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From Space System Engineering to Earth System Engineering

A new method for developing technologies being compatible with society, ecology and economy

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ABSTRACT:
No other field of science has influenced imagination and vision more than the research and outcomes related to space exploration, either it is in terms of science fact, or science fiction. Innovative hardware components, computational technologies, telemetry concepts, highly insulating components, composite materials, lightweight construction methods, lightweight robots, water treatment systems, the extensive use of solar energy and new approaches to artificial intelligence are just a few well known technologies which have been first applied in space projects, and then accelerating in some cases, or even revolutionizing the developments of applications on earth. In this paper we give an overview of individual technologies and complex and integrating overall systems that had been developed for space system engineering and space missions. Strategies form both research fields are now becoming potentially interesting for modifying and maintaining resource efficient life on earth. Furthermore, we examine today's application scope of selected space concepts and space technologies and show their transformability to earth built environment permeated by emerging technologies and challenged by achieving more sustainability.

Conference Topic: The Earth/Desert/Green and Sustainable Buildings.
Keywords: Space Technology, Technology Transfer, Sustainability, Systems Engineering, Resource Management.

1. INTRODUCTION/ BACKGROUND

No other field of science has influenced imagination and vision more than the research and outcomes related to space exploration, either it is in terms of science fact, or science fiction. Innovative hardware components, computational technologies, telemetry concepts, highly insulating components, composite materials, lightweight construction methods, lightweight robots, water treatment systems, the extensive use of solar energy and new approaches to artificial intelligence are just a few well known technologies which have been first applied in space projects, and then accelerating in some cases, or even revolutionizing the developments of applications on earth. Especially in building and construction technology, which consumes about 40% of global raw materials for creating, running and maintaining our built environment and accounts for 30-40 % of the total primary energy used, a new attitude is needed. In space visions and space science, either it is in Cole's (Cole & Cox, 1964) space island visions, Gerard O'Neill's colonies (O'Neil, 1976), space inspired biosphere projects, or in existing space shuttles or space stations, the application of technologies and strategies which exponentiate the efficiency of resources and energy have been considered to be a standard. Now almost 30 years later, further, concepts of artificial intelligence (McCandless et al., 2006) or immobile robots (Roush, 2003) applied in space missions, space ships and space stations might help us to find control concepts for our increasingly intelligent buildings (Bock & Linner, 2009). Learning from space and extra terrestrial research gives incentives to tackle the upcoming challenges on earth by making use of innovative and advanced technologies. All in all, learning from space could be extremely useful to create advanced building and construction technologies for future earth environments, for regions of extreme climate, as well as for ordinary building areas. The paper outlines today's application scope of selected space concepts and space technologies and examines their transformability to earth built environment permeated by emerging technologies and challenged by achieving more sustainability.

2. MANKIND GOES INTO SPACE: WHAT WOULD HAPPEN?

Several times in history, space technologies have been activated for earth applications, especially in terms of sustainability and resource efficiency. The challenging environmental circumstances which have to be faced in earth orbit, or on other planets surfaces required an efficient, safe and long time lasting technology. Whereas on earth the illusion of unlimited resources and the comparably low costs of less advanced systems still hampers the implementation of high tech solutions on a larger scale. Nowadays, subsystems for harvesting energy, air condition, insulation, have reached a comparably high standard, yet the problem of how to coordinate theses systems and their requirements efficiently within the entire project, remains. As a result of this problem, it is not the lack of appropriate systems, principles and components, that causes problems, it is the approach of how such systems complexity is identified and handled. Examining the processes of the technological developments of space technologies at first glance, the components and products are identified as being characteristic. At second glance it is less the technology itself, it is the way of how problems are identified and how systems for their solution are designed, by always keeping the entire processes and requirements, as well as the single parts and components, in mind. If, from one day to another, we had to leave our planet due to a catastrophic climate shift, or an unexpected impact of a meteorite, what would take along with us? Would it be lots of resources of our planet surface, as gasoline, steel, aluminum, wood, food, water, oxygen? Considering that we had the technology to enable a comparably small diaspora from planet earth, would these things be decisive for the survival on a long trip through space? It is clear that we have to speak in terms of at least several years of travelling time for such a project. So, how long our spared resources would be sufficient to sustain live in the spaceship? Or wouldn't it be much more functional to take along devices, which enable the processing of mission critical resources out of space materials, and technologies which enable the reuse of air, water, or even food, and which enable the transformation of solar power for various tasks (Fig.1)? Taking into account this kind of strategy, necessary resources could be gained on the travel itself, so the total amount of materials to be taken along would be reduced to a minimum. Sustaining live on a travel through space is less a question of the total amount of consumable resources, as these amounts would be quite huge consumed after a certain period. It is more a question of the technologies which would be installed. These technologies and their interactions could be called sustainable. The reader may ask why the authors have chosen such an extreme example. But is it really extreme? Just increase the size of the spaceship and the passengers, including the available resources. As Buckminster Fuller described it within his famous book "Operating Manual for Spaceship Earth" (Fuller, 1969), our example is fully scalable in terms of time, resources, and technologies to be applied for its use. So, sustainability of technological systems can easily be coined out by the analysis of current state of the art space technologies. It may be an expansion of this approach that most of the mission critical technologies applied in space could be entirely activated for gaining sustainability for most of the systems applied on the surface of our planet earth.

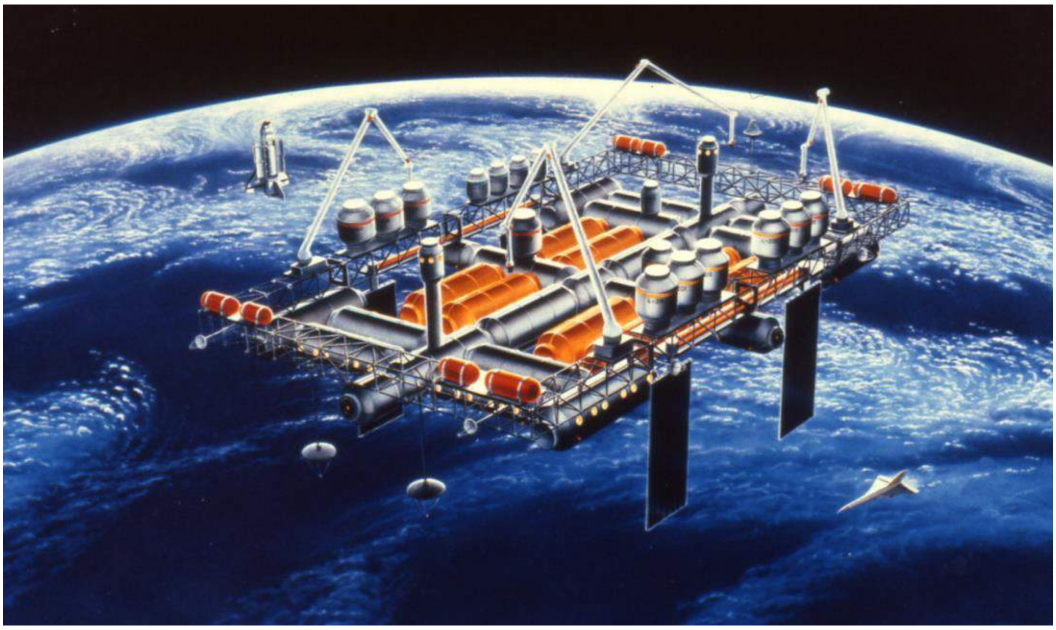

Fig. 1: the automated deployment of near earth space station (NASA)

3. FRONTIER ENGINEERING AND MANAGEMENT

In this chapter give we an overview of individual technologies (3.1) and complex and integrating overall systems (3.2) that had been developed for space system engineering and space missions. Strategies form both research fields are now becoming potentially interesting for modifying and maintaining resource efficient life on earth.

3.1. Examples for Space-Earth transfer of simple stand-alone applications

In order to start with more simple and clearly focused technologies, we first outline several examples that explain the space-earth transfer of simple stand-alone applications. In section 3.2 we will then explain complex systems which are based on networks or ecologies of individual technologies.

3.1.2 Lightweight Robots

When going to space, robots are indispensable. They are needed in various application scenarios form research and experiments to construction and personal assistance. Yet in spaceflight every kilogram matters in terms of fuel consumption and fuel cost. Additionally robots in space have to work in the direct operating range of human beings without posing a severe safety risk. The result of these challenges is a completely new concept for ultra light, sensitive and cooperative robotics: lightweight robots. A standard industrial robot for medium loads weights about 700 kg and is able to move loads of about 30 to 60 kg depending on the speed with which it is operated. Lightweight robots (LWR) on the contrary have a load to weight ratio of 1:2 (Mitsubishi PA10), 1:1 (Kuka LWR) or even better. The most advanced example states the Kuka LWR (DLR, 2010), which had been developed by the German aerospace center for space exploration missions (DLR) and which had later been sold to Kuka Robotics Company. Kuka has since then developed further the concept and has recently commercialized the concept for industrial and domestic service tasks. The robot is lightweight, made from carbon fiber, contains force-torque sensors in all joints and can work in cooperation with humans without regular safety restrictions. Additionally it can be programmed intuitively and in an interactive manner by the so called “teaching” process. Lightweight Robots are supposed to play a vital role in the upcoming mass customizing industry. Mass Customization is accounted as being *the* future concept for our industry as it allows the production of individual goods, components and products on demand thus eliminating a tremendous amount of stock, resources input and waste. The strategy is based on flexible production systems and a functioning cooperation of human beings and production robots in advanced production scenarios.

3.1.2 Advanced Control Systems: Immobile Robots

To control the complex systems, since spacecrafts are being extensively equipped with Microsystems technology, new control concepts had to be developed (Fig.2). Today NASA considers space vehicles and space stations equipped with various networked subsystems and intuitive and multimodal control interfaces as “ImmoBots”. A common characteristic of “ImmoBots” is that they are able to control their internal subsystems autonomously for achieving certain goals, thus reducing mental stress of human beings interacting with them. Environments enriched with “sensor” and “actor” systems given certain autonomy and able to control their complex internal functions are considered as “ImmoBots”: Immobile Robots (Roush, 2003). In general, those systems can cover networked building energy systems as well as power grids or reconfigurable traffic systems. “ImmoBots” are able to coordinate a multitude of internal subsystems with a model based programming approach. In the future it is expected that complex and multilayered cities equipped with smart subsystems, their infrastructures, traffic systems, their power grids and their resource distribution and waste collection systems can be operated automated and with the higher level goal of optimized resource consumption by Immobile Robots (Roush, 2003).

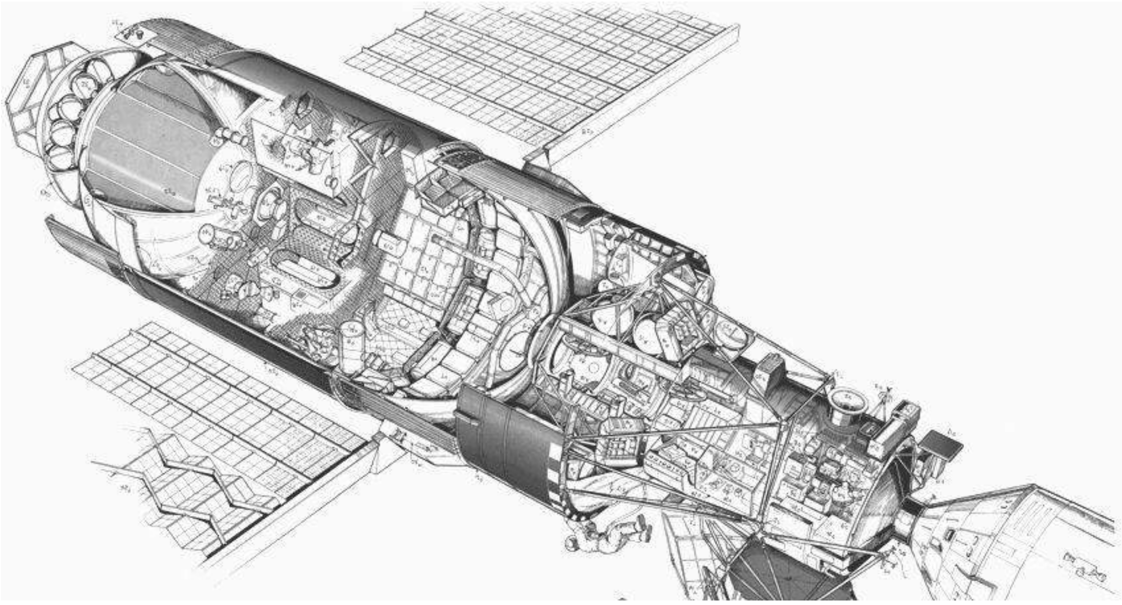

Fig. 2: complex systems and interior of Skylab (NASA, Picture from Flightglobal)

3.1.3 Fuel Cells

With the beginning of civil space missions, an increasing complexity of technological systems and energy consumption required a sufficient safe and durable light weight energy source. Moreover a long term durability, small size and performance were meant to be some of the main characteristics of such a system. “Besides the functionality in total absence of gravity, the size of the asset played an important role, as the capsule supplied only little space for its installation” (Schmidt, 2010). The early predecessors of current space vehicle were still equipped with batteries to supply all on board systems. But soon the increasing energy consumption of more advanced systems made the use of batteries an inapropriate solution. Especially within the research for long term manned spaceflights the lack of a sufficient energy source became obedient. With the introduction of fuel cell technology as a space technology many characteristic of this invention could be used for the entire systems improvement. The fuel cell could activate the rocket engines main resources: Oxygen and Hydrogen. Compared to the total consumption of energy for the propulsion, the fuel cells needed only small amounts of these resources. Besides this main fact, there were also other advantages: “The possibility to produce drinkable water for the crew, and the circumstance that the cost for the necessary fuel (hydrogen) was considerably few due to the huge amounts required for the propulsion of the rocket, contributed to confirmation of NASA, to continue with the use of fuel cells within the Apollo Program.” (Schmidt, 2010) Moreover the conventionally disturbing characteristics of waste heat production could be positively activated within the entire systems structure: “The surplus warmth was also used for the heating of the module, as well as for the heating of the cooled Hydrogen (-173K) in advance of its entering the fuel cell itself.” (Schmidt, 2010) The example of the development of fuel cells is a prototype for a project derived from a strict set of requirements. The characteristics of the used subsystems have been fitting perfectly to the characteristics of the entire system and technical structure. As a result, additional functionalities such as clean water production, and heating had been enabled for the use within the entire system. Here, the concept of solving technical problems was to identify a certain requirement or set of requirements, and to develop a highly specific technical system to perform the needed characteristics in order to create functionality for the entire system. The new system was totally different from any other approach to generate energy in a spacecraft, yet it fit very well into the already existing concepts and structures, and even created unplanned additional values.

3.1.4 Electrical Vehicles

Already in 1881- 5 years before the official invention of the car through Carl Benz- F. Gustave from France presented an electric three wheeler at an exhibition in Paris. Although the more fuel consuming concept of the combustion engine has been commercialized in a big scale then, there were many interesting attempts promoting electrical vehicles up to now. Further, indeed, concepts as Naro (Narrow City Vehicle; Narrow, 2010) and CLEVER (Compact Low Emission Vehicle for Urban Transport; BMW, 2010) which are brought up by major car companies today and which are supposed to be compact, light weight, extremely flexible and resource saving are not new. The Lunar Roving Vehicle (LRV, 2010) of the Apollo 15 Mission, the first vehicle for lunar exploration, anticipated and pioneered today's concepts already 50 years before: its development began in 1969. The LRV finally only weighted 210kg and could carry up to 490 kg, it was powered by 4 electric motors integrated into the wheel and equipped with advance navigation and life support systems.

3.1.4 Environmental Control and Life Support Systems

As Architects and Designers become concerned with advanced building technology and "home care" strategies, the focus shifts towards the creation of multidimensional environments supporting elderly people, patients or other persons, in need to measure and/or maintain their daily activity, mobility, cognition, emotional, physiological and psychological state, nutrition and medical condition (Bock & Linner, 2009). For today's researches our future built environment house will be more like a "supportive machine" connecting to the inhabitant through modular mobile devices and incorporating and controlling various assistive subsystems and multiple senor networks to enhance the quality of life for inhabitants. Already several decades before today's home care attempts came up, human space flight has provoked the development of so called Environmental Control and Life Support Systems (NASA-1, 2010). ECLSS continuously measure "health" parameter as blood pressure, breathing and heart rate of the space vehicle's crew and adjust in real time life relevant parameters as temperature, cabin pressure and air oxygen rate. ECLSS Data can be use by doctors and medical staff on ground for diagnosis and routine check. A famous ECLSS subsystem is "Life Guard" (NASA-2, 2010), an advanced wearable sensor system which had been developed in cooperation of NASA and Stanford University. Further the RCAST Group (Rcast, 2010), a joint venture between the University of Tokyo and JAXA, has to be motioned. RCAST is developing rehabilitation equipment which could be used in space and later be transferred for use in hospitals and other recreational facilities.

3.1.5 New Crew-Vehicle Interaction Systems

Due to continuous engineering advances in the decades since the Space Shuttle was developed, a multitude of new technologies have been integrated into spacecrafts making them so complex that completely new crew-vehicle interaction concepts have to be developed to ensure an efficient and safe control by human beings during space missions (McCandless et al. 2006). Similar to approaches known from "Ubiquitos Computing" and "Human Computer Interaction", NASA's Human-Systems Integration Division (HSID, 2010) tries to apply new concepts for interaction of humans and on board computer systems. Do we not have similar problems on earth, where houses, offices, hospitals and care facilities integrated with more and more smart technologies rising the question of control and interaction? It will be inevitable that concepts of cooperation with complex systems and new human-vehicle interfaces have to be developed.

3.1.6 Adaptive and Self-Repairing Systems

Highly adaptive systems are already gradually introduced in a variety of application areas. Researchers for example have recently tried to implement self-organizing and self-coordinating swarm robots as sun shading system continuously adapting to changes happening inside and outside the building. And a multitude of similar applications in the conception of high-tech facades or high-tech architecture in general can be imagined and researchers even aim to make systems more self-learning and even self-repairing. Basic principles which are used today in those research fields have been pioneered by space exploration already decades ago (Wilcox et al., 1992). As researchers developing systems e.g. for long-distance mars exploration could not predict what the exploration robots might encounter, they had to develop systems that can improvise, improve and evolve by themselves. Those concepts are extended today for use on earth for example by Cornell University's "Starfish" and "Molecubes" concepts (Lipson, 2007).

3.2. Examples for Space-Earth transfer of complex systems and strategies

In the following section we describe entire system and their necessary subsystems. Entire systems are space infrastructure and organization projects aiming both at saving and activating further resources in order to enable a resource saving and less destructive economy on earth.

3.2.1 New Site and land use concepts

The examples above have shown how a specific task or requirement was matched by the development or the improvement of an existing technology. These subsystems were designed in order to perform and interact nearly perfectly with the already planned or existing technological and human environments. But there are also possibly less prominent but highly advanced approaches towards the design of sustainable environments and technologies for the application in space. Here certain sets of problems, physical characteristics and matching technologies were put together in a way, that the entire structure and system generated unexpected advantages, outcomes and automatically problem solving habits. When NASA scientist Gerard K. O´Neill started with his week- end seminars, together with colleagues and interested students, he did not calculate with the incredible outcome of these multidisciplinary team studies (O'Neill, 1976). The main question they were trying to answer was, if it is possible to economically make use of the near earth space, and to go further than just to make use of communication satellites. The approach intended to activate raw material, as well as energetically usable resources in space for earth applications (Fig. 3). The economy in space should be designed self sufficient from a certain stage, and later on even payback and overcome the investments of necessary research and construction. The initial germ cell was designed within a background of physical circumstances near to earth, the effective gaining of raw material and energy, the activation of processes only possible in zero gravity environments, the design of self sufficient agriculture and closed loop environment design (O'Neill, 1976) (Fig. 04).

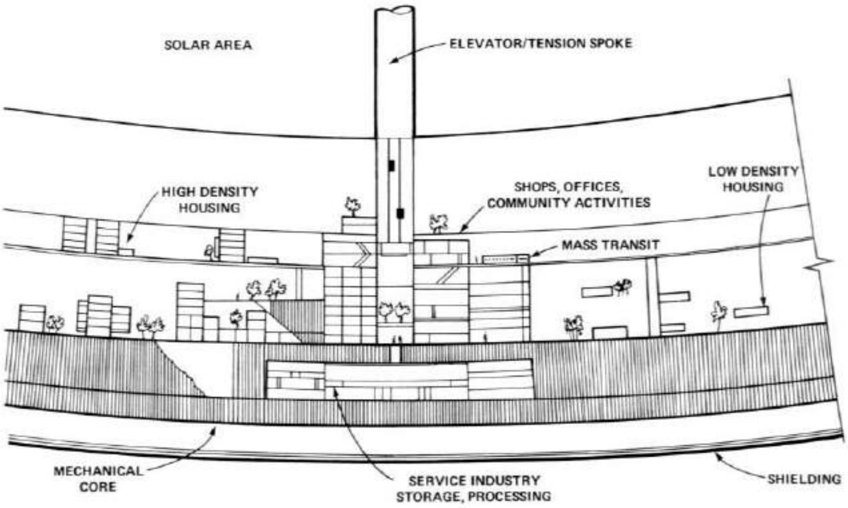

Fig.3: High Density Housing and Optimized Organization in space (O'Neil, 1976)

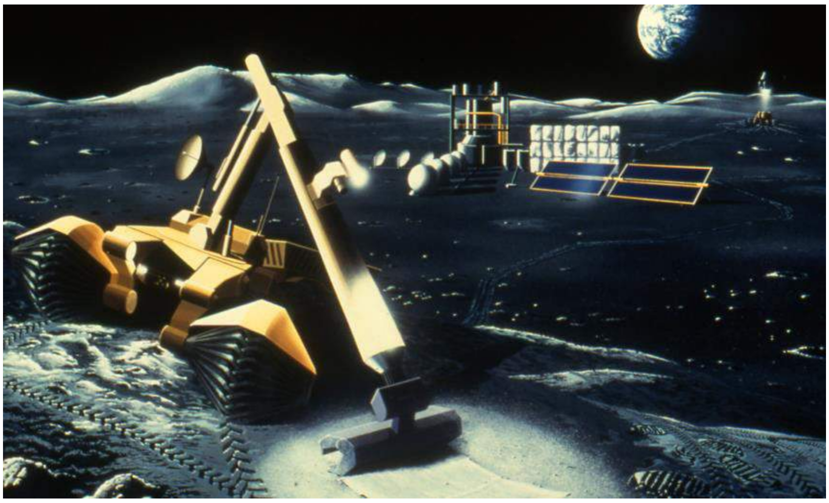

Fig. 4: gaining raw materials on the moon, (NASA)

On a first step the ideal position of a larger space station close to earth was identified. The Lagrangian area (L5) should be used as a basement for the central processing and manufacturing core. L2, L3 and L4 should be used mainly as logistical crosspoints, as well as for the assembly of further systems (Fig. 05). In this scenario, mining on the moon should supply the Lagrangian station with raw material, as the use of these materials from earth requires 20 times more energy, than the same amount from the earth satellite. The highly economically active central processing and habitat core should then be assembled and finished out of these materials.

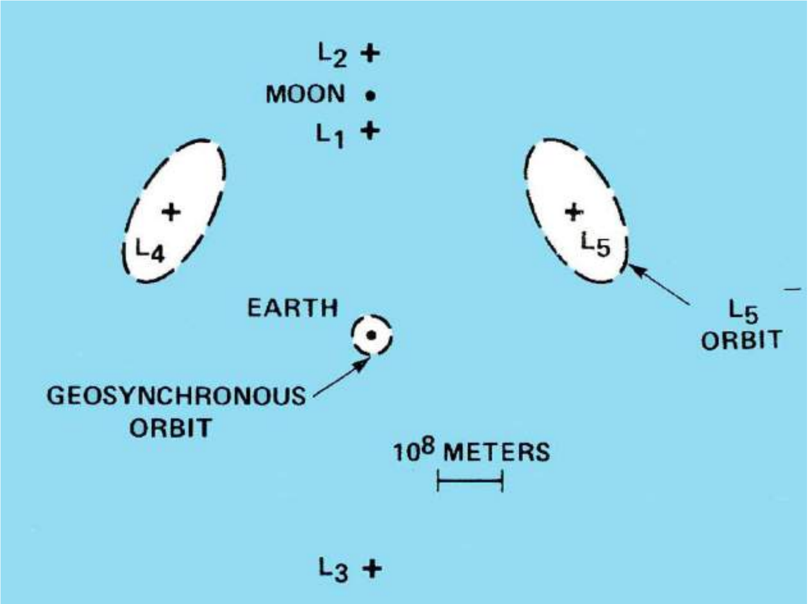

Fig. 5: Lagrangian areas between earth and moon (O`Neill, 1976)

Since the finishing of this comparably huge space station, it would take human workers and manufacturing technologies, to either build further habitats, or to supply the earth with products made in space (Fig.06). The incomes of these economic and technological systems should be used for the implementation of larger processing cores and habitats, to increase the range and the complexity of these products. The entire system and its necessary subsystems could be described as a space infrastructure project, to activate further resources and to enable a resource saving and less destructive economy on earth (Fig.07).

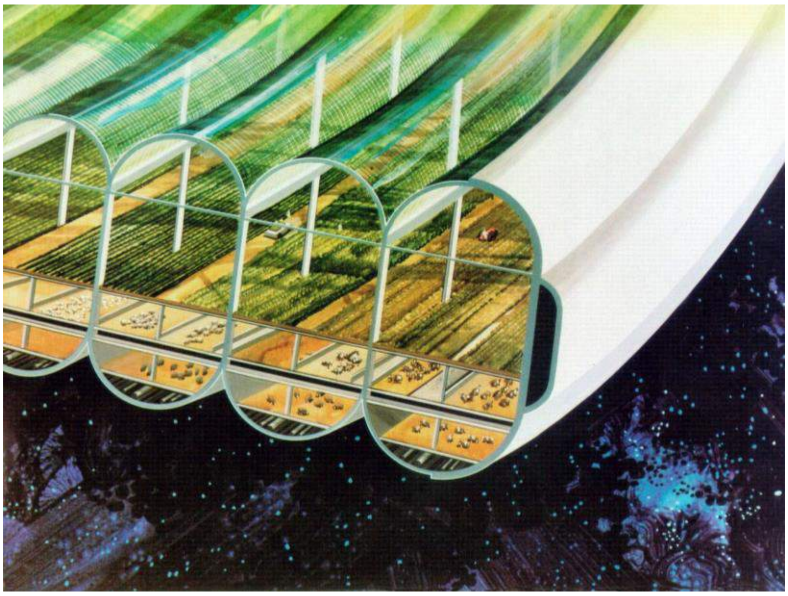

Fig. 06: Optimized and highly efficient Agriculture in Space (O`Neill, 1976)

The successful design of self sufficient agricultural systems in combination with the appropriate and reliable technologies was identified as mission critical for the execution of such plans. Therefore the biosphere one and two projects (Poynter, 2006) were initiated to find out more about closed loop biologically active systems.

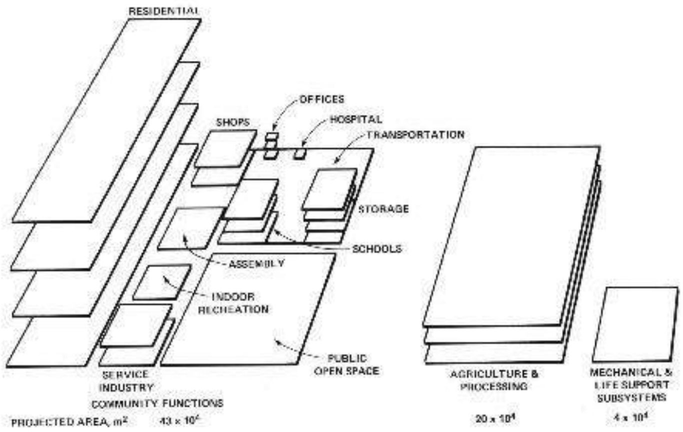

Fig. 07: Functional distribution in a space station (O`Neill, 1976)

Considering this broadly spread approach of solving problems, O`Neill and his colleagues also identified that the economic system into which these technologies and plans are embedded is decisive for the successful implementation of a totally new infrastructure.

"It has been said that new wealth requires three components: energy, materials and intelligence. … The third component is the human organization of machinery a human effort in a productive way. Productivity can be described by the ratio of output products to the input of human labor. If measured in non-monetary terms (tons per person per year), the ratio automatically takes into account the effects of inflation" (O'Neill, 1976, p. 116). Shortly after publishing the work of O´Neill`s teamstudies, Paolo Soleri anticipated the basic ideas of the technological and infrastructural dense structures that were called Islands in Space. He remarked that such structures have also advantages on earth when it comes to material effectivity, consumption of land, and energy, as well as they had advantages in social means.

3.2.3 Independent Resource Design

Another approach of combining several technologies to form a new and substantially system, which means a high grade of independently organized resource flow, is the so- called Mainboard Design (Bock et al., 2010). A physical and digitally integrating platform that combines several subsystems for water cleaning, energy supply, organizes the consumption and special requirements of each of the functional components. The mainboard is not only meant to be a physical grid to achieve operational interchangeability, is also a concept of efficient IT and software to hardware communication. The result will lead to a nearly totally resource independent device, which in an early scenario of use, could be applied after catastrophes, and later, on spread within regions with low infrastructural density to complementary supplement the existing technologies. Later on it could even be used to gain full independence of housing structures.

4. Conclusion: From Space System Engineering to Earth System Engineering

The already presented technologies and organizational approaches should give an overview of how can we be successful in our world getting smaller and smaller, with more and more constrained resources. This is vital for engineering a future anthrop. sphere in a sustainable manner. The high technological and social densities are a key for environmental sustainability. Space Laboratories as Skylab, MIR, ISS have proven that it is possible to be kept running with very few resources on board. As any sustainable system these use primary energy resources only for initializing the processes running within these structures. Whereas most of our current systems on the planet`s surface are consume the initializing resources for future technologies. These consumption chains are not closed on earth which leads to the high exploitation rate of our resources in nearly any field of technology. In space these resources are not available and lead to the design of closed loop technological organization systems. Future technological systems have to be designed in a way that the primary resources are used only as a booster for these closed loop processes. Then the already gained procedural knowledge can be activated for the design of substantially sustainable systems. The technological knowledge solely will not permit the development of such systems, as it can only be used for the incremental improvement of already existing components and subsystems. The use of closed loop resources and energy flow within all processes could then be described as sustainability, by means of socio cultural developments, as well as economic and technological improvements. Until now sustainability projects are mainly focused towards the implementation of innovations within the context of gradually improving the resource, energy, or waste reduction effectivity. This procedural approach on solving technical problems leads to a strongly increasing cost curve for its continuous improvement. “The reason for the vulnerability of technology is that adjustment mechanisms have cost. The costs of technology and the market are reckoned in resources, energy, money, labour and capital. These costs tend to rise nonlinearly as limits are approached.” “It is fairly inexpensive to remove 50% of the nitrogen oxide emissions. There is a rising but still affordable cost for removing almost 80%. But then, there is a limit, a threshold, beyond which costs of further removals rise enormously”. “In fact, growth takes an economy up a nonlinear cost curve to the point where further abatement becomes unaffordable” (Meadows & Randers, 2009). As long as the particular technology as well as the entire surroundings are not designed and adjusted with the same priority, the increasing development costs for subsystems will inevitably lead to an economic trap. It is not just a question of how to gain technological effectivity that may lead to a true sustainable overall system, it also a question of economic dynamics and of their understanding of the future system builders. Maybe these strongly increasing costs are the price for practicing ignorance for the interdependencies between economics, knowledge management, and the need for substantial technological system change on a broad basement. Moreover theses hidden costs are one important factor contributing to the economic crisis, as we possibly have reached a point where the prices for incremental improvements are too high in comparison to the possible wins. This article supports the approach of designing the systems periphery as well as the single components in order to introduce new systems that substantially may be described as being sustainable. These systems will be based much less on one specific innovation such as the combustion engine, they will base on various innovations, regionally differentiated, and properly adjusted to economic and users needs as well as to environmental circumstances.

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