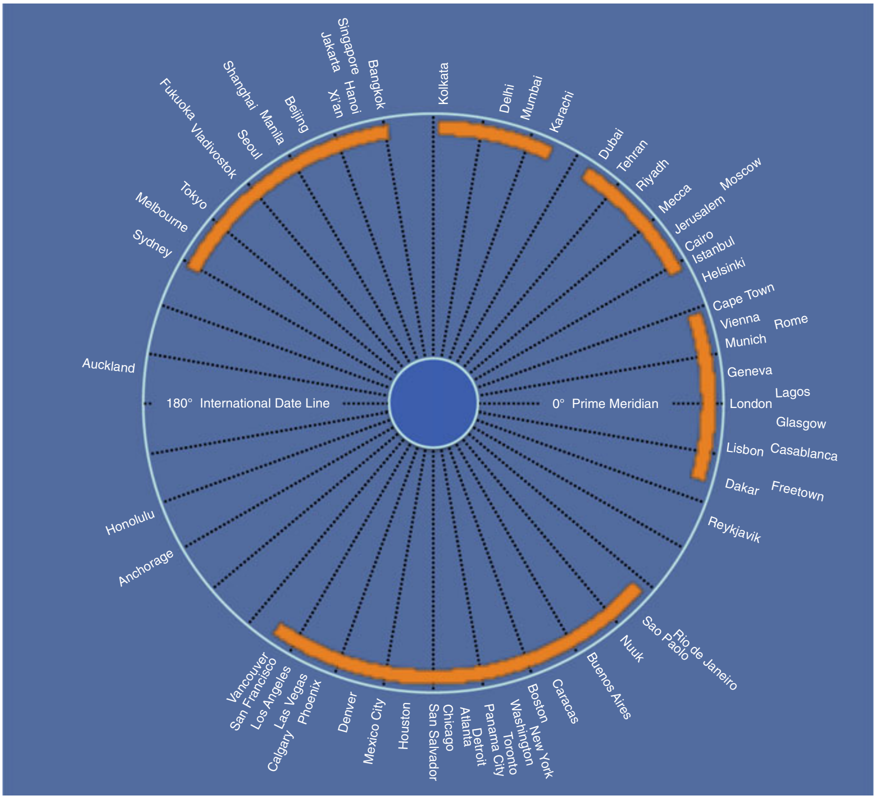

Fig. 2.18 Human geography viewed from GEO: projecting longitude of major population centers onto GEO (Earth shown to scale) shows diverse cultures becoming unlikely neighbors when Earth's electricity "comes from the sky." Today's major spacefaring powers (the US, Europe, Russia, India, China, and Japan) all have obvious regional interests (Sherwood)

fleets of robot workers, and onsite crews to construct and operate platforms in space with a total area comparable to the US National Highway System.

The space architecture challenge centers on routine and continuous access by technical work crews totaling several hundred people, throughout vast arcs of the geosynchronous belt, to a fleet of robots that build and maintain enormous power stations. Dormitories, maintenance shops, in-space shuttle "buses," and seasonal rotation of crews from Earth would all be needed—systems without precedent and not currently being developed. How far could today's ISS-based life-support subsystems and habitable modules go in supporting this scenario? How could a habitat large enough to support social assembly of such a human community be built and verified? What functions, features, and leisure facilities would be needed for hundred-person work crews? Modern shale-oil extraction encampments in the US upper Midwest offer a template for the type of accommodations appropriate for work and life on an industrial frontier, but very little design analysis has been done so far to understand how to adapt these lessons for space flight.

Space operations based on high power would quickly open additional space resources and their derivative industries: materials, tourism, and manifold service industries not yet conceived. Albeit grandiose, the vision of industrializing space for power requires no miracles. It could be done, if one or more spacefaring nations chose to lead humanity through an orderly transition to a sustainable, post-petroleum world.[12]

Today though, *Exploit* does not yet drive any nation's space flight priorities. Only Japan—with 40 % the population of the United States but just 4 % the land area, most of it mountains—and perhaps China and India appear interested in demonstrating the feasibility of power from the sky. None of the most accomplished space exploration leaders (the US, Russia, and Europe) have yet connected their capabilities in launch, human space flight, and space operations with the looming geopolitical issue of clean, sustainable energy; Earth's non-renewable energy sources are still too available, affordable, and profitable.

2.6.5 Experience

By mid-century, two-week vacations in Earth orbit could be routine. Like cruise ships today, orbital resort hotels would course silently over the planet once every ninety minutes, through eighteen sunrises and sunsets each day. Architects imagine the amenities: weightless staterooms with awesome views; gourmet meals prepared from space-grown and globally imported fresh foods; "zero-g" recreation including spherical swimming pools, weightless discotheques, and free-fall sports, games, and performing arts; guided telescope tours of the home planet below; and suited excursions into the vacuum of space.

Leisure travel in Earth orbit is a marketable *Experience*: the ride of your life (ten minutes up and forty-five down); the incomparable sensations of sustained weightlessness; and the solar system's most poignant, beautiful, ever-changing view out the window. As happened with air travel in the first half of the 20th century, demonstration of consumer-level flight safety would unleash a mass market. While today neither sufficient safety nor compelling destinations exist, both are achievable with focused investment.

The space architecture challenge includes everything needed for routine operation of resort destination complexes: spaceliners to ferry scores of passengers at a time between Earth and orbit; large-volume pressure vessels built and certified for occupancy in space; big windows to make the most of the glorious views; "kitchen science" for chefs operating in free-fall; leisure architecture of many types; space

[12]Further Reading: Sherwood, Brent. 2012. Space Architecture for Industrial-Scale Space Solar Power, AIAA 42nd International Conference on Environmental Systems (San Diego), American Institute of Aeronautics and Astronautics (Reston), 2012, AIAA 2012-3574.

surgery; perhaps rotating artificial gravity; and many others. Today no government is developing any of this; unless some do, this amazing yet feasible future will remain far off.

Without technology help, privately funded commercial orbital leisure travel will be a very slow-growing market, catering only to the hyper-rich and interrupted by the kind of spectacular accidents that teach aerospace lessons. The research and flight rate required to approach airline-like safety are far beyond the means of today's commercial space flight entrepreneurs, all of whose plans and machines adapt technology originally developed by NASA. And today's space "destination systems" also depend on technologies developed by and for government projects. One outspoken former NASA Administrator used to pound on the podium and declare, "Space tourism is not my job!" But why not? NASA's own predecessor agency (NACA, the National Advisory Council for Aeronautics), created during World War I, developed the airfoil and engine technologies inside every modern commercial and military jet. As a result, air travel enables the way we live today.

If NASA and its partners decided to transform our world again, by developing the technologies to enable hundreds of thousands of ordinary people to fly in Earth orbit every year, they could jumpstart whole new industries including orbital resorts and one-hour travel between London and Tokyo. Many secondary industries would emerge around this core market, making the *Experience* of space viscerally central to mid-century society.

2.6.6 Settle

Imagine living in a human community committed to taming a hostile frontier, putting down roots and raising families in a strange, faraway place full of unique challenges, experiences, and joys. Eventually humankind will settle space. Expansionary and adaptable, *Homo sapiens* has "built to suit" everywhere on Earth. Given territories to explore, resources to exploit, and experiences to sell, human civilization will expand, settle down and set up shop.

Settlement would bring space flight and architecture fully together in the most complete and fundamental way. Far beyond laboratories for researchers, cargo vessels and dormitories for workers, and spaceliners and cruise ships for tourists, settlers would need the thousands of big and little items and services that make human communities self-sustaining in any place. They would generate power, find and extract raw materials, grow and make food, fabricate and recycle building materials and commodity goods, import and export specialized products, raise children, create governments, establish cultures, and leave legacies—all off Earth, in circumstances without precedent. Learning to "live off the land" in space would teach us countless lessons, methods, and technologies useful back on Earth, where we see the human imprint on our natural world looming larger with each passing decade.

No space agency has yet decided to aim to *Settle* space. This may seem illogical: doesn't government investment to explore also advance the settlement purpose? It does, but only weakly. A determined focus on settlement would drive major investments in different directions. Foremost would be routine heavy traffic between Earth and the settlement site. Here especially, the Moon or SE Lagrange points would "win" due to the enormous costs of large, reusable space transportation systems and operations. Rocket systems would be optimized for economy and reusability, and they wouldn't all need to be human-rated. Then, settlers would need technologies for the large-scale extraction of volatiles, metals, ceramics, and glasses from the ground; the manufacture of end products from these resources; and civil engineering to build with them. How would usable products of all types be made; indeed, how could everyday products be re-designed so that they could be manufactured in the settlement, from local materials? What would community-scale life-support and food-production look like on the Moon—clearly it could not be based on warehouses full of finicky machinery. What would it mean to architects to re-invent the broad spectrum of capabilities to support human living, literally from the ground up? None of these questions is a focus of government research today.

Conflating a future vision to *Explore* with one to *Settle* is not optimal for either. The former is about expanding the human range of direct experience as far away as possible; the latter is about expanding human civilization as sustainably as possible. Despite persistent fantasies of Martian colonies, economics strongly favors settling the Moon first: just three days away; rich in raw materials for rocket propellant, construction, and biomass; with low but useful gravity; and with a view of the blue-marble Earth in the black sky. However practical the settlement of Mars will ever be, the Moon will always offer a simpler, safer, quicker, and less expensive way to learn how to *Settle*.

While we can imagine a space settlement slowly growing wherever there are raw materials and energy, fueled by a self-contained barter economy within its expanding population, no place in space is hospitable as found. Horses, pickaxes and grit are insufficient for this frontier, where the very means to stay alive—let alone expand—are high-tech, expensive, and all necessary immediately and continuously. The high capital cost to seed a settlement, and the ongoing challenge of maintaining and elaborating its complement of advanced equipment until it could establish indigenous high-tech production capacity, mean that someone has to invest for a long time. This scale and type of investment requires government commitment, which would in turn hinge on strategic or economic return.

Neither is remotely defensible for Mars. Lunar settlement might conceivably be motivated by competition between China and the West, at least for a time. But long-term justification would still require that the Moon export to back Earth something economically valuable: services, experiences, energy, or materials. The markets for space services and experiences so remote from Earth are precious thin; and the Moon is an impractical platform for beaming energy directly to Earth. This leaves extraction and export of strategic elements as the only foreseeable economic driver for growing a lunar settlement. This same logic drove O'Neill's vision of settling EM-L5, funded by lunar mining to construct GEO platforms to supply Earth with electrical power.

2.6.7 Architecting Our Path

Fewer than a thousand people have flown in space so far. For those who grew up with the "space program," this nonetheless amounts to an astounding total, so large it precludes household recognition of today's astronauts. But out of a human population of seven billion it is a tiny fraction. All spacefarers so far have been carefully selected and highly trained for their missions. Despite our hard-won experience accommodating these explorers and researchers in space, we know nothing at all about how to accommodate other types of potential spacefaring populations: leisure passengers, large-scale industrial crews, or settlers.

By the end of this century we could understand through experience the basics of space architecture for any of the four alternative Programs, but likely not all of them. Private investment in space flight is just beginning, and the barriers to rapid or sustained growth are many and severe. Because space technologies are so complex and expensive, global public investment via government space flight programs will continue to dominate the human space flight agenda deep into this century. So it is vital that, by our investment choices today, we decide consciously which futures to open and which to defer.

Are all big rockets the same? We could design for human-rated throw capacity to deep space, or for economical high-rate delivery to construction sites, or for passenger reliability. Which future should we enable first?

Are all life-support systems interchangeable? We could design for maintainability without resupply, or for closing the loop to minimize mass, or for scalability to large populations. What type of space travelers should we prepare for?

Is reusability important? We could design for rare expeditions to remote places, or for routine exchange of goods, services, and people with a colony. Which vision should we enable?

Figure 2.19 is a simple roadmap that shows how we could make the fastest progress opening all four futures. Everything accomplished in the first half-century of human space flight up through the International Space Station is encapsulated in the two milestones at the lower left: developing the capability to get humans into and out of space, and to sustain them there. Both resulted from government investment, which now (with the SLS and Orion) is extending NASA's human space flight domain throughout cis-lunar space.

The NASA vision then reaches for Mars, at the lower right. But optimistically, even the most skeletal architecture cannot land a tiny crew on Mars until about 2040. This is because the bottom half of the figure is "top-line constrained" since it depends on the NASA budget (and arguably, the companion budgets of cooperating agencies around the world focused on the *Explore* vision). No realistic scenario can increase the agency budget by enough to make a significant difference in the rate of progress, and no amount of exhortation can change this fact. The only way to break out of the top-line constraint is to attract private capital in addition to, and on par with, government funding, and this cannot occur for a roadmap that generates no wealth.

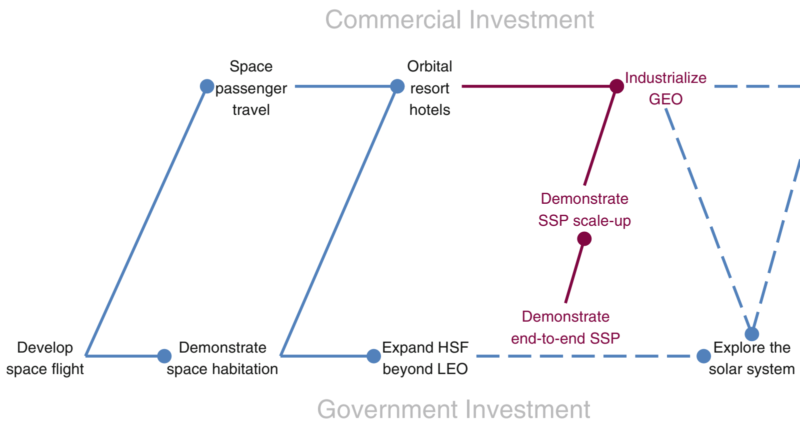

Fig. 2.19 Human travel beyond Earth orbit is too expensive for the traditional space-agency exploration model. A more robust path would first build a commercially based, high-power operations infrastructure. Industrializing GEO for clean energy has the capacity to attract the private capital needed to leverage government investment budgets (Sherwood)

Interestingly, while NASA focuses on SLS and Orion, the potential space passenger travel market is indeed beginning to attract small amounts of private capital (i.e., outside the NASA top-line budget) to develop flight systems based on technologies developed by NASA, RSA, ESA, JAXA, and CSA. Exemplified by companies like SpaceX, Blue Origin, Sierra Nevada Corporation, Bigelow Aerospace, and Virgin Galactic, this path emerges across the top half of the figure.

The large agencies now face a fork, even without realizing it. They could fixate on the bottom path, sights set on exploring Mars, and devote all their resources to making headway on that challenge. Or, they could choose to make space flight integral once again to solving one of the most pressing problems of our era. The Cold War that drove Apollo may be over, but today's world does not lack vexing problems. By investing only a few billion dollars in technology development and end-to-end tests of space solar power, we could demonstrate to the public and to energy investors how industrializing GEO could, at once, benefit Earth and generate profit.

With proof in hand (for example, signs in Times Square and Ginza lit by power from the sky), government and commercial co-investors could establish a public-private partnership to develop and demonstrate the many capabilities needed for industrial-scale implementation (cutting across the center of the roadmap to bridge the worlds of government and commercial investment). Achieving that milestone would clarify the issues, risks, and costs of a large-scale enterprise—hard information needed to attract large-scale corporate and government investment to develop and deploy operational systems.

This new, profit-making space energy sector would create large demand for transportation between Earth and space for both cargo delivery and work crew rotation, as well as crew habitation systems. Both of these expanding markets could be served completely by genuinely commercial providers, after strategic government investments in enabling technologies. Because the large-scale enterprises all occur in the top half of the roadmap, government involvement in these businesses could be limited to regulation, taxation, and security, as in most industries on Earth.

In such a future, space flight, rather than being an effete high-tech industry, would be evident throughout society: integral to the economic and environmental health of society and the Earth. Civilization's transition to a post-petroleum state might be managed with less disruption than otherwise appears to await us in this century.

If space flight became societally central again, and especially if large-scale space operations became as routine, robust, commercially based, and power-rich as they would have to be to industrialize GEO for terrestrial electricity, then human exploration and settlement would both be much smaller steps than the insurmountable cliffs they are today. Perhaps our dreams of walking on faraway sands, and of settling other worlds, are feasible, but not just yet. However, if we first become a trans-Earth civilization, these ambitions become in turn natural.

The US spends about ten billion dollars a year investing in human space flight; the other spacefaring nations altogether invest about as much. This enormous sum is more or less focused on the *Explore* path, motivated by Mars in the US, and it is proving to be very hard, with few opportunities for space architecture. If sustained through mid-century, this investment could put a few humans on an alien world more than twenty light-minutes away. Alternatively, capitalism and the strategic value of space resources might turn our space flight investment toward tangible societal benefits: we could bring the *Experience* of space flight within reach of mass markets, or we could choose to *Exploit* the inexhaustible clean energy available near Earth to transform humankind's impact on our home planet. Either of those paths would create a need for space architects to solve a broader, deeper range of design problems than getting a crew to Mars and back. By far the richest set of space architecture challenges—tabula rasa for designing our built environment and the most fundamental opportunity since our profession began—would arise if humanity set out on the path to *Settle* space.

The roadmap described here does not require us to suppress anybody's dream, or even reverse course; it uses everything already done or being built today. Its only novelties are to recognize that private capital must be attracted if progress is to accelerate; that *Exploit* is a defensible, practical, and achievable purpose that can do this while making space flight central again to a core societal challenge; that the profitable exploitation of space resources would in turn accelerate growth of the *Experience* industry; and that this commercial foundation would then significantly enable the *Explore* and *Settle* goals dreamed about for decades. If humankind threads the needle of this century's most vital terrestrial challenges, then someday we may make a second home for humankind—and take our first steps toward inhabiting the infinite.[13]

[13]See also: Sherwood. Brent. 2011. Inhabiting the Solar System, Open Engineering, 1(1), 2011, pp 38–58, DOI: 10.2478/s13531-011-0004-y. Springer, March 2011.

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