An Interdisciplinary Approach to the Conceptual Design of Inhabited Space Systems

Von der Fakultät Luft- und Raumfahrttechnik
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vorgelegt von

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Abstract

The conceptual design (project phase 0/A) of systems for long-duration manned space missions poses a significant challenge to the traditional design approach used for robotic or short-duration missions. Yet the success of planned expeditions to Mars and beyond depends on the ability of system designers to create an overall concept that maximizes crew efficiency and minimizes cost as well as the risk of catastrophic failure, while at the same time integrating a wide array of technological, crew-related and political boundary conditions.

The interdisciplinary approach presented in this report proposes putting the focus on the most efficient integration of the crew into a space system as one solution to this conceptual design problem. Thus, human-rated space structures – be they inhabited orbital or planetary stations, or piloted interplanetary transfer vehicles – are treated by the designers not as "machinery-with-attached-crew" like earlier spacecraft, but primarily as habitats, in order to assure mission success under conditions of long-term isolation, confinement and risk.

The proposed approach is based on space systems engineering methodology and associated software tools, with key elements from terrestrial architectural practice added. It also provides software specifically developed for the analysis of life support systems – a crucial component of human-rated space systems – during the early phase of conceptual design. Several examples are given to demonstrate the validity of this truly interdisciplinary approach.

"But I put forth on the high open sea
With one sole ship, and that small company
By which I never had deserted been."

Ulysses, in: Dante, The Divine Comedy

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> *„Die Eroberung des Weltraums wird den Menschen von seinen verbleibenden Ketten befreien: den Ketten der Schwerkraft, die ihn immer noch an diesen Planeten binden."*
>
> *Wernher von Braun*

Zusammenfassung

THE FOLLOWING PAGES PROVIDE A SUMMARY OF THIS REPORT IN GERMAN.

Auf den nächsten Seiten werden die wichtigsten Ergebnisse dieser Arbeit in deutscher Sprache zusammengefaßt.

Übersicht

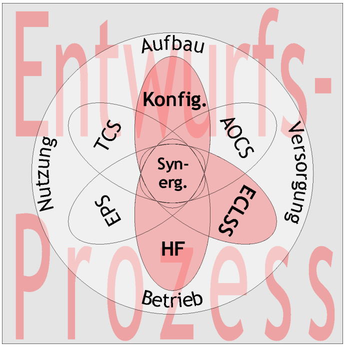
Der Entwurf von Systemen für bemannte Langzeit-Weltraummissionen (Projektphase 0/A) stellt den herkömmlichen Entwurfsansatz, wie er für unbemannte oder Kurzzeit-Missionen verwendet wird, vor erhebliche Herausforderungen. Der Erfolg geplanter Expeditionen zum Mars und darüber hinaus hängt jedoch davon ab, ob es dem Entwurfsteam gelingt, ein Konzept zu entwickeln, welches die Produktivität der Besatzung maximiert und Kosten sowie Risiko minimiert, und das gleichzeitig eine große Anzahl technologischer, finanzieller, politischer und sozialer Randbedingungen berücksichtigt.

Die im vorliegenden Bericht vorgestellte interdisziplinäre Methodik zeigt einen Weg zur Lösung dieses Entwurfsproblems auf. An vorderster Stelle steht dabei die bestmögliche Integration der Besatzung in ein zu entwerfendes Raumfahrtsystem, d.h. die Behandlung bemannter Weltraumstrukturen nicht als „Maschinen mit angegliederter Besatzung", wie oft bei früheren Raumfahrzeugen, sondern als integrierte Lebensräume. Grundannahme dabei ist, daß die Produktivität und Effizienz der Besatzung durch eine an den Menschen angepaßte Gestaltung der Umgebung erhöht wird.

Der vorgestellte neue Ansatz basiert auf einer validierten Ingenieursmethodik zum Vorentwurf von Raumfahrtsystemen samt zugehöriger Computerprogramme. Diese Methodik bezieht jedoch die für bemannte Systeme zentralen Aspekte der besonderen Möglichkeiten und Anforderungen, die sich durch die Anwesenheit einer Besatzung ergeben, nicht im nötigen Maße ein. Deswegen ist sie um wichtige dementsprechende Entwurfsregeln erweitert worden.

Hinzu kommen Elemente aus der „irdischen" Architekturpraxis. In dieser geht es ebenfalls um den Entwurf von Lebens- und Arbeitsräumen für Menschen; sie stellt daher auch entsprechend angepaßte Entwurfswerkzeuge zur Verfügung.

Ferner wurde speziell zur Analyse von Lebenserhaltungssystemen (ECLSS) und deren synergetischen Verknüpfungspotentialen während der Vorentwurfsphase eine Software entwickelt, die eine frühzeitige Auslegung dieses für bemannte Raumfahrtsysteme unverzichtbaren Subsystems ermöglicht. Die Grafik rechts zeigt diese vom neuen Ansatz besonders berücksichtigten Bereiche.



Der vorliegende Bericht ist in fünf Hauptkapitel gegliedert. In Kapitel 1 werden nach einer kurzen Darstellung des Ziels der diesem Bericht zugrundeliegenden Arbeit und der Motivation für die bemannte Raumfahrt die wichtigsten Herausforderungen an den Entwurfsprozeß beschrieben. Zusätzlich werden relevante bemannte Raumfahrtprojekte der Vergangenheit vorgestellt sowie zukünftig zu erwartende Projekte identifiziert.

Kapitel 2 führt dann in die Elemente ein, auf denen der neue Entwurfsansatz beruht: Vorentwurfsmethodik im Ingenieursbereich, menschenbezogene Aspekte sowie Entwurfsprozeß und Entwurfswerkzeuge der irdischen Architekturpraxis.

In Kapitel 3 wird die neuentwickelte Entwurfsmethodik dargestellt. Diese vereinigt die in Kapitel 2 beschriebenen Elemente in den Bereichen „Entwurfsprozeß", „Wissen" und „Software".
Kapitel 4 dokumentiert Beispielanwendungen der neuen Methodik im Rahmen von interdisziplinären Entwurfsprojekten und Workshops.
In Kapitel 5 werden schließlich die gewonnenen Erkenntnisse zusammengefaßt und ein Ausblick auf weitere Entwicklungsarbeiten gegeben.
Am Ende des Berichts findet sich eine Auflistung der verwendeten Literaturquellen, ein Abkürzungsverzeichnis sowie ein Index.
Die Gliederung der folgenden deutschen Zusammenfassung orientiert sich an der des englischsprachigen Textes.

Hintergrund

Vor Beginn eines Raumfahrtprojektes sollte die dahinterstehende Motivation geklärt sein, da diese den Verlauf des Entwurfs beeinflussen kann. Speziell für bemannte Missionen sind in der Vergangenheit eine Vielzahl von Begründungen vorgebracht worden, die sich in zwei Kategorien aufteilen lassen.

Auf der einen Seite stehen Nützlichkeitserwägungen, wie z.B. die Argumentation, daß die Raumfahrt ein Hochtechnologiebereich ist, der durch bemannte Missionen gefördert bzw. erhalten werden kann, oder auch der Verweis auf die möglichen gewinnbringenden Anwendungen der bemannten Raumfahrt [Feustel95].

Die zweite Kategorie von Argumenten für die bemannte Raumfahrt zielt nicht auf wirtschaftliche Resultate ab, sondern eher auf soziokulturelle Aspekte [Eckart00]. So befriedigt die bemannte Erforschung des Weltraums den im Menschen innewohnenden Drang zur Ausdehnung des Wissens und der Grenzen der Zivilisation ([Founding98], [Turner21]) und fördert vielfältige positive Wechselwirkungen mit dem kulturellen und politischen Geschehen auf der Erde [Zubrin96]. Weiterhin hält die bemannte Raumfahrt die Möglichkeit offen, bei globalen Gefährdungen der Erde (z.B. durch Kollisionen mit Himmelsobjekten) Gegenmaßnahmen zu ergreifen oder zumindest die Folgen zu mildern [Young00].

Der Großteil der entwurfsbeeinflussenden Faktoren findet sich jedoch auf der programmatisch-technischen Seite eines Projekts. Aufgrund der Kosten, Komplexität und langen Programmlaufzeiten bemannter Raumfahrtmissionen spielen bei deren Entwurf im Vergleich zu anderen Hochtechnologieprojekten zusätzliche Faktoren eine Rolle, die so früh wie möglich berücksichtigt werden sollten, d.h. bereits während der Vorentwurfsphase.

Wie durch die derzeitigen Terminprobleme bei der Internationalen Raumstation (International Space Station, ISS) und durch die Projektgeschichte ihres Vorgängerprogramms „Freedom" demonstriert wird, hängt der Erfolg oder Mißerfolg komplexer technologischer Unternehmungen häufig nicht allein von der Ingenieurskompetenz des Entwurfsteams ab, sondern von wechselnden politischen Rahmenbedingungen [Bizony96]. Daher sind unter dem Stichwort „Systemelemente" bei bemannten Projekten nicht nur Flughardware, Technologie, Auswahl und Training der Besatzung und direkte Betriebsfaktoren zu berücksichtigen, sondern auch die Integration von Randbedingungen wie politischen Faktoren, kulturellen und anderen Motivationsaspekten, etc.

Sowohl diese Elemente als auch die eigentlichen technischen Subsysteme einer geplanten Raumstation sind eng miteinander verknüpft (Abbildung 0.1). Dies führt zu einem „bösartigen" Planungsproblem [Rittel92]. Um eine möglichst optimale Gesamtlösung zu erhalten, scheint ein iterativer, kooperationsorientierter[1] Ansatz erfolgversprechend.

Die Berücksichtigung technologischer Rahmenbedingungen ist allerdings die Voraussetzung für einen erfolgreichen am Menschen orientierten Entwurf. Daher beruht der in diesem Beitrag beschriebene Ansatz auf einer Ingenieursmethodik, die speziell zum Vorentwurf bemannter Raumstationen entwickelt worden ist [Bertrand98].

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[1] Kooperation bedeutet in diesem Zusammenhang einen Prozeß des „verteilten Erschaffens", in dem Experten einzelner Disziplinen zusammenwirken, um ein „gemeinsames Verständnis zu erreichen, das die einzelnen vorher nicht besaßen und auf sich allein gestellt auch nicht erreichen konnten" [Schrage90].

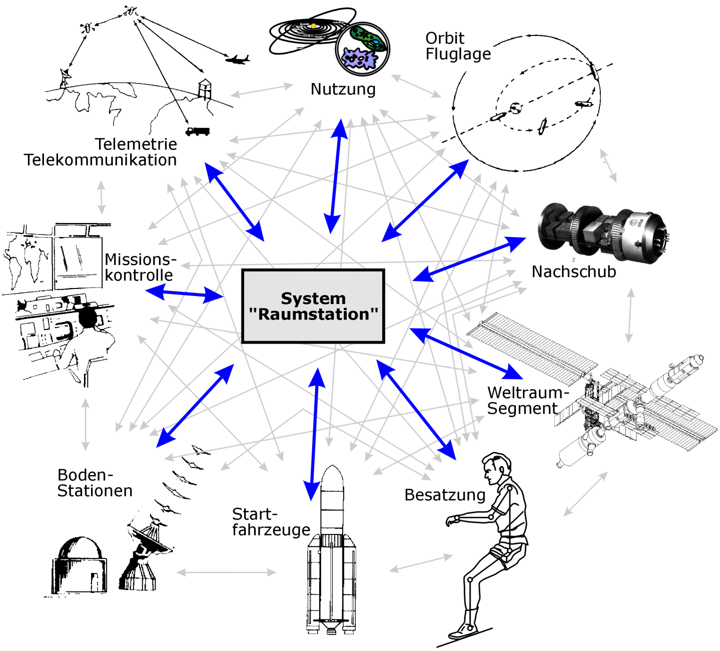

Abbildung 0.1: Verknüpfungen der Elemente des Systems „Raumstation"

Beiträge

Nachfolgend werden sowohl die erwähnte Ingenieursmethodik als auch Elemente aus dem Erfahrungsschatz „irdischer" Architekturpraxis vorgestellt. Zusätzlich werden die Grundlagen des für die Vorentwurfsphase relevanten menschenbezogenen Know-Hows angesprochen.

Methodik zum Vorentwurf im Ingenieursbereich

Der Entwerfer komplexer Weltraumsysteme ist mit einem Satz von Entwurfsproblemen konfrontiert, die teilweise aus der angesprochenen „Bösartigkeit" solcher Probleme herrühren, teilweise von den Besonderheiten der Weltraumumgebung und den dadurch auferlegten Randbedingungen verursacht werden. Diese sind ([Messerschmid99], [Larson99]):

- ✧ Unscharfe Aufgabenstellung
- ✧ Starke Wechselbeziehungen zwischen Systembestandteilen
- ✧ Inverse Beziehung zwischen der zu einem Zeitpunkt verfügbaren Information und den Folgen von auf deren Basis getroffenen Entscheidungen (Abbildung 0.2)
- ✧ Extreme Umweltbedingungen
- ✧ Extreme Belastungen
- ✧ Minimierung der Masse
- ✧ Begrenzter Zugang nach Indienststellung

Um einem Entwurfsteam beim Bewältigen dieser Herausforderungen zu helfen, ist am Institut für Raumfahrtsysteme der Universität Stuttgart eine Methodik für den Systementwurf von Raumstationen entwickelt worden, die auf einem quasi-linearen, iterativen Entwurfsvorgehen und der Verwendung unterstützender, speziell

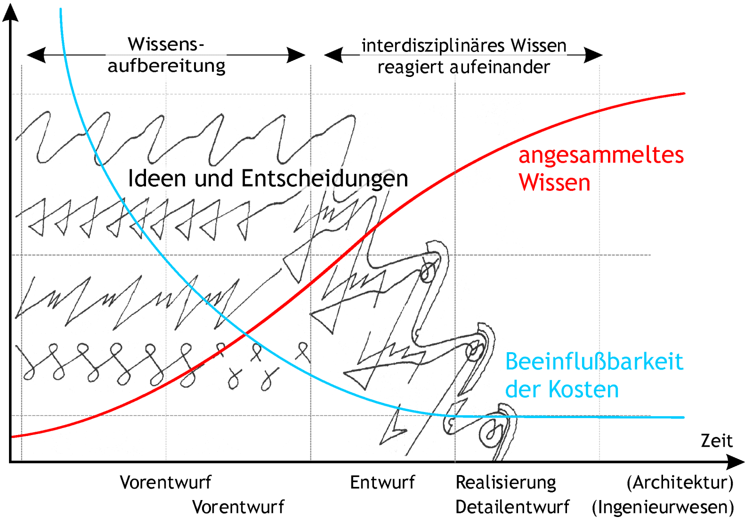

Abbildung 0.2: Inverse Beziehung zwischen Wissen, Entscheidungen und Kostenfestlegung während des Entwurfsprozesses in der Architektur und im Ingenieurwesen [Uhl00]

entwickelter Softwarewerkzeuge beruht ([Bertrand98], [Messerschmid00b], [Hinüber01]). Diese Methodik mit dem Namen „Space Station Design Workshop“ (SSDW) berücksichtigt insbesondere folgende Elemente:

- Abschätzung der Lage- und Bahnstabilität (AOCS)
- Auslegung des Lebenserhaltungssystems (ECLSS)
- Auslegung des Energie- und Thermalsystems (EPS/TCS)
- Bestimmung der Nachschubmassen
- Berechnung der Mikrogravitations-Qualität
- Abschätzung synergetischer Verknüpfungen zwischen Subsystemen
- Aspekte von Start, Zusammenbau und Nutzung

Dieser Ansatz ermöglicht es einem Entwurfsteam von Ingenieuren (oder Ingenieurstudenten aus höheren Semestern), innerhalb weniger Tage den Vorentwurf einer Raumstation auszuführen. Dies ist mehrfach durch die erfolgreichen „Space Station Design Workshops” demonstriert worden, die in den letzten Jahren am Institut für Raumfahrtsysteme durchgeführt worden sind [SSDW01b][2].

Systemkomponente Mensch

Roald Amundsen, einer der erfahrensten Erforscher von Arktis und Antarktis im frühen 20. Jahrhundert, hat festgestellt, daß *„der menschliche Faktor drei Viertel jeder Expedition ausmacht”* [Stuster96]. Dies gilt auch für Langzeit-Weltraummissionen, bei denen *„das Subsystem Mensch die größte Gefährdung des Missionserfolgs darstellt”* [Adams00b] – aber auch das größte Erfolgspotential bietet. Kenntnis dieses „menschlichen Faktors”, d.h. der Besatzung und ihrer Möglichkeiten und Grenzen, ist unverzichtbarer Bestandteil jedes Entwurfs eines bemannten Raumfahrtsystems.

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[2] Diese Quelle enthält auch weitere Informationen zu SSDW-Methodik und Werkzeugen, die hier aus Platzgründen nicht aufgeführt werden können.

Die in diesem Bericht beschriebene, aus einer Überlagerung von Methoden des Ingenieurwesens und der Architektur hervorgegangene neue Entwurfsmethodik legt daher Wert darauf, die in den Bereichen Human Factors (HF), Habitability, Mannschaftspsychologie und Lebensraumentwurf gesammelten Erfahrungen einfließen zu lassen. Diese basieren auf drei Quellen: direkte Raumfahrterfahrung (z.B. mit Mir oder Skylab), analoge Situationen auf der Erde (z.B. Antarktisexpeditionen oder Unterseestationen) und Ergebnisse experimenteller und theoretischer Studien.

Deren Resultate belegen den starken Zusammenhang zwischen Umgebungsbedingungen und der Effizienz der Besatzung bei der Durchführung ihrer Mission. Sie zeigen auch, daß die Annehmbarkeit der Wohn- und Arbeitsumgebung nicht nur von der ergonomischen Gestaltung einzelner Ausstattungselemente abhängt, sondern auch von übergeordneten Faktoren, die eine Ausrichtung der Umgebung als Ganzes an der menschlichen Besatzung erfordern.

Entwurfsmethode der Architektur

Das Hinzufügen ausgewählter Elemente aus der Praxis des „irdischen“ Architekten zu der oben beschriebenen traditionellen, ingenieurzentrierten Methodik verspricht, den Entwurfsprozeß und daher dessen Ergebnis zu verbessern ([Adams98a], [Maier96]). So stellt Rechtin fest [Rechtin91]:

> *„Architektur, das Planen und Bauen von Strukturen, ist so alt wie die menschliche Zivilisation und so modern wie die Planung der Erforschung des Sonnensystems. Sie entstand als Antwort auf Probleme, die zu komplex waren, um sie durch vorher festgelegte Regeln und Abläufe zu lösen.“*

Durch die Einbeziehung passender Entwurfselemente aus der Architektur kann dem Konzept eines am Menschen orientierten Vorentwurfs von Lebensräumen im Weltraum Rechnung getragen werden: auf der einen Seite durch die Betonung der *Rolle des Architekten* im Entwurfsprozess, auf der anderen Seite durch Verwendung von relevanten Teilen des *architektonischen Handwerkszeugs*.

Der Architekt begleitet das zu entwerfende System während seines gesamten Lebenszyklus, vom ersten Entwurf über Entwicklung und

Konstruktion bis zum Einsatz. Dabei bemüht er sich um *„Verringerung von Komplexem und Auswahl von Realisierbarem"* [Rechtin91], er überwacht die Arbeit der Detailkonstrukteure, die mit der Umsetzung des schließlich ausgewählten machbaren Entwurfs befaßt sind, unter Verwendung eines ganzheitlichen Modells des Entwurfsobjektes. Bewahrung der ursprünglichen Absicht des Designers dient als Absicherung gegenüber schleichenden Mehranforderungen und erhöht die Konsistenz und Klarheit des Entwurfs.

Irdische Architekturpraxis liefert darüber hinaus etliche nützliche Methoden, die in den in diesem Bericht beschriebenen interdisziplinären Ansatz eingeflossen sind. Diese werden nachfolgend kurz erwähnt; für eine genauere Beschreibung sei auf den englischen Text (ab Seite 42) verwiesen. Die verwendeten Elemente sind:

- Intensive Verwendung von Handskizzen
- Überprüfung der Machbarkeit des Entwurfs durch Betrachtung von Schlüsseldetails
- Bewußte Entwicklung von alternativen Entwurfslösungen und deren Varianten
- Sorgfältige Aufarbeitung von Hintergrundwissen
- Organisieren der Kreativität des Entwurfsteams
- Ausrichtung wichtiger Entscheidungen an übergeordneten Entwurfsprinzipien
- Bewegliche Zielfindung [Uhl00] während des Entwurfsprozesses

Neue interdisziplinäre Methodik

Die im vorhergehenden Abschnitt vorgestellten Elemente sind im Rahmen der neuentwickelten interdisziplinären Entwurfsmethodik in konkreten Regeln für das Entwurfsteam zusammengefaßt, welche die Bereiche „Entwurfsprozeß", „Entwurfswissen" und „Software" betreffen. Nachfolgend werden die wichtigsten Bestandteile erwähnt; eine vollständige Darstellung findet sich im Haupttext (Kapitel 3, ab Seite 57).

Integrierter Prozeß

Der Ablauf des Entwurfsprozesses ist in der Tabelle auf Seite 62 dargestellt. Er folgt dem der konventionellen SSDW-Methodik, bleibt aber dennoch flexibel dadurch, daß zeitweises Vorausgehen oder Rückiterieren zugelassen sind, falls solche Abweichungen dem kreativen Prozeß oder dem Verständnis des Entwurfsproblems zugute kommen. Ferner sind die wichtigen Schritte der Entwurfsprozeß-Vorbereitung und der abschließenden Dokumentation durch ihre explizite Einbindung hervorgehoben. Der Arbeitsfluß wird außerdem unter anderem durch folgende Prinzipien geleitet:

- Die Mitglieder des Entwurfsteams sehen sich als kooperationsorientierte Fachleute. Sie kennen sich mit kreativitätsfördernden Techniken aus und entwickeln Ideen im fachübergreifenden Kontakt. Durch Teilnahme am Entwurfsprozeß erweitern sie ihr eigenes Wissen und bringen es gleichzeitig ein.
- Der Frühphase des Entwurfsprozesses (Analyse der Aufgabenstellung, Sammeln und Verstehen von Hintergrundinformation, Entwickeln von Alternativen) kommt große Bedeutung zu. Sie wird daher so lange wie möglich ausgedehnt.
- Handskizzen spielen eine wichtige Rolle bei der Entwicklung, Vermittlung, Überprüfung und Dokumentation von Ideen.
- Nicht gewählte Alternativen werden nicht verworfen, sondern weiter zur Referenz, als Ideenquelle, oder als Rückfalloption bei sich ändernden Anforderungen oder auftretenden Schwierigkeiten behalten.
- Wichtige Details werden früh im Entwurfsprozeß identifiziert; sie werden weiterentwickelt, sobald relevante Randbedingungen genügend bekannt sind; von Anfang an helfen sie so bei der Konzentration auf das Entwurfsziel und ermöglichen Kontinuität.

Integriertes Wissen

Die Besatzung wird nicht als eines von vielen Subsystemen behandelt, sondern in den Mittelpunkt des Entwurfs eines integrierten Lebensraums gestellt. Das dazu nötige Wissen ist im Rahmen dieser Arbeit aus einer Vielzahl von Literaturquellen gesammelt und in Form von Faustregeln in leicht überschaubarer Tabellenform zusammengetragen worden (siehe Seiten 66 bis 79). Diese Faustregeln betreffen z.B. die Bereiche „Programmatische Aspekte", „Konfiguration", „Habitability", und „Lebenserhaltung". Der nachfolgende Auszug zum Thema „Habitability" (siehe Seite 70) gibt einen Eindruck von Aufbau und Inhalt dieser Tabellen mit für einen am Menschen orientierten Entwurf äußerst wichtigen Faustregeln.

Tabelle 0.1: Habitability-Faustregeln (Auszug)

Bereich	**Regel**	**Quellen**
Allgemeines	✧ Je länger die Mission, je höher das Risiko und der Grad an Isoliertheit, desto wichtiger wird Habitability.	[Connors85], [Sturgeon00], [Adams99]
	✧ Die Inneneinrichtung jedes Moduls soll eine einheitliche Oben-Unten-Orientierung aufweisen. Nach Möglichkeit sollte diese in allen Modulen gleich sein.	[Adams99]
	✧ Wichtige „Alltagsprobleme", an die schon beim Vorentwurf gedacht werden muß, sind Lagerung, Nahrung, Lärm, Abfallbeseitigung, und Hygiene.	[Godwin99]
Räumliche Einteilung	✧ Auch die Raumaufteilung sollte sich während der Missionsdauer entsprechend den Vorlieben und Erfahrungen der Besatzung anpassen lassen. ✧ Wohn- und Arbeitsbereiche sollten getrennt sein; laute Geräte sollten zusammen angeordnet werden, weit entfernt vom Wohnbereich.	[Adams99]
Platzangebot	✧ Es sollte genügend Platz eingeplant werden, um häufig verwendete Ausrüstung aufgebaut lassen zu können.	[Adams99]

Tabelle 0.1: Habitability-Faustregeln (Auszug)

Bereich	Regel	Quellen
	✧ Beispiele für Schlafplatz-Volumen: U-Boot 0.8 m^3, Unterseestation 1 m^3, Skylab 1.5 m^3, Langzeitmissionen 2 m^3 bis 7 m^3 (laut Studien; Durchschnitt 4 m^3).	[Stuster96], [Wise85]

Integrierte Software

Zum Vorentwurf des Lebenserhaltungssystems (ECLSS) – einem der unverzichtbaren Bestandteile jedes bemannten Raumfahrtsystems – sind numerisch intensive Simulationen notwendig, um dessen stationäres und dynamisches Verhalten so früh wie möglich abschätzen zu können. Zu diesem Zweck steht im Rahmen des neuen Entwurfsansatzes eine eigens entwickelte Simulationssoftware zur Verfügung. Dieses Programmpaket namens ELISSA („Environment for Life Support System Simulation and Analysis“, Umgebung zur Simulation und Analyse von Lebenserhaltungssystemen) stellt mehrere Bibliotheken vordefinierter Komponenten des Lebenserhaltungssystems und verwandter Systeme (Lage- und Bahnregelung, Energieversorgung) zur Verfügung, die vom Benutzer auf intuitive Weise in einer graphischen Umgebung zu Simulationsmodellen des ECLSS zusammengebaut werden können.

Die Abbildung auf Seite 86 veranschaulicht, wie mittels einfacher Mausaktionen aus einer solchen Komponentenbibliothek ein Systemmodell erstellt werden kann. Auf Seite 89 sind die verschiedenen Hauptbibliotheken mit ihren Komponenten abgebildet. Die Software ist in einem ausführlichen Handbuch beschrieben [Osburg01].

Anwendungen der neuen Methodik

Der im Rahmen dieser Arbeit neuentwickelte interdisziplinäre Ansatz wurde bereits erfolgreich auf konkrete Entwurfsaufgaben angewendet. Ein erstes Projekt befaßte sich mit dem Entwurf einer Raumstation durch ein kleines interdisziplinäres Team von Studenten der Luft- und Raumfahrttechnik sowie der Architektur im Rahmen mehrerer Studien- und Diplomarbeiten. Darüber hinaus fand im Frühjahr 2001 ein einwöchiger, multinational besetzter „Space Station Design Workshop" statt, bei dem die neue Entwurfsmethodik ebenfalls mit Erfolg angewendet wurde.

Beide Anwendungsbeispiele sind im Haupttext ab Seite 93 dokumentiert. Die wichtigsten Entwurfsergebnisse – Konfiguration der Stationen, Innenbereich, Simulationsergebnisse von Lage- und Bahnregelungssystem (AOCS) und ECLSS, technische Daten – sind aus den Abbildungen und Tabellen in diesem Kapitel ersichtlich und werden daher aus Platzgründen hier nicht wiederholt.

Zusammenfassung und Ausblick

Es ist eine an die besonderen Gegebenheiten des Entwurfs von bemannten Raumfahrtsystemen für Langzeitmissionen angepaßte Methodik entwickelt und durch mehrere erfolgreiche Anwendungen im Rahmen praktischer Entwurfsprojekte demonstriert worden. Der neue interdisziplinäre Ansatz basiert auf drei Komponenten: einer bewährten Ingenieursmethodik zum Vorentwurf von Raumstationen, gesammeltem Wissen um die besonderen Bedürfnisse und Fähigkeiten des Menschen im Weltraum, sowie Elementen aus der „irdischen" Architekturpraxis.

Der vorliegende Bericht hat diese neue Methodik in einer Form beschrieben, die für ein Entwurfsteam konkret umsetzbar ist. Er hat die erarbeiteten Leitlinien für den Entwurfsprozeß selbst sowie die aufgestellten Faustregeln zur optimalen Integration des Menschen dokumentiert. Ferner hat er das Programm vorgestellt, das zur Unterstützung des numerisch intensiven Vorentwurfs von Subsystemen wie dem Lebenserhaltungssystem entwickelt worden ist.

Zukünftige Erweiterungen werden sich mit der vollständigen Integration aller verwendeten Software unter einer Bedienoberfläche sowie mit der Einbindung von Techniken der Virtual Reality in den Entwurfsprozeß befassen.

Die in diesem Bericht präsentierte interdisziplinäre Methodik für den Vorentwurf bemannter Weltraumsysteme kann somit dazu beitragen, die beginnende Phase der Ausbreitung der Menschheit in einen neuen Lebensraum – den Weltraum – zu unterstützen.

> *"A beginning is the time for*
> *taking the most delicate care that*
> *the balances are correct."*
>
> *Frank A. Herbert, Dune*

1 Introduction

The design of systems for human space exploration not only calls for the use of the most advanced technologies in the "classical" engineering fields of propulsion, structures, communications or power generation, but it also requires the design team to take into account the crew's complex physical and psychological needs, and the integration of the mission itself into the terrestrial socioeconomic environment. This includes simple measures such as providing basic life-support functions as well as more involved considerations, like optimizing the group dynamics of the crew through suitable spatial and procedural arrangements. Proper consideration of this "human" aspect throughout the design process predetermines the crew's ability to carry out its mission successfully and to return to Earth safely [Bishop99].

At the same time, the majority of consequential design decisions are made during the conceptual design phase (Phase 0/A) [Messerschmid99]. Even though little detail is known at that point, the design team is forced to make assumptions and simplifications in order to be able to generate an overall concept that links the space and ground segments, the crew, operational aspects, and other system elements together in the most efficient way.

1.1 Objectives of this Dissertation

The current state-of-the-art conceptual design process for inhabited space systems is represented by approaches such as the "Space Station Design Workshop" (SSDW) methodology developed at the Space Systems Institute (cf. Section 2.1, [Bertrand99]). However, this approach is not specifically adapted to the requirements, limitations and possibilities imposed both by the human presence on board and by the human design team tasked with conceptualizing the space station.

The objective of the doctoral dissertation research underlying this report was therefore to enhance the traditional approach in areas relevant to optimizing crew integration and, consequently, crew performance and associated mission success.

The SSDW traditionally implemented a purely engineering-based approach to conceptual design with few dedicated human-centered elements included at the process level. Additionally, with respect to the conceptualization of crew-related subsystems, basic Environmental Control and Life Support System (ECLSS) design was included in the methodology, but analysis of its potential synergistic interactions with other subsystems was only partially supported by simulation software. The crucial issues of internal configuration and Human Factors were not addressed in sufficient depth either.

Therefore, the focus of this research was placed on improvements in the following areas of the SSDW (Figure 1.1):

- ✧ Incorporating human-centered elements into the overall design process (cf. Sections 2.1.2, 2.3 and 3.1)
- ✧ Intensifying the attention given to Human Factors and Internal Configuration issues (cf. Sections 2.2 and 3.2)
- ✧ Improving simulation capabilities for ECLSS and for synergistic effects among related subsystems (cf. Sections 2.1.3 and 3.3)

Due to the links among system elements (cf. Figure 2.1), this of course also affected all other areas addressed by the SSDW conceptual design methodology (Attitude and Orbit Control System, AOCS; Electrical Power System, EPS; Thermal Control System, TCS; and external configuration; assembly, operations, utilization, and resupply).

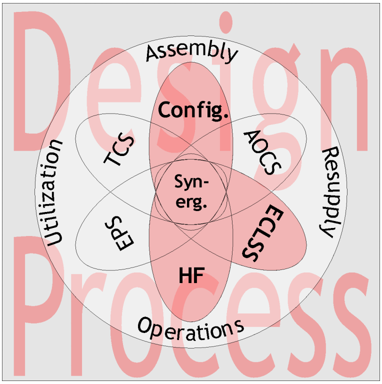

Figure 1.1: Elements of SSDW methodology; those directly affected by this research are emphasized in color

1.2 Motivation and Background

Before continuing with the presentation of this approach itself, however, a brief look at the reasons for undertaking manned spaceflight, as well as an overview of its history, present state, and future projects, is subsequently taken. This will define the environment in which the conceptual design of human space exploration systems is taking place. The question of "why" will be answered first, since improving the design process for such systems only makes sense if their useful purpose is understood.

1.2.1 The Case for Human Space Exploration

Various reasons have been given over the last several decades arguing in favor of human spaceflight. In this context, two main approaches can be identified: one might be called "utilitarian" justification, the other, "cultural" rationale.

Some examples referring to the former include: the socioeconomic benefits of supporting high-tech industries [Feustel95], commercializing potential spin-off technologies, and exploiting planetary mineral deposits and other space resources; scientific results gained from space exploration and from using space infrastructures [Crawford98]; economic benefits of commerce with future space

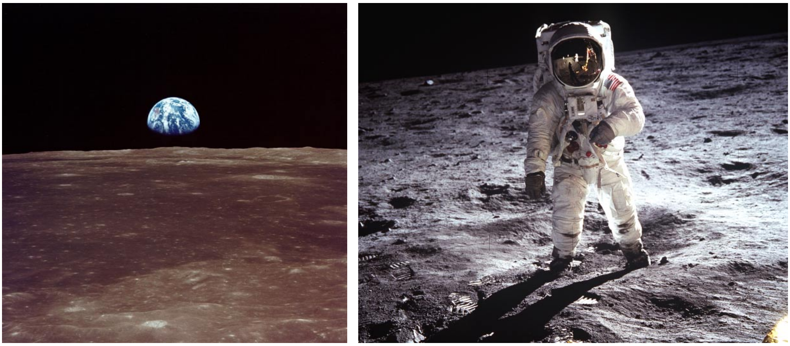

Figure 1.2: Earthrise, as seen by the Apollo 11 crew [Apollo01]

colonies; political advantages gained from the domination of space; and more. A human mission to Mars or other inspirational space projects also provide focus for vigorous technology development efforts, and will thus also directly benefit future terrestrial undertakings.

But utilitarian arguments fail to account for man's desire to explore [Eckart00]. This is where the latter justification – the cultural rationale – comes in. It refers to rather intangible causes: the urge to *"boldly go where no man has gone before"* and to discover uncharted realms being deeply embedded in human nature; potential cultural and spiritual benefits that can be derived from confronting and conquering the unknown, from finding out more about who we are as a species, and from establishing outposts and colonies in frontier territory [Founding98]; the obligation towards future generations to continue pushing the limits in order to avoid *"stepping downward on the ladder of evolution"*; and similar arguments [Zubrin96].

The existence of a physical frontier has historically been beneficial to the vitality and advancement of the societies associated with it [Turner21], and stagnation has often set in when the frontier was finally conquered and subsequently vanished. Looking back at Earth from far away (Figure 1.2) has emphasized this *frontier* aspect of space, and forever altered the way humanity sees its home planet [Apollo75].

An additional case can be made that is part of the cultural rationale for human space exploration: Several times in its history, Earth has undergone dramatic changes in its ecosystem that were triggered by external (e.g. asteroid impacts, solar changes) or internal (e.g. volcanic eruptions, atmospheric changes) events [Becker01]. In every case, the formerly dominant species faced extinction. Mankind is the first species in the history of our home planet to possess the means of avoiding such global disasters, either by detecting and deflecting external threats or by establishing autonomous off-Earth refuges ahead of time to mitigate their consequences. Manned spaceflight is required to prepare for either scenario since humans cannot be replaced by machines in the complex and little-known environments of outer space [Young00].

Whichever of these reasons are the main drivers behind a specific space mission, they will invariably influence the design process and its reception by the public (and thus e.g. funding decisions) from the very beginning.

1.2.2 Challenges of Human Space Exploration

From the ample literature concerned with long-duration manned spaceflight missions, several areas of interest can be identified as contributing to overall mission success. The factors that must be considered when designing a human-rated space system can be organized into the following categories (Figure 1.3):

- Motivation
- Available and required technologies
- Mission and flight hardware architecture
- Crew
- Interactions with the terrestrial environment

These categories jointly influence the way in which a human space exploration mission is planned, implemented and carried out, from top-level considerations such as mission objectives to details such as airlock design. They are closely linked to each other, so synergistic interactions among them must be taken into account. Issues such as crew quarters design, communications and hierarchy, station con-

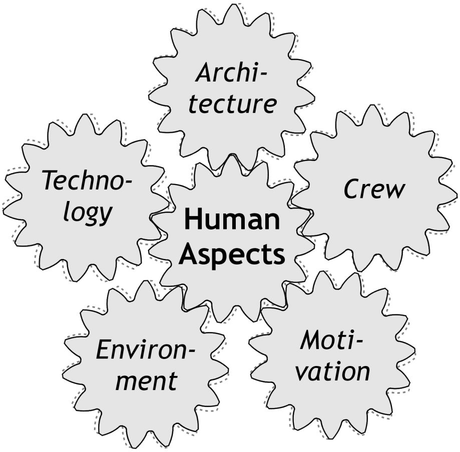

Figure 1.3: Interacting factors in manned spaceflight conceptual design

figuration[3], etc. can be categorized under one or more of these five headings, thus emphasizing the fact that they are linked as well.

However, present methodology generally deals with these in an individual fashion (cf. Section 2.1). Literature provides recommendations on ergonomic matters, crew psychology, ECLSS design, etc. but no comprehensive approach including all these individual contributions. As will be demonstrated in Chapters 2 and 3, the successful integration of these factors is a crucial step towards truly human-centered design.

While the "motivation" aspect has already been discussed (cf. Section 1.2.1, p. 3), the other items will be briefly mentioned below in order to provide an initial overview, and subsequently expanded upon in Chapter 2.

Available and Required Technologies

Space and most planetary surfaces are very hostile environments, and the task of keeping the crew alive and operational is a formida-

---

[3] In the context of conceptual design, "configuration" refers to the physical arrangement of a space station orbital segment, which includes location of structures and functions, but also aspects of interior architecture, flight mode, orbit, and attitude.

ble one. Thus, human spaceflight, by its very nature, calls for some of the most advanced technologies available. When state-of-the-art technology is insufficient to satisfy the demands on safety and functionality for a mission, improvement or new development is required. Yet, increasingly, budgetary restraints pose limitations on the selection of technologies to be employed and on the amount of mission-specific development to be performed.

The interaction between technology, budget, crew safety, mission capability and development time forces this issue to the forefront of the designers' work, with the inclusion of technical boundary conditions being a prerequisite for successful human-oriented engineering. The approach described in this report is therefore based on an engineering methodology specifically created for the conceptual design of space stations [Bertrand98].

Mission and Flight Hardware Architecture

On Earth, architecture refers to the process of creating buildings and other structures for habitation and use by man, and also to the outcome of this process. Joining and coordinating individual components in order to create a whole that not only fulfills the requirements of basic functionality, but also satisfies higher-level demands and expectations, is the hallmark of successful architecture. In this regard, architecture also finds its application in the design of human-rated space systems.

Their design requires careful balancing of space and ground segments, crew, operational aspects, and other mission elements. Any design approach must provide ways of integrating differing ideas and concepts in order to reach a compromise between conflicting requirements without compromising mission success. Here, designers can fall back on some proven methods used by architects on Earth.

Flight hardware design for manned missions poses equal challenges. The space equivalent of a house on Earth - used for living, working, relaxing, meeting, protection - must be designed with even greater regard for the needs and desires of its users, their well-being, functionality considerations, aesthetic appeal, and, last but not least, the significance of the mission at hand within the overall cultural context of human space exploration. Architecture as an intermediary between technology and art is well suited for this role.

Crew

Long-term manned space missions pose special challenges to the human system component: *"[As] mission duration and the level of crew autonomy increase, the human system emerges as the primary risk to mission success."* [Adams00b] – but it also emerges as the largest contributor to that success.

Issues influencing the efficient performance of the crew (and thus mission success) that must be addressed by the designers include questions of privacy and isolation, hierarchy, communication, group dynamics and habitability.

Interactions with the Terrestrial Environment

Especially in the area of human spaceflight, no project will be likely to succeed unless its planners and managers take into account the manifold interactions with the "outside world", namely the opportunities and limitations inherent in the political, financial and social environment in which a space mission is planned and carried out.

Manned spaceflight activities are traditionally government-funded, since their cost, inherent risk, and long development periods discourage the involvement of commercial enterprises [Feustel95]. This public nature, on the other hand, also entails support or opposition from political adversaries, the media and the general populace, as well as associated controversies about emotionally charged aspects, which often make or break a project independently of its scientific merit or the technical competence of its design team. The troubles with the Cassini mission [Nuclear99] serve as a textbook example here, as do the project histories of Shuttle-Mir [Burrough98] and Freedom/International Space Station (ISS) [Bizony96].

The reverse – implications of space missions and technological development on human society – must also be considered. In addition to direct spin-offs and the terrestrial utilization of space resources, further-reaching consequences are possible. Generally invigorating effects on society were already mentioned in Section 1.2.1. Another example is the influence that the development of reliable and compact life-support equipment and in-situ resource utilization technology required for space exploration missions will have. This technology might enable self-sufficient, independent settlement in extreme environments on Earth, thus opening up a new terrestrial frontier, with associated change in society and increase in diversity.

Any design approach must provide ways of integrating these interactions.

1.2.3 History and Present State of Human Space Exploration

Humans first reached space in the 1960s, through projects Vostok, Mercury, and Gemini [Wade01], culminating in the first landing of men on the Moon in 1969 [Apollo75]. The 1970s saw space stations Skylab and Salyut, with the first medium-duration stays of crews in low-Earth orbit. Since then, progress in manned spaceflight has been noticeable, but not as fast as initially expected.

For example, the Space Shuttle – the mainstay of current manned space transportation – has been in service for twenty years at the time of this writing, with no successor system on the horizon yet, and Shuttle as well as the Russian piloted spacecraft, Soyuz, are designed for short-duration missions only.

Even recently-launched modules of International Space Station "Alpha" are based on decades-old design:

- The ISS Service Module is based on the base block of space station Mir, which in turn is based on the 1974 design of the Salyut-6 module. Even though cosmonaut feedback has been indicating serious shortcomings in the area of basic habitability, the design has not been significantly changed [Adams00a].
- Pressurized modules on the western segment are dimensioned to fit into the Space Shuttle cargo bay, which in turn is based on the "*largest unit which can be transported on the [US] highway and rail system*" [Adams00a].

- ✧ The ISS-USOS interior (four-standoff configuration, rack-based components) was the result of a design competition in the 1980s [Mount00b].

But signs of progress are definitely visible: after extensive (and expensive) planning and preparations, ISS is operational and will soon be fully assembled in orbit, in spite of technical and political difficulties (Figure 1.4; [Shepard01], [Sensenbrenner98]). A multitude of relevant research on human integration and general systems design has been performed since Apollo (cf. Chapter 2), experience with life in space and in Earth-based analogs has been gained, and validated concepts for the next generation of space technology are available ([Burrough98], [Bauer94], [LMLSTP00], [Kennedy99], [MDRS02], [Micheels99]).

1.2.4 The Future of Human Space Exploration

Even if current space technology and achievements are a far cry from even conservative predictions made during the heydays of the Apollo Moon race, progress during recent decades has now reached a point where longer-term manned missions can be prepared. At the same time, a paradigm shift from basic survival-in-space to habitability and crew efficiency issues more appropriate to long-term missions can be observed (cf. Chapter 2). This includes the research carried out in this dissertation and the resulting new approach presented in Chapter 3.

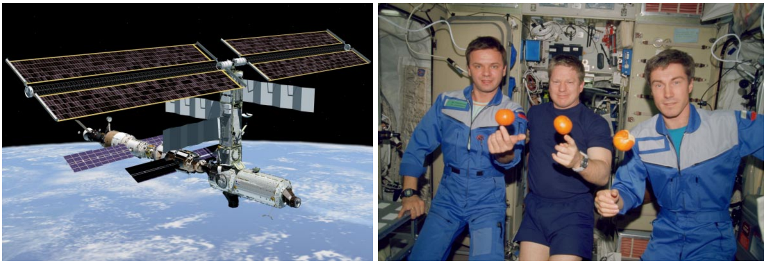

Figure 1.4: International Space Station “Alpha”: mankind’s current outpost in space (left: outside view of ISS, March 2001; right: ISS inside view with Expedition One crew Gidzenko, Sheperd, and Krikalev [NASA01])

The next several years will therefore hopefully see a new round of development of space exploration technology. The short-term prospects are for the commercialization of spaceflight, at least in low-Earth orbit, from access [Diamandis01] to research aboard ISS [Uhran00] to tourism ([Mir01], [Chaikin01]). Further steps will depend on the experience derived from these new ventures, and on the motivation of decision-makers in politics and industry, driven by popular demand ([Robinson93], [Cameron99], [Founding98]). These long-range steps might range from new Low-Earth Orbit (LEO) space stations to returning to the Moon to the first human expedition to Mars (Figure 1.5; [Eckart00], [Hoffmann97], [Drake98]).

1.3 Organization of this Report

This chapter gave an introduction to the motivation for undertaking human space exploration missions as well as to the challenges involved in their design process, and it briefly described examples of past, current, and future projects. This lays the groundwork for the subsequent main chapters of this report.

Chapter 2 identifies elements that play a key role in the conceptual design of human space systems: conceptual systems design methodology, human aspects, and terrestrial analogs in architecture and extreme-environment design.

This information serves as a foundation for the new approach to the conceptual design of human-rated space systems presented in Chapter 3, which was developed as part of this dissertation. The creative focus for this new approach was on identifying the elements outlined in Chapter 2 and integrating them into the areas of processes (Section 3.1) as well as knowledge (Section 3.2). Additionally, Section 3.3 provides a detailed description of the dedicated software tools that were developed by the author for use in conjunction with this new design approach.

Chapter 4 contains examples of the practical application of the approach described in Chapter 3 to interdisciplinary design projects and workshops. The results are presented along with a discussion of the experience gained.

The final chapter offers conclusions regarding the approach and the supporting software, and it points out possibilities for further research.

At the end of this report, a listing of referenced literature and an overview of terms and acronyms are provided, as well as an extensive index.

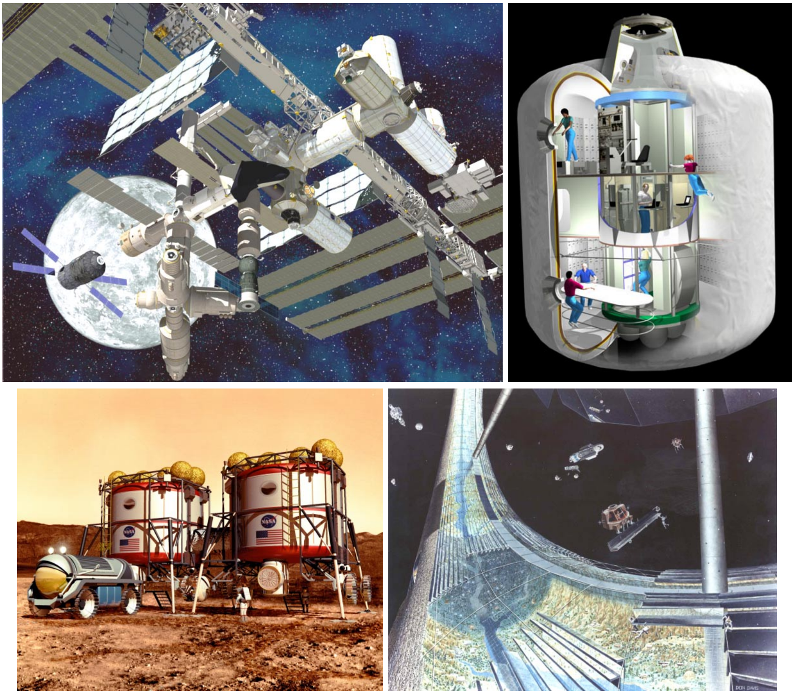

Figure 1.5: Future manned spaceflight projects: ISS Assembly Complete (short-term) [ESA01], TransHab inflatable module (mid-term), first Mars base (long-term) [NASA01], and space colony (visionary) [NASA75]

"The sea is dangerous and its storms terrible, but these obstacles have never been sufficient reason to remain ashore."

Ferdinand Magellan, Explorer, 1520

2 Contributors to the Design of Human-Rated Space Systems

At the time of this writing, four decades have passed since the first manned spaceflight took place, and over three decades since humans first set foot upon the Moon. Even though, since then, progress in spaceflight has not been as extensive as was expected during the first period of competition-driven space exploration, or as fast as could be hoped for when comparing with other advanced fields such as computer technology or biomedical research[4], projects like Skylab, Spacelab, Mir, the Space Shuttle, and the International Space Station represent real success and have laid the foundations for future progress.

Due to these and other endeavors, a large body of human spaceflight know-how has been acquired that allows for the development of new approaches to conceptual design such as the one proposed in this report. The most relevant issues are presented in this chapter.

Its first section will cover current engineering methodology for the top-level conceptual design of inhabited space systems. In Section 2.2, a more detailed review of Human Factors (HF) and related issues will be given, due to the importance of that field to the human-centered design of space habitats. The third and final section will document elements from the field of terrestrial architecture that

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[4] This is due in part to the extremely high risk and cost factors, long project schedules, low production quantities, and the physically and politically challenging environment associated with manned spaceflight projects (cf. Section 1.2.2, page 5).

were integrated into the new approach. The description of this approach in Chapter 3 will frequently refer to the present chapter for explanation and background.

2.1 Conceptual Design in Engineering

The designers of complex space systems – human-rated or not – are faced with a set of challenges stemming in part from the general "wickedness" of the design problem [Rittel72], which makes it impossible to apply linear, "scientific" approaches to their solution [Rittel73], and in part from the special environment of space and the boundary conditions which it imposes. These include ([Messerschmid99], [Bertrand98]):

- **Fuzzy problem formulation:** Objectives and boundary conditions are initially vague. The details of the mission must be developed in parallel with the space system.
- **Strong interdependencies between system elements:** The complexity of designing a space system stems from the network of links among its elements (Figure 2.1). These preclude the separate, sequential definition of individual elements, but instead require a methodological approach that enables the designers to see (and deal with) the system as a whole.
- **Adverse relationship between available information and consequences of conceptual design decisions:** By defining system elements during the conceptual design stage, central decisions about mission performance, system architecture, risk, developmental effort, cost, and organizational structure are made, even though sufficient information on which to base these decisions is usually not available (Figure 2.2). Subsequent design phases provide more information, but design decisions that are made then have to stay within the envelope defined during the conceptual phase and

are thus limited in their mitigative potential. Most mistakes that occurred at the beginning cannot be corrected in the later stages, even with great effort.

- **Extreme boundary conditions:** Compared to other systems of comparable technological complexity, space systems are subject to much tighter technological boundary conditions: they have to operate in the harsh space environment (temperature, vacuum, radiation, microgravity, debris) as well as withstand high g-loads during launch, they must be designed for minimum weight, and must be maintainable under difficult access conditions.

Designing a human-rated space system adds the complications of life support requirements, increased safety and reliability demands, crew integration, as well as a high degree of public scrutiny, and a politicized design environment.

This section describes select approaches to conceptual design that have been proposed and were successfully applied in the past, which can help a design team deal with successfully overcoming those challenges.

2.1.1 Conceptual Design and Systems Engineering

Conceptual design at the system level is at the start of every new design project. “Classical” systems engineering is defined by Blanchard and Fabrycky [Blanchard90]:

> *“[Systems engineering] involves the application of efforts to*
>
> 1. *Transform an operational need into a description of system performance parameters and a preferred system configuration through the use of an iterative process of functionality analysis, synthesis, optimization, definition, design, test, and evaluation;*
> 2. *Incorporate related technical parameters and assure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and*

> 3. *Integrate performance, producibility, reliability, maintainability, manability, supportability, and other specialties into the overall engineering effort."*

Larson et al developed a widely accepted approach to systems engineering that is tailored to the design of unmanned [Larson92] and manned [Larson99] space systems (and which defines "*mission architecture*" as the set of "*physical and functional elements*" and their interrelationships that define a space system; cf. Figure 2.1).

NASA has similarly codified a methodology adapted to the needs of large government-led spaceflight projects [Systems95]. The concept of systems engineering, when understood and applied correctly, already includes what Rechtin and Maier call "Systems Architecting" ([Rechtin91], [Maier96]; [Bertrand98]).

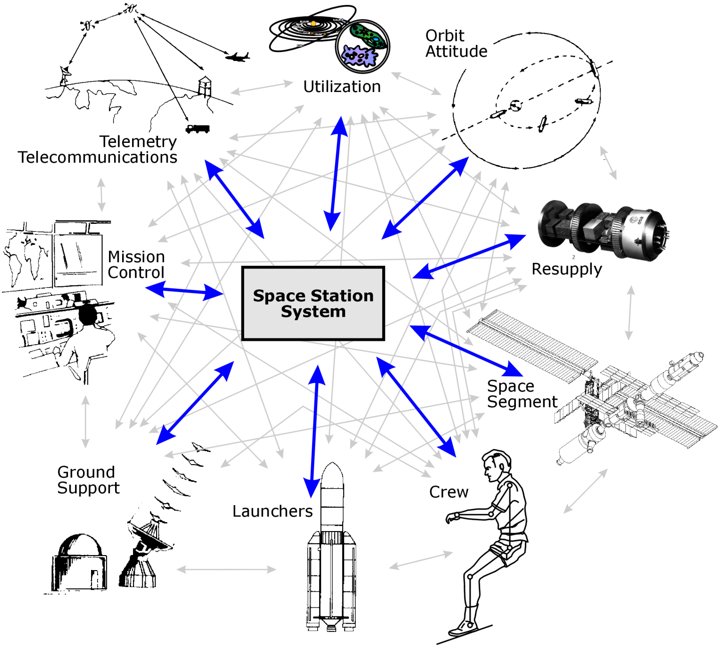

Figure 2.1: Space station system elements and their interrelations

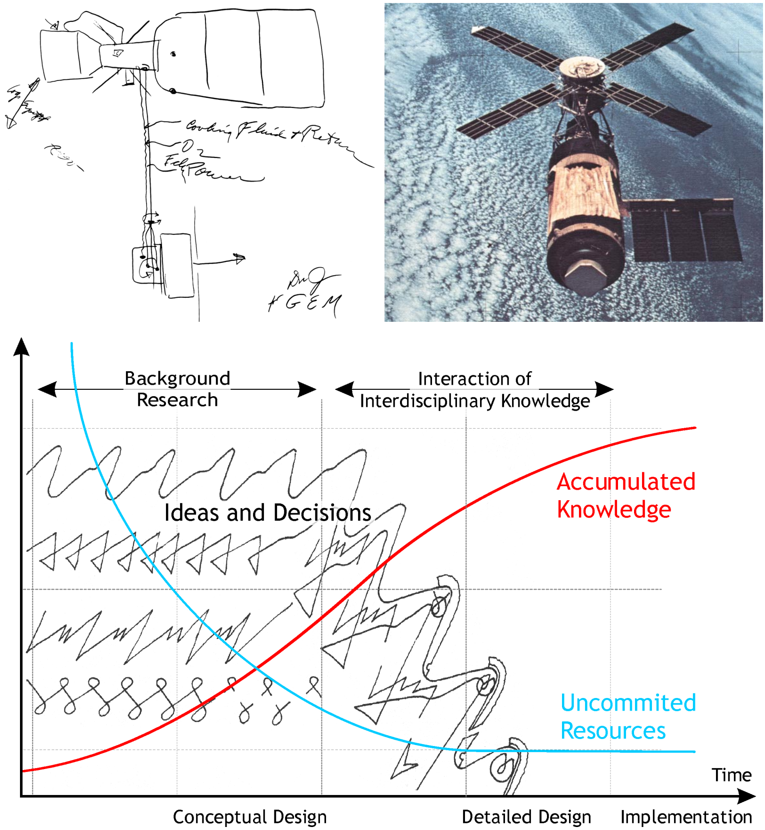

Figure 2.2: Adverse relationship between knowledge, design integration and committed cost [Uhl00], exemplified by initial sketch and post-deployment photograph of US space station Skylab (top, [Skylab77])

To help obtain an optimized, well-balanced overall solution to a systems design problem, a collaborative[5], iterative approach in conjunction with the concept of systems engineering/architecting ap-

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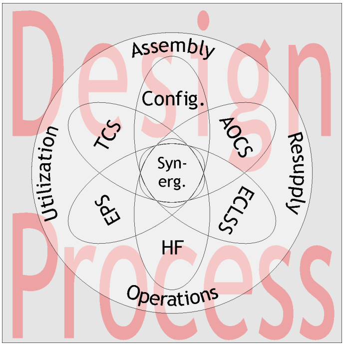
[5] Collaboration refers to a process of "*shared creation*", where disciplinary experts interact "to create a shared understanding that none had previously possessed or could have come to on their own" [Schrage90].

pears promising. Chapter 3 of this report will expand upon that concept, formalizing an engineering/architecting[6] approach that is geared towards the design of inhabited space systems.

2.1.2 An Engineering Process for Space Station Design



A systems engineering methodology aimed at the efficient conceptual design of space stations has been developed at the Space Systems Institute (University of Stuttgart, Germany). It relies on a quasi-linear, iterative design flow and the use of supporting dedicated software tools [Bertrand98]. This methodology, named "Space Station Design Workshop" (SSDW), served as the basis for the engineering side of the new approach described in this report (cf. Section 3.1, page 58). It will therefore be summarized in appropriate detail in the following sections. For a more thorough presentation, see [Bertrand98], [Messerschmid99] or [Larson99].

Overall Design Process

The objective of the design team during the conceptual design phase is *"to compare and evaluate different candidate system concepts in order to identify a small number of concepts [...] that can meet the objectives best"* ([Bertrand98], p. 7). The methodology specifically addresses the following issues:

- ✧ Attitude and orbit stability and performance assessment
- ✧ Life support system analysis

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[6] In this context, the integration of architecture refers to something quite different from the notion of "considering architectural issues" as it can be found in spaceflight Human Factors literature such as ESA's HF handbook [Human94] and NASA-STD-3000 [Man95]. The discussion there rather refers to the "interior design" aspects of architecture, and not to its possible contributions to overall systems design. These contributions will be described in Sections 2.3.1 to 2.3.9 of this report, and then integrated into the new approach presented in Chapter 3.

- Power and thermal control subsystems sizing
- Determination of resupply requirements
- Determination of microgravity quality
- Assessment of synergistic linkages between subsystems
- Launch, assembly and utilization issues

This approach enables a team of design engineers to conduct the conceptualization of a space station within one week, as demonstrated by the highly successful Space Station Design Workshops (SSDWs) that have taken place over the past several years at the University of Stuttgart [SSDW01b]. It also supports more thorough conceptual design work, if desired. However, the issue of human integration is not covered in the required depth; therefore, integrating this crucial aspect – as well as improving the ECLSS and synergistic simulation capability and enhancing the overall design process – was accomplished in the course of the dissertation research described in this report (cf. Chapter 3).

Table 2.1 summarizes the main design steps that are executed during the traditional SSDW design process in order to reach this objective. Due to the complexities of the design problem, the systems design process will usually include several iterations, resulting in loops between the steps outlined in Table 2.1.

Defining Objectives, Requirements and Constraints

Defining mission objectives and translating them into quantifiable requirements is at the beginning of the process. These objectives are usually stated in vague terms initially, but nevertheless provide an invaluable starting point for further qualitative refinement, and for the derivation of quantifiable requirements. A high degree of interaction between the customer and the design team is crucial for this refinement process to be successful.

Overall mission objectives can be categorized in three ways: utilization-driven objectives (e.g. "provide capabilities for research under microgravity conditions", "establish a satellite servicing center"); mission-derived objectives (e.g. "provide accommodations for exploration crews"; "provide logistics support for a planetary base"), and tertiary objectives (e.g. "demonstrate technology leadership",

Table 2.1: SSDW Methodology Steps [Bertrand98]

Step	Details
Define Objectives	A Develop Broad Objectives B Develop a Preliminary List of Requirements and Constraints
Characterize the System	C Develop Alternative System Concepts D Characterize System Elements
Evaluate the System	E Prepare System Budgets F Evaluate Mission Utility G Select System Baseline
Verify Requirements	H Define Technical Requirements I Allocate Requirements to System Elements

"advance international cooperation"). All three categories are usually present in a customer's initial "wish list" and should be taken into consideration.

Deriving requirements and constraints is the next action to be carried out by the design team. In this context, constraints refer to boundary conditions imposed on the design process as a whole, or generated by the technological limits of system elements, which cannot be changed without major effort/cost. Constraints perform the helpful role of guiding the variety of initial ideas towards feasible solutions but must be subject to critical review in order to assure that they do not pose undue limitations on the design team's options [Uhl97]:

> *"Constraints foster creativity. The more obstacles, the stronger the restrictions, the richer the cunning ideas that are necessary, the more numerous the thoughts that surface."*

Requirements, on the other hand, act as design guidelines for the system element that the requirement relates to. They are subject to trade in order to allow for optimization, especially during the early design phase. Subsystem requirements are derived from system-level requirements once these have reached a sufficient degree of maturity. It is important, though, to understand, as [Bertrand98] states:

> *"[...] that system design does not primarily mean to satisfy given requirements and constraints, but to find the best solution in meeting the client's objectives. [Requirements and constraints] are also important for verification of the design and [of] the actual system against the design goals. This can be done by establishing system budgets and by comparing the results of the budgets to the initial requirements and constraints."*

The complex interaction between system elements, as mentioned at the beginning of Section 2.1, results in equal interactions between the constraints and requirements related to these elements. Careful analysis of these cross-effects before the freezing of constraints and requirements, e.g. using an "Interference Matrix" as proposed by Bertrand [Bertrand98, p. 41], helps the design team deal with these complications.

Developing Alternative System Concepts

The system characterization step aims at looking for alternative conceptual approaches that seem to be promising with respect to fulfilling the objectives, constraints and requirements set in the first step. Elements of these proposed system solutions have to be identified and characterized regarding their function in order to prepare for the system evaluation in the following step. During this step, the most important creative action takes place.

Designing alternative solutions for the space segment itself, which includes the space station hardware which will be placed into orbit, along with payloads and crew, starts with selecting the station class: module-based, truss-based, or a combination of both. The advantages and disadvantages of these two concepts are compiled in Table 2.2, which also gives an initial example of the use of design heuristics to support the design team's efforts in an efficient way.

Tables 2.2 to 2.5 are directly integrated into the new approach (cf. Section 3.2) and are therefore given here to provide a reference for designers using it. The expansion of the SSDW methodology as described in Chapter 3 will provide numerous additional heuristics tables.

System elements to be defined at this stage include the following:

- ✧ Orbit and flight mode
- ✧ Initial subsystem choices for Electrical Power System (EPS), Life Support (ECLSS) and Attitude and

Table 2.2: Module-Based Versus Truss-Based Configurations [Bertrand98]

Class of Orbital Segment	**Characteristics**	**Examples**
Pressurized Module Backbone	✧ Positive aspects: • Subsystems are integrated into pressurized modules, resulting in a large degree of autonomy between elements • High structural stiffness, g-Jitter at higher frequencies • Higher redundancy • Continuous, flexible growth potential ✧ Negative aspects: • Limited power density • Limited external payload accommodations ✧ Especially suited for: • Medium-sized configurations • Well-defined mission profiles • Less than ten years of lifetime • Moderate power and heat rejection needs	Salyut 7, Mir, ISS-ROS
Truss Backbone	✧ Positive aspects: • Good external payload accommodations • Savings through centralization of subsystems • Higher power densities attainable • Higher usable volume in pressurized modules • Favors separate functional areas and use of Orbital Replacement Units (ORUs) ✧ Negative aspects: • g-Jitter at lower frequencies • Greater efforts to coordinate distribution of resources (power, thermal, data) ✧ Especially suited for: • Diversified mission profile • High power and heat rejection needs • More than ten years of lifetime • Multinational programs	Early US concepts (CDG), Freedom, ISS-USOS

Orbit Control System (AOCS)

- Module types and key system parameters
- Space segment topology[7]

Orbit and flight mode selection is mainly driven by utilization, logistics, and safety issues. For Low-Earth Orbit (LEO) space stations, minimum altitudes that allow for missed reboosts, maximum altitudes that permit resupply and crew exchange flights using common launchers, launcher performance, orbit mechanics, visibility aspects for Earth observation, and reduction of atmospheric drag and torque – and thus resupply cost – are among the issues to be considered by the design team. Flight mode determination is additionally affected by considerations of solar array tracking, and crew psychology. Table 2.3 summarizes the implications of the two main flight modes, Earth-oriented and inertial.

Because some subsystem issues can have significant impact on the overall design, defining key subsystems for each concept alternative must take place during the earliest design phase. Selection of power sources (solar arrays vs. solar dynamics vs. nuclear), selection of AOCS thruster types and propellants (combustion vs. cold gas vs. electrical), selection of a thermal control strategy, determination of life-support components and resupply requirements, and inclusion of possible synergistic couplings among those subsystems lay the foundation for subsequent estimation of key system parameters.

Before the topology of the space segment, i.e. the geometric location of pressurized and unpressurized elements, can be determined, it is necessary to list the components to be integrated into it, and to estimate key system parameters such as the dimensions of pressurized modules and unpressurized elements, including the sizing of solar arrays and radiators based on preliminary results of the respective subsystem designs. When designing the topology, design rules such as those listed in Table 2.4 help the design team to come up with an initial viable configuration, without the need for iterative numerical simulations e.g. for attitude stability. Note that significant

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[7] In this context, "topology" refers to the geometric arrangement of major space station components, such as pressurized modules and photovoltaic arrays.

Table 2.3: Earth-Oriented Versus Inertial Flight Modes [Bertrand98]

Flight Mode	**Characteristics**
Earth-Oriented	✧ Positive aspects: • Favorable for Earth observation and telecommunications • Gravity gradient usable for attitude stabilization[8] • More flexibility for positioning of microgravity payloads • Earth provides reference for crew orientation (EVA and IVA) • Rendezvous and docking operations are easier • More flexibility for assembly and growth of orbital segment ✧ Negative aspects: • Needs solar array and radiator tracking • Variable lighting conditions during EVAs
Inertial	✧ Positive aspects: • Favorable for astronomy • Simplified collectors and radiators (no tracking required) • Constant lighting conditions during EVAs • Constant thermal control conditions ✧ Negative aspects: • Gravity gradient always acts as perturbation • Difficult to keep optimum mass distribution during assembly and orbital segment growth

additions to this table will be presented in Section 3.2 (Table 3.4 on page 67, Table 3.5 on page 70, and Table 3.7 on page 76), which will address critical human-related issues.

A design usually cannot fully comply with all of these guidelines, since some are contradictory. To help the design team find a viable compromise, the relative importance of adhering to those rules has also been given in Table 2.4, with Ⓐ being the highest and Ⓒ the lowest in importance.

Table 2.4: Heuristics of Space Station Topologies ([Bertrand98], adapted)

Aspect	**Design Rules for Earth-Oriented Flight Mode**
Attitude Stability and Controllability	Ⓐ Distribute mass along Zenith-Nadir axis for gravity gradient stability (I_{xx}, $I_{yy} >> I_{zz}$) Ⓐ Avoid mass distribution asymmetries relative to the orbit

---

[8] Larger stations should be designed to use the gravity gradient as compensation for the aerodynamic torque, in order to limit attitude-control fuel usage.

Table 2.4: Heuristics of Space Station Topologies ([Bertrand98], adapted)

Aspect	Design Rules for Earth-Oriented Flight Mode
	plane (I_{xz}, pitch instability) and to the plane perpendicular to the velocity vector (I_{yz}, roll instability)
Aerodynamic Drag	Ⓑ Minimize aerodynamic incidence areas (pressurized module orientations, collector and radiator surface areas)
	Ⓐ Balance the mean aerodynamic incidence areas (aerodynamic center) such that the sum of gravity gradient and aerodynamic torque lead to a Torque Equilibrium Attitude (TEA) Ⓐ Keep aerodynamic center of moving surfaces close to the center of mass (CM)
Growth Potential and Configuration Flexibility	Ⓐ Analyze attitude stability for all assembly configurations Ⓐ Accommodate frequently changing modules, e.g. logistics vehicles, so that effects on overall station aerodynamics and tensor of inertia are minimized
Microgravity Levels	Ⓐ Integrate µg facilities close to the line parallel to the direction of flight through the center of mass Ⓑ Avoid long, flexible structures
Rendezvous and Docking	Ⓐ Provide access corridors in radial or orbit-tangential direction with sufficient clearance for all foreseen resupply and crew vehicles
	Ⓒ Avoid dedicated docking orientations that are different from nominal attitudes
Pressurized Module Configurations	Ⓒ Allow for redundant access to each pressurized module, and for two escape routes from each of them Ⓒ Minimize aerodynamic and debris incidence area
Solar Arrays	Ⓑ Provide tracking (α and β) Ⓑ Check fields of view for payloads and sensors Ⓑ Check rendezvous and docking physical/thruster plume interference Ⓑ Keep the collector's center of pressure close to the center of mass of the space station to avoid TEA changes caused by tracking Ⓑ Best array location to minimize shading: away from pressurized modules in POP direction

Table 2.4: Heuristics of Space Station Topologies ([Bertrand98], adapted)

Aspect	**Design Rules for Earth-Oriented Flight Mode**
Radiator Panels	Ⓐ Minimize fluid feed lines and feed-throughs in joints Ⓐ Check fields of view for payloads and sensors Ⓐ Check rendezvous and docking physical/thruster plume interference
	Ⓒ Provide tracking for best performance Ⓒ Avoid drag by orienting panels' normal vectors perpendicular to velocity vector
AOCS Thrusters	Ⓐ Check for contamination and interference Ⓐ Avoid long propellant feed lines Ⓐ Orbit control thruster positioning: line of force parallel to velocity vector and close to CM Ⓐ Attitude control thruster positioning: maximize leverage (i.e. distance to CM) for low propellant consumption
Human Integration	Ⓐ *see Table 3.4 and Table 3.5 on page 67 ff.*
ECLSS	Ⓐ *see Table 3.7 on page 76*
Observation and Communication Payloads	Ⓐ Check field of view and shading Ⓐ Astronomical payloads need tracking and steering Ⓐ May be sensitive to contamination (thrusters, airlock)

Evaluating the System

Evaluation of the alternative systems designed in the previous step starts with the preparation of system budgets. These budgets quantify the performance of the various alternatives using overall system parameters like mass, electrical power, volume, etc. Table 2.5 contains a more detailed listing of recommended items to be budgeted. They allow for the design team to compare among the alternatives in order to identify and select the concept that seems most promising with respect to fulfillment of the objectives, and for the customer to make a "go/no-go" decision with respect to the continuation of the project.

Verifying and Allocating Requirements

The subsequent verification and more detailed definition of system requirements and their allocation to specific system elements of the baseline system concept selected in the preceding step concludes the early phase of the conceptual design process. It makes sure that the baseline system is documented thoroughly, and it prepares the ground for the subsequent detailed design phase.

2.1.3 Engineering Design Tools

Support from appropriate software programs is indispensable for a rapid and efficient conceptual design process, especially if several iteration loops – and thus repetitive executions of numerical analysis tasks – are required. The tools used to support the SSDW consist of custom-developed software dedicated to the conceptual design of space stations as well as commercially available general-purpose software. Figure 2.3 presents an overview of the tools used within the SSDW design context. The most important elements are described below.

Visual Model Generation and Editing

For configuration modeling and editing, GISSAD, a proprietary add-on for the commercially available computer-aided design tool AutoCAD R12 is used [Messerschmid00]. Its output contains a plain-text description of the topology and mass properties of the space station developed by the designers. This output is subsequently read by the IRIS software (see below) for attitude and orbit control simulations.

GISSAD supports rapid modeling and accommodates limited hardware resources through the use of geometrical primitives, as shown in Figure 2.4. A successor software is currently under development.

Orbit and Attitude Simulation

A custom-developed numerical simulation package (called IRIS) is used for the attitude and orbit analysis of the orbital segment. Inputs are a file containing the geometry and mass distribution of a space station or platform, which is generated by GISSAD or edited manually, and a file with simulation/mission commands. Outputs are:

- Attitude dynamics based on the numerical integration of 6D-Euler equations of motion, taking into account actuators like momentum wheels, thrusters, and magnetic torquers
- Orbital dynamics, based on osculating elements using equinoctical orbit parameters, allowing for orbit control strategies using permanent or impulsive thrust, and taking into account advanced perturbation models (J4 gravity field, atmosphere, magnetosphere, user-defined arbitrary forces)
- Energy budget, based on photovoltaic and solar dynamic power generation systems, and including the simulation of orbital influences (tracking, eclipse)
- Microgravity levels at arbitrary locations within a space station

The latest version of IRIS, IRIS++, provides enhanced simulation capability as well as Virtual Reality Modeling Language (VRML) output for quick configuration display ([Messerschmid00], [Hinüber01]).

Life Support System Simulation

The original SSDW tool for the design and analysis of the space station life support system (ECLSS) is called MELISSA, which stands for "Modular Environment for Life-Support Systems Simulation and Analysis" [Osburg98]. Using drag-and-drop techniques, the user graphically models the ECLSS to be analyzed before starting simulation runs.

Interactive simulation control allows analysis of dynamic problems, and also permits real-time operator training. A graphical user interface provides convenient simulation features. A small library of predefined components exists for the life support and power supply subsystems. An improved tool for the simulation of the ECLSS and synergistically linked subsystems was developed as part of this dissertation (cf. Section 3.3.1 on page 82).

Top-Level Subsystem Assessment

A spreadsheet application, Microsoft Excel [Excel01], is used during workshops and research projects for budgeting, estimations, accounting, generation of system balances, and postprocessing of simulation results.

2.1.4 Application of SSDW Methodology

The space station design methodology presented in the preceding section has been successfully applied to research and design projects ([Bertrand98], [Messerschmid00], [Schmid00], Fehrenbacher98]), as

Table 2.5: Parameters for System Budgets [Bertrand98]

Parameter	Budget Items	Required For
Mass	✧ Mass breakdown for orbital segment	✧ System concept comparison and selection ✧ Obtaining design data for AOCS, assembly planning, cost estimates
Inertias	✧ Inertia tensor of orbital system	✧ Obtaining design data for AOCS ✧ Evaluation and optimization of topology
Orbit Control	✧ Reboost mode and cycle duration ✧ Thrust levels ✧ Propellant needs	✧ Obtaining design data for AOCS ✧ Logistics planning ✧ Subsystem, utilization and operations planning
Attitude Control	✧ Perturbation torques ✧ Accumulated momentum ✧ Propellant needs ✧ Torque Equilibrium Attitude (TEA)	✧ Obtaining design data for AOCS ✧ Logistics planning ✧ Evaluation and optimization of configuration
EPS/TCS	✧ Total installed power ✧ Power allocations	✧ Obtaining design data for EPS and TCS ✧ Configuration verification ✧ Subsystem, utilization and operations planning
Consumables	✧ Resupply budget	✧ Logistics planning
Assembly	✧ Assembly sequence	✧ Launch and operations planning
Crew	✧ Crew time allocations	✧ Subsystem, utilization and operations planning

well as during several interdisciplinary hands-on design workshops held at the University of Stuttgart from 1997 to 2000 [SSDW01b].

The objective of these workshops was to generate viable conceptual designs of space stations, starting from scratch, in a multinational, interactive, team-centered environment. At the same time, the participating graduate students were given an opportunity to gain first-hand knowledge and experience of the challenges of the conceptual design process. The design results included system budged data (cf. Table 2.5, page 29), configuration drawings, simulations, and scale models.

Due to the success of this hands-on verification, the improved approach presented in Chapter 3 was also validated in this manner, during the Space Station Design Workshop 2001 (Section 4.2).

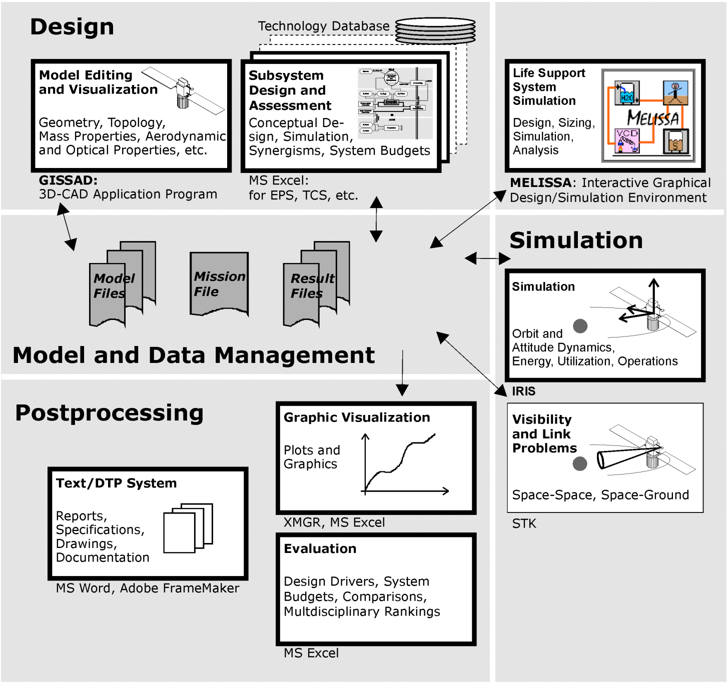
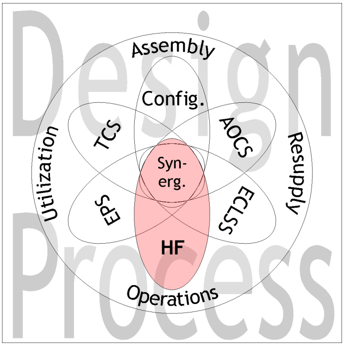


Figure 2.3: Software tools associated with the SSDW methodology

2.2 Human Aspects



According to Roald Amundsen, one of the most experienced Arctic and Antarctic explorers of the early 20th century, *"[the] human factor is three quarters of any expedition"* [Stuster96]. This is also valid for long-duration space missions, where *"the human system emerges as the primary risk to mission success"* [Adams00b] – but of course also represents the largest potential contributor to such success.

Knowledge of this "human factor", i.e. of the crew and its limitations and potential, is an indispensable part of any approach to the design of inhabited space systems. It transcends the purely engineering-oriented design of the Life Support System and of user interface ergonomics. It is only marginally addressed in the traditional engineering-centered SSDW methodology (cf. Section 2.1.2); consequently, it was integrated as part of the new approach presented in this report.

To prepare for this integration, an overview of key concepts and findings in the areas of Human Factors, habitability, crew psychology, and habitat design is given in this section. The concrete de-

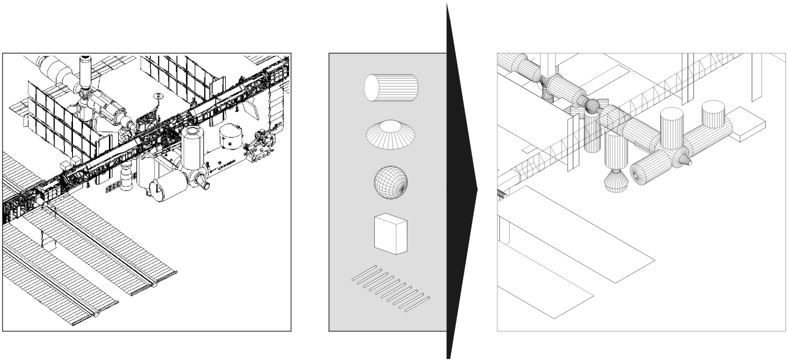


Figure 2.4: Geometry modeling with primitives [Messerschmid99]

sign rules that can be derived from them are then presented in the form of tabulated, easy-to-use design heuristics in Section 3.2. The sources of this knowledge are threefold:

- Actual spaceflight experience
- Results of dedicated experimental or theoretical studies and simulations
- Experience from analogous situations on Earth

Actual space missions have generated a vast and priceless amount of knowledge, those to the Skylab ([Biomedical75], [Skylab77]) and Mir [Gazenko87] space stations of the past (including Shuttle-Mir [Burrough98]), as well as recent missions to ISS [Shepard01]. Astronauts have lived and worked in space for up to 437 days [Wade01], and much of their experience has found its way into the planning of ongoing missions.

Valuable knowledge has also come from earth-based studies and simulations. Even though many lack the real-life authority that actual spaceflight experience conveys, they allow for systematic research and evaluation, indicate potential problems, and point out solutions that can then be tested in space.

The third body of knowledge which can be drawn upon is analogous situations on Earth, as offered e.g. by research expeditions to remote areas such as the Arctic and Antarctica. It is not by chance, therefore, that the crew rotation increments to ISS are called “expeditions”, since this is what manned long-term space missions are[9].

Based on these sources, the following subsections will address the optimal integration of the human crew from various angles: first, from the point of view of crew efficiency and mission accomplishment, then, with a focus on ergonomics and habitability, and finally, from the perspective of Human Factors and design. Examples of terrestrial analogs conclude this section.

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[9] Similarities between the exploration of Earth and space can even be seen in the historic development: first, the heroic phase, with single or few explorers; then, the establishment of first research outposts; then their growth into larger outposts; and finally, routine commercial endeavors [Palinkas87].

2.2.1 Crew Efficiency and Mission Accomplishment

Sir Ernest Shackleton, another famous Antarctic explorer of the early 20th century, recruited the crew for his legendary expedition with the following advertisement in London newspapers [Stuster96]:

> *"Men wanted for hazardous journey. Small wages, bitter cold, long months of complete darkness, constant danger, safe return doubtful. Honour and recognition in case of success."*

Shackleton found a crew, and his voyage – even though its original mission was never accomplished – turned out to be one of the most impressive examples of perseverance, endurance and overcoming incredible odds in history [Alexander98]. But many other expeditions failed because the human element was not sufficiently taken into account. Surviving under austere conditions is sometimes feasible, but it reduces the crew's efficiency and its ability to accomplish the mission. In emergencies, mere survival can depend on the amount of additional mental stressors that are caused by a suboptimal environment [Volovich93].

Such experiences emphasize the central, well-validated assumption of all human-centered systems design: increased crew comfort and safety, i.e. increased habitability, means increased crew productivity and therefore an increased likelihood of mission success [Cohen90]. This leads directly to the notion of designing a system *around* the crew, as opposed to designing a "machine-with-attached-crew" in the traditional approach. This includes much more than regular workplace ergonomics [Evans87]:

> *"Habitats which are designed to serve not only the work objectives but also the residential ones will help improve the health and productive qualities"*

Such an approach is corroborated by actual astronaut experience gained from long-duration missions [Wolf98]:

> *"[It] is impossible to separate habitability issues from productivity in scientific research. They're one and the same – from food, toilets, and a good layout of workstation space."*

2.2.2 Ergonomics and Habitability

Habitability, in the context of manned space systems, is defined as the ability of a facility to support a productive and efficient mission team [Adams00b]. This includes – but is not limited to – the life support subsystem as well as the ergonomic design of individual workstations and other internal elements. In general terms, space station habitability is about [Cohen87b]:

> *"... what happens when a soft, articulate, intelligent life form comes into close contact with a hard, fixed, inanimate object for considerable lengths of time in hostile circumstances at very great expense."*

The Space Human Factors Office at NASA-Ames defined habitability as follows [Wise85]:

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

Several voluminous references are available to the designers of inhabited spacecraft that are mainly providing detailed ergonomics-related information and specifications related to the interior outfitting of a given overall station/module configuration ([Man95], [ISS95], [Human94]). Terrestrial Human Factors literature also focuses on ergonomics and the workplace environment, due to the commercial importance of worker efficiency and safety [Sanders93].

Table 2.6 presents an example of anthropometrics-based design guidance. Even in the early phase of the conceptual design, such detailed data is important (all proposed configurations must allocate enough space to provide the crew with sufficiently large sleeping quarters), so the design team has to be as aware of these numbers as they are of e.g. launcher data.

Spaceflight and Earth-analog experience thus shows that crew efficiency and mission success depend on the integrated view of a manned space system as a *habitat*. This notion will play an important role in the new approach described in Chapter 3.

2.2.3 Human Factors and Design

Cohen addresses the influence of Human Factors knowledge on design issues at the system level [Cohen90]:

> *"The key to designing human productivity into space vehicles and habitats is to develop measures of human performance suited to future long-duration space missions. These new measures should indicate that the design process focus on living and working activities that foster crew creativity rather than on economies of equipment packaging. Ultimately, the architectural design will shape the functional and social productivity of the space microsociety it shelters."*

Several examples of actual "space architecture", i.e. the deliberate involvement of architects in human-oriented space design projects, can already be identified:

- ✧ Designing planetary bases [Cohen98]
- ✧ Designing and building an Earth-analog of a planetary base (FMARS, Figure 2.5, [Micheels99])

Table 2.6: Anthropometry-Derived Design Guidelines [Adams99]

Area	**Item**	**Dimensions**
Space Inside Compartments	✧ Crew quarters (incl. sleeping restraint), hygiene compartments	✧ 215 cm high, 105 cm wide, 105 cm deep (2.4 m^3)
	✧ Toilet compartments	✧ 201 cm high, 90 cm wide, 105 cm deep (1.9 m^3)
	✧ Stowage compartments	✧ Maximum depth inside stowage units 60 cm
Free Space Around Equipment	✧ Galley	✧ 215 cm high, 100 cm wide, 100 cm deep
	✧ Treadmill	✧ 245 cm high, 100 cm wide, 150 cm long
	✧ Sleeping restraint	✧ 215 cm long, 85 cm wide, 85 cm deep (1.5 m^3)
	✧ Computer workstation	✧ 205 cm high, 101 cm wide (at elbows), 90 cm deep (1.8 m^3)
Translation Paths	✧ Free space between activity stations	✧ 215 cm height, 85 cm width (single person)/110 cm width (two persons)
Egress Paths	✧ Several doors joining at same level	✧ Minimum width 105 cm
	✧ Dead-end paths	✧ Maximum length 15 m

- Designing and testing an inflatable pressurized module (TransHab [Kennnedy99], cf. Figure 1.5 on page 12)
- Performing mission integration for Space Shuttle missions [Jones00]
- Investigations into habitation module interiors [Nixon89] and into the role of gravity for space habitats [Hall94]

In addition, architecture-oriented design programs and projects, e.g. at the University of Houston [SICSA00] and at the University of Munich [Vogler00], have dealt with applying architectural knowledge and approaches to the design of human-related space hardware.

2.2.4 Extreme-Environment Analogs on Earth

Issues ranging from Human Factors and crew psychology to the design of physical structures in hostile environments can be researched and tested using terrestrial analogs. Opportunities for collecting information and performing experiments and tests using preexisting facilities that have a different primary purpose include:

- Polar bases in the Arctic and Antarctica (Figure 2.6) provide an expedient testing ground for crew selection policies and extreme-environments psychology under conditions of isolation, confinement, risk, and environmental stressors. This is witnessed by a multitude of research (e.g. [Stuster96], [Palinkas00]). Antarctica is generally considered best for such research, due to similar scientific and political objectives between research stations there and future planetary bases, and due to heterogeneous crews, a high level of required skill and organization, long crew rotation periods, a hazardous/stressful environment, and comparable confinement and isolation [Palinkas87]. Such stations even allow for ECLSS-related research [Flynn94].

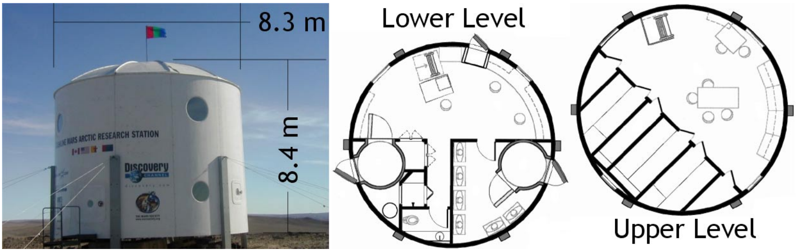

Figure 2.5: The Mars Society's Mars Arctic Research Station: exterior view and floor plans of upper (habitation) and lower (laboratory) decks [Mars00]

- Additional resources for HF research are provided through research on military platforms like nuclear submarines and strategic missile shelters. These are generally considered less valid due to highly stringent preselection and homogeneity of crews, and the extreme monotony of service in these environments [Stuster96].
- Underwater habitats for saturation divers also provide an interesting opportunity to gain insight into human behavior under prolonged confinement in a technology-dominated, high-risk environment. Due to their commercial nature, the focus here is mainly on the relationships between habitability and productivity[10].
- Biosphere 2 (Figure 2.7), a large closed-system facility for ecological research, also provides the opportunity for concomitant space exploration-related ECLSS and HF experiments [Biosphere01].

Dedicated space-analog facilities have also been built:

- Closed-chamber simulations have been performed specifically for space HF research, e.g. EMSI ([Bauer94], [ESA90b]) or SFINCSS [SFINCSS99].

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[10] It is of interest to note that in this context, too, *"design must go beyond Human Factors consideration"* [Taylor84].

- For testing and validation of ECLSS components and system concepts along with some HF research, additional closed-chamber testing has been done, e.g. NASA's Lunar-Mars Life Support Test Project ([Lewis98], [Mount00a]; a larger version, BioPlex, is currently under preparation at JSC [Tri99]).
- A dedicated, high-fidelity simulation facility for planetary stations, the "Flashline Mars Arctic Research Station" (FMARS), was built in 2000 in northern Canada by the Mars Society ([Micheels99], [Mars00]; cf. Figure 2.5 on page 37). A similar facility, the "Mars Desert Research Station" (MDRS), was built in the deserts of Utah in 2001 [MDRS02]. Both provide simulation capability for life support technologies, Human Factors research, operational issues, as well as planetary science procedures.

Lessons learned and ideas generated from these research facilities will facilitate the planning and operation of the first real off-Earth bases. Key results that are immediately applicable within the context of the conceptual design of inhabited space systems are compiled in Section 3.2, beginning on page 64.

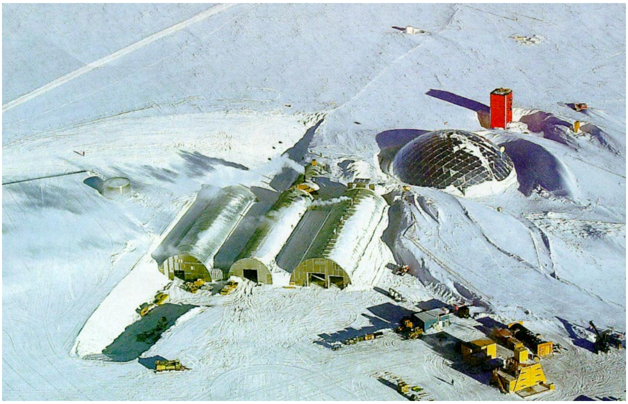


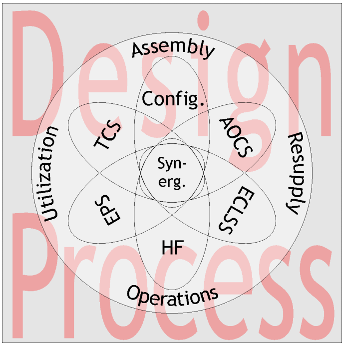
Figure 2.6: Scott-Amundsen South Pole station: extreme-environment design and a precursor to future planetary research stations [Anderson]

Figure 2.7: Biosphere-2, an Earth-based research facility for closed biological systems [Biosphere01]

Chapter 3 will apply the relevant experience and ideas gained in these undertakings to the conceptual design of the overall system.

2.3 Terrestrial Architecture

Adding carefully selected, relevant design methods, tools and components derived from terrestrial analogs to the engineering-centered methodology outlined in Section 2.1.2 will improve the design process and thus its outcome ([Adams98a], [Maier96]). The most promising elements, which will be demonstrated below, can be found in the area of terrestrial architecture. The integration of these elements into the new interdisciplinary design process will be described in Chapter 3.



2.3.1 Role of the Architect

Vogler et al define the architect’s mission in a way that makes the connection to designing manned space structures obvious [Vogler00]:

> *“Developing functional spaces for people to live and work in is the core competence of an architect. Planning these spaces successfully is a complex process and not only requires design talent, but experience and knowledge.”*

On a more general level, Rechtin states [Rechtin91]:

> *"Architecting, the planning and building of structures, is as old as human societies*[11] *and as modern as planning the exploration of the solar system. It arose in response to problems too complex to be solved by preestablished rules and procedures*[12]*."*

The knowledge gained in this long history, with respect to the *design process* as well as regarding the *design tools* employed by it, can be utilized to improve the overall design of inhabited space systems.

2.3.2 Architectural Design Process

The systems architect directs and accompanies the designed system throughout its life cycle, from conception to development to construction[13] to operation. That person keeps an eye on *"reducing complexity and selecting workability"* [Rechtin91], guiding the work of the design engineers tasked with implementation of the selected viable design. Preservation of the original designers' intent throughout the design process serves as a safeguard against requirements creep and increases design consistency and simplicity. Jones describes the architects' role such [Jones00c]:

> *"In any building project, the Architect's role and skill is to balance the client's requirements with the available technology, a site and a budget. Time, place and resources set the boundaries and constraints of the project. A successful project is one that abides by those constraints and successfully meets the client's needs. The design and assembly of large-scale space facilities, whether in orbit around or on the surface of a planet, require and employ these same skills."*

An experienced design engineer with the appropriate interdisciplinary mindset can fill this role as well as an architect who is equipped

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[11] This tie between buildings and societies is emphasized by design theorist Valery, who refers to buildings as the *"foundations of civilization"* [Valery94].

[12] This already hints at the architectural tool of "Exploration by Design", which will be detailed in Section 2.3.9.

[13] Here, construction refers to the physical act of building, not to the construction of solutions that takes place during the design phase, and which Valery equated with *"composition"* [Valery94].

with a thorough understanding of engineering and an open mind to interdisciplinary cooperation. Vitruvius, a prominent architect of ancient Rome, gave this classical illustration of the ideal architect's profile [Vitruvius99]:

> *"Therefore, [the architect] should be inventive and fond of learning, because neither with inventiveness alone nor with learning alone can one construct a perfect building. He should also be a good writer, expert in drafting, learned in geometry, knowledgeable about history; he should be versed in the works of philosophers, know music, should be not ignorant of medicine, understand the laws, and should be familiar with the interrelationships of the celestial bodies."*

These skills define the architect's role as one of generalist, integrating various sub-disciplines into a holistic concept of the overall structure. They are still valid today. Replacing "structure" by "system" yields the job description for a systems engineer-architect.

The architectural design process is quite similar to the engineering equivalent (cf. Sections 2.1.1 and 2.1.2) insofar as it contains the following steps [Locher91]:

- ✧ An initial phase which encompasses analysis and determination of needs, metaplanning (planning of the design process), negotiations with the customer,
- ✧ A concept exploration phase, which generates a global system architecture, identifies interfaces, and looks at feasibility, and
- ✧ A design phase, which lets the accumulated multidisciplinary knowledge interact, takes care of integration and system planning, estimates dimensions and materials, provides for the use of synergistic effects, and harmonizes disciplinary contributions.

Section 3.1 starting on page 58 of this report represents the transformation of the findings presented above into concrete ground rules for the design team.

Architectural Design Tools

The terrestrial architectural process also employs several useful methods that can be incorporated into an interdisciplinary conceptual design process for inhabited space structures. These are:

- Thorough background research
- Extensive use of hand sketches
- Checking on design feasibility through development of important details, from the earliest design phase on
- Deliberate development of alternative design solutions and their variants
- Organizing the creative potential of the design team
- Use of design principles
- Exploration by design

Table 2.7 identifies how theses tools can support the SSDW design process during each phase (cf. Table 2.1 on page 20). A thorough description of these elements, as well as the rationales for incorporating them, will be presented in the following section.

2.3.3 Thorough Background Research

The first design decisions made by the design team have an extraordinary influence on the final result (cf. Figure 2.2 on page 17). As Rechtin puts it [Rechtin91],

> *"[i]n architecting a new aerospace system, by the time of the first design review, performance, cost, and schedule will have been predetermined. One might not know what they are yet, but, to first order, all the critical assumptions and choices will have been made that determine those parameters."*

Making the right choices requires obtaining and processing information, i.e. background research. This research, and the thorough comprehension of the knowledge gathered, is the prerequisite for directed creativity and the successful creation of alternatives and variants, even if it seems dry and cumbersome.

Such comprehension requires time, for the cognitive mental processes that are involved, as well as for the subconscious "fermentation" of the information gathered, but it will lead to a balanced, holistic understanding of the design task and its possible solutions. Few things endanger the creative design process more than the precocious "brilliant idea" that becomes a favorite before the task and the background information are fully analyzed and understood [Uhl98]. Such ideas will linger in everyone's mind, biasing incoming new information due to the formation of patterns of perception

Table 2.7: Potential Contributions of Architectural Tools to SSDW

SSDW Process		Architectural Tool						
Phase	Topic	Background Research	Hand Sketches	Important Details	Alter-natives	Organized Creativity	Design Prin-ciples	Exploration by Design
A	Develop Broad Objectives	●				●	●	●
B	Prelimin. Require-ments/Constraints	●	○	○	○	○	●	●
C	Develop Alterna-tive Concepts	●	●	○	●	●	●	●
D	Characterize System Elements	○	●	●	●	○	○	○
E	Prepare System Budgets			○				
F	Evaluate Mission Utility		○	●				○
G	Select System Baseline	○			○	○	●	○
H	Verify Requirements	○		○			○	
I	Allocate Requirements		○			○	○	○

●: main contributor ○: auxiliary contributor

[DeBono94]. They will push the designer towards their realization, and discount all alternatives in the process.

2.3.4 Use of Hand Sketches

One of the central tools of the architect's trade is the sketch. Why use hand sketches instead of computerized drawings? There is still a place for manual sketches in conceptual design beyond the "dinner napkin drawing" commonly associated with this issue (cf. the Skylab drawing in Figure 2.2 on page 17). The sketches referred to here are neither the fanciful explanatory illustrations generated after a design is finished, nor the discipline-specific analytic drawings and plans that use symbols defined by accompanying legends. Instead, they are a third kind – sketches that contain icons identical to the properties which they reflect, which therefore make their meaning immediately obvious; sketches that contain delicate, uncertain lines – which can play such an important role in conceptual design [Uhl01].

When sketching, exploring solutions and reflecting on the task are in the foreground, carried out through the simultaneity of sketching and thinking, as opposed to mere computer-aided documenting of preconceived concepts[14]. A quote by practicing architect and design theorist Uhl supports this [Uhl98]:

> *"Therefore, the sketch has its place at the beginning [of the design process]. Sketching is a manual exercise that uses visualized language in order to put the visible and invisible properties of objects onto paper. Sketching thus builds a bridge between those things that can only be thought of, and those that can also be drawn. To some extent, thinking is externalized into the drawing pencil, into the moving lines [it produces]. In this manner, the designer's thoughts are exercised twice: by sketching and by thinking."*

Sketches are visualized language. They visibly communicate and document the designer's/drawer's intent in a condensed, concrete form and thus assure efficient transfer between individual disci-

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[14] In addition, hand sketches are usually accomplished more quickly than similar computer-generated drawings.

plines. Abstract sketches focus on the core issues. Reduction of visual complexity, as enforced by a manual sketch, fosters understanding [Uhl01]:

> *"Abstract sketches represent accumulated knowledge about the properties of objects. The lines themselves take on the properties that they reflect. These content-rich, line-based sketches promote concentration on the essentials."*

Sketches emphasize that the design task is about determining relationships[15] – of which there are an infinite number – and not about shapes[16], which are finite and already known.

On the other hand, unlike the streamlined, interchangeable lines of a CAD drawing that feign an exactness that is just not there during the early phase of the design process, the special appearance of a sketch often fosters the creative process through ambiguity[17]: the same sketch appears different if examined with increased knowledge, or by different persons, or at a different location or time: *"A sketch always appears in plural"* [Uhl01].

The viewer, however, must have sufficient practice in interpreting sketches and the lines that make them up, i.e. possess an "imaginative eye" that can read the inherent networks of relationships from a sketch[18] [Uhl00]. Noted design philosopher Bense says in this regard [Bense75]:

---

[15] E.g. space station configurations

[16] E.g. the library of presssurized modules on ISS and Mir, such as the base block, the US lab, or the nodes.

[17] Uhl describes it thus [Uhl98]: *"At the outset, the multitude of sketches displays the initial set of possibilities. Maybe those sketches irritate [the viewer] by their imprecise, undulating [lines]. But they foster creativity and gradual progress when – from within their unsightly, uncertain lines – increasingly more precise, illuminating lines emerge [...]. Or, [this can also happen] when an imaginative eye can read those lines and thus finds traces of solutions. The insecure beginning, the sketchiness, results in mobility. It also results in organizational structures that bring all decisions together."* Schinkel remarks in this respect [Uhl01]: *"The added value of a sketch is that it gives up the rule of pedantic-systematic knowledge in order to achieve a result of higher degree."*

[18] *"Sketches do not depict that which one can see; instead, they reflect it by assuming the properties of the object that is seen."* [Uhl98]

> *"[Sketches] indicate the twofold mental process that is the hallmark of each creative architect and that seems incompatible only to the ignoramus: improvisation and precision, with improvisation expressing an aesthetic category, and precision a technological one. Each sketch [...] prepares the set of possibilities of the creative repertoire within the realm of improvisation, from which the moments of precision can be drawn like finer and firmer threads."*

This process of developing precision from abstractness and ambiguity – i.e. the main challenge of each and every design process – by means of subsequent sketches is exemplified in Figure 2.8.

Ambiguity (i.e. the presence of multiple possibilities) in a design sketch is the prerequisite for creative imagination, but only *"as long as the trained imaginative mind can read the lines, and can thus get closer to seeing the solutions"* [Uhl01]. It corresponds to ambiguous design requirements as well as to the unfinished state of the system during the conceptual design process, where many ideas can gain transient dominance. The transparent superposition of several layers of lines on the sketch relates to the varying superpositions of uses and configurational states of a space station during its life cycle.

Sketches can integrate varying levels of detail in one display, and concurrently present context in large, desk-filling formats, which an observer can read immediately, and which are impossible to repeat on the computer screen. Therefore, sketches are more than the actual plans and technical drawings which will be extracted[19] from those same sketches at some later point [Uhl01]:

> *"Before being put into a plan, the idea is in the realm of imagination [i.e. it is a sketch]. Then, contours become more pronounced, redundancy and noise are suppressed, and silhouettes*

---

[19] Uhl says about this process of extraction [Uhl98]: *"Thus, by omitting possibilities, the sketch is transformed into the more and more precise drawing/plan, which then picks up the inevitable conventions and necessities, thus moving into the reality of architectural media. A reality where infinite possibilities of the creative beginnings can still be noticed."* A sketch chooses, assumes properties of the subject, expresses substance with few lines (if the sketching person is proficient in this art) [Uhl01].

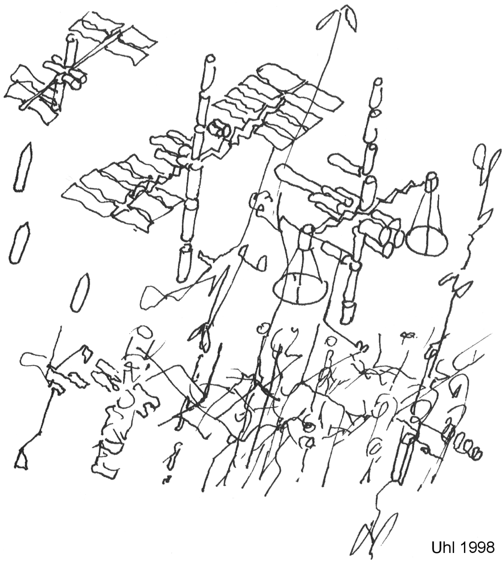

Figure 2.8: Abstracting a station configuration (top left) from the "thunderstorm of lines" (bottom right) [Uhl98]

> *of relationships step forward from this thunderstorm of lines. The completed version is more precise, but always poorer.[20]"*

Simultaneously, hand sketches provide a constant reality check for the designer (*"Sketchability assures transferability. Only what can be sketched can be built"* [Uhl98]), thus guiding the thought process toward feasibility[21] [Zubrin96]:

> *"A good engineering artist can make extraordinary contributions to a design effort by forcing you to think and explain how this fits into that, and how someone could get from here to there."*

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[20] Cocteau refers to this as *"the sketch melting away like snow"* at the moment that drawings can be made [Uhl01].

[21] This is a more precise statement of Schinkel's concept of building and buildings [Schinkel01]: *"Architecture leads to realization of the mentally-existing building, which precedes the physical one."* Valery states the subjective corollary: *"It is the spirit of a building that makes its impression on the human senses."* [Valery94]

Last but not least, the aesthetic appeal of a sketch corresponds to the aesthetic element that is part of each physical object. In the area of habitat design, this aesthetic aspect is also linked to functionality, since aesthetic appeal is a strong conscious and subconscious contributor to habitability.

Jolk and Gerum summarize these aspects [Jolk98]:

> *"This is where the sketch, as a design method from architecture, makes its contribution, since it visualizes thoughts and thereby makes them available in a finite state for debate within the team. [...]*
>
> *"The sketching designer discloses his view of the issue to the observer but still leaves it as something preliminary, which is therefore open to discussion. The teammate then finishes an only partially visualized thought.*
>
> *"At the same time, a sketch – or a multitude of sketches – can depict a thought much more thoroughly and inclusively than the engineer's traditional numbers-based approach is able to. This simultaneous combination of vague, infinite presentation – which includes the possibility of complete rejection – with a desire to visualize a thought completely, offers an ideal forum for the employment of additional intuition-/association-based creativity techniques.*
>
> *"This means enrichment for all design participants, which facilitates communicating about the design goal within the design team. 'Designing by sketching' thus has a central role in the interdisciplinary design process.*
>
> *"Visualizing visual thoughts is an art that must be properly trained, and which, after such training, enriches the thought in turn. Knowingly-logical and insecurely-trying, the sketcher visualizes thoughts. Iteration is included as a matter of course."*

2.3.5 Focus on Important Details

Performing the detailed design of selected elements during the conceptual design phase of the overall system – which is common in architectural practice – runs counter to the traditional top-down engineering approach. Nevertheless, key details have an extraordinary

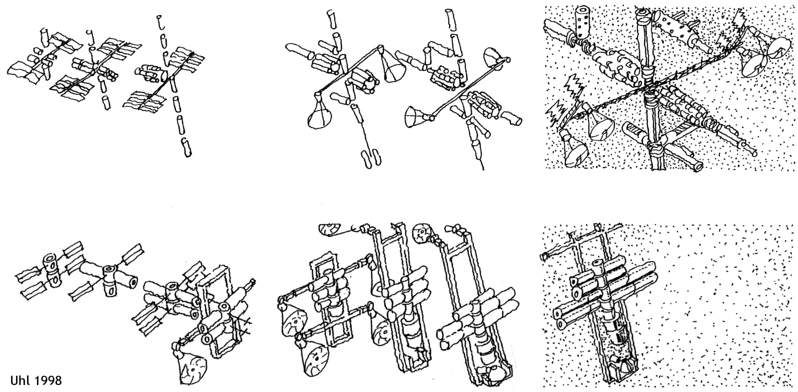

Figure 2.9: Space station configuration sketches: two alternative concepts (top/bottom rows) with variants for their respective buildup [Uhl98]

amount of influence on the overall system layout, and sometimes determine project feasibility[22].

Pre-designing significant details offers guidance to designers in subsequent steps, thus preserving the system architect's intent and focus. Looking at important details early in the design process also satisfies the inquisitive nature of human thinking, promoting the creative flow as long as the designers keep their overall focus on the top-level design and avoid getting lost in details[23].

2.3.6 Development of Alternatives and Variants

During the early stages of conceptual design, above all, generation of a number of alternative system designs that are feasible (and that

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[22] For example, the interior design of NASA's BioPlex simulation facility was made difficult due to the fact that overall habitation module dimensions were set before design drivers based on human dimensions (cf. Table 2.6 on page 35) were taken into account [Adams00a].

[23] The design results presented in Section 4.1 (pages 94 to 98) provide a good example for the appropriate use of details (ISPR-based crew quarters rack, Phase III). It also demonstrates a positive side effect of this approach: The timeframe of the original top-level task (Phase I/II, 2020 to 2030) caused an open mindset that allowed for thinking "out of the box", resulting in a creative detailed design solution that is applicable today.

can be analyzed) is vital in order to increase the chances of finding a viable solution that will satisfy all requirements and constraints, especially if additional ones might be introduced by the customer or others later on. A conscious decision is therefore made to develop alternatives – i.e. solutions to the design problem that differ significantly from each other [Locher91] – even if one solution seems to be workable from the beginning.

From each alternative, a number of variants (at least three, [Uhl98]) are generated, by applying task-derived rules (e.g. assembly) to patterns (e.g. modules), controlled by certain parameters (e.g. time from first launch to IOC), as demonstrated by the sketch in Figure 2.9. Ideally, this process takes place almost subconsciously[24], during the exploration-by-sketch outlined in Section 2.3.4. Variants present a choice of possibilities that can be maintained far into the design process. They put issues into perspective, show where objective reasoning ends and unavoidable subjective choices of the designer come into play ([DeBono94], [Uhl00]).

After comprehensive analysis, the decision among equally rated options is often a personal choice of the system architect(s), weighing numerical analysis results – e.g. quantifiable parameters such as "cubic meters of useful volume" in case of laboratory or crew modules [Taylor86] – against qualitative evaluation based on experience. Alternatives that are not selected for further investigation at this stage are nevertheless not discarded, but respected for their useful content and retained for future reference.

2.3.7 Organized Creativity

Generating viable alternatives, designing and communicating with sketches, as well as identifying and developing important details

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[24] Consider the declaration of Picasso, the artist, when describing his approach: *"I do not search. I find."* [Uhl01]

also require a large amount of creativity on the part of the architect or the design team[25]. Uhl defines creativity such [Uhl98]:

> *"Creativity is the search for unusual combinations of the already known, triggered by tasks that require a fresh approach."*

To optimize the creative process, a maximum amount of information must be made available at the beginning of the conceptual design phase through thorough and focused background research (cf. Section 2.3.3; [DeBono94] and [Uhl00]), and tools must be provided to support creative thinking (cf. Table 3.1 on page 59). Sketches (cf. Section 2.3.4) are valuable for processing information as well as for communicating candidly within the team [Uhl01]:

> *"The person sketching identifies the properties of [design] subjects for the design team, and he gives those back to the team in his sketch. [The sketcher himself] changes by executing this role. He must guard against the desire to please his teammates by drawing 'appealing' sketches. Searching for solutions through a sketch requires the opposite. On the other hand, sketching ability fosters confidence in dealing with a team."*

Equally valuable are face-to-face encounters among the design team and confrontation with external stimuli that trigger the unexpected, which supports the notion of locating all members of the design team in close physical vicinity – preferably in a setting that allows for seclusion as well as for unexpected encounters outside of the design team environment [Uhl01].

Organizing incoming information and identifying areas where more research is required can be achieved using a matrix format e.g. of design categories and aspects [Uhl00] or of system element interferences [Messerschmid99]. In addition, structured lists, e.g. of design areas or construction materials, are used extensively in terrestrial architecture (e.g. the American *CSI master format* [Cohen98], or its German equivalent from *HOAI* [Locher91]). These provide a standard format for documenting and communicating individual issues and for assuring that nothing is forgotten in the design. They

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[25] Bense draws a parallel to physics [Bense75]: *"The more complex a system, the higher the likelihood of something unlikely occurring."* Alternatively [Uhl01]: *"The new is found only by assuming that the unknown is possible."*

can be readily adapted for space mission planning and space system design (Table 2.8).

Care must be taken, however, to incorporate the increased amount of linkages and synergisms – positive and negative alike – that exist among the individual items in such a list when space systems are concerned (e.g. the effects of configuration on attitude stability; cf. Table 2.4 on page 24).

2.3.8 Use of Design Principles

Design principles are another important element of terrestrial architectural practice that can also be utilized for the design of inhabited space systems. As Adams et al state [Adams00b]:

> *"Any human-rated mission should be designed from its earliest conceptual phase according to a clear set of design principles. These principles should not be confused with engineering requirements or other technical issues. Good design principles [constitute] the highest level of criteria for selection and evaluation of engineering and technical scenarios. Using this approach allows the designers to review and to check or correct their own work on a regular basis."*

Examples for design principles guiding a Shuttle ISS assembly mission include, in this order, *"safe crews, safe station and shuttle, perform mission assembly task, perform subsequent tasks, perform additional tasks"* [Jones00c]. A manned expedition to Mars could be guided by the principles of *"habitability, simplicity/efficiency, risk minimization"* [Adams00b]. Finally, the generic design principle of *aesthetics*, i.e. of the quality of form that affects habitability, deserves mention. It is defined here by distinguished 19th-century architect Schinkel[26], [Schinkel01]:

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[26] Schinkel also defines other design principles for buildings that are readily applied to space habitats [Schinkel01]: *"Appropriateness, well-balanced comfort, reduction of effort, evidently superior design work."*

Table 2.8: Structured List of Construction Elements ([Cohen98], adapted)

CSI Master Format Division	**Space Habitat-Related Aspects**
1. General Provisions	Assumptions regarding crew health and fitness, system concept, redundancy
2. Site Planning and Site Work	Orbital or planetary-surface environmental conditions, accessibility, assembly sequence, logistics, launcher constraints, in-situ resources
3. (Concrete)	(Not applicable to space settings)
4. Masonry	Locally available raw materials, processing
5. Metals	Aluminum primary structures, secondary structures and connectors, utility volumes
6. Plastic and Composites	Composite primary structures, inflatables, interior structures and elements
7. Thermal and Moisture Protection	External thermal protection, internal heat and moisture removal
8. Doors and Windows	Internal doors, pressure-shell airlocks/windows
9. Finishes	Fire resistance, toxic outgassing, fibers and particulates protection
10. Specialties	Lockers and stowage, fire extinguishers, partitions, hygiene accessories, sun shades
11. Equipment	Building infrastructure, crew support, maintenance, audio-visual, waste management
12. Furnishings	Crew accommodations, workspace furnishings
13. Special Construction	Sound and vibration control, debris and radiation protection, Attitude and Orbit Control
14. Conveying Systems	Robotic and piloted rovers, robotic manipulators
15. Mechanical Systems	Life support and laboratory equipment
16. Electrical and Data Systems	Issues of access, interference/shielding, security, power needs

> *"Aesthetics, in general, addresses all those properties of objects which satisfy the visual sense, or through it alter the state of the soul, or please the reasoning spirit, and this by three different ways, one by directly affecting the eye, the other by affecting the sense of spatial relationships inborn in all men, and the third by first affecting reason, and then – through the cognitive process – emotion."*

2.3.9 Exploration by Design

During the earliest steps of the design process, the designers must first come to an understanding of – and an agreement on – what it is that they are designing. This definition of the problem is an inevitable part of the design process [Cohen87a]. Understanding the design problem while/by trying to tackle it – along the lines of "*exploration by design*" [Cohen90] – is more efficient in the initial phases of the conceptual design process than the rigid following of work breakdown structures[27]. It starts with the realization that the design objectives are initially hypothetical in nature; that they will change during the course of the design process [Uhl01].

This exploratory aspect of the design process requires the same thorough search for information and the same time for "fermentation" that was mentioned in Section 2.3.7. It entails letting thoughts explore synergies within the ambiguous realm of possibilities as long as feasible [Uhl00]. Several other tools used for the design itself come into play: sketching (to explore the task and the structure of the design process, and to introduce iterations in case of conflicting process requirements), structured representations (to support a controlled work flow), important details (detailed breakdown of key process steps), and design principles (which in this case are referring to principles according to which the design process itself should be guided).

At the end of this section, a quote from Picasso sheds some light on the duration of the design process [Uhl98]:

> *"Have you ever seen a finished picture? A picture or anything else? Woe you if you say you are finished! [...] Finishing a work!*

---

[27] Cf. the quote from Rechtin on page 40.

> *Finishing a picture! How ridiculous! To finish an object means to kill it, to take away its soul [...]. It is quite an annoying thing for artists to do. [...] The design process is always unfinished, it is just called off at some point."*

2.4 Summary

This chapter described the current status of major contributors to the conceptual design process on the engineering as well as the architectural side. It also introduced relevant aspects of Spaceflight Human Factors. The synergistic combination of these elements will result in the integrated, interdisciplinary approach to the conceptual design of inhabited space systems that will be presented in the following chapter.

"Where there is no vision,
the people perish."

Proverbs 29:18

3 Proposal of an Interdisciplinary Approach

Based on the elements presented in the previous chapter, a proposed new approach to the interdisciplinary conceptual design of human-rated space systems will be described in the following. The focus will be on the human aspects, given that, as stated in [Bertrand98],

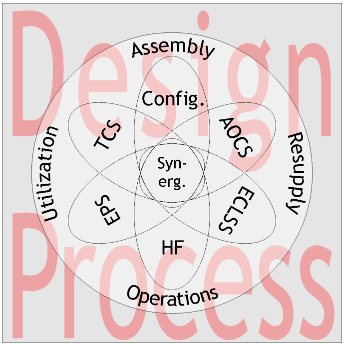
> *"[t]he main system driver is human presence itself since it largely determines overall design and cost by technical and safety requirements."*

This expands the design methodology summarized in Section 2.1 and results in a truly human-centered approach, as is appropriate for permanently inhabited space structures.

The first section will define the design process, consisting of a combination of engineering and architectural elements. Then, a compilation of relevant, human-specific design knowledge will be provided to give a design team a concise tool to facilitate implementing human-centered design. Finally, software that supports those parts of the approach where numerical simulation is required, like life support system design, will be presented.

After this, Chapter 4 will document how this new approach was applied to actual design projects in order to validate it.

3.1 Integrating the Process: Architectural Engineering



The design and construction of space stations like ISS represent one of the most complex technological endeavors ever undertaken. It represents the pinnacle of current human spaceflight projects and will therefore be the focus of the integrated process presented here[28]. Just as the *design result*, i.e. the space station, has to accommodate the capabilities and limitations of the human crew, the *design process* must also be adapted to the limitations and capabilities of the designers. Since, historically speaking, terrestrial architects have gathered significantly more experience with designing habitats than have space station engineers, the inclusion of the time-honored elements of architectural practice outlined in Section 2.3 into the traditional engineering methodology described in Section 2.1.2 promises to result in an improved space station design process.

The main elements of such an improved approach are stated in this section. To increase its immediate usefulness to a design team, these elements are expressed as specific guidelines. They are grouped into the areas of design flow, human-specific issues, and design team composition. For the underlying rationale and for details, the reader is asked to refer to Section 2.3.

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[28] At the same time, a space station is an icon of the cultural significance of pushing the space frontier, a tangible expression of mankind's indomitable spirit. This calls for appropriate expression both in the physical configuration and in the operation of such a space station.

3.1.1 Design Team Composition and Collaboration

The first central element is the composition of the design team and its mode of collaboration. The following ground rules should be adhered to as much as possible:

- All members of the design team see themselves as cooperation-oriented experts in their respective fields, instead of as isolated subsystem specialists. They are aware of (and willing to learn about) the nuts and bolts of creativity-fostering processes and techniques (e.g. Table 3.1), and can make use of them.

Table 3.1: Design Support through "Thinking Tools" [DeBono94]

Purpose	**Tool**	**Details**
Stimulating Creativity	"Escape Method"	✧ Identify what is taken for granted, then make deliberate effort to imagine how things might be different. This encourages subconscious "fermentation" of knowledge.
	"Random Stimulation"	✧ A random word serves as an idea stimulator, to tap into lines of thought that would otherwise be hidden.
	"Provocative Operation"	✧ Deliberately generate a nonsensical or provocative idea, even if it has no direct value to the design, as a stepping-stone to reach the next idea.
Comparing Alternatives and Variants	"Plus-Minus-Interesting"	✧ Scan one minute each for positive, negative, and interesting points of an idea or alternative, in that sequence.
	"Consequence and Sequel"	✧ Focus on consequences that decisions might have in each of four consecutive time zones. ✧ Time zones are: less than one year, one to five years, five to twenty years, more than twenty years.
Constructive Thinking	"Examine Both Sides/Other People's Views"	✧ Reconnoiter and map both sides of a design conflict with neutrality and objectivity. ✧ Compare results for both sides in order to better understand the conflict, and systematically look for starting points for constructive ideas and solutions.

- ✧ Design team members come from different fields and backgrounds but develop a common language. This suggests that they share joint experience in designing – and in the methods of organized creativity – gained through participation in previous design projects, or in hands-on training workshops such as SSDWs (cf. Sections 2.1.4 and 4.2).
- ✧ Design team members look for solutions based on their disciplinary experience, but their ideas are triggered by interdisciplinary face-to-face interaction and by the unexpected brought out by it. Ideas are measured with respect to their usefulness in the total system environment.
- ✧ Designers are aware of the design process also being a two-tiered learning process: the process allows them to learn about the problem, which is understood better and better as the design progresses, and also to increase their own knowledge from interdisciplinary exchange and hands-on design experience [Cohen87a].
- ✧ Objectives are seen as hypotheses, and adapted according to the progress in knowledge that occurs over the course of the design. This even includes design team issues such as changeout of participants if new disciplines are identified as important or others become obsolete.
- ✧ Design team leaders, by personality[29], are eager for face-to-face communication and learning experiences, and can deal with and accept imperfections

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[29] Uhl further elaborates on the issue of design team leader personality [Uhl97]: *"Personalities can generate answers from the conflict between logically-derived [i.e. objective] and personally-preferred [i.e. subjective] design solutions, that can utilize the tension between public or corporate demands and logical reasoning. [...] Personalities can credibly and competently override design-by-majority with decisions generated by such reasoning. This is impossible for committees, which by definition depend on majorities, and which are susceptible to rhetoric."*

during the search for solutions (but not in the final result). They integrate team members' contributions and have the strength to push logically-derived solutions to group acceptance [Uhl01].

- Hand sketches are used extensively and deliberately, for generating and communicating ideas among design team members, and as a constant reality check. As a corollary, computer-based tools are mainly used to document and visualize existing designs, and prepare for their numerical analysis.
- The design team sees itself as an agent and advocate of the customer, i.e. the (space and ground) crew tasked with the proposed mission. It assures fulfillment of customer needs – which might even differ from the written requirements – and interfaces with the builder/detailed designers of the system throughout the design process.
- Top-level design principles are developed and adhered to (i.e. each design decision is checked for compatibility with them), including principles of design flow as outlined in Section 3.1.2, and human-specific principles as presented in Section 3.1.3.
- Designers are on the lookout for the usual hazards of requirements creep, fuzziness, departmental or disciplinary infighting, and marginal performers.

3.1.2 Principles of the Design Process

The proposed interdisciplinary design process is outlined in Table 3.2. It generally follows the traditional SSDW process summarized in Table 2.1 on page 20, but it stays flexible by allowing the designers to temporarily "jump ahead" or iterate back if such deviations help the creative process or the understanding of the design problem. Design team preparation and background research prior to launching the design itself, as well as thorough documentation afterwards, are explicitly included (see italicized entries in Table 3.2) so as to emphasize their importance for a quality design.

The workflow is further guided by the following design process principles:

- ✧ Design team members realize that the early phase of the design effort (involving task analysis, gathering and understanding of background information, finding out about design references, examples and "lessons learned" from spaceflight experience and terrestrial analogs, collecting ideas, generating multiple design alternatives) is crucial, but it takes time and should therefore extend far into the design process. This is aided by the use of structures that assure all "must-have" aspects are covered, and by the use of accumulated, easily accessible

Table 3.2: Interdisciplinary Conceptual Design for Inhabited Space Systems

Step	**Details**	
Prepare Design Process	*I*	*Assemble Design Team*
	II	*Inform Team on Design Task, Process and Tools*
	III	*Perform Thorough Background Research*
Define Objectives	A	Develop Broad Objectives
	B	Develop a Preliminary List of Requirements and Constraints
Characterize the System	C	Develop Alternative System Concepts
	D	Characterize System Elements
Evaluate the System	E	Prepare System Budgets
	F	Evaluate Mission Utility
	G	Select System Baseline
Verify Requirements	H	Define Technical Requirements
	I	Allocate Requirements to System Elements
Document	*XIII*	*Document Baseline Design*
	XIV	*Document Alternative Designs and Design Process*

knowledge in the form of design heuristics (cf. Section 3.2).

- Alternatives not selected are not discarded, but kept for future reference as sources of ideas, or as fallback options in case of changing requirements or design impasses.
- Variants are created by applying task-derived rules to existing structures, guided by design parameters, thus opening the path for new thoughts and new solutions – sometimes seemingly without conscious effort.
- Important details (e.g. crew quarters, solar array tracking mechanisms) are identified early in the design process, as soon as the task is properly understood; they are developed as soon as relevant boundary conditions have sufficiently evolved; and from the beginning, they help to provide focus and continuity for the designers' intent.

3.1.3 Principles of the Design

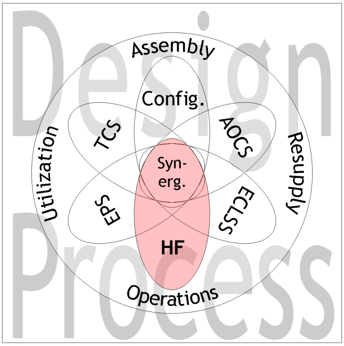
The addressing of human-specific aspects by the design team is emphasized. For each step of the design process, the designers are encouraged to adhere to the following conventions:

- The "human element", i.e. the crew, is not treated as a subsystem among many, but is emphasized as the overall design driver; the design objective is the creation of a *habitat* that optimizes crew efficiency. To this end, the heuristics of human aspects (Section 3.2) are understood and adhered to.
- Human possibilities and limitations determine the types of modules to be used and their internal layout (*"Archetypes"*, [Adams98b]), as well as the dynamic linking of these modules within the overall habitat (*"Choreography"*, [Adams98b]).
- The influence of the human presence on all subsystems, ranging from maintenance options to

ECLSS demands to zero-g disturbances, is taken into account.

On a cautionary note, however, the design team should realize that this human-centered paradigm of inhabited space systems conceptual design must be seen in the context of overall design limitations. While the proposal here is to optimize with respect to habitability (and thus crew efficiency), history shows that expedition participants have frequently been able to withstand extreme levels of discomfort [Stuster96], although this significantly reduced their operational efficiency. Exaggerated fear of the *"Human Factors Dragon"* [Zubrin96] carries the risk of jeopardizing overall mission feasibility. As with subsystem issues, the integration of key requirements into the overall system concept is preferable to subsystem-specific or discipline-specific local optimizations with limited scope.

3.2 Integrating the Knowledge: The Heuristics of Human Aspects



The vast body of knowledge related to optimizing human integration and human performance that has been assembled during the past several decades – for earthbound and space-based applications alike – represents a crucial resource to the designers of inhabited space systems (cf. Section 2.2) and must be reviewed in depth during the background research phase of the design process (cf. Sections 2.3.3 and 3.1.2). This adds crucial information to the engineering knowledge already provided by the traditional design approach (cf. Section 2.1.2).

However, these insights are spread out over a large number of publications, which vary in quality/density of content and presentation, and only a few sources can be identified that provide extensive amounts of information relevant to the conceptual design of inhabited space systems in a concise manner: "Human Spaceflight Mission Analysis and Design" [Larson99] and "Space Stations" [Messerschmid99] for system-level topics; "Spaceflight Life Support and Biospherics" [Eckart96] and "Designing for Human Presence in Space" [Wieland94] for ECLSS; and "Man-Systems Integration Standards" [Man95] for HF.

In order to efficiently support the design team with more of the information it needs, an additional collection of the most significant findings and rules for manned space systems design – extracted from hundreds of sources – is provided in this section. The form chosen for this compilation is that of tables of design heuristics. Heuristics (comparable to "rules of thumb") are an important element of the conceptual designer's tool kit (cf. [Rechtin91], [Bertrand98]; Section 2.1.2). They are especially suited for subjects which cannot be expressed or optimized using only equations and numerical simulation, and are thus ideal for addressing most human-related aspects of spaceflight during the conceptual design phase. The following topics are covered within this section:

- ✧ Heuristics of Programmatic Issues (p. 66)
- ✧ Heuristics of Space Segment Configurations (p. 67)
- ✧ Heuristics of General Habitability (p. 70)
- ✧ Heuristics of Crew Issues (p. 72)
- ✧ Heuristics of Life Support (p. 76)
- ✧ Heuristics of Medical Issues (p. 78)
- ✧ Heuristics of Operational Aspects (p. 79)

The design team adapts and expands these heuristics according to the priorities and requirements given by their specific design project, using the referenced sources as a first stop for more information. To support the design team's decision among potentially conflicting heuristics, their relative importance is stated as well (cf. Table 2.4), with Ⓐ indicating highest priority, and Ⓒ lowest.

Table 3.3: Heuristics of Programmatic Issues

Aspect	Design Rules	Sources
General	Ⓐ Future space expeditions will resemble sea voyages much more than test flights, which have served as models for all previous space missions	[Stuster96]
	Ⓒ Be aware of "cultural ballast" that might influence the design, especially when inferring from terrestrial analogs	[Cohen87b]
	Ⓐ Occam's Razor: The simplest solution is usually the correct one Ⓐ Extreme requirements should remain under challenge throughout system design, implementation, and operation Ⓐ When inevitable choices must be made using inadequate information, choose the best option available and then watch to see whether future solutions appear faster than future problems. If so, the choice was at least adequate Ⓐ The efficient architect, using contextual sense, continually looks for likely misfits and redesigns the architecture so as to eliminate or minimize them	[Rechtin91]
	Ⓐ Accept no unnecessary risk, but accept risk when benefits outweigh the cost Ⓐ After identifying and assessing risk, anticipate and manage it	[Risk01]
	Ⓐ Pause and reflect on the task frequently Ⓑ Build in and maintain options as long as possible; document them	[Rechtin91], [Uhl01]
	Ⓑ Especially in international projects, continuity of individual participation, experience, and interpersonal relationships on all levels are critical to program success	[Fullerton00]

Table 3.3: Heuristics of Programmatic Issues

Aspect	**Design Rules**	**Sources**
	Ⓑ A shorter development schedule (e.g. ten years instead of 30 years) actually increases likelihood of mission realization, due to the fact that cost = people * time, and because of the vagaries of the political environment	[Zubrin96]
System Concept	Ⓐ For critical phases (launch, land), stick to proven simple technology	[Adams00b]
	Ⓐ Biggest blunders are made on the first day that the concept is established Ⓑ Maximum leverage exists at the interfaces	[Thangavelu01]
Design Reviews	Ⓐ Perform integrated engineering reviews with respect to *functions* (not hardware)	[Novak98]
	Ⓑ Equivalent System Mass should be used as prime parameter when comparing system alternatives	[Messerschmid99], [Levri00]

Table 3.4: Heuristics of Space Segment Configurations

Aspect	**Design Rules**	**Sources**
Dimensions and Mass	Ⓐ Launch constraints drive available dimensions	[Adams00b], [Isakowitz99]
	Ⓑ Avoid minimizing volume (beyond launcher-driven constraints) hoping to save cost: the complications resulting from required item miniaturization, loss of habitable volume, etc. are not worth a slight mass benefit	[Cohen87b]
	Ⓐ Consider inflatables to increase inhabitable volume while adhering to launcher volumetric constraints	[Kennedy99], [Konopek99]

Table 3.4: Heuristics of Space Segment Configurations

Aspect	Design Rules	Sources
Station Topology	Ⓑ Deliberately use architectural space inside the modules, instead of giving the crew whatever is leftover after fitting all hardware in Ⓒ Use architectural typologies to support systematic search for configurational alternatives Ⓑ Incorporate flexibility so that post-deployment modifications are facilitated	[Cohen87b]
	Ⓐ Identify required degree of proximity of modules/functions through adjacency matrix (network analysis)	[Wise85]
	Ⓐ Additional topology heuristics are summarized in Table 2.4 on page 24	[Bertrand98]
Artificial Gravity	Ⓑ Conflicts with μg utilization Ⓑ Requires large structures to avoid debilitating side effects (Coriolis) Ⓑ Increases crew post-landing capabilities and efficiency Ⓑ Possible compromise: local gravity using centrifuges (however, they cause μg disturbances)	[Hall00]
Interior Configuration Aspects	Ⓑ Issues to be considered: o Programmatic: cost, schedule, weight, flexibility o Engineering: commonality/standardization, tooling, assembly, integration o HF: anthropometrics, zero-g posture, efficient layout and traffic patterns, access to external walls, volumetric efficiency, use of zero-g advantages, ground training Ⓑ Use of full-scale mockups is recommended before interior configuration decision is made	[Mount00b]
	Ⓑ Appropriate dimensions for various functional areas (translation paths, sleeping, etc.) are given in Table 2.6 on page 35	[Adams99]

Table 3.4: Heuristics of Space Segment Configurations

Aspect	**Design Rules**	**Sources**
	Ⓑ Provide at least one accessible window for Earth/space viewing Ⓑ Preferred window locations: conference/dining area, exercise area, quiet area (but: cf. Table 3.8, "Radiation", p. 78)	[Godwin99], [Adams99], [Perner92]
Interior Configuration Concept Examples	Ⓒ Rack "walls", built-in "floor" and "ceiling" (**Spacelab**-like): high roominess, easy manufacturing and training, but restricted maintenance/reconfiguration for sub-floor components, lack of flexibility Ⓑ Vertical (**Skylab/TransHab**-like): good laboratory/office environment, efficient work spaces, less advantageous for crew quarters, difficult manufacturing and training Ⓒ "**Center beam**" (all equipment in modular packages interfacing to central beam along module axis): high reconfigurability, optimum zero-g use, reduced maintenance access to equipment due to high packing density, small attach points requiring launch supports, permanent division of module, no standard packaging system, difficult manufacturing and training Ⓒ "**Center core**" (equipment in center): good for standardized packing of equipment, unobstructed wall access, two narrow corridors for circulation, reduced maintenance access to equipment due to high packing density, less open environment Ⓑ "Four-standoff" (**ISS**-like): spacious, easy manufacturing and training, enables use of single modular rack, high reconfigurability, easy wall access through pivoted racks, distributed utilities with low packing density in standoffs	[Mount00b]

Table 3.5: Heuristics of General Habitability

Aspect	Design Rules	Sources
General Issues	Ⓐ Habitability requirements increase with mission duration, risk, degrees of isolation and confinement Ⓑ Provide customizable elements of the environment, since a good fit between person and environment increases comfort	[Connors85], [Sturgeon00], [Adams99]
	Ⓐ Adhere to local vertical in the interior design of each module; try to aim for common vertical for all modules Ⓑ Permit the crew to behave in ways that are natural to them to remove numerous minor stress factors from their daily routine	[Adams99]
	Ⓑ Crucial "everyday" issues are stowage, food, acoustics, waste management, inventory system and hygiene	[Godwin99]
	Ⓒ Provide space and technology for crew to store and use some personal items (music, images, books)	[Evans87]
Zoning and Privacy	Ⓐ Provide for separation of functions Ⓑ Provide for zoning variability and on-orbit reconfigurability to give crew a sense of control over their environment Ⓑ Cluster and isolate noisy equipment, locate far from habitation zone	[Adams99]
	Ⓒ Provide two separate habitation areas: one for quiet/individual activities and individual crew quarters; one for group activities, wardroom, exercise Ⓒ Offer area for person-to-person meetings, with privacy level in between bedroom and wardroom	[Cohen87b]

Table 3.5: Heuristics of General Habitability

Aspect	Design Rules	Sources
	Ⓑ Privacy has two aspects: exposure (how easily can others get in touch with crewmember) and accessibility (how easily can crewmember get in touch with others) Ⓒ Crowding is influenced by the flow of information between people, through vision, hearing, smell and touch; mitigation of crowded conditions therefore means reducing signal strength Ⓒ Ability of crewmembers to withdraw to private quarters is extremely important to mitigate effects of transient negative moods on group morale	[Harrison85]
Spaciousness	Ⓑ Quantify spatial habitability issues (lines-of-sight, volumetrics, other metrics) for objective ranking of alternatives Ⓒ Spaciousness increases with neatness and degree of organization, with skillful distribution of furnishings and visual cues Ⓒ Spaciousness is influenced by required or possible movements of inhabitants; the more variability, the better	[Wise85]
	Ⓑ Avoid interior volumes that are so large that crewmembers can get "stuck" in mid-air without access to walls or translation aids Ⓒ Provide plenty of standardized translation aids and attachment points for them throughout the interior	[Novak98]

Table 3.5: Heuristics of General Habitability

Aspect	Design Rules	Sources
	Ⓑ Provide enough space to keep equipment that is in regular use (exercise, dinner table, etc.) deployed Ⓐ Dinner/conference table and surrounding area must be large enough to accommodate entire crew Ⓑ Provide some long line-of-sight distances in local "horizontal" direction	[Adams99]
	Ⓑ Reference sleeping compartment dimensions: submarine (0.8 m^3), undersea lab (1 m^3), Skylab (1.5 m^3), long-term studies (2 m^3 to 7 m^3; 4 m^3); see also Table 2.6 on page 35	[Stuster96], [Wise85]
Aesthetics	Ⓒ Use proportions and patterns to create order; respect time-proven "golden section" ratio of 1:1.618	[Cohen87b]
	Ⓑ The level of aesthetic accomplishment increases with the product of its constituents, their variety, and their unified presentation; this can only be achieved gradually	[Ehrenfels22]

Table 3.6: Heuristics of Crew Issues

Aspect	Design Rules	Sources
Selection	Ⓒ Adhere to medical criteria established for astronaut selection by space agencies	[ESA90a]
	Ⓐ Acknowledge paradigm shift from identifying effective individuals to identifying effective teams Ⓒ Pre-existing attitudes and interpersonal skills are important for successful group dynamics, since training cannot fix everything	[Helmreich87]

Table 3.6: Heuristics of Crew Issues

Aspect	Design Rules	Sources
	Ⓑ Most successful selection: by experienced expedition leader performing personal interviews; least successful: by standardized psychological test alone	[Connors85]
	Ⓒ Have final-round candidates for a long-term mission identify whom of the other candidates they would prefer to go on a mission with; select most compatible group	[Holland00], [Stuster96]
	Ⓑ Crews composed of individuals with shared attitudes and values will likely be compatible; heterogeneous crews increase likelihood of conflict	[Connors85], [Sturgeon00], [Stuster99]
	Ⓑ The best predictor of future performance is past performance Ⓒ Action-oriented people tend to volunteer for special work, such as going on a space mission, but the conditions of long-duration isolation and confinement favor just the opposite type of person	[Stuster96]
	Ⓒ Personality types with a low need for social interaction seem to thrive under conditions of isolation and confinement	[Palinkas00]
	Ⓒ Characteristics of a successful expedition leader: can tolerate intimacy and status leveling, can swing between authoritarian and delegatory leadership styles as needed, must be committed to mission and its goals, must have a background in leadership and experience in space, must not be afraid to make final judgment on a problem	[Sturgeon00]

Table 3.6: Heuristics of Crew Issues

Aspect	**Design Rules**	**Sources**
	Ⓑ Critical proficiencies for long-duration spaceflight (in order of importance): 1. Emotional stability (self control, self confidence) 2. Stress performance (perform under threat to life, adaptability) 3. Group living skills (interaction, multicultural adaptability) 4. Teamwork skills (conflict resolution, priority of team over personal goals, followership skills) 5. Family issues (cope with separation from family and friends) 6. Motivation (intrinsic work and achievement motivation, perseverance, goal orientation) 7. Decision making (sound judgment, situational awareness) 8. Conscientiousness (responsibility, attention to detail, integrity) 9. Interpersonal communication skills 10. Leadership capability (team leadership, effective resource management, accountability)	[Galarza99]
Pre-Mission Training	Ⓒ Overtrain on mission-critical skills, but leave some non-critical subjects for in-flight training if there is a lull in activities (e.g. during interplanetary transfer)	[Connors85]
	Ⓑ Strengthen crew cohesiveness and group identity through training, ideally as high-fidelity mission simulations in hostile environment, e.g. survival training for (rare) unscheduled landings	[Cushing98], [Kanas99] [Palinkas87], [Stuster99], [Volovich93]
	Ⓑ Flexibility increases by using skill-based training (Russian approach) instead of procedures-based training (Shuttle approach); "engineer"-type astronauts are better suited for this than "scientist"-type astronauts	[Trevino00]

Table 3.6: Heuristics of Crew Issues

Aspect	**Design Rules**	**Sources**
On-Board Training	Ⓒ Computer-based training is cost-effective, motivating, and available for pre-mission training as well as for on-board training	[Massart99]
General Group Dynamics	Ⓒ Physical and emotional stressors have synergistic effect	[Palinkas87], [Stuster96]
	Ⓑ Interpersonal and leadership-acceptance problems, as well as problems between crew and ground support, increase with mission-elapsed time	[Kanas99], [Sturgeon00]
	Ⓐ Design crew autonomy and teamwork into system for increased productivity	[Cohen90]
	Ⓑ Available space and spatial arrangements can indicate or influence hierarchy; they must therefore be congruent with actual hierarchy structures	[Wise85]
Activities and Schedule	Ⓒ Performing various social and functional roles during the day/week increases comfort in most crewmembers	[Connors85]
	Ⓑ Schedule frequent regular group activities (dinner, conferences) to keep morale and productivity high	[Adams00a]
	Ⓑ Provide marker events (holidays, celebrations) to structure long missions	[Evans97]
Privacy	Ⓑ Privacy issues are twofold: among crewmembers (provide opportunities for withdrawal as well as openness), and between crew and ground (avoid one-way surveillance) Ⓑ Establishing pre-mission rapport reduces crowding problems	[Connors85]

Table 3.6: Heuristics of Crew Issues

Aspect	Design Rules	Sources
	Ⓑ Crew selection for agreeability and flexibility should mitigate cross-cultural issues Ⓒ Provide secure channels, e.g. via encrypted e-mail, for personal communications of crew with friends and family on ground	[Kanas99], [Holland00]

Table 3.7: Heuristics of Life Support

Aspect	Design Rules	Sources
General Design Principles	Ⓐ Reliability, safety, and redundancy of ECLSS equipment are most important Ⓑ Allocation of ECLSS equipment to individual modules should also be guided by possible interactions with the spacecraft environment (noise, vibrations, heat loads) Ⓒ Variable ECLSS infrastructure (piping, conduits) should be provided by each module	[Messerschmid99]
Biological Systems	Ⓐ Fully-closed, purely biological life support systems are an option only for very large and very long-term stations, therefore BLSS and P/C technologies must be integrated	[Drysdale00]
	Ⓑ Biological systems cannot be compartmentalized and modularized as physico-chemical systems can; this makes for complex design, analysis and simulation, and operation	[Osburg01]

Table 3.7: Heuristics of Life Support

Aspect	**Design Rules**	**Sources**
Food	Ⓐ The food system is a crucial ECLSS and HF mission component, since it affects both the physical and the psychological health of the crew Ⓑ Preplanned menus are seldom adhered to by crew, but preference-only menus tend to be nutritionally incomplete Ⓒ Pantry-style (collective) food stowage is preferable to individual stowage (i.e. by meal or by crewmember)	[Bourland99]
	Ⓑ Plan for at least one common meal per day at which the whole crew participates	[Bourland99], [Stuster96]
	Ⓑ For missions up to several years, stored food supply with some select "fresh" items produced on-site seems preferable Ⓑ If station is large enough (long-term mission), a few select food resupply items enable on-site food production that is otherwise complete	[Jones00a], [Drysdale00], [Hunter98]
Physico-Chemical Systems	Ⓐ Must-have regenerative elements (significant resupply reductions can be expected) include waste water treatment and regenerative CO_2 removal	[Messerschmid99]
	Ⓑ Provide enough internal volume for ventilation ducts (they take up a lot of space if they are large enough to be low-noise) Ⓐ Provide three layers of redundancy for critical species (e.g. CO_2 removal: redundant molecular sieves + LiOH containers as backup; O_2 generation: electrolysis, oxygen "candles", pressurized storage)	[Haigneré00]
	Ⓐ Consider opportunities for synergistic linkages among ECLSS, AOCS and EPS	[Osburg00a]

Table 3.7: Heuristics of Life Support

Aspect	**Design Rules**	**Sources**
Safety	Ⓑ Identify emergency egress paths Ⓒ Provide emergency equipment (oxygen mask, flashlights, fire extinguishers, intercom, etc.) in standardized locations for all pressurized modules	[Sampaio]
ECLSS Analysis	Ⓒ Process kinetics are important for mass budget (e.g. water inside processing tank) Ⓑ Crew maintenance access volumes are important for volumetric calculations	[Levri00]
	Ⓑ Simulate partial and complete component failures in addition to normal operations in order to determine margins of safety	[SSDW01a]

Table 3.8: Heuristics of Medical Issues

Aspect	**Design Rules**	**Sources**
Hygiene	Ⓑ Hygiene is a very personal/culturally dependent function that affects crew health as well as crew psychology; lack of personal hygiene is a predictable source of intra-crew conflict; therefore, hygiene standards and procedures must be clearly established	[Hygiene88], [Stuster96]
	Ⓑ Mandatory exercise requires suitable body cleansing facilities	[Connors85]
	Ⓑ Build-up of organic matter (hair, skin cells, dust) behind racks and installations requires that they must be removable for cleaning	[Haigneré00]
Medical Supplies and Facilities	Ⓐ Permanent/dedicated "sick bay" is not required due to difficulties in treating severe injuries and possibility of evacuation (at least for LEO stations)	[Kirkpatrick98], [Simmons99], [Oberg01]

Table 3.8: Heuristics of Medical Issues

Aspect	Design Rules	Sources
	Ⓑ ISS-style health care system appropriate for stations with quick-return capability Ⓒ At least two crewmembers must have advanced medical training	[Furgiuele96], [CHeCS00]
Radiation	Ⓑ Small doses of radiation exposure spread out over a prolonged time are tolerable, even if the same dose received over a short time would be detrimental	[Zubrin96]
	Ⓐ Avoid windows in locations where crew must spend more than two hours each day (e.g. sleep quarters, laboratory)	[Adams99]
	Ⓐ The radiation dose received by the crew of a LEO station is affected drastically by changes in inclination (higher inclination ⇒ higher dose)	[Wilson96]

Table 3.9: Heuristics of Operational Aspects

Aspect	Design Rules	Sources
Assembly	Ⓐ At every assembly stage, the station configuration must include an operational EPS, TCS, and AOCS Ⓐ All individual components must have autonomous rendezvous and docking capability, unless assembly is performed manually by on-site crew with robot arm support	[SSDW01a]

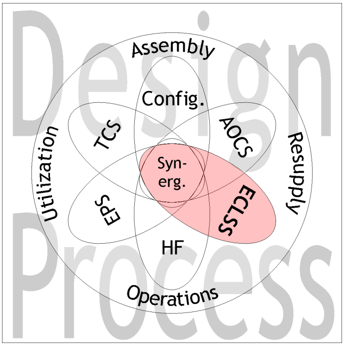
Table 3.9: Heuristics of Operational Aspects

Aspect	**Design Rules**	**Sources**
EVA	Ⓑ Overall preparation time per EVA is approximately 40 crew-hours Ⓒ One hour of task-related EVA work requires approximately 5 hours of overhead EVA time (opening/closing airlock, translating, etc.) Ⓐ Airlock must be sufficiently sized to accommodate two suited crewmembers and an inward-opening outer hatch	[Fullerton00]
	Ⓒ Direct preparation time per EVA (prebreathe, donning suit, etc.) is several hours	[Godwin99]
Resupply	Ⓑ Provide enough dedicated storage sites for organized storage of parts, otherwise inventory management will become very time-consuming	[Fullerton00]
	Ⓒ Any new crew or resupply flight should bring informal gifts/surprises	[Godwin99], [Kanas99]
Automation	Ⓑ General issues: o Automation changes human activity and imposes new demands on crew, often in ways unintended and unanticipated by the designers o Consequences of proposed automation on crew performance should be primary evaluation criterion; issues to consider: mental workload, situation awareness, complacency, and skill degradation o Automation candidate areas: acquisition of information, analysis of information, selection of action, implementation of action o Plan for "noisiness" of real world	[Parasuraman00]

Table 3.9: Heuristics of Operational Aspects

Aspect	Design Rules	Sources
	Ⓑ Characteristics favoring machines: o Speed and precision for simple tasks o No fatigue during repetitive or challenging tasks o Data storage and recall capabilities o Handling of complex operations o Insensitivity to extraneous factors Ⓑ Abilities favoring humans: o Perceive patterns and generalize o Improvise and adapt to unexpected events o Recall relevant facts o Reason inductively and use judgment o Perform fine manipulations o Perform when overloaded o Detect certain forms of energy	[Man86]

3.3 Integrating the Software: Intuitive Interactivity



The heuristics presented in the preceding section address qualitative design issues. For those of a quantitative nature, numerical simulation is required. Subsystems affected during the conceptual design phase include the Attitude and Orbit Control System, the Life Support System, and the Power and Thermal Control subsystems. For the latter, simple spreadsheet-based estimations of collector surface area, battery sizing, etc. are sufficient [SSDW01a]. AOCS and ECLSS, though, require more thorough numerical treatment to provide meaningful results to the system-level design effort.

In the SSDW, AOCS simulation is addressed by a separate simulation tool (IRIS, cf. Section 2.1.3 on page 27), and only a user-friendly front-end for that tool was conceptualized as part of this research (cf. Section 3.3.2, page 88). The following section therefore deals with computer-assisted conceptual design of the ECLSS and its synergistic linkages to other subsystems such as EPS and AOCS. It introduces the software package that was developed in the course of this research to allow for the intuitive, interactive top-level design and simulation of the ECLSS (and of synergistic ECLSS/AOCS/EPS concepts), with only moderate demands on computing hardware.

3.3.1 Synergistic Life Support System Simulation

Due to the many design iterations and the interdisciplinary nature of conceptual design, software operation should be intuitive, and allow for interactive exploration of the design space. Additionally, software should facilitate documentation and communication of designs and simulation results. User-friendly modeling and interactive simulation can also serve to demonstrate the dynamic behavior of subsystems for systems engineering education. A high degree of flexibility is also required of any simulation tool for use during conceptual design to allow for models with varying levels of detail and for the simulation of innovative designs.

The ELISSA software was developed to address those demands. "ELISSA" stands for "Environment for Life Support System Simulation and Analysis". Its development was facilitated by the availability of predecessor software ([Osburg98], [Osburg00a]; cf. Section 2.1.3 on page 28) which proved the concept and permitted a first round of user feedback to be gathered.

The ELISSA environment consists of an underlying off-the-shelf programming and run-time environment, predefined libraries of ECLSS and other subsystem components, and a custom-made approach to modeling the systems under analysis. Especially when used as a teaching tool, ELISSA emphasizes the synergistic links within and among the individual subsystems modeled.

Using common engineering symbols like wires and icons, the user can simply "patch together" the life support system of a space station or spacecraft[30], and interactively observe its stationary behavior as well as its dynamic reactions to varying operating conditions. Compared to other existing ECLSS simulation software, it offers specific benefits for an application within the environment of conceptual design (Table 3.10).

ELISSA was successfully applied to the design of life support systems during the Space Station Design Workshop 2001 (cf. Section 4.2 on page 98). Its predecessor was validated during the Space Station Design Workshops from 1997 to 2000, and additionally through its application in various research projects ([Fehrenbacher98], [Labadie99], [Schmid00]). An extensive user manual that includes a step-by-step tutorial is provided to the user [Osburg01], along with complete HTML documentation of all library components.

ELISSA Basics

The software underlying ELISSA is LabVIEW (Version 5.1), a commercial off-the-shelf product developed by National Instruments Corporation, Austin, Texas [LabVIEW00]. It is aimed mainly at supporting measurement data acquisition and control hardware and analyzing the data gathered by such hardware. For this purpose, LabVIEW contains instrument driver libraries, hardware support interfaces, a powerful graphical programming language, *G*, as well as an intuitive user interface [Jamal97].

For ELISSA, only the programming/user interface aspects of LabVIEW are used since all simulations take place on the computer, and no actual hardware is attached. It is easily possible, though, to integrate data acquisition interfaces to real-world components, in case the user wanted to perform hardware-in-the-loop simulations. LabVIEW comes well-documented [LabVIEW98], which adds to the user-friendly approach of ELISSA.

In order to simulate and analyze a life support system with ELISSA, subsystem modules are inserted into the simulation model from ELISSA component libraries using a drag-and-drop approach.

---

[30] First step in this modeling process, as specified in the ELISSA user manual [Osburg01], is again a manual sketch of the system to be designed/modeled, in accordance with Section 2.3.3.

Linking modules with virtual wires defines the data flow between them, which mirrors the species flows in the corresponding real-world system (Figure 3.1). Due to the fully graphical environment, no further programming effort is needed. Text-based instructions, as known from line-oriented traditional programming languages such as C or Ada, are avoided completely. All information required to perform simulation runs is contained in the graphical model (Figure 3.4 on page 91), which at the same time is the executable code.

ELISSA simulation runs are highly interactive, controlled from a graphical "Simulation Control" panel (Figure 3.2). The user can set initial parameters for each component and for the simulation time step. During run-time, the user can control the simulation as well, e.g. by changing parameters or the time step, or by switching components off and on to simulate failures. A disk storage subroutine is provided for simulation data storage and subsequent post-processing with standard spreadsheet software.

Simulations are based on numerical iteration. For each simulation step, individual modules perform calculations on the species flows they receive. The transition from species flows to species amounts is done only where needed, i.e. in species tanks; simple time-discrete integration is used there [Osburg98].

ELISSA Libraries

Predefined component libraries are provided for the ECLSS as well as for those subsystems with potential synergistic linkages to the life support system. This allows the user to model life support systems, such as the one envisioned for ISS, rapidly [Wieland98]. Table 3.11 gives an overview of available components. Figure 3.3 shows the corresponding graphical menus available to the user.

As all predefined components are themselves programmed in LabVIEW's graphical programming language, the user can easily add or modify modules if specific analysis or design requirements demand it, guided by the principles given in the ELISSA user manual.

The screenshot in Figure 3.5 (page 92) represents an example of the graphical code of such a predefined ELISSA library module, in this case a Sabatier reactor. It was modeled based on top-level systems data of an actual prototype reactor given in [Eckart96] and [Wydeven88].

The upper part of the code in Figure 3.5 calculates the amount of CO_2 that can be processed during the simulation step, as long as the unit is switched on. In the upper right-hand side, molar mass ratios are used to determine how much H_2O and CH_4 are output, depending on CO_2 turnover.

The amount of H_2 required for processing is determined in the same manner, as visible in the lower left area. Power consumption (bottom left) and heat output (lower right) are also calculated and output, along with the estimated mass of the unit.

Table 3.10: Overview of ECLSS Simulation Tools ([Osburg98], adapted)

Type	Name	Advantages	Disadvantages
Dedicated ECLSS Simulation	Spreadsheet e.g. [Yeh99]	Standardized software, fast, optimization-capable	Static analysis only, monolithic, low educational value
	CASE/A [Wieland94]	ECLSS-specific libraries, accuracy	No PC version, hard to customize, availability
	ECOSIM [Perez99]	ECLSS-specific libraries, accuracy	Cost, complexity
	TRIALLS [Doll92]	ECLSS-specific data, enables quick trade studies	Static budget estimation only, availability
Process Engineering Flowsheet	Aspen Plus [Aspen97]	Detailed modeling of chemical and physical processes, powerful simulation functionality	Cost, complexity, only steady-state simulation, detailed knowledge of system and components required
	DIVA [DIVA97]	Detailed modeling of chemical and physical processes, enabling of dynamic simulation (non-steady state)	Detailed knowledge of system and components required, hard to customize, complexity
Automation and Control	Matlab/ Simulink [Math01]	Time-continuous simulation through state-space modeling	Large resulting state vector, primitive graphical user interface
	ROSE [Rose98]	High precision, powerful simulation functionality	Cost, no PC version

Synergistic Simulations

Reducing resupply mass is one of the main ways of cutting life-cycle cost for permanently inhabited space platforms such as the International Space Station or its successors.

One promising approach to achieving this goal is the use of synergies derived from linking subsystems that are related by common functions or common process fluids [Messerschmid99]. Taking into account possible interactions between these subsystems early in the conceptual design phase of a space station facilitates the tapping of synergistic potential during detailed design later on.

The subsystems for attitude and orbit control (AOCS) and for environmental control and life support (ECLSS) are especially well-suited as candidates for synergistic linkages, due to the similarity of species that can be used in both subsystems (water, oxygen, hydrogen) and to their high individual shares in any space station's logistics budget [Fehrenbacher98].

In the case of the Space Station Freedom program, for example, designers planned to use resistojet thrusters fueled with ECLSS wastewater for altitude control [Heckert87]. Moreover, arcjet thrusters fueled by water steam are currently being developed, thus in-

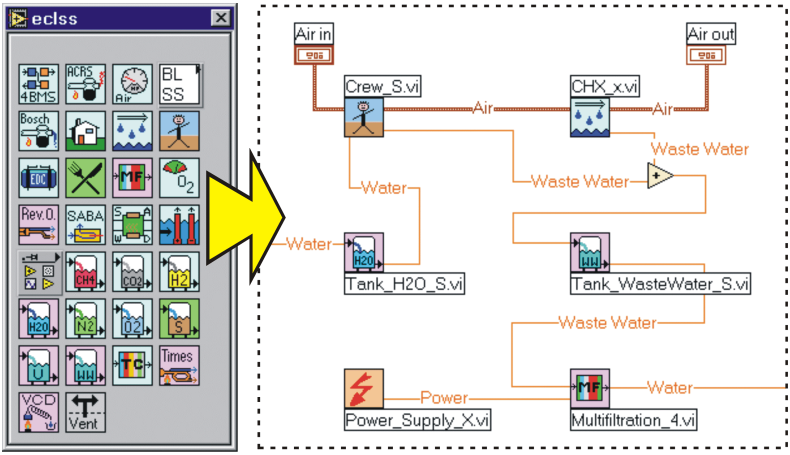
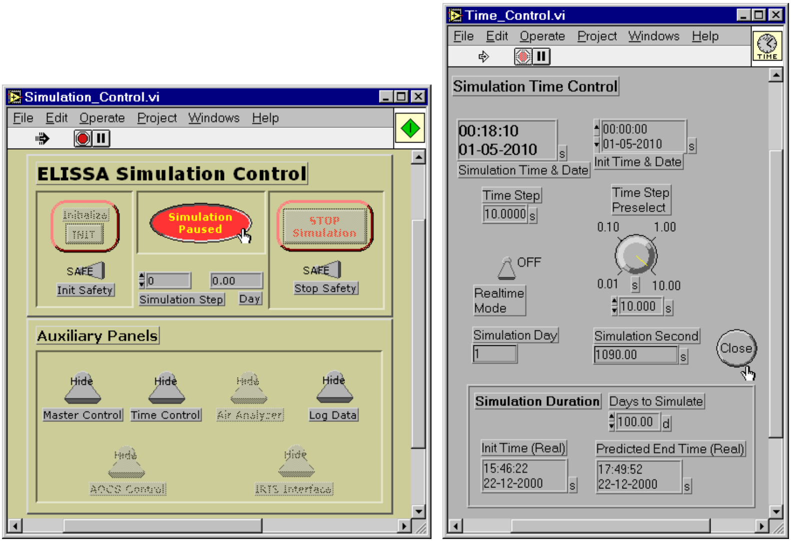


Figure 3.1: From ELISSA library to (simplified) ECLSS simulation model



Simulation Step: 0
Day: 0.00

Simulation Time & Date: 00:18:10 01-05-2010 s
Init Time & Date: 00:00:00 01-05-2010 s
Time Step: 10.0000 s
Time Step Preselect: 0.01 0.10 1.00 10.00 s; 10.000 s
Realtime Mode: OFF
Simulation Day: 1
Simulation Second: 1090.00 s
Days to Simulate: 100.00 d
Init Time (Real): 15:46:22 22-12-2000 s
Predicted End Time (Real): 17:49:52 22-12-2000 s

Figure 3.2: ELISSA simulation control panel (left) and time control panel

creasing the potential for introducing synergistic linkages between ECLSS and AOCS ([Bertrand96], [Messerschmid99]).

ELISSA enables a design team to estimate possible gains from introducing synergistic couplings and helps design engineers and engineering students understand the complex dynamics of such a synergistic system. The software not only provides predefined components of the attitude and orbit control system (cf. Table 3.11), but attitude and orbit simulation data generated by IRIS (cf. Section 2.1.3) can also be automatically integrated into the simulation of synergistic ECLSS/AOCS systems in ELISSA.

Table 3.11: Provided ELISSA Components

Library	Components
ECLSS Sources: [Eckart96], [Edeen98], [Jones00b], [Labadie99], [LMLSTP00], [Messerschmid99], [Volk95], [Wydeven88]	*Air loop (physico-chemical):* advanced carbon-formation reactor; air analyzer; Bosch reactor; cabin; condensing heat exchanger; electrochemical depolarized CO2 concentrator; four-bed molecular sieve; oxygen regulator; Sabatier reactor; solid amine water desorption reactor; trace contaminant control *Water loop (physico-chemical):* multifiltration; reverse osmosis; static feed water electrolysis; thermoelectric membrane evaporation; vapor compressed distillation *Biological components:* aerobic slurry bioreactor; biomass production chamber; food processor; harvest storage; immobilized cell bioreactor; packed bed bioreactor; plant growth tray; tanks for acid, biowaste, and nutrients; trickling filter bioreactor *Other components:* crew; food storage; tanks for CH4, CO2, H2, H2O, N2, O2, solid waste, urine, and waste water; vent
AOCS Sources: [Fehrenbacher98], [Prinz97]	*General components:* AOCS control unit, control momentum gyros; propellant tank *Thrusters:* various types of arcjets; chemical thrusters; custom thrusters; reboost thruster; various types of resistojets
EPS Sources: [Kurtz92], [Messerschmid99]	Power storage; generic power supply; shunt; solar array with eclipse simulation
Miscellaneous Hardware	Master control panel; radiator
Simulation	Initialization; IRIS interface; simulation control; simulation data storage; time control; auxiliary components

3.3.2 AOCS Simulation Interface

The SSDW software tool used for attitude and orbit simulation, IRIS (cf. Section 2.1.3 on page 27) is a command-line oriented program using text input files to provide mission parameters such as orbital altitude or attitude control strategy. Editing and changing this text file is cumbersome and does not concur with the user-friendly approach of other SSDW software such as ELISSA or the graphical station configuration modeler.

In order to provide similar functionality for the AOCS tool, the utility software "MISSONCONTROL" was conceptualized. Like ELISSA , it is based on the graphical interface elements provided by Lab-

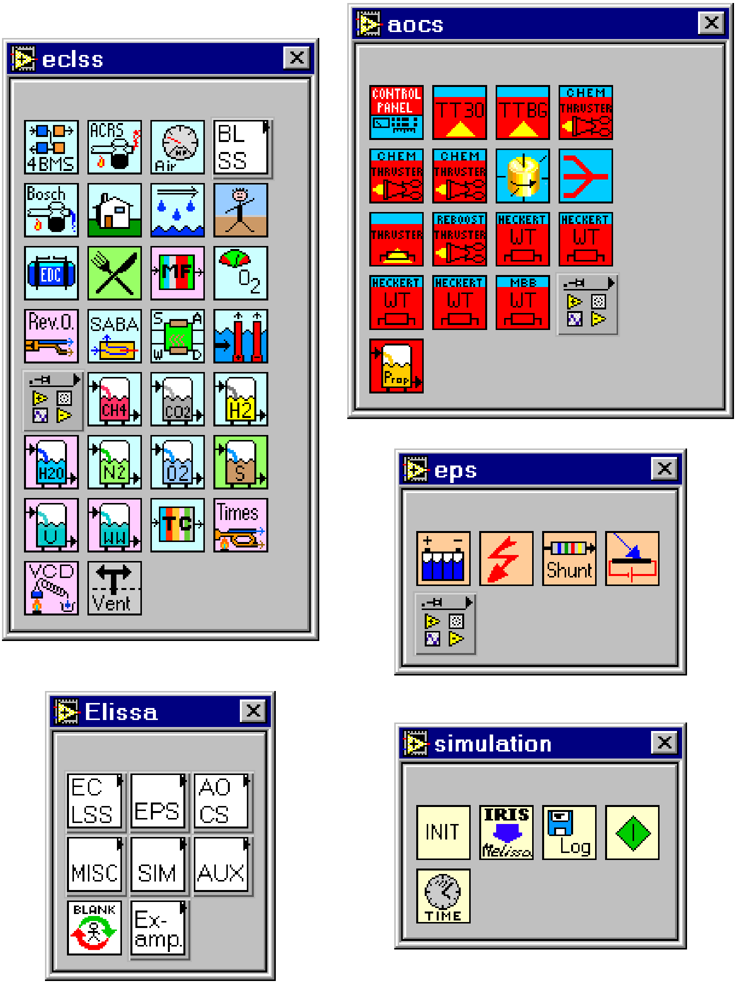


Figure 3.3: ELISSA library menus

VIEW, and it relies on the *"G"* graphical programming environment for its implementation. Its main front panel permits the selection of various sub-panels for data entry into the mission simulation command file, and the launch of IRIS and the display of simulation results. This concept can easily be implemented for future versions of the AOCS simulation software, such as IRIS++ (cf. Section 5.3 on page 112).

3.4 Summary

This chapter presented an interdisciplinary approach to the conceptual design of inhabited space systems. Based on elements from the areas of systems engineering, Human Factors, and terrestrial architecture, the new approach addresses the issues of design team composition and collaboration, principles of the design process, and principles of the design itself. It also provides heuristic knowledge and numerical simulation capability for human-related aspects such as Human Factors and ECLSS design and analysis. The following chapter will document several applications of this new approach.

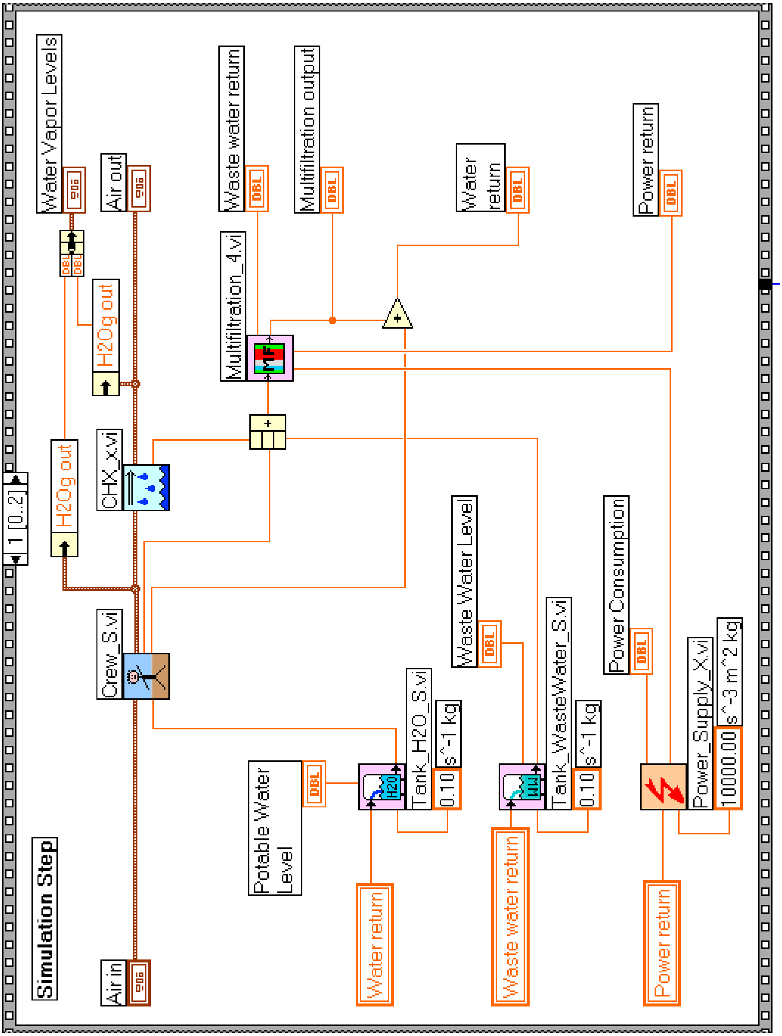


Figure 3.4: Actual ELISSA simulation model of a simple ECLSS

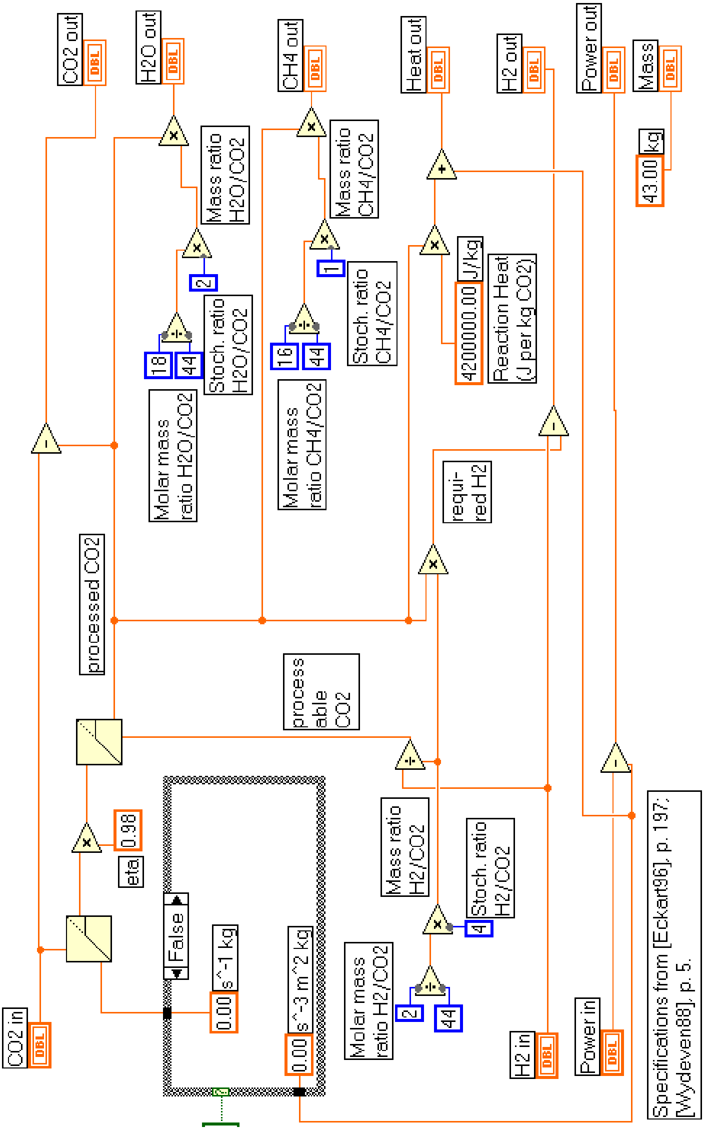


Figure 3.5: Code of the predefined ELISSA component "Sabatier Reactor"

> *"Ships and sails suitable for the heavenly air should be fashioned. Then there will be people who will not shrink from the bleak vastness of space."*
>
> *Johannes Kepler to Galileo Galilei, 1609*

4 Applications of the New Approach

In order to develop and validate the new design approach described in the preceding chapter, it had to be applied to *"real problems in the real world*[31]*"* [Cohen87a].

Therefore, a graduate-level interdisciplinary space station design project was started in 1998. It involved students from the Space Systems Institute (Department of Aerospace Engineering) and from the Department of Architecture of the University of Stuttgart, Germany. This project and its results are documented in the following section.

Additionally, to demonstrate the impact of the new approach on projects with larger design teams and shorter design cycles, it was used to guide the participants during the "Space Station Workshop 2001" held at the Space Systems Institute. This experience is described in Section 4.2.

---

[31] Valery, in his 19th-century diction, makes a strong case for this practical application [Valery94]: *"He who has never dared to undertake the adventure of designing [...], who, on the untouched white of a new sheet, has never seen an image that was plaintive of all the possibilities that had to be regretfully excluded from the choice, who has never had a vision of structures to be erected, who has never felt faintness when realizing the distance from the objective and the scarcity of means available to reach it [...], he does not know – whatever his other education – the richness and the fertility and the mental powers that are illuminated by the act of designing."*

4.1 Interdisciplinary Space Station Design Project

This project took place from 1998 to 2000 and was divided into three phases. In its first phase, the participating graduate students of architecture and aerospace engineering were tasked with conceptually designing a space station dedicated both to commercial utilization and to supporting the preparation of human exploration missions to Mars. The design process was executed in accordance with the approach outlined in Chapter 3.

4.1.1 Phase I: Initial Design

After analyzing the design task and performing thorough background research, a variety of configuration alternatives were generated. Figure 4.1, left, shows some of the options that were analyzed. The three most promising alternative configurations were modeled

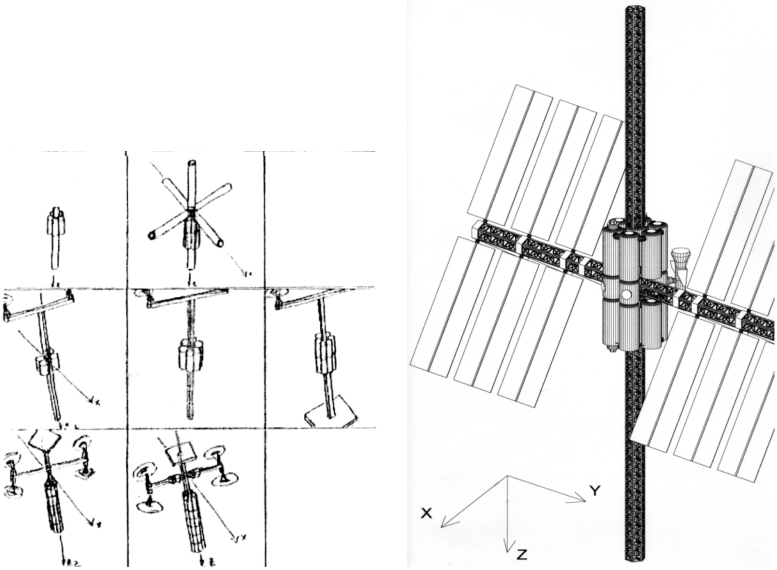


Figure 4.1: Sketches of analyzed assembly sequence options (left) [Jolk98]; CAD model of selected configuration at assembly complete (right) [Holmig99]

using the SSDW software, and AOCS simulations were performed to determine attitude stability and resupply requirements [Jolk99]. The optimum configuration was then developed in greater detail [Jolk98]. A public exhibition at the Planetarium of Stuttgart, Germany presented the outcome of this design phase.

4.1.2 Phase II: Optimization

The second phase of the design project started with a new interdisciplinary design team tasked with optimizing the internal configuration of the station concept developed during phase one. The emphasis was on human-centered design, with issues ranging from standardization and layout of pressurized modules to definition of interior translation paths. The second phase also permitted another iteration on the overall configuration to be performed, leading to mass savings (more compact pressurized modules) and reduced programmatic risk (replacement of solar dynamic technology by photovoltaic EPS). Figure 4.1, right, depicts the computer model of the final configuration after design phase two. The design included developing detailed level-by-level cross-sections of the interior station configuration, similar to floor plans of terrestrial buildings, and renewed AOCS and assembly sequence simulations based on the modified configuration [Holmig99].

In concurrence with the new approach, key details were also conceptualized during the second phase. This included innovative “fold-out” crew quarters, a human-powered centrifuge module, and a combination table/seat rack. The results of this design phase were presented in an exhibition at the seat of the State Chamber of Architects (“Landesarchitektenkammer”) in Stuttgart.

4.1.3 Phase III: Crew Quarters Detail

A third phase was launched to continue the design of the crew quarters concept developed in phase two. This included the manufacturing of a high fidelity, life-size mockup for HF analysis, as well as the generation of a virtual model of a habitation module equipped with the new crew quarters for visualization and “fly-through” Virtual Reality (VR) evaluation. These results were part of a public design

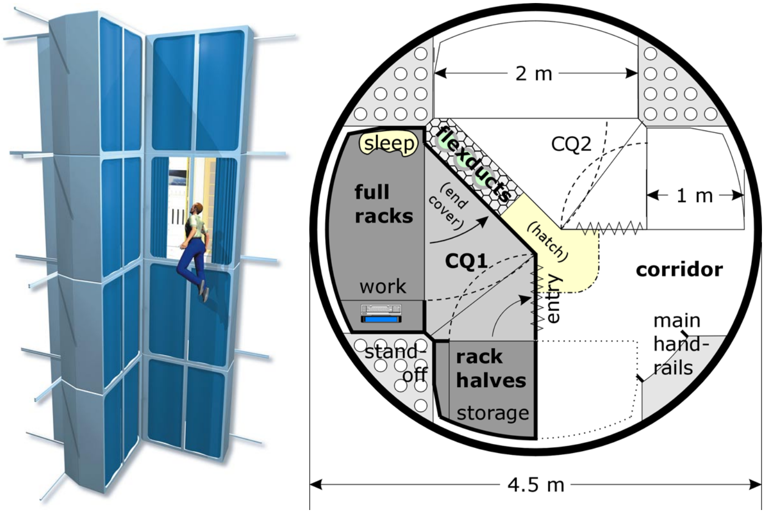


Figure 4.2: Virtual Reality model (left) [Hirche00] and cross-section (right) [Osburg00b] of proposed crew quarters, installed in a habitation module

exhibition at the State Chamber of Commerce ("Haus der Wirtschaft") in Stuttgart.

The proposed crew quarters provide ample living and working space for crewmembers, while maintaining rack standardization and full rack exchangeability. Each crew quarters unit consists of two laterally connected full racks (ISPRs, as used on ISS) and two laterally connected ISPR halves oriented at a 90° angle (cf. cross-section shown in Figure 4.2, right). When installed, the rack fronts are swiveled outwards into the module corridor and connected there, thus increasing the habitable space for each crewmember to about 7 m^3 (cf. Table 2.6 on page 35). Figure 4.2, left, shows a rendering taken from the Virtual Reality model of eight such crew quarters installed inside an ISS-type pressurized module. In the picture, the module walls and auxiliary systems are removed for clarity, and only crew quarters racks and standoffs visible.

The quarter-cylinder shaped area of the module corridor that remains after deployment of the crew quarters still provides sufficient translation space, considering that the habitation module will not be a high-traffic environment. When the crew quarter walls are not swiveled outwards, the full racks can nevertheless be used as makeshift sleeping quarters, and the rack halves for storage.

This concept represents an initial approach to actual operational crew quarters. Issues to be addressed in subsequent detailed design would include ventilation, light fixture placement, microgravity HF analysis, choice of materials, deployment procedures, etc.

4.1.4 Discussion of Design Results

For the first design project which applied the new human-centered design approach presented in Chapter 3, the design teams were small, but participants had several months to develop their designs. These conditions encouraged thorough background research, as well as deliberate development and analysis of alternatives for all system elements. Due to the interdisciplinary composition of the design teams, mutual learning, efficient communication, and creative encounters were emphasized. Participant motivation was high throughout the process, since both the design topic and the newness of the design process were perceived as stimulating. The previous participation of design team members in one of the Space Station Design Workshops offered by the Space Systems Institute provided them with joint design experience and initial exposure to hands-on space systems design. Tools such as hand sketches, consideration of important details, human-related design heuristics, and numerical simulation were utilized. Iteration was explicitly included through the tasking of the second phase design team, but also occurred within each phase.

The resulting design shows an innovative gravity-gradient-stabilized configuration centered on a pressurized-module core, with a truss extending in the vertical direction providing stability and abundant accommodation opportunities for external payloads and storage tanks. A horizontal truss holds tracking photovoltaic power generators and radiators. Both trusses, as well as the pressurized-module core, can be easily expanded, thus offering flexibility for future growth.

The habitability rating of the configuration is high, due to the proximity of the pressurized modules, their consistent orientation, and their high degree of internal standardization (which improves the adaptability and variability of the internal configuration). Additionally, the allocation of functions to pressurized modules respects zoning and adjacency requirements. Safety is enhanced by dual-egress/redundant-access capability being integral to each module, and by core modules being outfitted as shelters. Manufacturing cost is minimized due to standardized module types, while logistical effort is reduced because the station's inherent stability and compact configuration which requires little AOCS fuel resupply.

A key detail of great importance to the overall configuration (cf. footnote 22 on page 49), the crew quarters module offers a generous amount of private space for individual crewmembers, while allowing for unproblematic integration into the overall station (and even into a standard ISS module, due to its being based on ISS standard payload racks[32]). Its spaciousness and habitability qualities were verified through the construction of a life-size, high fidelity mockup. The crew quarters design provides sufficient flexibility for subsequent detailed design efforts.

4.2 Space Station Design Workshop 2001

The second application of the new approach, the SSDW 2001 international design workshop took place at the Space Systems Institute in March 2001. It was modeled after the previous SSDWs (cf. Section 2.1.4, page 29), but the approach and software tools used were those described in Chapter 3 of this report. Eighteen graduate students from France, Germany and Spain, divided into two competing design teams ("Team BLUE" and "Team GREEN"), spent one week designing a space station and then evaluating the results. In accordance with the interdisciplinary character of the approach, participant backgrounds were not only in aerospace engineering, but also in architecture, economics and mathematics. The mission statement for the design teams read [SSDW01a]:

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[32] A smaller type of fold-out crew quarters unit, based on a single ISPR, was designed and built at NASA's Johnson Space Center, and installed inside the US Laboratory module of ISS in September 2001 [TeSS00].

> *"Situation: the year 2005. You are a group of design engineers employed by EMSI ('European Manned Spaceflight Industries'). ESA invites you to tender for a design study on a joint European-Japanese space station project. The space station shall demonstrate JP-EU cooperation [...], be an absolute minimum configuration with future growth possibilities [...], shall offer direct and permanent access to microgravity and to the LEO environment in a permanently manned research laboratory [...], and shall also be used to support the preparation of the first human expedition to Mars."*

In the following sections, the design and evaluation results as well as the experience gained in applying the new approach described in Chapter 3 are presented.

4.2.1 System-level Design Results

Table 4.1 compiles system-level design results for both designs, from mass and AOCS issues to a listing of major components. Figure 4.3 shows the configuration of design BLUE and also gives an impression of the evolution of its design process.

The hand sketches in Figure 4.7 on page 109 demonstrate the assembly sequence of design GREEN and also show its final configuration. Solar arrays and radiators in both figures were sized corresponding to the results of spreadsheet-based EPS/TCS subsystem calculations. Table 4.2 presents the same key parameters of the International Space Station for comparison.

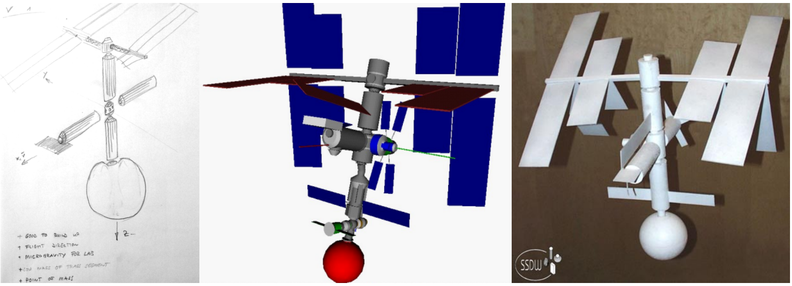


Figure 4.3: SSDW 2001 – stages of design BLUE: first configuration sketch (left), VRML output of AOCS simulation software (center), and 1:100 scale model made of cardboard, wood and styrofoam (right) [SSDW01a].

4.2.2 Subsystem Design Results

Numerical attitude and orbit control simulations served to validate the configuration with respect to attitude stability, and to perform CMG sizing, AOCS resupply calculations, and estimations of micro-gravity levels. The simulation results displayed in Figure 4.6 on page 108 show that the new design approach led directly to a configuration with a high level of inherent gravity-gradient stability, i.e. a torque equilibrium attitude at only a few degrees of pitch with ac-

Table 4.1: Summary of SSDW 2001 Design Results [SSDW01a]

Parameter	**Design BLUE**	**Design GREEN**
Mass	Approximately 175 t	Approximately 170 t
Major Components	1 core module (modif. ISS-FGB) 1 lab. (ISS-JEM with cupola, robotic arm and external facility) 1 habitation module (ISS-US Hab) 1 inflatable Mars training module (Konopek Sphere, [Konopek99]) 2 nodes (modif. ISS-Node 2) 1 airlock (ISS-US Airlock) 1 CRV with docking adapter 1 Shuttle docking adapter (Mir) 1 Soyuz, 1 ATV Truss with photovoltaic arrays and radiators	1 core module (modif. JEM) 1 laboratory (modif. ISS-COF, with external facility) 1 habitation module (modif. Spacelab) 1 Mars training module (modif. and extended JEM) 2 nodes (ISS-Node 1 and ISS-Node 2) 1 airlock (ISS-US Airlock) 1 CRV with docking adapter 1 ATV Truss with photovoltaic arrays and radiators
Orbit	Circular, 300 km - 350 km, inclination 30.2°, partially continuous reboost (ECLSS-fed arcjet)	Circular, 385 km - 400 km, inclination 51.6°, impulsive reboost
Attitude	Earth-oriented, gravity-gradient stabilized (TEA 4.63°)	Earth-oriented, gravity-gradient stabilized (TEA -1.09°)
Crew	7	3 - 8
Pressurized Volume	Approximately 800 m^3	Approximately 600 m^3
Regenerative ECLSS Elements	TIMES water processors, condensing heat exchangers, CO_2 molecular sieves, Sabatier and ACRS CO_2 processing, O_2 electrolysis	TIMES water processors, condensing heat exchangers, CO_2 molecular sieves, Sabatier and ACRS CO_2 processing

ceptable maxima of the cyclic momentum accumulation around the x-, y-, and z-axes.

Both teams used ELISSA to simulate the physico-chemical life support systems proposed for their designs, and to investigate their performance with respect to basic functionality, consumables resupply requirements, and failure effects analysis. Figure 4.4 shows a comparative analysis of cabin CO_2 levels, after CO_2 scrubber failures, for redundant and non-redundant system designs (Team BLUE).

Emphasis was also put on the Human Factors component of the design effort, which ranged from module type selection and location

Table 4.2: ISS Parameters for Comparison with SSDW 2001 Design Results

Parameter	**ISS (October 2001) [ISS01]**	**ISS (Assembly Complete) [ISS98], [ISS01], [ISS99]**
Mass	Approximately 130 t	Approximately 460 t
Major Components	1 core module (FGB) 1 laboratory module 1 service module (SM) 1 robotic arm 1 USOS Node 1 airlock 1 Soyuz 1 truss segment with PV and radiators	See "ISS, Sept. 2001", plus: 3 USOS labs (JEM, COF, Centrifuge) 1 external platform (JEM-EF) 2 ROS labs 2 ROS docking modules 6 truss segments with PV and/or radiators 2 USOS nodes (1 unfunded) 1 ROS node 1 habitation module (unfunded) 1 CRV (unfunded)
Orbit	400 km, inclination 51.6°, impulsive reboost	Same as "ISS, Sept. 2001"
Attitude	Earth-oriented, TEA 87°	Earth-oriented, TEA > 5°
Crew	3	3 - 7
Pressurized Volume	Approximately 300 m^3	Approximately 1100 m^3
Regenerative ECLSS Elements	O_2 electrolysis, CO_2 molecular sieves, condensing heat exchangers	See "ISS, Sept. 2001", plus: Sabatier CO_2 processor, potable/hygiene water processor, urine processor

to intra-module zoning to crew quarters conceptualization (Figure 4.5).

4.2.3 Discussion of Design Results and Design Approach

The second application of the new approach was for a project with relatively large, competing design teams and a compressed design schedule. The present section will discuss the design results (including how they were assessed by the workshop participants themselves) and trace the impact of the new approach on those results and on the process that led to them.

Self-Evaluation of Design Results by Participants

On the last day of the SSDW 2001, participants were assigned into six evaluation teams that had to rate the BLUE and GREEN designs with respect to the evaluation criteria given in Table 4.3 on page 107. This not only served to provide a first assessment of the competing designs, but it also gave participants an opportunity to apply relevant knowledge and experience acquired during the previous hands-on design phase.

Numerical scores for each evaluation criterion were determined based on weighted subscores and added to provide a total score for

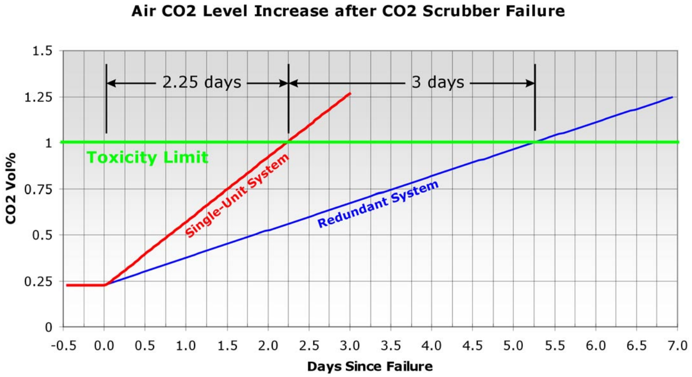


Figure 4.4: Design BLUE ECLSS analysis demonstrates advantages of redundant CO_2 scrubber design vs. single-unit design: three extra days are available in case of scrubber failure before CO_2 toxicity level is reached.

each design. This calculation showed that both designs were considered viable, with total scores differing by less than 1.5%.

Evaluation of the Design Results

Both designs have inherently stable Earth-oriented configurations with Torque Equilibrium Attitudes close to LVLH (cf. Figure 4.6). This reduces the fuel resupply mass required for attitude control. Most modules are based on existing hardware which was designed and built for ISS, and which therefore could be reproduced without excessive cost.

Laboratory modules are allocated close to the stations' Centers of Gravity, which – in combination with the benign deviations from LVLH – provide in excellent microgravity conditions for research.

Comparison with ISS data (cf. Table 4.2) shows that both designs offer a pressurized volume between current ISS status and ISS Assembly Complete. Mainly due to their use of relatively large modules with high volume-to-mass ratios, especially in case of the inflatable module of the BLUE design, the total mass is rather low. A larger degree of ECLSS loop closure, using physico-chemical life support technology more advanced than what is baselined for ISS, was made possible by moderate assumptions regarding the availability of Advanced Life Support (ALS) technology in the near future.

The GREEN design exhibits an overall configuration similar to the one developed in [Bertrand98]. It features relatively few innovative elements, but most ISS-based modules require significant modifications, which tends to increase cost.

The BLUE design's topology is slightly less conventional, with a certain similarity to NASA's Power Tower space station concept [Messerschmid99]. Few of the ISS-type modules it utilizes need to be modified, which tends to save on cost. The obvious exception is the inflatable spherical module for the required Mars mission training activities. However, since this element is placed at the nadir of the station, it is not critical to the overall configuration. This preserves programmatic flexibility in case of development delays. At the same time, the inflatable element offers significantly more habitable volume than a conventional element of comparable launch dimensions, which decides a risk-to-benefit analysis in its favor.

Impact of the New Design Approach

The new design approach influenced both the design results and the design process. To demonstrate this impact, representative observations are given below. They are ordered in the same sequence in which the elements of the approach were presented in Chapter 3.

The principles of design team composition and collaboration outlined in Section 3.1.1 were applied by both teams. Participants with backgrounds in certain areas (ECLSS, AOCS, etc.) could be observed sharing their knowledge with the team, thus enriching the design experience and laying the foundations for the self-evaluation phase mentioned above. Sketches were also used extensively to support the search for solutions, communication and decision-making and to foster creativity in each team (cf. Figure 4.3 and Figure 4.7).

Guidelines for the design process (Section 3.1.2) permitted a highly structured yet flexible design flow, which resulted in an efficient design process that led both teams to develop realistic system concepts within a few days. In addition, attention to important details (e.g. to issues of Crew Quarters integration, cf. Figure 4.5, and to ECLSS mass balances for joint AOCS/ECLSS subsystem design) enabled the incorporation of synergisms (cf. design Blue, Table 4.1) and prevented the emergence of flawed configuration and subsystem concepts at this crucial stage, thus reducing the risk of extensive redesign in later phases.

As mandated by the principles of the design itself (Section 3.1.3), the inclusion of HF concerns into the overall design from the beginning – instead of treating them as isolated subsystem issues – led to a better-balanced design and increased habitability. Providing the designers with concise heuristics in this and other areas also allowed for fast design convergence, especially with respect to station configuration. Given below is a selection of heuristics (cf. Section 3.2) that were successfully applied by the teams:

- For critical phases and components, proven technology was used (e.g. ISS-type pressurized modules, use of existing launcher constraints, etc.).
- Both configurations are gravity-gradient stabilized, as recommended in Table 2.4 on page 24.
- Zoning requirements regarding proximity or separation of functions were taken into account in both designs (cf. the isolated locations of the Mars training modules or the analysis of intra-module zoning shown in Figure 4.5).
- The assembly sequences were analyzed and modules were adapted as necessary for each design (e.g. by specifying the addition of AOCS packages where required).
- Regenerative physico-chemical ECLSS technology was used, providing all functions recommended in Table 3.7.

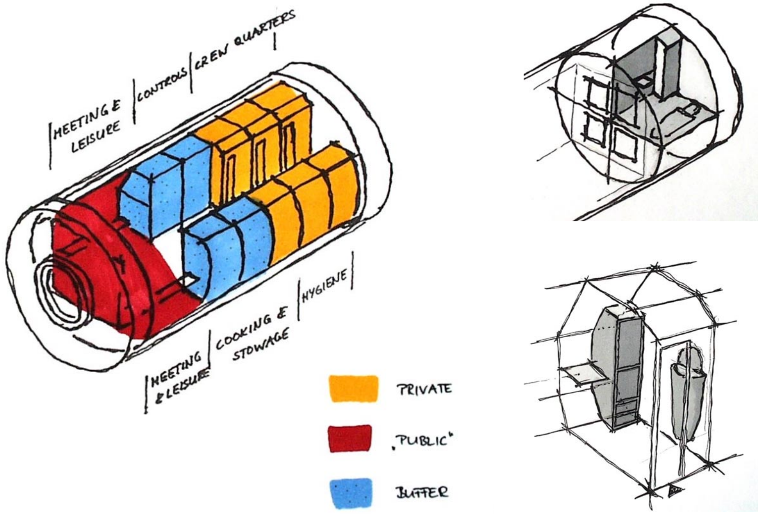


Figure 4.5: Design GREEN habitation module zoning (left) and crew quarters design options (right) [SSDW01a]

- ✧ Synergistic links were identified and integrated (cf. design BLUE, Table 4.1).
- ✧ Finally, both teams used the simulation software described in Section 3.3 to design the life support systems for their respective stations. Basing the design of these subsystems on actual simulation results that were obtained with an intuitive, rapid-turnaround tool which enabled dynamic, interactive simulation, enhanced the learning experience and also allowed the teams at this crucial stage of the overall design process to avoid poor ECLSS concepts.

4.3 Summary

The new approach to the conceptual design of inhabited space systems presented in Chapter 3 was applied to multiple realistic design tasks. The first application used small design teams working for several months each. The second application demonstrated the value of the approach for large design teams performing their task within one week.

Both applications resulted in viable design results that would serve as a good basis for subsequent detailed design and implementation. Participant feedback was collected, which resulted in various suggestions for future improvement, as did the evaluation of the impact of the new approach given in the previous section. These recommendations will be summarized in Section 5.3.

Table 4.3: SSDW 2001 Participant Self-Evaluation [SSDW01a]

Evaluation Teams and Criteria	**Design Team**					
	Blue			**Green**		
Utilization and Programmatics						
Utilization Potential	3	x 4	12	3	x 4	12
International Cooperation	2	x 2	4	3	x 2	6
Operations	3	x 1	3	2	x 1	2
Weighted Subtotal			**19**			**20**
Overall Configuration						
Overall Mass and Size	3.5	x 2	7	3.5	x 2	7
Hardware Concept	2.6	x 1	2.6	2.8	x 1	2.8
Module & External Configuration	3.2	x 4	12.8	2.8	x 4	11.2
Weighted Subtotal			**22.4**			**21**
System Deployment and Growth						
Minimum Configuration and Growth	3	x 2	6	3	x 2	6
Launch and Assembly	2	x 3	6	3	x 3	9
Rendezvous and Docking	3.5	x 2	7	3	x 2	6
Weighted Subtotal			**19**			**21**
Attitude and Orbit Control						
Attitude Stability and Controllability	3.1	x 4	12.4	3.3	x 4	13.2
Orbit Control and Reboost	3.2	x 3	9.6	3.6	x 3	10.8
Weighted Subtotal			**22**			**24**
Subsystem Issues						
Power Generation	3	x 3	9	3	x 3	9
Thermal Control	1	x 2	2	3	x 2	6
Propulsion	3	x 2	6	3	x 2	6
Weighted Subtotal			**17**			**21**
Human Aspects						
ECLSS	3	x 4	12	3	x 4	12
Human Factors	4	x 3	12	2	x 3	6
Weighted Subtotal			**24**			**18**
Total Score	**123.4**			**125**		

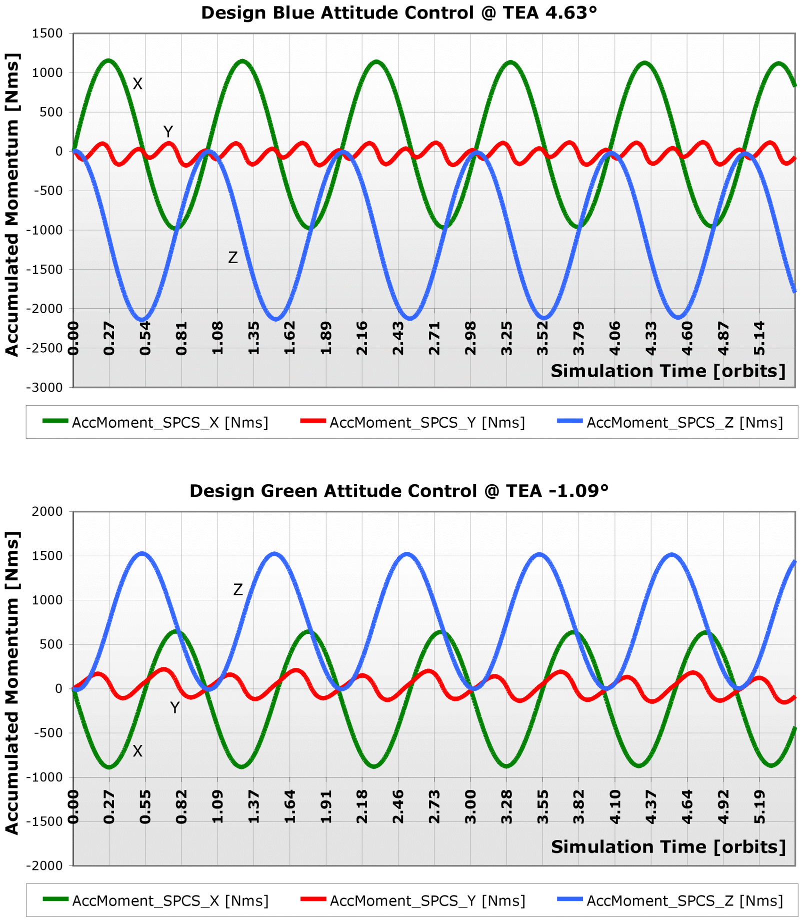
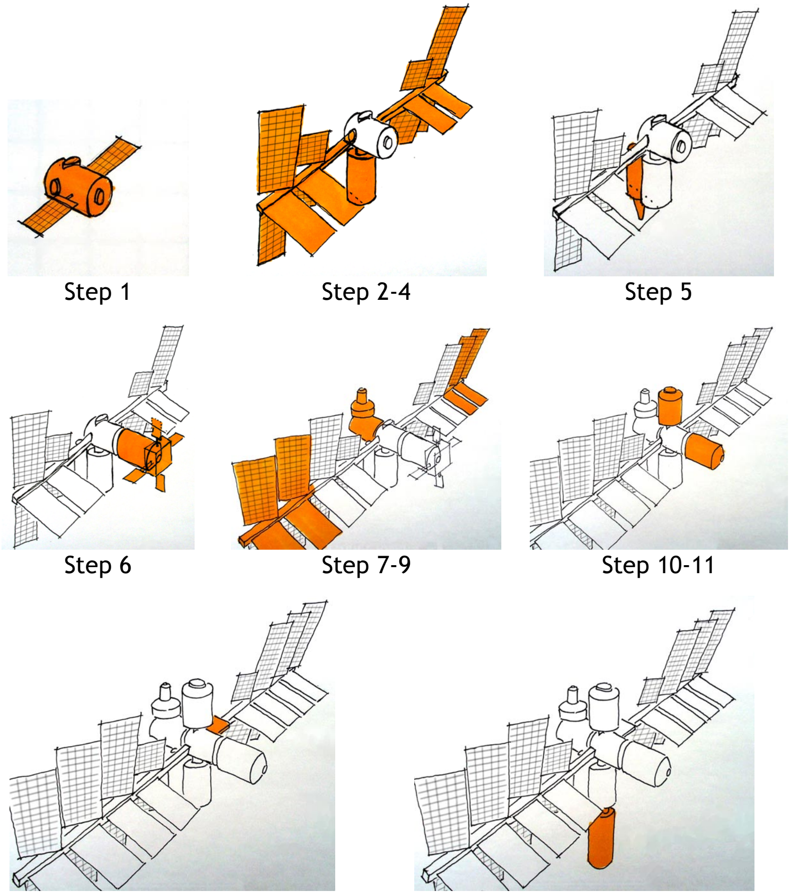


Figure 4.6: Attitude simulation results showing inherent attitude stability with negligible deviations from LVLH [SSDW01a]



Step 1

Step 2-4

Step 5

Step 6

Step 7-9

Step 10-11

Step 12

Step 13

Figure 4.7: Design GREEN assembly sequence [SSDW01a]

"There can be no thought of finishing, for 'aiming at the stars', both literally and figuratively, is a problem to occupy generations, so that no matter how much progress one makes, there is always the thrill of just beginning."

Robert H. Goddard, 1932, in a letter to H.G. Wells

5 Conclusions

5.1 Approach and Verification

An interdisciplinary methodology for the conceptual design of inhabited space systems has been developed and was described in this report. It incorporates a human-centered approach, is based on existing and well-validated systems engineering methodology, and includes elements from the domain of terrestrial architecture. Its main components are:

- An integrated process, Architectural Engineering, addressing design team composition and collaboration, design flow, and human-specific issues
- A concise compilation of significant design heuristics focusing on human aspects, derived from extensive literature research and organized in tabular format to provide easy access
- Custom-developed simulation software which allows for intuitive, interactive analysis of ECLSS concepts and synergistic ECLSS/AOCS approaches, as well as for user-friendly access to AOCS simulation (cf. Section 5.2)

Several interdisciplinary space station design projects successfully used the new approach, which demonstrated its application and validated its usefulness in the context of realistic design tasks.

5.2 Supporting Software

Software supporting the new design approach in areas that require numerical treatment was developed. This software, ELISSA, allows the performance of simulation and analysis of physicochemical or biological life support systems, and examination of synergistic effects among the ECLSS and the attitude and orbit control system. Application of ELISSA during the Space Station Design Workshop 2001 demonstrated the viability of this concept and its implementation.

ELISSA is based on a user-friendly graphical modeling and simulation environment. Its accuracy is sufficient for comparative studies during the conceptual design phase. It can easily be adapted to the user's needs by integrating additional component data or by performing hardware-in-the-loop simulations.

A front-end utility for the SSDW attitude and orbit control simulation tool IRIS was also conceptualized. This "MISSIONCONTROL" utility is based on the same graphical environment as ELISSA, and therefore benefits from commonality effects.

5.3 Next Steps

The new design approach presented in this report advanced the Space Station Design Workshop methodology to a truly interdisciplinary level, and it also provided an improved version of the associated ECLSS simulation software.

Subsequent work will concentrate on producing the follow-on versions of the remaining software tools, mainly the graphical configuration modeler/editor, and implementing the MISSIONCONTROL utility for the new AOCS simulation software IRIS++. Additional work is under way to look into the use of Immersive Virtual Reality tools for developing configurations and performing Human Factors-related analysis [Hale95]. These new components will again be validated by means of Space Station Design Workshops, the first of which took place in spring of 2002 at the European Space Agency's ESTEC facility [SSDW02].

Long-term projects will include implementing a radiation model for the assessment of radiation doses accumulated by the crew, expanding the AOCS software to include planetary environments other than Earth, and integrating all SSDW software under a common user interface.

Methodological enhancements will also be considered. A stochastic/design-of-experiments approach seems promising for optimizing those design elements that can be dealt with by numerical simulation (ECLSS, AOCS), especially when the simulation is too complex to perform a large number of optimization runs ([Mavris97], [Ryan96]). Additionally, a structured method for capturing the voices of the customer and the manufacturer could also benefit the design process, since the design team acts as intermediary between these two, and the outcome of the design process depends on the successful integration of that information. The "House-of-Quality" approach [Sanchez93], which has already been successfully applied to the design of the ECLSS simulation software [Osburg98], appears worthy of further investigation in this context.

5.4 Conclusion

Life on Earth has always been planet-bound, and so has our species ever since it first began millions of years ago. Now, the means for humankind to follow the "imperative of life" – to explore and expand – beyond the boundaries of our home planet are finally available. We should heed this calling and set our collective sights on the Moon, Mars and beyond. The approach and the ideas presented in this report will hopefully make a small contribution to this immense quest: taking the next steps on the stony and yet inevitable path to the stars.

> *"When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong."*
>
> *Arthur C. Clarke: First Law of Prophesy*

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Acronyms

ACRS	Advanced Carbon-Formation Reactor System
AIAA	American Institute of Aeronautics and Astronautics
ALS	Advanced Life Support
AOCS	Attitude and Orbit Control System
BLSS	Biological Life Support System
CAD	Computer-Aided Design
CDG	Concept Development Group
CM	Center of Mass
COF	Columbus Orbital Facility (of ISS)
CQ	Crew Quarters
CRV	Crew Rescue/Return Vehicle
CSI	Construction Specifications Institute
CTV	Crew Transfer Vehicle
DGLR	"Deutsche Gesellschaft für Luft- und Raumfahrt" (German Professional Aerospace Society)
ECLSS	Environmental Control and Life Support System
EF	External Facility (of a space station)
ELISSA	Environment for Life Support System Simulation and Analysis
EMSI	Experimental Campaign for the European Manned Space Infrastructure

EPS	Electrical Power System
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
EVA	Extravehicular Activity
FGB	Functional Cargo Block (of ISS)
FMARS	Flashline Mars Arctic Research Station
GISSAD	Graphical Interface for Space Station Analysis/Design
HF	Human Factors
HOAI	"Honorarordnung für Architekten und Ingenieure" (Fee Regulations for Architects and Engineers)
HTV	H-II Transfer Vehicle
IEEE	Institute of Electrical and Electronics Engineers
IOC	Initial Operational Capability
IRIS	"Interaktives Raumstationsspezifisches Interpretations-System" (Interactive Space Station-Specific Interpretation System)
IRS	"Institut für Raumfahrtsysteme" (Space Systems Institute)
ISPR	International Standard Payload Rack
ISS	International Space Station
IVA	Intra-Vehicular Activity
JEM	Japanese Experiment Module (of ISS)
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LEO	Low Earth Orbit
LMLSTP	Lunar-Mars Life Support Test Project
LVLH	Local Vertical Local Horizontal
MELISSA	Modular Environment for Linked Subsystem Simulation and Analysis
MDRS	Mars Desert Research Station

NASA	National Aeronautics and Space Administration
ORU	Orbital Replacement Unit
P/C	Physico-Chemical (Life Support)
POP	Perpendicular-to-Orbit Plane
PV	Photovoltaic (Array/Generator)
ROS	Russian Orbital Segment (of ISS)
SAE	Society of Automotive Engineers
SFINCSS	Simulated Flight of International Crew on Space Station
SM	Service Module (of ISS)
SSDW	Space Station Design Workshop
TCS	Thermal Control System
TEA	Torque Equilibrium Attitude
TIMES	Thermoelectric Integrated Membrane Evaporation System
TRIALLS	Tool for Rapid Intelligent ALS System Selection/Sizing
USOS	United States Orbital Segment (of ISS)
VR	Virtual Reality

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