BALANCE OF MATERIAL FLUXES WITHIN A CLOSED-LOOP HABITATION SYSTEM

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An effective and self-sustainable artificial habitat design is essential for human spaceflight and expansion of mankind into orbit or towards other celestial bodies. To successfully establish a future habitat, it is imperative to reach a high degree of self-reliance and sustainability. Various products like higher plants (e.g. vegetables, fruits, crops), animal husbandry (e.g. fishery, insects), fuel gases (e.g. Hydrogen, Oxygen), building materials (e.g. structural and isolation materials), but also consumables (e.g. clothes) as well as base maintaining services (e.g. water or waste recycling) and power supply will be provided and where applicable recycled in such a system.

To draft an initial system concept of a terrestrial Facility of Laboratories for Sustainable Habitation (FLaSH) a habitat design workshop has been held in DLR's Concurrent Engineering Facility (CEF) at the Institute of Space Systems. The closed-loop approach for a habitat is the most critical issue causing a complex interrelation between the overall system and components design. Therefore tracking the balance of material fluxes by the help of a material trade matrix has been one focus of the system domain during the FLaSH study. In this paper it is described how the matrix has been used to adjust material fluxes in a consistent manner by adding up the individual fluxes of each domain into a complete sum. Furthermore the process of communicating necessary design changes during the study based on the matrix like on a stock exchange floor is elaborated.

I. INTRODUCTION

Worldwide there are only a few selected closed systems for long durations that enforce research for strictly responsible handling of resources, e.g. Bios-3, CELSS, Biosphere 2, CEEF or MELiSSA [1]. As soon as we can economically handle closed cycle habitation systems, we can also sustain the "habitation system" we are living in: Earth. This correlation led to the DLR's initiative of designing a laboratory infrastructure where the technologies and lessons learnt from on-going research could be qualified and furthered in a modular way. In addition to space application, Earth driven technology shall be pushed forward by potential synergies between space and Earth needs. The title of the project as a whole and also for the facility will be "Facility of Laboratories for Sustainable Habitation (FLaSH)". The first habitat design workshop has been held in autumn 2011 at the DLR Institute of Space Systems applying the Concurrent Engineering (CE) principles [2]. The primary goal within the initiative's first step is to test different technologies that can be used in order to create nearly closed-loops within a habitat. Additionally, long term psychological investigations of the test crews shall be applied but subject to inaccuracies from actual off-world simulations as necessary to allow a flexible technology test campaign.

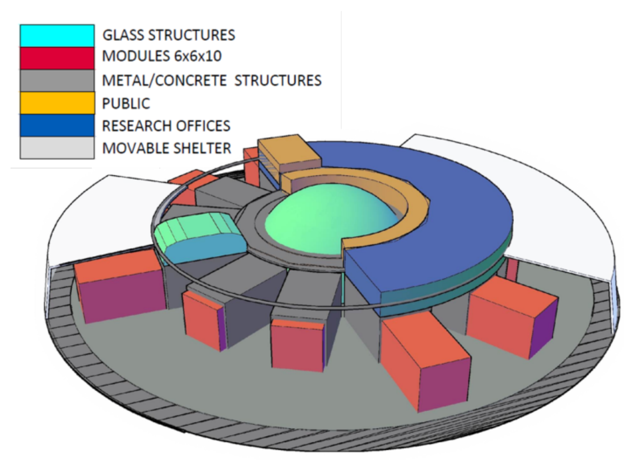

Fig. 1: Architecture's impression of FLaSH.

With study objectives and requirements described in [3] with a team of engineers, scientists and human factors the architecture's impression of FLaSH in Fig. 1 was developed. It shows twelve modules (red) surrounding an arboretum (glass hall in the centre), offices on top (blue) and public engagement areas (orange).

II. THE FACILITY OF LABORATORIES

The main focus of the CE study was the design of the needed functional units that are placed into standardized modules, i.e. Air, Water, Waste, Animal, two Greenhouse Modules, Sickbay, Workshop, ISRU, Living Module, Food Processing Facility plus one spare module. The size of each module was given by 6 m x 6 m x 10 m separated into two floors with predefined connections and interfaces to the whole facility.

The major requirement affecting the habitat configuration was the need for exchangeability and accessibility. The modules should allow for a fast and easy access and exchange of module components from the inside, as well as the exchange of complete modules from the outside (see Fig. 2).

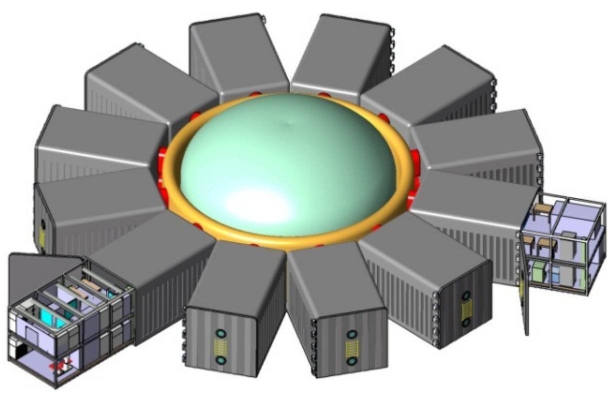

Fig. 2: FLaSH configuration showing two modules extracted.

III. DESCRIPTION OF THE TOOL

In order to lay-out and size the modules' sections, the material fluxes, each component contribute to the whole habitat system, must be known. Because of the system complexity and the interdependencies between the modules an a priory assumption for each function, e.g. amount of water regeneration, was rather difficult.

During the study preparation it became clear that there was a need for a tool that allows for balancing all important material fluxes inside the closed-loop between the modules. At the date of the study the common tool for the data exchange in use at the DLR's CE facility was Excel based, called Integrated Design Model (IDM) provided by the European Space Agency (ESA). Therein the subsystems equipment including mass, power, dimensions and temperature are the main parameters foreseen for the data exchange. In order to provide appropriate means for the habitat design we prepared our own Excel based tool.

In this Habitat Matrix, as we called it, for each module a table with four levels of detail, reflecting the taxonomy defined in Fig. 3, was developed as input interface. The window arrangement, rows and cells are protected and only specific cells can be filled with the requested information, in order to protect the layout from damage caused by the users. Herein each module expert can split its module components into different sections and subsections containing the needed equipment. As can be seen in Fig. 4 the Animal Module as an example contains e.g. one fish section with 13 fish ponds consisting of a heater, illumination, a brailer, containing 150 fishes etc., but also one breeding section with 20 small ponds, and so on.

For each equipment row input cells are foreseen for dimensions, mass and power analogue to the IDM. All values are automatically multiplied by the quantity and summed up on the next higher level. Additionally it is possible to overwrite the values on each level manually. Because of the early design stage of the habitat and the goal of building a research laboratory infrastructure, information about mass and power were only an add on.

The most important parts of the tool besides the equipment list are the input parameters and output parameters of each module. Thus analogue to the above described cells for mass, there are columns for the demand (the need, consumption or input of a process) and the output (the product or outcome of a process), which are multiplied by the quantity and summed up on the next higher level. At the end of the study there were demand fields and input fields for 24 different material fluxes, i.e. anorganic solid waste (old metal or appliances), Ar, $C_6H_{12}O_6$ (glucose), CH_4, CO, CO_2, drinking water, evaporated water, fertilizer, food, green water (rich of nitrate), grey water (from washing), H_2, liquid waste (containing faeces and toxic pollution), Mars atmosphere, Mars soil, N_2, O_2, oil/brine, organic solid waste (kitchen waste), raw materials, regolith, trace gas and yellow water (containing urine).

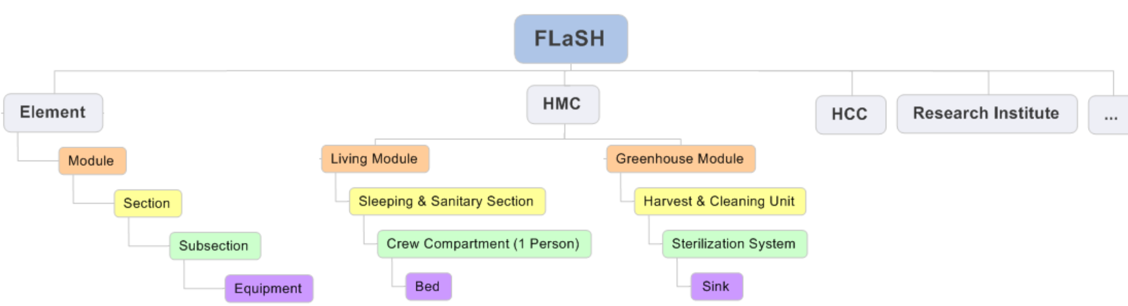

Fig. 3: Taxonomy of the four levels of detail for structuring the FLaSH components (HMC stands for Habitation Module Complex; HCC stands for Habitat Control Centre).

	Module		Section		Subsection		Equipment	drinking water demand per unit in kg/day		total drinking water demand in kg/day	
quantity		quantity		quantity		quantity		manual	auto	manual	auto
1	Animal Module								960,48		960,48
		1	Fish Section						624,00		624,00
				13	Fish Ponds				48,00		624,00
						1	Heater 500W				0,0
						1	Illumination 75W HQI				0,0
						1	Brailer				0,0
						1	Ponds 1000l	48,0			48,0
						1	Trickle-Filter with Filling				0,0
						1	Pump 1000l/h				0,0
						1	Water 1000l				0,0
						150	Fish				0,0
						1	Rescue Water Pump				0,0
		1	Breeding Section						96,00		96,00
				20	Small Ponds 100l				4,80		96,00
						1	Heater 50W				0,0
						1	Illumination 20W Neon Bulb				0,0
						1	Brailer				0,0
						1	Trickle-Filter				0,0
						1	Pump				0,0
						1	Water 100l	4,8			4,8
						100	Fish small				0,0
						1	Pond 100l				0,0
		1	Harvesting Section						0		0
				2	Harvesting Bench				0		0
						1	Brailer				0,0
						1	Knives				0,0
						1	Laboratory Table				0,0
						1	Laboratory Shelf				0,0
						2	Stainless Steel Bowls				0,0
						1	Wash-Bowl				0,0
						0,5	Push Stick				0,0
						0,5	Kill Box				0,0
		1	Anatytic and Cleaning Section						240,00		240,00
				2	Laboratory Bench				120,00		240,00
						1	Water Analytics Test Equipment				0,0
						1	Laboratory Equipment				0,0
						1	Laboratory Table				0,0
						1	Laboratory Shelf				0,0
						1	Water	120,0			120,0
						0,5	Dryer for organic Material				0,0
		1	Insect Section						0,48		0,48
				20	Cages for different insects100l				0,02		0,48
						1	Heat Foils for up to 40°C				0,0

Fig. 4: Excerpt of the Habitat Matrix's interface for the Animal Module.

One requirement for FLaSH was to accommodate six to eight permanent residents for a period of at least one year. Together with the assumption of 200 g edible fish filet per resident every day that was the starting point for the expert of the Animal Module to calculate the needed amount of fish and the surroundings [3]. Additionally e.g. insects and infrastructure for harvesting and analysis were planned to be part of the Animal Module. As can be seen in Fig. 4, its total demand of drinking water at the end of the CE study sums up to 960.48 kg per day, which must be provided by some other modules within the habitat system.

IV. THE MATERIAL TRADE MATRIX

Besides the demand of drinking water the Animal Module also has a demand of O_2, organic solid waste and glucose (both to feed the animals). On system level that is the Habitation Module Complex (HMC) the Habitat Matrix reads out the values out of all module sheets and creates an overview of the demands of all modules and all material fluxes in kg per day (Fig. 5). During the study week with growing maturity of the module's design this table filled up with more and more values. In addition to the drinking water there appear some big amounts of green water demand by the Greenhouse Module (720 kg/day) to supply the plants and grey water demand to be processed by the Water Module (554.48 kg/day). That shows that the dominant material flux within the habitat is the loop of different types of water. In Fig. 6 an output overview of all modules was generated by the Habitat Matrix. Here the systems providing e.g. the different types of water are listed. The main suppliers for drinking water are the Water Module (560.48 kg/day) and the Greenhouse Module (557.71 kg/day), for green water the Animal Module (720 kg/day) and for grey water besides others also the Animal Module (240 kg/day), the Greenhouse Module (123.81 kg/day) and the Living Module (58.72 kg/day). On the Water Module there is also a big demand and output of liquid waste documented, which is pumped internally inside the Water Module.

How the outputs and the demands fit together in the overall system is covered by the so called Material Trade Matrix as part of the Habitat Matrix (Fig. 7). There the sum of the budget of each module's material flux is being built. As soon as all material sums equal zero, the habitat loop is closed. As one main tool of the habitat design the Material Trade Matrix was discussed during the CE process with the whole team of domain experts.

Parameter Demand	Air Module	Animal Module	Food Processing Facility	Greenhouse Module	ISRU Module	Living Module	Sickbay	Waste Module	Water Module	Workshop Module
total anorganic solid waste demand in kg/day	0	0	0	0	0	0	0	1,79	0	0
total C6H12O6 demand in kg/day	0	6,45	34,84	0	0	0	0	0	0	0
total CH4 demand in kg/day	0	0	0	0	0	0	0	0	3,45	0
total CO2 demand in kg/day	60,58	0	0	16,45	0	0	0	0	0	0,01
total drinking water demand in kg/day	24,78	960,48	50	0	0	153,6	0	23	0,5	10
total Evaporated Water demand in kg/day	28,10	0	0	0	0	0	0	0	0	0
total fertilizer demand in kg/day	0	0	0	46	0	0	0	0	0	0
total food demand in kg/day	0	0	28,15	0	0	0	0	0	0	0
total green water demand in kg/day	0	0	0	720	0	0	0	0	1	0
total grey water demand in kg/day	0	0	0	0	0	0	0	0	554,48	0
total H2 demand in kg/day	0	0	0	0	1,13	0	0	0	0	0
total liquid waste demand in kg/day	0	0	0	0	0	0	0	60	2405	0
total Mars atmosphere output in kg/day	0	0	0	0	20	0	0	0	0	0
total Mars soil demand in kg/day	0	0	0	0	105	0	0	0	0	0
total O2 demand in kg/day	0	34,4	0	0	0	6,56	0	2,58	15	0,70
total organic solid waste demand in kg/day	0	92,92	0	0	0	0	0	15	0	0
total regolith demand in kg/day	0	0	0	0	405	0	0	0	0	0
total trace gas demand in kg/day	0	5,0	0	0	0	0	0	0	0	0
total yellow water demand in kg/day	0	0	0	0	0	0	0	12,92	0	0
total ... demand in kg/day	0	0	0	0	0	0	0	0	0	0

Fig. 5: Demands within the Habitat Matrix as used during the FLaSH study.

Parameter Output	Air Module	Animal Module	Food Processing Facility	Greenhouse Module	ISRU Module	Living Module	Sickbay	Waste Module	Water Module	Workshop Module
total anorganic solid waste output in kg/day	0	0	0	0	454	0	0	0	0	1,79
total Ar output in kg/day	0	0	0	0	0,08	0	0	0	0	0
total C6H12O6 output in kg/day	41,30	0	0	0	0	0	0	0	0	0
total CH4 output in kg/day	0	0	0	0	1,81	0	0	3,45	0	0
total CH4 output in kg/day	0	0	0	0	1,81	0	0	3,45	0	0
total CO output in kg/day	0	0	0	0	6,37	0	0	0	0	0
total CO2 output in kg/day	0	52,1	0,6	0	4,76	8	0	5,54	10,8	0
total drinking water output in kg/day	0	0	0	557,71	17,15	0	0	0	560,48	0
total Evaporated Water output in kg/day	0	8,5	6,8	0	0	14,45	0	0	0,4	0
total fertilizer output in kg/day	0	0	0	0	0	0	0	46	0	0
total food output in kg/day	0	2,35	0	26,35	0	0	0	0	0	0
total green water output in kg/day	0	720	0	0	0	0	0	0	0	0
total grey water output in kg/day	28,10	240	43,2	123,81	0	58,72	0	51,92	0	5
total H2 output in kg/day	0	0	0	0	0,01	0	0	0,014	0	0
total liquid waste output in kg/day	0	0	0	0	0	60	0	0	2400	5
total N2 output in kg/day	0	0	0	0	0,1	0	0	0	0	0
total O2 output in kg/day	44,06	0	0	11,96	36,82	0	0	0	0	0
total oil/brine output in kg/day	0	0	0	0	0	0	0	0	0,5	0
total organic solid waste output in kg/day	0	0	33,5	57,63	0	1,8	0	15	0	0
total raw materials output in kg/day	0	0	0	0	5	0	0	0	0	0
total trace gas output in kg/day	0	0	0	5	0	0	0	0	0	0
total yellow water output in kg/day	0	0	0	0	0	12,92	0	0	0	0
total ... output in kg/day	0	0	0	0	0	0	0	0	0	0

Fig. 6: Output within the Habitat Matrix as used during the FLaSH study.

Parameter Demand	Sum	Air Module	Animal Module	Food Processing Facility	Greenhouse Module	ISRU Module	Living Module	Sickbay	Waste Module	Water Module	Workshop Module
total anorganic solid waste	454,00	0	0	0	0	454	0	0	-1,79	0	1,79
total Ar	0,08	0	0	0	0	0,08	0	0	0	0	0
total C6H12O6	0,01	41,30	-6,45	-34,84	0	0	0	0	0	0	0
total CH4	1,81	0	0	0	0	1,81	0	0	3,45	-3,45	0
total CO	6,37	0	0	0	0	6,37	0	0	0	0	0
total CO2	4,76	-60,58	52,1	0,6	-16,45	4,76	8	0	5,544	10,8	-0,01
total drinking water	-87,02	-24,78	-960,48	-50	557,71	17,15	-153,6	0	-23	559,98	-10
total Evaporated Water	2,05	-28,10	8,5	6,8	0	0	14,45	0	0	0,4	0
total fertilizer	0,00	0	0	0	-46	0	0	0	46	0	0
total food	0,55	0	2,35	-28,15	26,35	0	0	0	0	0	0
total green water	-1,00	0	720	0	-720	0	0	0	0	-1	0
total grey water	-3,73	28,10	240	43,2	123,81	0	58,72	0	51,92	-554,48	5
total H2	-1,11	0	0	0	0	-1,12	0	0	0,01	0	0
total liquid waste	0,00	0	0	0	0	0	60	0	-60	-5	5
total Mars atmosphere	-20,00	0	0	0	0	-20	0	0	0	0	0
total Mars soil	-105,00	0	0	0	0	-105	0	0	0	0	0
total N2	0,10	0	0	0	0	0,1	0	0	0	0	0
total O2	33,60	44,06	-34,4	0	11,96	36,82	-6,56	0	-2,584	-15	-0,70
total oil/brine	0,50	0	0	0	0	0	0	0	0	0,5	0
total organic solid waste	0,01	0	-92,92	33,5	57,63	0	1,8	0	0	0	0
total raw materials	5,00	0	0	0	0	5	0	0	0	0	0
total regolith	-405,00	0	0	0	0	-405	0	0	0	0	0
total trace gas	0,00	0	-5,00	0	5,00	0	0	0	0	0	0
total yellow water	0,00	0	0	0	0	0	12,92	0	-12,92	0	0

Fig. 7: The Material Trade Matrix as used during the FLaSH study (units: kg/day).

Like on a stock exchange floor it was asked for more suppliers if there was a request on one material or for more consumption if there was an oversupply of one material, at the same time trying to avoid too many changes on dependent material fluxes.

Within the five days CE study the progress of filling out the Habitat Matrix just allowed for the last three days to work on this iterative balancing procedure. Looking at the sum of the drinking water in the Material Trade Matrix in Fig. 7 there is still a demand of 87.02 kg/day left. Compared to the overall drinking water flux in the loop of 1221.86 kg/day (demand) this is only 7.1 %. The balance of the green water is better reached with just 1 kg/day demand left, accordingly 0.1 % of the total green water flux (demand) in the loop. With 0.7 % off there is also a small overall demand on grey water so far. Grey water is an outcome of most of the modules. The only module that processes it is the Water Module. Consequently a next iteration step could be to raise the amount of grey water demand on the Water Module by 3.73 kg/day, which would also helpfully lead to a bigger output of drinking water on the Water Module's site. But still there is a leakage or loss of water to other Modules. The fertilizer flux and the yellow water material flux are perfectly levelled off, but hidden water can be found e.g. in glucose, evaporated water or food, which are all oversupplied. Such deviation can only be solved by balancing on atomic level. Additionally there could be errors in the input and output calculation within each module. For example within the Animal Module the sum of each output minus each demand is -76.3 kg/day which should be equal to zero for the conservation of mass. That means that there is a calculation error within the Animal Module or a forgotten input or output. Because of the Animal Module's high demand of drinking water, this could also be the reason for the seemingly loss of it on habitat level. Only assuring that each module's input and output is balanced would avoid such failure sources.

Another noticeable number in Fig. 7 is the left-over of 454 kg/day anorganic waste. Looking at the ISRU Module one can see that there is a lot of regolith and Mars soil processed to small material fluxes of e.g. water and oxygen putting out the biggest fraction of planetary materials as anorganic waste, which logically should count as open loop as well as the in-situ resources.

Nevertheless even though the balancing process using the Material Trade Matrix is not finished yet, the qualitative behaviour of the material fluxes within our habitat design could already be drawn shown in Fig. 8.

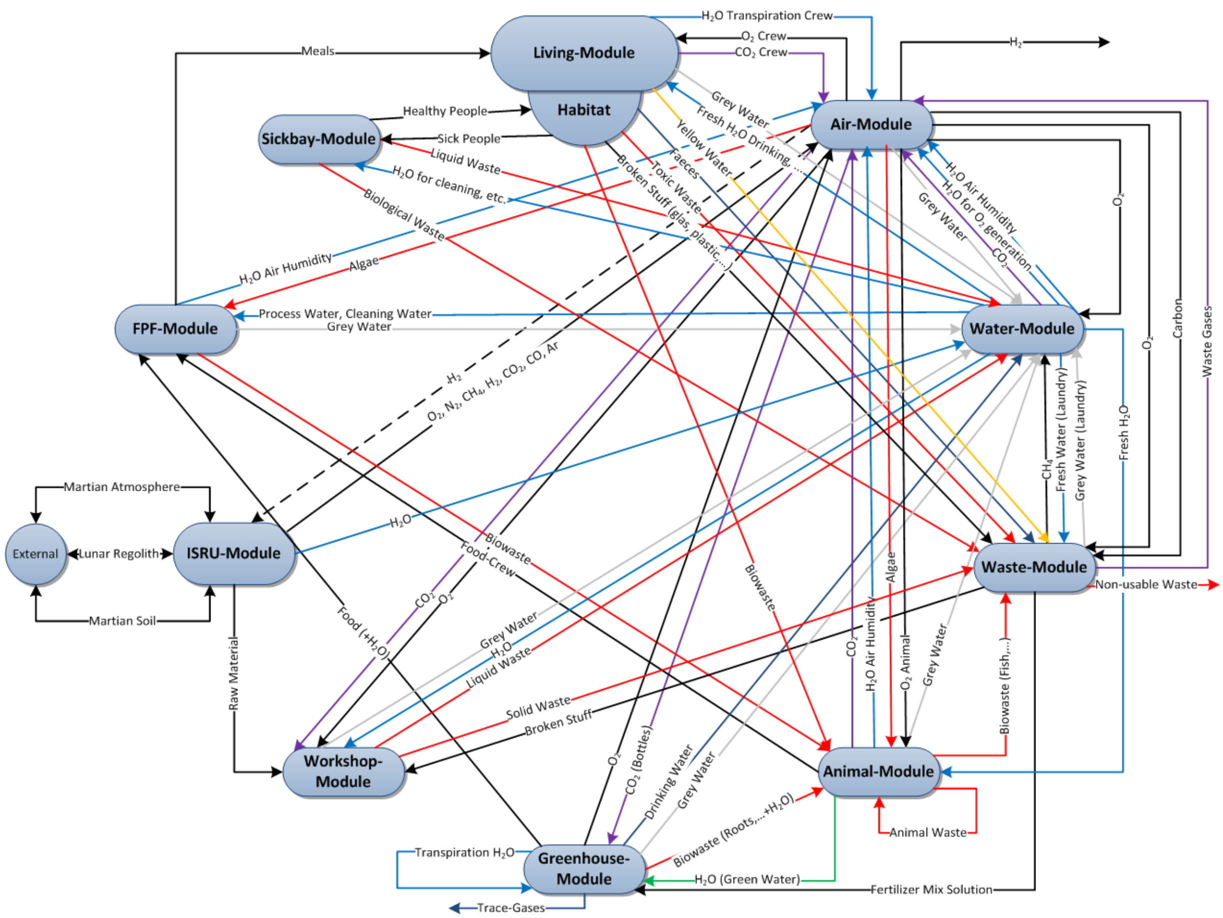

Fig. 8: Qualitative materials exchange between the modules.

V. CONCLUSION

During the five day's workshop applying the Concurrent Engineering principles for the initial design of a Facility of Laboratories for Sustainable Habitation at the DLR, the Habitat Matrix using Excel was an essential tool for dimensioning each needed process to achieve a closed loop material flux. It helps to document all considered components ordered by modules, sections and subsections including the respective material fluxes whilst the main purpose was to generate an overview of all material fluxes on habitat level. On the basis of that Material Trade Matrix the whole team of experts was able to adapt the subsystems sizing with the goal to achieve a balance between demands and supplies of circulating materials within the habitat. Although five days of work were not enough for achieving a fully balanced closed-loop habitat from scratch meeting our requirements, the outcome is a promising basis and has proven our approach. As a lesson learnt the principle of the Habitat Matrix will be retained for following closed-loop studies and potentially transferred to the alternative model based software Virtual Satellite [4], which was developed under the lead of the DLR Institute of Simulation and Software.

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Fig. 9: Multidisciplinary team of the FLaSH CE study at the DLR's CEF 2011.

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