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AN INTERDISCIPLINARY APPROACH TO THE CONCEPTUAL DESIGN OF INHABITED SPACE SYSTEMS

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ABSTRACT

The special skills and abilities of a human crew are the major resource of every manned spaceflight venture. Mission success therefore depends on the ability of the designers to focus both on the optimal integration of the crew into its living and working environment, i.e. the spacecraft, and on the optimal adaptation of this environment to the abilities and limitations of the crew. The research described in this paper proposes to make use of the vast experience gained in the design and building of Earth-based “living and working environments” by adding appropriate elements from the field of terrestrial architecture to the engineering process used for designing inhabited space systems. The outcome is an interdisciplinary approach that promises to result in designs supporting the desired high crew productivity. It features a straightforward, yet flexible design process, and it offers concise heuristics-based guidance regarding human-related issues such as habitability, as well as a number of practical tools to support the designers. Several examples of its application, including the recent multinational “Space Station Design Workshop” held at the European Space Agency’s ESTEC facility, demonstrate the value of this interdisciplinary approach to the conceptual design of inhabited space systems.

INTRODUCTION

Designing systems for manned long-term space missions (Project phase 0/A) poses significant challenges to the traditional design approach used for robotic or short-term missions. Success of planned expeditions to Mars and beyond depends on the design team developing a concept that maximizes crew productivity, minimizes cost and risk, and takes into account a large number of technological, psychological, and political boundary conditions.

The interdisciplinary approach presented in this paper shows one possible way to solve this conceptual design problem. It emphasizes integration of the human crew into a space system, i.e. treatment of human-rated space structures not as “machinery with attached crew”, but primarily as habitats. This is based on the assumption that crew productivity and efficiency – and thus mission success – are increased by providing a well-adapted environment.

The new approach is based on a validated engineering methodology for the conceptual design of space stations, including associated software. However, this methodology did not sufficiently address the special requirements imposed by the presence of a crew. Therefore it has been expanded by adding relevant heuristics, and by incorporating elements from terrestrial architectural practice, as this field also deals with designing living and working environments for human inhabitants, and therefore provides appropriate some design tools.

Furthermore, software for the interactive, intuitive simulation and analysis of the life support system was developed, enabling an early design of this crucial component of every human-rated space system and its integration into the overall system, allowing for the use of synergistic linkages with other subsystems where appropriate.

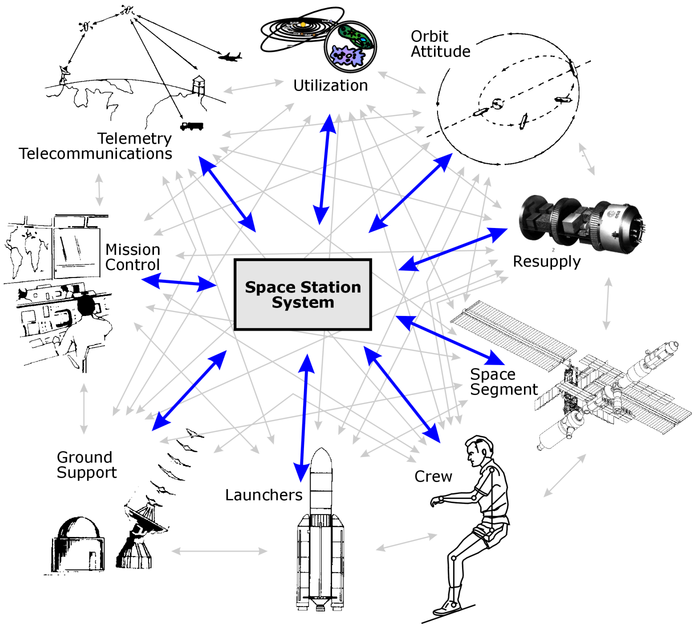

Figure 1: Space Station system elements and their interrelations[10]

The next section of the paper presents some background and rationale for emphasizing the integration of the crew in order to maximize productivity and mission success. Subsequently, the individual contributors from the areas of engineering and architecture are presented before the new interdisciplinary approach is introduced. Its application to actual design problems is then documented. Conclusions and a list of references are given at the end of the paper.

BACKGROUND

Prior to the start of a space project, the motivation behind it should be made clear, as this will have a strong influence on the course of the project. For manned space missions in particular, the multitude of possible reasons can be organized into two categories.

On one hand is the utilitarian rationale, e.g. pointing out the advantages that high-technology industry can receive from working on manned space missions; or, referring to potential profits that might be derived from spaceflight[1].

The second category does not aim at economic results, but rather at socio-cultural aspects[2]. Manned space exploration satisfies humankind's inherent urge to expand its knowledge and the boundaries of civilization[3,4], and fosters manifold positive interactions with cultural and political issues on Earth[5]. Manned spaceflight also provides a chance of preventing global-scale threats (e.g. collisions of celestial objects with Earth), or at least to mitigate the consequences of such events[6].

However, the majority of design drivers can be found on the programmatic and technical side of a project. Due to the cost, complexity and long schedules of manned spaceflight missions, additional factors come into play that need to be considered as early as possible, i.e. during the conceptual design phase.

As demonstrated by the current schedule difficulties of the International Space Station (ISS) project and the project history of its predecessor, Space Station Freedom, success or failure of complex technological projects often depends not on the engineering abilities of the design team, but on changing political boundary conditions[7]. Therefore, the system elements of manned spaceflight projects not only comprise flight hardware, technology, crew selection and training, and direct operational aspects, but also boundary conditions like political factors, cultural and motivational aspects, etc. These elements, as well as the technical subsystems of a planned space station, are tightly linked to each other (Figure 1), leading to a "wicked" planning problem[8]. To obtain the best possible overall solution, an iterative, cooperation-oriented approach seems promising.

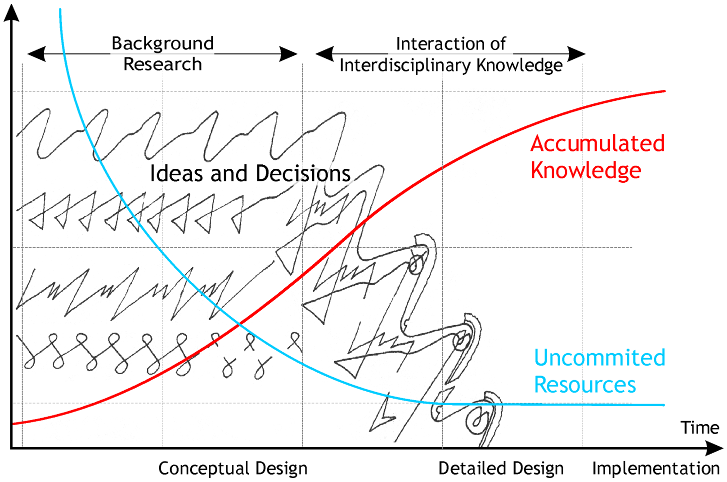

Figure 2: Adverse relationship between knowledge, design integration and committed cost[25]

CONTRIBUTIONS

Integrating technological boundary conditions, however, is the prerequisite for successful human-centered design. The new approach described in this paper is therefore based on an engineering methodology that was specifically developed for the conceptual design of space stations[9].

In the following, this engineering methodology as well as relevant elements from terrestrial architecture that were added to it will be introduced. Furthermore, the issue of human-related know-how will be addressed, since it is significant during the conceptual design phase of inhabited space systems.

CONCEPTUAL DESIGN METHODOLOGY IN ENGINEERING

The designer of complex space systems is confronted with a set of design problems that stem in part from the aforementioned “wickedness” of such problems, and in part from the special conditions imposed by the space environment. These are[10,11]:

- “Fuzzy” task
- Strong interactions between system components
- Adverse relationship between information available and consequences of decisions based on that information (Figure 2)
- Extreme environmental loads
- Minimizing mass
- Limited maintenance access

To support a design team in dealing with those challenges, a methodology for the system design of space stations has been developed at the Space Systems Institute which is based on a quasi-linear, iterative design process and the use of supporting, custom-developed software tools (cf. Figure 3)[9,12,13]. This methodology, named “Space Station Design Workshop” (SSDW), specifically addresses the following elements:

- Estimation of attitude and orbit stability (AOCS)
- Conceptualization of life support systems (ECLSS)
- Design of the Power and Thermal Systems (EPS/TCS)
- Determination of resupply requirements
- Calculation of microgravity quality
- Estimation of synergistic links among subsystems
- Aspects of launch, assembly and utilization

This methodology enables a design team of engineers (or graduate engineering students) to perform the conceptual design of a space station within a week. It has been demonstrated by the successful “Space Station Design Workshops” that have been held in recent years at the Space Systems Institute[14].

THE HUMAN SYSTEM ELEMENT

Roald Amundsen, one of the most experienced explorers of the Arctic and Antarctica in the early

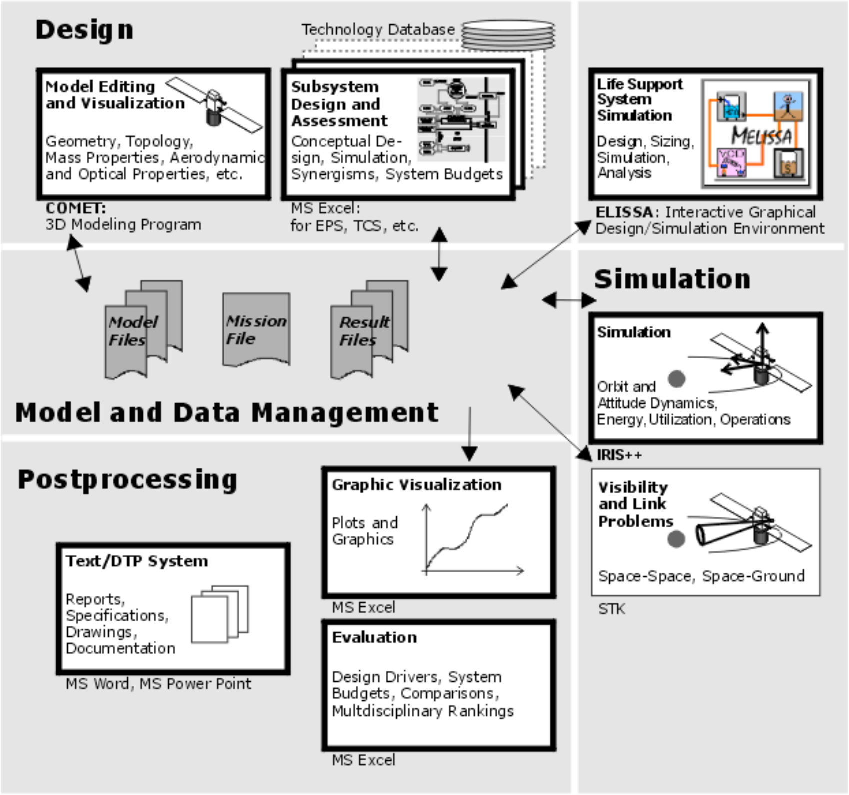

Figure 3: Space Station Design Workshop Tools[14]

20th century, noted that “the human factor is three quarters of every expedition[15]”. This holds true for long-duration space missions, where “the human system emerges as the primary risk to mission success[16]” – but also as the largest potential contributor to this success. Knowledge of this “human factor”, i.e. the of the crew and its potential as well as its limitations, is a key part of designing an inhabited space system.

The new design approach described in this paper, which resulted from superimposing methods of engineering and architecture, emphasizes the integration of knowledge accumulated in the areas of Human Factors, habitability, crew psychology and habitat design. These derive from three sources: direct experience gained from space missions (e.g. on Mir, Skylab or ISS), analog situations on Earth (e.g. Antarctic expeditions or planetary station simulators like the Mars Desert Research Station [MDRS][17]), and experimental and theoretical studies.

The results document the strong correlation between environmental conditions such as habitability and crew efficiency (and thus mission success). They also show that overall habitability not only depends on the ergonomic design of individual equipment, but also on higher-level factors, which necessitate designing the environment as a whole with a focus on the human crew.

CONCEPTUAL DESIGN APPROACH IN ARCHITECTURE

Adding select elements from the practice of terrestrial architects to the traditional engineering-centered methodology described above promises to result in an improved design process and thus in an improved outcome[18,19]. Rechtin states in this context[20]:

> *“Architecting, the planning and building of structures, is as old as human societies 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”*

By integrating suitable elements taken from architectural practice, a truly human-centered approach to the conceptual design of inhabited space systems can be implemented: on one hand, by emphasizing the role of the architect in the design process, as explained in the next paragraph; on the other hand, by using relevant

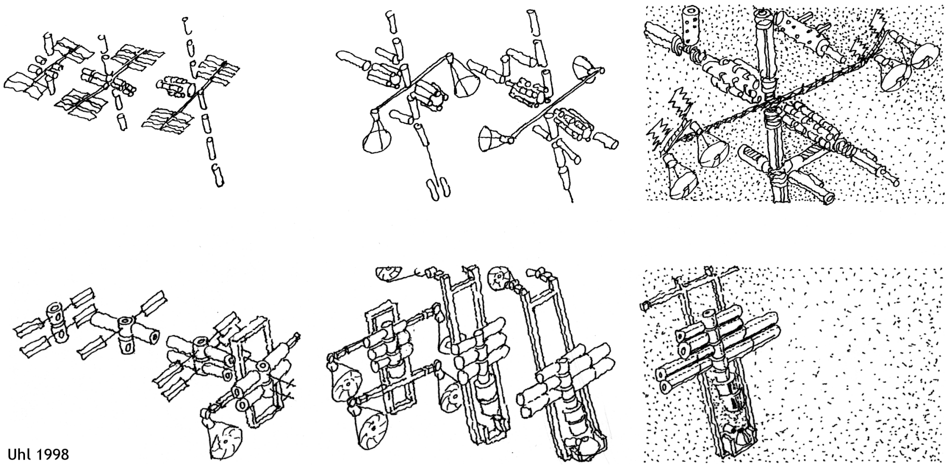

Figure 4: Development/documentation of space station assembly phase variants[21]

the other hand, by using relevant portions of the architectural toolkit.

Role of the Architect

The architect accompanies the system under design during its life cycle, from conceptualization to detailed design and construction to use. He or she strives to *“reduc[e] complexity and selec[t] workability[20]”*, and supervises the work of detailed designers who are tasked with the implementation of the finally selected feasible design. Throughout the process, he or she maintains a holistic model of the object under design[18]. Preservation of the original intent of the conceptual designers serves as a safeguard against requirements creep and increases consistency and clarity of the design.

NASA space architect Rod Jones, writing about ISS assembly missions, describes the architect’s role such[22]:

> *“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 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[23]:

> *“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 not be ignorant of medicine, should 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.

Architectural Tools

Terrestrial architectural practice also provides numerous useful techniques that have been integrated into the new interdisciplinary approach. These are[24]:

- Thorough processing of *background knowledge* to jump-start the design process
- Use of *hand sketches* to enhance design team creativity and communication

- Early detail-designing of *key details* to assure overall design feasibility
- Deliberate development of design *alternatives* and their variants to explore all of the design space
- *Organizing the creativity* of the design team to make the design process more efficient
- Using top-level *design principles* to assure that primary objectives are met
- Helping designers understand the design problem and its possible solutions through *exploration-by-design*

NEW INTERDISCIPLINARY APPROACH

For the new interdisciplinary approach, the process elements presented in the preceding section were transformed into concrete rules for the design team covering the areas of design process, design knowledge, and software. Below, the most important components will be mentioned[24].

INTEGRATED PROCESS

The design process is summarized in Table 1. It follows that of traditional engineering methodology, but allows for flexibility in permitting temporary "jumping ahead" or reiterating if it benefits the creative process or the understanding of the design problem. Additionally, the important steps of design process preparation and design result documentation are emphasized. Workflow is also guided by the following principles:

- All members of the design team see themselves as cooperation-oriented experts in their respective fields, instead of as isolated subsystem specialists. They know about creativity-enhancing tools and develop ideas based on interdisciplinary exchanges.
- The early phase of the design process (analysis of the task, compiling and understanding relevant background information, developing alternatives) is crucial and therefore should extend far into the design process.

Table 1: Design Process Flow

Step	Details
Prepare Design Process	1. Assemble design team 2. Inform team on design task, process and tools 3. Perform thorough background research
Define Objectives	4. Develop broad objectives 5. Develop a preliminary list of requirements and constraints
Characterize the System	6. Develop alternative system concepts 7. Characterize system elements
Evaluate the System	8. Prepare system budgets 9. Evaluate mission utility 10. Select system baseline
Verify Requirements	11. Refine technical requirements 12. Allocate requirements to system elements
Document	13. Document baseline design 14. Document alternative designs and design process

- 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.
- 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.
- 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.

INTEGRATED KNOWLEDGE

The crew is not treated as one 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 are understood and adhered to. Such heuristics are provided as part of the interdisciplinary approach described in this paper. They were derived from evaluating hundreds of literature sources and compiling the most relevant heuristics in an easily accessible tabular format. These tables cover the topics "Programmatic Issues", "Space Segment Configurations", "General Habitability", "Crew Issues", "Life Support", "Medical Issues", and "Operational Aspects". To facilitate trade-offs between conflicting heuristics, their relative importance is stated as well, with (A) indicating highest priority and (C) lowest. Table 2 gives an impression of the content and structure of this valuable resource.

INTEGRATED SOFTWARE

Numeric simulations are required for the conceptual design of the Environmental Control and Life Support System (ECLSS) – a key part of every manned space system – to assess its stationary and dynamic behavior as early as possible during the design process. For this purpose, the new approach described in this paper provides custom-developed simulation software named ELISSA ("Environment for Life Support System Simulation and Analysis"). The software contains several predefined component libraries for the ECLSS and related subsystems (AOCS, EPS), enabling the user to efficiently model and simulate proposed life support systems in an intuitive, graphical environment.

Figure 5 demonstrates how a system model can be built from such a library using simple drag-and-drop. Table 3 lists the various libraries and the components contained in them. The software is documented in a comprehensive manual[31].

Table 2: Heuristics of General Habitability (Selection)

Aspect	**Design Rule**	**Source**
General Issues	(A) Habitability requirements increase with mission duration, risk, degrees of isolation and confinement	26, 27, 28
	(A) Adhere to local vertical in the interior design of each module; try to aim for common vertical in all modules	28
	(B) Crucial "everyday" issues are stowage, food, acoustics, waste management, inventory system and hygiene	29
Zoning and Privacy	(A) Provide for separation of functions (B) Cluster and isolate noisy equipment, locate far from habitation zone (B) Provide for zoning variability and on-orbit reconfigurability to give crew sense of control over their environment	28
Spaciousness	(B) Provide enough space to keep equipment that is in regular use (exercise, wardroom table, etc.) deployed	28
	(B) 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 (avg. 4 m^3).	15, 30

APPLICATIONS OF NEW APPROACH

The interdisciplinary approach described in this paper has been successfully applied to several realistic design tasks. The first project dealt with conceptually designing a space station by small teams of graduate students of Aerospace Engineering and Architecture during the course of several Masters' theses[32,33]. Subsequently, a one-week, international, interdisciplinary "Space Station Design Workshop" (SSDW) with larger, competing design teams took place in 2001, also relying on the new approach and the associated tools[24]. The most recent SSDW took place in February 2002. This workshop will now be described in more detail, to give an impression of the capabilities of the interdisciplinary approach.

SSDW 2002

Prompted by the demonstrated success of the SSDW team in educating students and young professionals in space systems engineering, the European Space Agency (ESA) hosted the "Space Station Design Workshop 2002" at its European Space Technology and Research Centre (ESTEC), in February 2002. The event was supported by ESA's Directorate of Manned Spaceflight and Microgravity, as well as by ESA's Education Office and ESTEC's Conceptual Design Facility.

This SSDW gave 30 graduate students of Aerospace Engineering and related fields from 12 European nations - selected from over 180 applicants - a unique opportunity to work on a realistic, relevant space station-related design task chosen by the Directorate of Manned Spaceflight and Microgravity. They gained invaluable first-hand experience with the conceptual design process and its associated activities in a competitive, multinational, interactive, team-centered environment. A public presentation of the design results and their evaluation in ESTEC's ISS User Centre facility concluded this workshop. The SSDW 2002 also generated widespread public and media interest, thus furthering the cause of manned spaceflight.

Table 3: Provided ELISSA Components

Library	Components (selection)
ECLSS	*Air loop (physico-chemical):* advanced carbon-formation reactor; air analyzer; condensing heat exchanger; four-bed molecular sieve; oxygen regulator; Sabatier reactor; trace contaminant control *Water loop (physico-chemical):* multi-filtration; reverse osmosis; static feed water electrolysis; vapor compressed distillation *Biological components:* aerobic slurry bioreactor; biomass production chamber; immobilized cell bioreactor; packed bed bioreactor; plant growth tray; tanks *Other components:* crew; food storage; tanks; vent
AOCS	AOCS control unit, control momentum gyros; propellant tank, various types of chemical and electrical thrusters
EPS	Power storage; generic power supply; solar array with eclipse simulation

The task for this workshop was very realistic: the client had asked the participants to develop better alternatives to the currently envisioned "US Core Complete" configuration for the International Space Station. The primary objective of this conceptual space station redesign was to reduce the cost of final manufacturing, of assembly, and of operations, while still providing utilization opportunities similar to the original "ISS Assembly Complete" baseline. In particular, the space station should:

- Accommodate a permanent crew of six astronauts
- Facilitate microgravity research and Earth observation, and provide commercial and outreach activities
- Support long-term preparations for mankind's next steps in space, human expeditions to the Moon and Mars

Most of the redesign should be implemented within a few years to support early research and utilization activities. However, the redesign should also address mid- to long-term enhancements of ISS.

The workshop results are documented in the Final Report[34] and on the workshop website[14]. They include station configuration (cf. Figure 6), interior layout and zoning, simulation results of the Attitude and Orbit Control System, the Power Supply System, and the ECLSS.

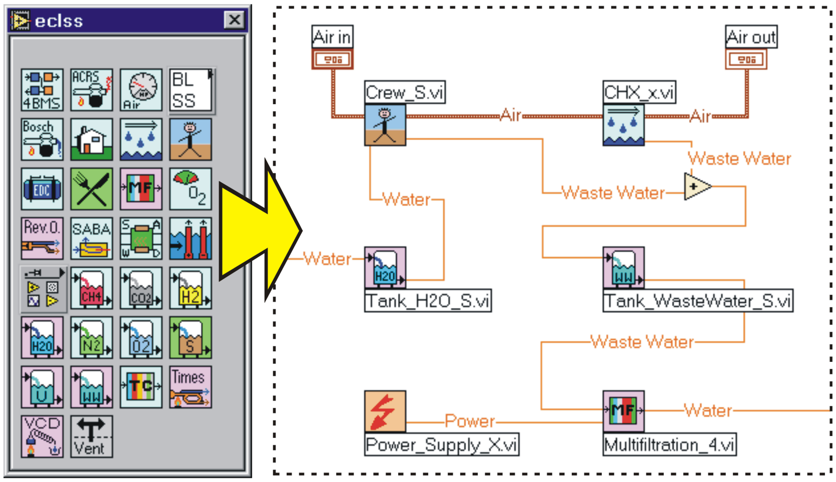

Figure 5: From ELISSA component library to graphical ECLSS model

Participant feedback indicated a high degree of satisfaction with the workshop methodology and tools. Client response to the designs produced by the workshop participants was equally favorable.

CONCLUSIONS

An interdisciplinary approach to the conceptual design of inhabited space systems has been developed. It is adapted to the special conditions imposed by manned long-term space missions, and it has been successfully applied to several realistic conceptual design tasks. The new approach is based on three main elements: validated systems engineering methodology, compiled knowledge relating to the particular needs and capabilities of humans in space, and contributions taken from terrestrial architectural practice. It is complemented by software specifically designed for simulating life support system concepts during the early phases of the design process.

Future enhancements will include the integration of all software under one interface, inclusion of robust design methodology, and implementation of Virtual Reality techniques for visualizing and evaluating proposed configurations.

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Last but not least, the author would also like to thank the SSDW team and all the graduate students who participated with great dedication in the design projects and workshops mentioned in this paper.

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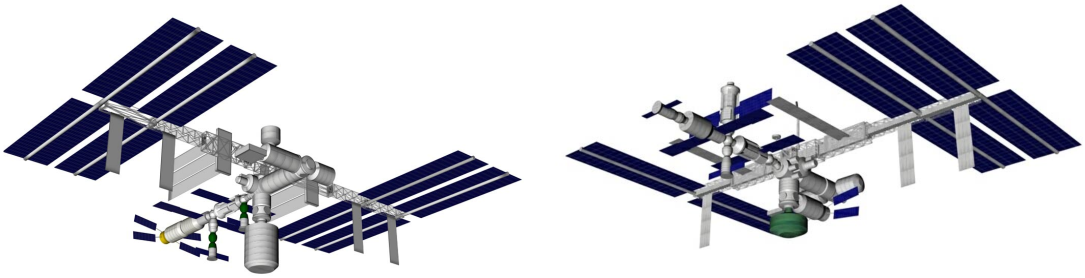

Figure 6: SSDW 2002 Design Results[34]: Space Station Configurations “Blue” (left) and “Green”

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ACRONYMS

AOCS	Attitude and Orbit Control System
ECLSS	Environmental Control and Life Support System
ELISSA	Environment for Life Support Systems Simulation and Analysis
EPS	Electrical Power Supply System
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
ISS	International Space Station
MDRS	Mars Desert Research Station
NASA	National Aeronautics and Space Administration
SSDW	Space Station Design Workshop
TCS	Thermal Control System