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Study of a FPPS

functional concept

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TABLE OF CONTENTS

Table of Figures

List of Abbreviations

EVA:	Extra Vehicular Activity
FPPS:	Food Production and Preparation System
FPU:	Food Preparation Unit
GU:	Germination Unit
HMI:	Human Machine Interface
HPS:	High Pressure Sodium
HVAC:	Heating, Ventilation & Air Conditioning
IR:	Infra Red
ISRU:	In Situ Resource Utilization
LED:	Light Emitting Diode
MH:	Metal Halide
MPP:	MELiSSA Pilot Plant
NCER:	Net Carbon Exchange Rate
PAR:	Photosynthetically Active Radiation
PCU:	Plant Characterization Unit
PPFD:	Photosynthetic Photon Flux Density
PPU:	Plant Production Unit
RH:	Relative Humidity
SU:	Storage Unit
TN:	Technical Note
VOC:	Volatile Organic Compound
WP:	Work Package

Keywords

Compartment:	In this work, the word compartment refers to a MELiSSA compartment. The MELiSSA loop comprises 5 compartments: The liquefying compartment (C1), the photo heterotrophic compartment (C2), the nitrifying compartment (C3), the photoautotrophic compartment (C4) composed of the algae compartment (C4A) and the higher plant compartment (C4B) and the crew compartment.
Sub compartment:	In this work, the word sub compartment refers to the compartmentalization of a MELiSSA compartment. In the present case, the higher plants compartment is assessed. The C4A (FPPS) consists of 4 sub compartments: The Plant Production Unit (PPU), the Germination Unit (GU), the Food Preparation Unit (FPU) and the Storage Unit (SU).

Reference documents

Ref 1 Statement of Work MELiSSA Food Characterization Phase 1; ESA Directorate of Technical and Quality Management; TEC-MCT/2008/3633/In/CP.

Ref 2 MELiSSA Food Characterization Phase 1; Technical Note 98.1.1, System requirements for a FPPS; ESTEC Contract No. 22070/08/NL/JC.

Ref 3 MELiSSA Adaptation For Space Phase 2 Technical Note 4, Life Support System Sizing; ESTEC Contract No. 20104/06/NL/CP; 1.July 2009.

Ref 4 MELiSSA Food Characterization Phase 1; Technical Note 98.3.32, Review of menu elaboration strategy, identification of critical points and proposed selection method; ESTEC Contract No. 22070/08/NL/JC.

1 Introduction

In this work package, the functional concept of a Food Production and Preparation System (FPPS) for a Moon or Mars surface mission is elaborated. The functional concept is based on a previously performed system requirement assessment which led to the Technical Note (TN) 1.1 (Ref 2). Furthermore know-how and research results gathered in the Food Characterization Project and other MELiSSA studies are used to elaborate concepts and their critical aspects.
Up to the current stage the requirements as well as the functional concept are subject to changes as scientific studies related to plant physiology and food processing run in parallel. Furthermore engineering aspects evolve due to ongoing work on chamber hardware, chamber and plant modeling and space transportation system development. Thus, this study provides a next iteration step towards the final concept. When several options for a specific function are available, these are mentioned with their respective implications (e.g. batch harvest vs. continuous harvest). Critical points and the work to be performed for a final choice are listed. As further insight into the underlying processes is gained and new technologies are developed, the functional concept as well as the requirements are updated.
In a next step the subsystems will be identified complying with the functional concept and (preliminary) subsystem requirements will be elaborated where already possible at this stage.

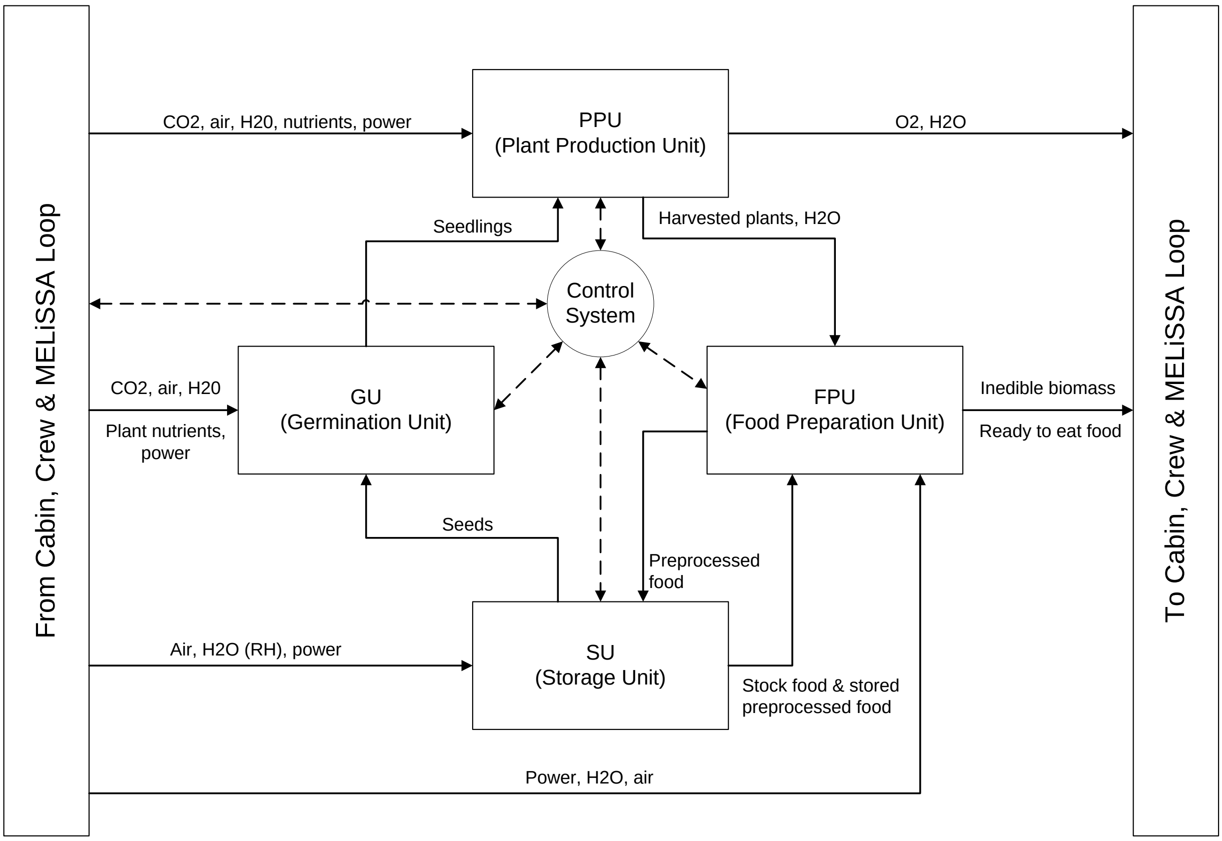

Fig. 1 FPPS sub compartments and interfaces

The primary goal of a FPPS system is to produce food with a constant quality that meets the nutritional and menu cycling requirements of a crew during a defined long-term mission. Besides this, the FPPS is responsible for water purification (through evapotranspiration) and oxygen production. The FPPS is divided into four sub compartments as seen in Fig. 1:
The Plant Production Unit (PPU) is a combination of growth chamber and associated hardware that allows established plants to grow and produce food.
The Germination Unit (GU) will be used to germinate the plantlets to be inserted into the PPU. At this stage it is not yet clear whether the GU and PPU can be combined into one compartment. Furthermore the question of seed to seed production or a seed stock is not yet solved.
The Food Preparation Unit (FPU) is an assembly of processing machinery that will first deliver the semi-finished products and will further combine these (with addition of resupply products if needed) for dish and menu elaboration.
And finally a Storage Unit (SU) is needed to stock fresh, semi processed and ready to eat food under the correct conditions. Storage of resupply food in the SU might also turn out to be advantageous. Generally resupply food is considered part of the mission. Extensive interface between the mission and MELiSSA systems will obviously be present. Resupply food will be integrated into the MELiSSA menu strategy. It remains TBD whether separate interfaced systems or one system is more optimal in terms of logistics, energy and system mass.
All sub compartments are interconnected by a centralized control system linked with the remaining MELiSSA compartments. This control system will perform the common control of the FPPS and be complemented by a food management system. The MELiSSA food management will be available at FPPS level (also including other MELiSSA food sources, i.e. Arthrospira platensis). As seen in Fig. 2 the FPPS will interface with the MELiSSA resource management which will provide the required information for FPPS external food sources.
This document concentrates primarily on a Moon surface mission. A Mars mission will have considerable differences in the logistics approach and automation degree. The impact on the functional concept proposed here is not yet fully understood. Where applicable, foreseeable differences for a Mars surface mission are mentioned.

2 Overall objective

In the final integrated state the MELiSSA loop shall provide at least 40% (dry weight) of the total required food amount of a 6 member (mixed gender) crew for a permanent mission on the moon. This is covered by edible plant biomass (produced in the FPPS, min. 35% of dry weight) and bacterial biomass (produced in C4a up to maximum 5% of dry weight). The other 60% of the food will be covered by embarked/resupply food, which can be chosen depending on the nutritional needs to be established. Furthermore the FPPS will contribute to a large fraction to the closure of the water and oxygen loop (a smaller fraction being contributed by the C4a). Water is recovered by collection and treatment of the condensate from the plants evapotranspiration. Oxygen is being produced by plants (and cyanobacteria) as a by-product of photosynthesis. By producing around 40% of the foods dry weight plants generate sufficient water and oxygen to support the crews’ needs close to 100%. The production strategy of the FPPS must also take into account a menu cycle as to be defined based on nutritional and psychological criteria. The FPPS has to interface with the MELiSSA closed loop regenerative system and external mission elements, as schematically presented in Fig. 2.

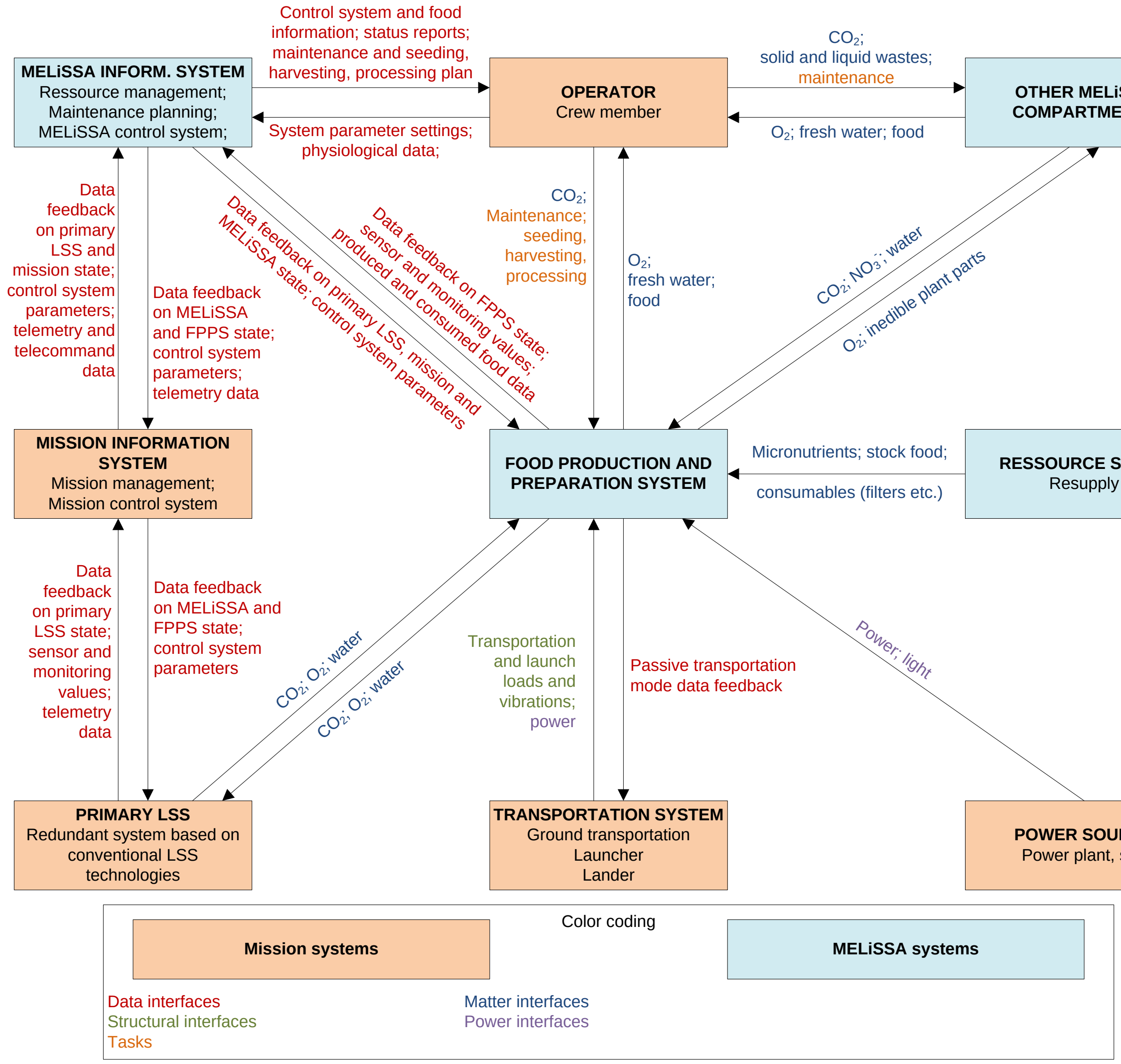

Fig. 2 FPPS context within a closed regenerative life support system

3 Major functions

3.1 Produce crops

Three different production strategies can be discerned. The choice of the best suited strategy will depend on a detailed evaluation of energy and mass implications as well as other ALiSSE criteria such as crew time. Furthermore as described below each strategy has an influence on other FPPS elements such as the logistics approach and the menu elaboration strategy. at this stage no final decision can be taken. Further studies are required to determine the impact of each production strategy on the ALiSSE criteria and other processes

3.1.1 Batch cultivation

All plants of one crop are seeded at once. This results in one large harvest per growth cycle and increased processing and storage needs. The storage and processing might also need adaptation as the produced food needs to be stored over a prolonged period of time (approximately 4 months for one growth cycle). Since the water and O_2 production rates are strongly dependent on the plants age, large buffer capacities are needed to compensate the low production at the beginning of the growth cycle and the large production towards the end. If separate chambers are used for individual crops, equalization can be achieved by staggering the cycles of the different crops.
The advantage of batch cultivation is that less hardware is needed for plant production (e.g. one hydroponic system per crop, no conveyor belt). Usually one large chamber will be more effective in terms of energy and mass than several small chambers with the same production capacity. For the Germination Unit (GU) batch cultivation will require a larger surface area for intermittent germination of larger seed quantities. Thus batch cultivation implies down times of the GU during most of the growth period.

3.1.2 Staggered cultivation

To overcome the problems of the large buffer capacities required to equalize the fluctuating O_2 and water production rates and to avoid the increased processing and storage needs, staggered cultivation can be used. Here each crop is grown in several small batches shifted by a defined period of time. For a crop with a 4 months growth cycle, for example a 1 month seeding/harvest interval could be reached by splitting the growing area into 4 distinct areas. Splitting the growing area can either be done by using several small chambers which are seeded and harvested in intervals or by seeding and harvesting in intervals in one large growth chamber.
Again, one large chamber is more effective in terms of energy and mass than several small ones. However, having plants of different ages in the same atmosphere and/or liquid medium can induce physiological problems. Plants often release substances to their surrounding environment (e.g. ethylene in air or hormones in nutrient solution) which can have negative

influences on plants at a different life stage. Besides this some plants need a distinct nutrient solution composition for each growth phase. Potatoes require for example high nitrogen content in the solution for vegetative growth. To induce tuberization the nitrogen content must be reduced. From this point of view a common hydroponic system or atmosphere will be impossible for a staggered cultivation of certain crops.
As a conclusion the staggered cultivation will have lower mass and energy requirements for processing, storage and buffer hardware compared to a single batch cultivation. The menu cycle can also be formulated in a more flexible way as fresh harvests are available more frequently. However, the mass and energy requirements for the growth systems (hydroponic systems etc.) might be higher. If food processing techniques with a low automation degree are used, the crew time implication will also be higher due to the more frequently occurring processing steps.

3.1.3 Continuous cultivation

The optimum production strategy in terms of O_2 and water production fluctuation is certainly the continuous cultivation. In such a scenario plants are constantly seeded and harvested (e.g. once a day or once a week depending of the total size of the system). At any given time plants of all growth stages are present in parallel. The growing area of such a system is thereby directly related to the lifecycle duration of a single plant (which is equivalent to the retention time in the system) and the required biomass production rate. In principle the growing area demands are similar to a batch or a staggered cultivation as the same amount of biomass has to be produced per unit of time. The GU will require a smaller surface area which is permanently used to germinate seeds. Due to the small GU surface area and the manual manipulation steps required, a conveyor belt or other automated systems are not expected to be required therefore an increased hardware demand on the GU side is not expected for continuous cultivation.
However, the mass and energy requirements for the growing equipment in the PPU will be higher. Usually these systems rely on a conveyor belt and complex fluid handling systems. At least one completely separate hydroponic system with all its associated hardware is needed for each nutrient solution composition (respectively vegetative stage of the plant) to avoid negative influences on plants of different ages. It also remains to be determined whether a common atmosphere is tolerable. A common atmosphere should however not be a problem if the appropriate technologies for atmosphere revitalization and filtering (e.g. ethylene removal) are used.
Due to the constant supply of fresh harvest, the storage requirements can be kept low by keeping a safety stock in mind. Usually processing of such small quantities will be done with small scale processing equipment with low energy and mass requirements but involving manual work of the crew.

3.2 Process crops

The processing of the fresh harvest depends largely on the harvesting strategy and the menu plan. As stated in chapter 3.1, the following rules of thumb can be applied:
Batch harvesting will require larger scale (automated) processing equipment. Depending on the scale of automation, the crew time implication can be kept low at the cost of higher mass, peak power consumption and storage needs.
Continuous harvesting will rely on smaller processing equipment which will most likely consist of small manually operated units. This means a higher crew time implication at reduced mass and energy costs.
This shows how intertwined the harvesting, processing and menu strategy is. To be able to make an optimized choice, a structured assessment of the ALiSSE criteria on all three points is needed.

3.3 Prepare food

Two different strategies are available to prepare the FPPS produced elements of the daily menus. Both of these strategies can be combined and intermediate strategies can be applied (e.g. menus composed of pre-processed and fresh elements) to optimize the overall process. Both, the instant type and the freshly prepared food elements have to be complemented by the stock food brought from earth to fulfill all nutritional needs.

3.3.1 Instant type food

On the one side of food processing there is fully pre-processed material, stored as instant type food. This strategy implies that a large harvest (based on a batch or staggered cultivation) is processed at once. The advantages are a low crew time implication (both for pre-processing and meal preparation) and a simple implementation of replenishable safety stocks in the mission planning. High energy peaks due to the processing machineries could be counterbalanced by processing the biomass during dark periods (no plant illumination). The mass for processing equipment and the storage volume still have to be taken into account. Furthermore packaging could lead to a negative mass balance if non recyclable bags are used.
Preparing complete instant food meals for long term storage seems suboptimal since complex pre-processing (e.g. sterilization) procedures, packaging material and possibly energy consuming storage conditions (e.g. deep freezing) are needed. Furthermore the aspects of nutritional losses have to be taken into account. In general products stored over long periods of time will have a lower nutritional quality than freshly prepared food. Yet, negative effects can be minimized by applying optimal processing and storage conditions. In fact long term storage under freezing conditions can be better than short term storage under ambient conditions.
Another critical point of instant type food is the risk of microbial contamination. To ensure a safe food processing and storage, a prevention plan and technology must be elaborated. In a first view this strategy seems to be best suitable for crops difficult to grow in a continuous cultivation (equivalent to large batch harvests), where nutritional losses due to prolonged

storage is negligible and where energy economic storage conditions can be applied. Potatoes can for example be stored at ambient or near ambient conditions after simple pre-processing for a prolonged time (TBC if still applicable under space conditions). Another example would be pasta produced out of a fresh durum wheat harvest.

3.3.2 Freshly prepared food

On the other end of the list of food processing strategies there is continuous fresh harvest followed by direct consumption. This strategy implies a continuous cultivation or at least a high frequency staggered harvest. Storage and pre-processing requirements are here minimized. The crew time implication can (but not necessarily must) be higher (also taking into account equipment usage and cleaning after each meal). A preparation of a fresh dish will generally take longer than for instant type food. However, the time required for the initial pre-processing of the instant food could render this conclusion invalid.

Psychological aspects also play an important role in long term human missions. Preparing a meal together with other crew members can have positive impacts on the social dynamics of the group and have a relaxing effect. This statement is however not necessarily true under the confined conditions of a space mission and must be verified. Furthermore fresh food is generally of better taste and might increase the willingness of food intake of the crew. This is an important consideration as malnutrition is a critical aspect under space conditions.

Fresh food preparation might have a negative impact on the mass balance due to higher losses with leftovers and unprocessed remains. To avoid or minimize this, the production and harvesting strategy must be very accurate and fine tuned to follow the crew requirements and the menu cycle.

Thus, fresh preparation seems to be best applied to food elements which are difficult to store without critical nutritional losses (e.g. lettuce) and which can easily be grown under continuous cultures (respectively which have a flexible harvest time point). Again, a combination of fresh food with stored and pre-processed element seems most suitable.

3.4 Storage

3.4.1 Seeds

The long term goal is certainly to have stable seed to seed productions to further minimize the cargo/resupply quantities. Yet this strategy can lead to several problems: On one hand, the space environment and the limited gene pool can lead to negative effects due to genetic drift, mutations and inbreeding. On the other hand safety aspects must be taken into account in case of losses of harvests. These long term effects are still not sufficiently quantified and need further research.

A simpler solution which is less optimal in terms of mass is to take a seed stock for the whole mission duration. Thereby the problems of genetic drift and inbreeding are avoided. Difficulties related to safety aspects and with long term storage under the conditions in a lunar base remain to be solved. At an overall view the latter option is more likely to be applied for the first missions to the moon as a demonstration and testing of the whole loop will be the first goal. At later stages seed to seed production can be envisaged for permanent missions.
The optimal storing conditions for seeds still need to be determined. For safety reasons a storage in different batches is favorable to avoid a complete loss in case of a failure.

3.4.2 Pre-processed food

Seen from a storage point of view, continuous cultivation combined with fresh harvest is more optimal as less storage volume is required. Yet the consequences on the requirements of other sub compartments must be taken into account as mentioned in the above chapters.
From a logistics point of view the storage will require an elaborated stock/production management system to ensure a proper consumption/production cycle in accordance with the menus. Quality control and monitoring will be an important aspect of the storage compartments as detailed in chapter 3.10.

3.4.3 Stock food

For stock food the common techniques of current space flight are used. Dehydrated and pre-packaged food represents a safe and established source which will be combined with the produced food. Since the first FPPS system will be used only in combination with an already installed primary LSS, no further elaboration on this point is needed unless the stock food varies from common resupply food (TBC by the menu plan).

3.5 Provide menu cycle

A final conclusion on the menu cycle remains TBD. At this stage it is already clear that to avoid any effect of lassitude, a negative impact on the crews' mood and a reduction of nutritional intake, a sufficient variety of menus is important. To achieve this, the first proposal is to provide menu cycles of 4 weeks (28 days). In a second step, depending on the number of MELiSSA recipes, cycles of 6 to 8 weeks may be considered. According to Ref 4, dishes taking into account earth's seasons, birthdays, national holidays and religions might be introduced. MELiSSA menus will be based on the European food habits in a first step. In fact, in different countries, food and gastronomy can be very divers. It is important to consider international cuisine and occasionally add some specific regional recipes.

3.6 Food management

TBD

To be able to define a food management strategy, more information on the menu cycle and the production strategy is needed.

3.7 Atmosphere management

Generally speaking there are two different strategies for atmosphere management: Maintaining one common atmosphere for all compartments or keeping atmospheres of some compartments separate with possibly different compositions, temperatures and relative humidities.
In terms of hardware, a common atmosphere is simpler. Less equipment is needed resulting in a lower equipment mass, lower risk of failure, lower energy consumption and less crew time for maintenance of the atmosphere management systems. However plants generally grow more efficiently under atmospheres with increased CO_2 content. Humans on the other hand cannot live under excessively high CO_2 partial pressures. Storage conditions for fresh fruits and vegetables can also be improved by using reduced O_2 contents. Similar conclusions can be drawn for, temperature and relative humidity. Thus separate atmosphere handling systems allows to increase the overall process efficiency at the cost of a higher equipment mass, higher energy requirements, possibly higher risk of failure and higher crew time requirements for maintenance operations. In principle the atmosphere sealing does not need to be very tight as only relatively small partial pressure differences and temperature/relative humidity variations are expected. To avoid complex (and heavy) hatch and pressure equalization systems, total pressure differences should be avoided.

To go further with the choice of the atmosphere management strategy, the following points need to be elaborated:

- Quantification of process efficiencies for various atmosphere properties.
- Quantification of the impact on mass, energy, risk and crew time.
- Assessment of all ALiSSE criteria.

3.8 Purify water

The transpiration rate of plants is besides other factors also dependent on wind speed. Generally speaking, two mass transfer coefficients for water can be defined between the plant and the surrounding atmosphere:

The internal mass transfer coefficient represents all mechanisms occurring inside the leaf mainly regulated by plant physiological aspects (e.g. stomatal opening). The external mass transfer coefficient represents the diffusive mass transport and the convective mass transport outside the leaf. Clearly, higher air velocities will increase the external mass transfer coefficient leading to a higher transpiration rate. A detailed quantification of this effect is not yet possible and will require further R&D. Possibly this effect could be used to regulate the water production of the FPU to some extent giving a further variable useful for the overall control of the MELiSSA loop.

Besides these control issues, the quality of transpired (equivalent to distilled) water needs to be determined. First the condensate needs to comply with hygiene standards or needs to be post-processed to meet these. As the water is condensed quasi continuously (with variations between light and dark periods and over the growth cycle) and the nutritional/mineral content is very low (comparable to distilled water), microbial growth is inherently slow. The condensate handling systems must nevertheless allow cleaning and maintenance operations and avoid any stagnation zones.

For human consumption the collected water will require mineral addition. In the first scenarios this will mainly rely on cargo/resupply additives. A separation and purification of minerals compliant with the necessary standards for human consumption within the MELiSSA loop is unlikely at the first stages (TBC). Further assessment of the possible technical implementation of a separation/purification system and the impact on cargo mass for stock minerals remain TBD.

3.9 Cleaning in place

Usually cleaning in place (CIP) can only be applied to highly automated systems. In most cases CIP cannot be applied to equipment dedicated to manual work processes.

In the present case, the hydroponic system used for plant cultivation will in general be an automated system. CIP can be applied to clean the tubing, tanks and other fluid carrying elements. Food processing equipment which requires crew intervention (small scale mill, oven, cooker etc.) will usually require manual cleaning. At this stage no detailed functional concept can be defined. First more information on the liquid handling and food production strategies are needed.

3.10 Quality control

Especially in closed environmental systems, quality control is an important aspect. Due to the lack of large buffer capacities (atmosphere, oceans etc.) and the reduced biodiversity, negative factors such as parasites and diseases can spread faster and chemical elements can accumulate in the loop. Therefore quality control is already important at plant cultivation level. Quality control is also necessary for food storage and water, nutrient solution and atmosphere handling. Furthermore regular chemical analysis of the produced food, water and air and control of equipment cleanliness will be required.

In many cases, quality control involves complex analytical techniques. Automation is not always possible on a non-industrial scale as it is given in the present case. Wherever possible, automation should be used to minimize crew time needs. Besides the common automated pH and EC nutrient solution control, regular manual sampling and analysis of the solutions will be necessary. This implies on one hand crew time but has also an impact on the mass and power budgets for analytical equipment (e.g. chromatography, spectrometry). On the atmosphere side less manual quality control will be needed. A high quality level can be reached by using filters and stripping/separation techniques (e.g. for removal of VOCs) which are commonly used in human spaceflight. For safety reasons, periodic atmosphere quality control will still be necessary especially in the first missions where the detailed behavior of the system might still be uncertain and under evaluation.

For quality control and early detection of diseases, malfunctioning or deterioration of plants and stored food, bioimaging represents a promising technology. Bioimaging generally refers to techniques were specialized cameras (e.g. IR, thermal, fluorescence) are used for early detection of diseases and/or deficiencies. These technologies are not yet readily available but under investigation. More details and developments can be expected in the future. An automated bioimaging system would be a helpful tool for monitoring of plants and stored food. Image recognition software can automatically detect critical points and warn the crew or take other actions.

4 System Performance

4.1 Food quantity

TBD

At the current stage no detailed assessment of the required growing surface can be performed. A menu cycle needs to be defined first and crop performances must be evaluated in more detail. Preliminary estimations (see Ref 3) of required growing surfaces resulted in about 140 m^2 for a 6 member crew.

4.2 Temporal food availability

TBD

The temporal food availability will be defined based on the menu plan and the cultivation strategy.
In the current scenario, which is a lunar base, the way to and back from the lunar surface are not considered for food production. Small FPPS grown provisions for the way back may be included in the logistics approach.

4.3 Food quality

TBD

The food quality needs to comply with human nutrition standards. At this stage no functional concept to meet these requirements can be defined. The concept will require a maintenance plan, solutions for quality control and technology to obtain the required quality.

5 Physical concept

5.1 Main ALiSSE criteria

5.1.1 Mass

TBD

Concepts to minimize the total mass can only be elaborated once the overall functional concept becomes clearer. The rule of thumb relations between mass and the food production strategy defined in chapter 3 apply.

5.1.2 Volume

TBD

Volume estimation can only be established once the overall functional concept becomes clearer. The rule of thumb relations between the volume and the food production strategy defined in chapter 3 apply.

5.1.3 Energy

TBD

Concepts to minimize the total and peak energy consumption can only be elaborated once the overall functional concept becomes clearer. The rule of thumb relations between the energy consumption and the food production strategy defined in chapter 3 apply.

5.1.4 Crew time

The optimal scenario in terms of crew time implies a fully automated system with robotized seeding, harvesting, processing and dish preparation. Although technologies for these tasks are established on earth, it could from a resource-efficiency viewpoint be advisable to consider human intervention at several steps in first small-scale setups to reduce mass and energy implication. When the concept is proven, versions with a higher level of automatism could be established for larger scale production (larger crews). General plant chamber control functions which require regular and time consuming manual tasks (e.g. pH and EC adjustments) should be automated wherever possible. A more detailed crew time assessment will be performed once the choices of functional concepts for the production strategy and menu cycle are narrowed down.

5.2 Containment of emissions

5.2.1 Vapor, VOC, dust, particulate matter

The PPU is not expected to release important amounts of dust and particulate matter. Only vapor (plant evapotranspiration and hydroponic system evaporation) and VOCs will be released. Water vapor is condensed by the HVAC system and the condensate is further used in the MELiSSA loop. The VOCs are removed by conventional filters. The amount and composition of aerosols (biological particles) potentially released from the PPU is unknown at this stage and will require further research.
The FPU might produce considerable amounts of particulate matters and dust. Emission of solid particles is a major problem in microgravity. On the lunar surface large particles will settle down yet at slower speed than on earth. To avoid any accumulation of particles, clogging of air filters or unhygienic conditions, these processes should be sealed off or avoided in the first place. From this point of view, grinding of wheat is a critical process. Alternatives to the common techniques (e.g. wet grinding) or isolation technologies have to be developed. As for the PPU, some FPU equipments will release vapor, VOCs and possibly also aerosols (e.g. boiler and other kitchen appliances). Condensers, strippers and filters will be used here as well. The same is applicable to the storage compartment. Here especially the effects of ethylene accumulation in a closed environment have to be taken into account. Exposure to ethylene can influence the ripening of fruits and vegetables.

5.2.2 Heat/energy dissipation

Today the illumination systems for plant cultivation are usually composed of High Pressure Sodium (HPS) and Metal Halide (MH) lamps. The disadvantage of these lamps is the relatively high heat dissipation. Reusing the lamps heat for other processes (e.g. heating up of other MELiSSA streams) is possible in principle but might turn out to be ineffective in terms of secondary equipment mass (e.g. heat exchangers). Furthermore the illumination cycle might not necessarily be synchronous with the demands of the heat receiving process. A more detailed assessment of the potential integration of heat recycling is needed to come to a final conclusion.
In general a reduction of heat dissipation is always favorable for the overall energy budget. Thereby the heat rejection is not the most critical issue. Rejecting heat in a space environment can be done with radiators with a relatively small implication of equipment mass and energy consumption. A more critical issue is the primary energy source. Therefore all processes (especially illumination) should be designed to minimize energy consumption (and thereby heat dissipation). For the illumination system there is no final solution yet. LED illumination provides in principle an energy saving alternative to MH/HPS lamps. The problems of high density mounting (to obtain sufficiently high intensities), spectral bandwidth and cooling/efficiency at high currents remain to be investigated and solved. Another promising strategy is direct sunlight harvest. The highest energy demand in the whole FPPS system is the illumination system. Direct sunlight harvest would greatly improve the overall system energy balance. However problems with the spectral composition, radiation and meteorite protection

remain to be solved. In addition, direct sunlight harvest is limited to missions to permanently illuminated areas of the moon (some craters at the North Pole).

5.2.3 Radiation

The use of radiative equipment within the LSS compartments should be avoided. Applications could be disinfection or X-ray monitoring. None of these techniques is expected to be needed within the FPPS compartments as more convenient alternatives can be found (e.g. UV, heat or chemicals for disinfection).

5.2.4 Sound

Excessive levels of sound must especially be avoided in the vicinity of crew compartments. Negative effects of sound (within reasonable limits) on plants or bacteria are not known. Noise generating elements are mainly pumps, compressors and fans. Pumps and fans as commonly used in horticulture are not expected to generate excessively high noise levels. Compressors for gas storage (if needed) can be noisy and will have to be isolated from the crews living quarters or designed in an appropriate way.

6 Environmental constraints

6.1 Surface transit

For a moon mission no microgravity application is envisaged as the transit is relatively short. All equipment is stowed, transported and assembled on site. A full functioning is thus only necessary on the surface. For a Mars mission onboard food production could become interesting as the transit phase takes up a large part of the whole mission.

A concept to secure all technical elements, fluids and living matter (seeds, plantlets etc.) from accelerations, vibrations and radiation during transit will be elaborated once more information is available on possible launchers and the functional concept is more elaborated. Most likely the modules structures and the technical elements will be launched in a preassembled and stowed state with several heavy launchers. Heavy launchers usually have higher shock, vibration and noise loads compared to smaller launchers. Once deployed on the lunar surface, fluids and plants will be added.

6.2 Food production environment on extraterrestrial surface

The design of the FPPS takes into account all LSS related elements excluding the primary structure of the lunar base module. In the first (experimental) missions the FPPS sub compartments will be located inside an already present module. The final geometry and configuration of the module is not yet defined (e.g. inflatable vs. rigid module). To proceed with the FPPS functional concept it is assumed that the primary structure of the module provides a validated protection against radiation, micrometeorites and pressure. The lunar base will be equipped with a primary LSS which also provides a basic thermal control. Due to the high energy dissipation (especially of the illumination system) a separate thermal control system with specific interfaces will be required. It remains TBD whether some elements of the primary thermal system have sufficient margin to incorporate the MELiSSA loop requirements (e.g. external radiators). It is advantageous in terms of mass and energy if the main radiators, piping and cooling fluids of the lunar base can be used. Otherwise interfaces through the lunar base for a separate system have to be defined.
This chapter is divided into two sections: One describing the confined condition which represents all elements housed inside the base module with no direct connection to the space environment. The second section describes the partially confined conditions which correspond to all elements with a partial connection to the space environment. This could for example be an element housed inside a base module with a venting pipe. Completely exposed applications (i.e. specifically designed module) are not envisaged for now. Direct sunlight harvest will most likely fall under this category as a complete module with sun light collectors needs to be designed.

6.2.1 Surface environmental parameters under confined conditions

6.2.1.1 Gravity

As the lunar modules will be stationary (none rotating), the lunar gravity is imposed on all elements. This has to be taken into account for the design of all sub compartments. Mainly liquid handling systems and elements relying on convection and other gravitational effects (e.g. sedimentation) will be influenced by this. For the design of closed elements (pipes and tubes) without changes in potential energy gravity does not play a role. Pressure losses in all pipes and tubes remain the same independent from gravity. Gravity effects will have to be taken into account for any piece of equipment where hydrostatic pressure (e.g. pressure sensors, tank draining) or potential energy (inlet and outlet at different heights, e.g. gullies) play a role. To maintain the same retention time in the gullies and liquid layer thickness a steeper inclination is needed under lower gravity.

Altered convection will mainly play a role in the HVAC (Heating, Ventilation & Air Conditioning) design of the chambers and the lamp cooling. No critical issues are expected in this domain. The HVAC and the lamp cooling systems also use forced convection in earth applications. Therefore, for the moon, the same technology with minor adaptations (e.g. blower power and baffle geometry) can be used. Fluid dynamic simulation tools allow an accurate simulation and design of fluid systems under various gravity conditions. It is not expected that excessively higher air velocities are needed in the growth compartments to counterbalance the IR radiation heat load than on earth. In the FPU, convection will play a role for any process involving heat and fluids (e.g. water boiling or oven). Processing of food elements will have to take this into account. Again here no critical issues are expected as convection can easily be increased using fans or stirrers.

Sedimentation processes do not play an important role in the PPU. In earth based growth chambers particles accumulate occasionally at the bottom of the nutrient solution tanks. These particles are composed of small plant debris (e.g. dead roots) and rarely precipitated salt crystals. Due to the fact that the retention time in the tank is high, the degree of turbulence is relatively low and the particles only few in numbers no difficulties are expected under lower gravity. Sedimentation can however play an important role in the FPU for processing and food preparation steps. Milling will for example produce fine particles (flour) which need to settle down. Similarly phase separation processes (e.g. water-oil suspensions) will be slowed down. Here criticalities could emerge. As the menu cycle and the processing steps are not yet defined no functional concept can be elaborated at this stage. This point will have to be addressed later.

6.2.1.2 Radiation and micrometeorites

Radiation and micrometeorites are not a critical issue in the confined environment of the lunar base as protection is provided by the primary structure of the modules.

6.2.1.3 Pressure

A TBD ambient pressure will be maintained by the base module. If the sub compartments are hermetically sealed off to allow different atmospheric compositions, pressure compensation devices and possibly active pressurization devices (e.g. compressors and hatches) will have to be provided. From an equipment mass and energy point of view an equal pressure in all sub compartments is favorable. It remains TBD whether different pressures are favorable for the overall efficiency including all ALiSSE criteria.

If no active pressure control is necessary but different atmospheric compositions are required, pressure compensation devices are needed to compensate for thermal volume variations and fluctuations in total gas content (e.g. gas consumption or release). Depending on the flexibility of the primary base LSS, active or passive pressure compensation devices will be employed for each sub compartment. A passive pressure compensation device is usually composed of an expandable bag or membrane ensuring equal pressures on both sides. An active pressure compensation device uses compressors and buffer tanks to actively regulate the pressure.

6.2.1.4 Temperature

Temperature will certainly vary between sub compartments. The SU will most likely require several cold temperatures (e.g. fridge and freezer) and therefore needs to be compartmentalized.

It remains TBD whether the PPU will have a uniform temperature or separate temperatures for each storage good.

The FPU will most likely have the same atmospheric composition and temperature as the crew compartments but will have several equipments with variable internal temperatures (e.g. oven).

6.2.1.5 Atmosphere composition

The atmospheric composition has to be at least controlled to the extent that some elements (e.g. VOCs) are removed. In principal plant growth and food storage is possible under the atmospheric composition of the crew compartments. Yet the buffer capacity must be large enough to compensate fluctuations. This is not necessarily the case under the confined conditions of a lunar base. Therefore, active control of the composition will be needed on one hand to compensate for fluctuations (e.g. O_2 production rate of plants) and on the other hand to optimize plant growth and storage conditions.

The PPU will most likely have active CO_2 and O_2 control with associated buffer tanks and concentration devices (CO_2 concentrated from the crew compartment and other MELiSSA compartments, O_2 concentrated from the plant compartment). A more precise choice of the degree of atmosphere segregation between the sub compartments can only be done once more plant physiological data at different atmosphere compositions is available.

For the SU a protective atmosphere (e.g. nitrogen) might also be favorable. Here also more information on food deterioration under different atmospheres is needed.

6.2.2 Surface environmental parameters under partly confined conditions

Potential applications for storage could be freezing and freeze-drying of food by exposing it to the space vacuum. The problem hereby is the loss of precious matter. As one of the main goals of the MELiSSA project is to conserve and recycle matter to reduce the upload mass, this is not an option.

Another application with a higher potential is disinfection with space radiation. A completely open connection to the space environment should be avoided here as well to prevent outgassing and matter losses. Disinfection could however take place in a pressurized compartment with low radiation shielding. This would clearly represent a partly confined condition.

6.3 Planet protection

Protection of the planetary/lunar surface from organisms and biological matter is an important consideration. Uncontrolled waste disposal and outgassing must be avoided to prevent contamination. At FPPS level a direct production of unrecyclable waste is not expected. All outgoing streams will be fed back to the MELiSSA loop or consumed by the crew. Unusable matter will if at all only be generated in other waste or water treatment units in the MELiSSA loop and are therefore not addressed in this work. If a permanent disposal is envisaged at later stages, techniques to confine or to render the wastes inert will have to be developed to comply with planetary protection policies.

7 Operational concept

7.1 Operational mission description

7.1.1 Mission phases

The deployment of the MELiSSA technology will be performed in two steps. The MELiSSA loop will first be designed as an experimental LSS used in a lunar base with an already installed conventional primary LSS. At first a food production of 5% is targeted. This is accomplished with the bacterial compartments. At later stages the food production is increased to 40% dry weight. For this purpose the FPPS will be installed. Thus the FPPS is installed as an add-on to increase food production capacity.

7.1.2 Mission duration

The FPPS and the MELiSSA loop will be designed for a permanent lunar mission. At later stages Mars exploration applications will be envisaged.

7.1.3 Crew size

The first concept stipulates a mixed gender crew of 6. This remains TBC.

7.2 Required resources

The interfaces and resource streams within the FPPS and between the FPPS and eternal elements are schematically shown in Fig. 1 and Fig. 2.

7.2.1 External resources needed by the FPPS

7.2.1.1 MELiSSA resources

The FPPS will require the following resources originating from the MELiSSA loop:

- Water (a large portion of the water is recycled within the PPU (condensate recovery), TBD if and how much preprocessed water (possibly carrying nutrients, e.g. NO_3^- from C3) is transferred from other MELiSSA compartments or other resources)
- Nitrate
- CO_2 (produced by other MELiSSA compartments)
- Micronutrients for plants (originating from stock, not produced onboard)
- Consumables (filters, packaging, spare parts etc.). At this stage these items are considered part of MELiSSA as they will be specific to the system. It remains TBD whether these are finally provided by the mission storage or a separate MELiSSA storage.

- Stock food. As for the consumables this is considered part of MELiSSA as the stock food is specifically adapted to be combined with MELiSSA grown food. TBD whether mission systems are the actual source of these elements.
- Minerals for water conditioning for human consumption. As for stock food TBD whether originating from MELiSSA specific storage or mission systems.

Data on the state of other MEliSSA compartments and control system parameters will be needed from the MELiSSA information system.

7.2.1.2 Non-MELiSSA resources

The FPPS will require the following resources originating from non-MELiSSA sources:

- Electric energy
- CO_2 (the crew member is considered part of the mission system and is a major CO_2 source)
- CO_2, O_2 and water interfaces with the primary LSS might be needed.

Data on the primary LSS and mission state will also be needed for a proper FPPS functionning (this information might be routed through a general MELiSSA information system. A centralized data interface between MELiSSA and mission systems will most likely ease the implementation).

7.2.2 Internal FPPS resources

The following resources are transferred within the FPPS:

- Water
- O_2 and CO_2 to compensate photosynthesis and respiration during light and dark phases
- Seeds and seedlings
- Harvested plants
- Edible biomass
- Inedible biomass (TBD to what extent inedible bimass is conditioned within the FPU before it is transferred to the MELiSSA waste treatment)
- Preprocessed food

Interfaces between the FPPS subunits for internal control system functionality will also need to be specified in more detail at later stages.

7.3 Automation degree

The automation degree is TBD based on an assessment of the ALiSSE criteria. At the current stage no detailed information can be given (see chapters above).

7.4 Operational modes

The concept and particularities for each operational mode will be defined in more detail once more information on the production strategy and the technological options are given.

7.4.1 Calibration mode

The calibration mode will allow an access to each sensor separately while maintaining the system in a safe state. It remains TBD whether the calibration mode and the maintenance mode can be combined.
Some calibration steps do not require frequent repetition and can therefore be performed manually. If a calibration is required on a regular basis and involves time consuming manual steps (e.g. pH and EC electrode calibration) automation is favorable to reduce crew time needs. A review of alternative solutions to technologies requiring time consuming manual steps will be done once more details are available.

7.4.2 Routine, nominal operation - Functioning in closed loop system

In this mode the system reaches its full performance and all automated steps are running correctly. More details remain TBD.

7.4.3 Degraded, suboptimal operation mode

This mode activates automatically if the system senses problems or reduced performance. It puts the system in safe conditions (e.g. turning off or dimming of plant illumination if high temperatures are sensed) and sends an alarm to the crew respectively ground station. More details remain TBD.

7.4.4 Maintenance operational mode

7.4.4.1 Preventive maintenance mode

The preventive maintenance mode is activated manually or on schedule to allow ordinary maintenance tasks (e.g. changing of filters). It gives access to the elements requiring maintenance while keeping the remaining system in a safe mode.

7.4.4.2 Corrective maintenance mode

The corrective maintenance mode is activated manually to allow extraordinary maintenance tasks (e.g. repairing of a leak). It allows to isolate each subsystem for intervention and/or to activate available redundant systems while keeping the remaining system in a safe mode.

7.5 Control system strategy

The control system strategy can either be based on a fully centralized system controlling all MELiSSA compartments (including the FPPS) together or a networked system centralized at compartment level with interconnections and data feedback between the compartments. To avoid conflictual control situation, data feedback between each compartment has to be managed at a higher control level (i.e. supervision). In any case the goal of the MELiSSA project is a predictive controlling strategy including feedback algorithms between all compartments.
Further details are TBD.

8 Interfaces

8.1 Interfaces to conventional LSS

As mentioned earlier in this document, a primary conventional LSS will be installed and operational before the MELiSSA system is installed. The primary LSS will be sized to be fully operational without the MELiSSA system. Thus for the first phase, the MELiSSA system is fully redundant. At later stages the capacity of the conventional LSS can be reduced. To achieve a flawless cooperation of both systems, interfaces need to be defined. The FPPS system will interface with the primary LSS in terms of water, O_2 and CO_2 stocks. Detailed concepts for the interfaces of these elements remain TBD.
At this stage it is already clear that the primary LSS and the MELiSSA loop will be two separate systems. Therefore an online quantification of all matter transfer between both LSS is needed to allow a proper control and validation of the MELiSSA loop.

8.2 Interfaces to other MELiSSA compartments

The FPPS will also interface with the remaining MELiSSA compartments. At this stage only the type of interface can be defined. Flux quantities and technical concepts can only be specified once more explicit process information is known. Besides the material interfaces, data interfaces will also have to be defined at later stages. A schematic of the fluxes between the MELiSSA compartments is given in the figure below:

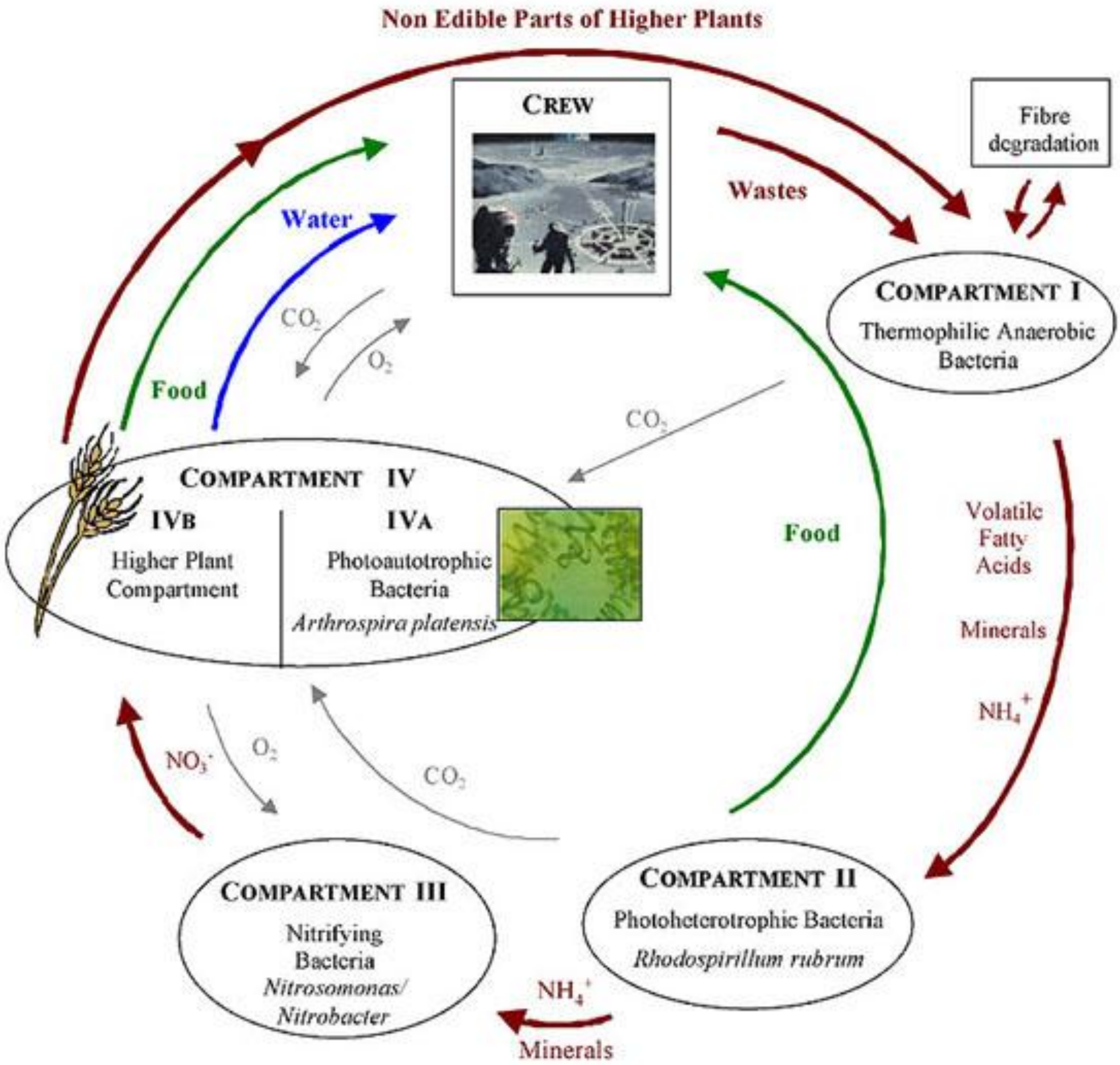

Fig. 3 Schematic of the MELiSSA loop

The following sections describes the material streams identified today between the FPPS and the MELiSSA loop:

8.2.1 C1 interfaces

Into FPPS:

- CO_2

Out of FPPS:

- Inedible biomass
- Water

8.2.2 C2 interfaces

Into FPPS:

- CO_2

Out of FPPS:

- Water

8.2.3 C3 interfaces

Into FPPS:

- NO_3^-

Out of FPPS:

- O_2
- Water

8.2.4 C4a interfaces

In principle there are no interfaces needed between the two photosynthetic compartments for their general functioning. However, O_2 and CO_2 transfers could help to balance fluctuating production/consumption rates during dark and light phases.

Into FPPS:

- O_2 (during dark phases)

Out of FPPS:

- CO_2 (during dark phases)
- Water

8.3 Interfaces within FPPS

As for the MELiSSA interfaces, no detailed concept for the FPPS internal interfaces can be provided at this stage. The information available now is limited to the general type of interface without specific details or quantification. A schematic showing the interfaces is given in Fig. 1.

9 Product assurance

Concepts to provide a sufficient level of product assurance are not yet available and remain TBD. Product assurance will imply the reliability ALiSSE criterion (e.g. through redundancy) and the risk to crew ALiSSE criterion (represented by microbial safety, handling safety and maintenance safety).

Reliability will in the first mission phases be given by the redundant primary LSS already installed in the base. At later stages, when the MELiSSA system takes over the role of the primary LSS, system internal redundancy will have to be provided. Functional concepts to guarantee a certain lifetime, fault tolerance and degradation properties for the FPPS elements will be defined once sufficient information is available as well as a conceptual maintenance plan.

Microbial safety will be addressed by an appropriate system concept, CIP and the maintenance plan. A functional concept to ensure handling and maintenance system will also be provided once the general concept is clearer.

10 Human factors

10.1 Crew time allocation ALiSSE criterion

10.1.1 Workload

As expressed at several places in this document, the crew time (ALiSSE criterion) implications of the FPPS will be assessed once sufficient information is available to proceed with the detailing of the functional concept. As a general rule of thumb crew time implication needs to be minimized to free up time for mission specific tasks.

10.1.2 Cognitive / leisure activity

In some scenarios plant maintenance is described as psychologically valuable and relaxing under the confined conditions of a space mission. Nevertheless a categorization of horticultural tasks as leisure activity is unlikely as the psychological perception of horticultural tasks is a personal matter. A relaxing value is not necessarily present for every individual.

10.1.3 Physical activity

The FPPS will most likely depend on some labor intensive manual tasks such a harvesting and processing. Although gravity is present on the moon, the lower values might require daily exercise to counteract muscle atrophy and bone loss similar to ISS missions. Depending on the mission duration and the general physical activity of the crewmembers an implementation of such arduous tasks in the training plan of the crew might be considered.

10.2 Human Machine Interface

At later stages, concepts for a user friendly Human Machine Interface (HMI) will be provided. The HMI will have to give nutritional and horticultural guidance to the crew. A flexible menu cycle is psychologically favorable for the crew. Technically speaking, a rigid menu cycle allows better optimized seeding, harvesting and processing cycles. A balance between both will have to be found. In this task a personal software assistant could provide guidance to the crew members combing (real-time) data from the plant growth chambers state, storage inventory and human physiology (e.g. body weight & physical activity) while allowing a certain level of freedom of choice top each crewmember.

11 Logistics

Logistic aspects will be elaborated at later stages. This will incorporate options and critical points of the launcher choice, the transit phase, resupply missions and a maintenance concept.