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Elaboration of subsystem requirements of a FPPS

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List of Abbreviations

CMS: Control and Monitoring System
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
PLC:	Programmable Logic Controler
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 photoheterotrophic 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 1.1, System requirements for a FPPS; ESTEC Contract No. 22070/08/NL/JC; September 2009.

Ref 3 MELiSSA Food Characterization Phase 1; Technical Note 1.2, Study of a FPPS functional concept; ESTEC Contract No. 22070/08/NL/JC; September 2010.

1 Introduction

In this work package the Food Production and Preparation System (FPPS) subsystems requirements are elaborated based on top level requirements identified in WP 1100 and the functional concepts elaborated in WP 1200. At this stage focus is set on the definition of the subsystems and an identification of critical areas. Detailed requirements cannot yet be provided as crucial information is still under research and the functional concept is not yet fully identified. Until now not one single functional concept has been defined but a list of potential strategies. Once the choice of options has been narrowed down in further project phases more specific requirements will be provided. Thus the subsystem requirements are defined at sub compartment level wherever possible at this stage. The requirements of the sub compartment subsystems cannot yet be defined. As for TN 98.1.1 and TN 98.1.2 the emphasis is put on a lunar surface system. Microgravity applications and a Mars mission are not considered.

1.1 Naming rules

TN 98.1.1 introduced a naming rule for the requirement structure for an easier tracking and management of individual requirements. Since at this stage the subsystem requirements will not be brought to a final and detailed state, this structure is not yet applied. The requirements defined in this version of the document will be kept general with a focus on critical points.

2 Overall system structure

At first, the overall structure of the system as defined by the functional concept is explained. The context of the FPPS is shown in the figure below.

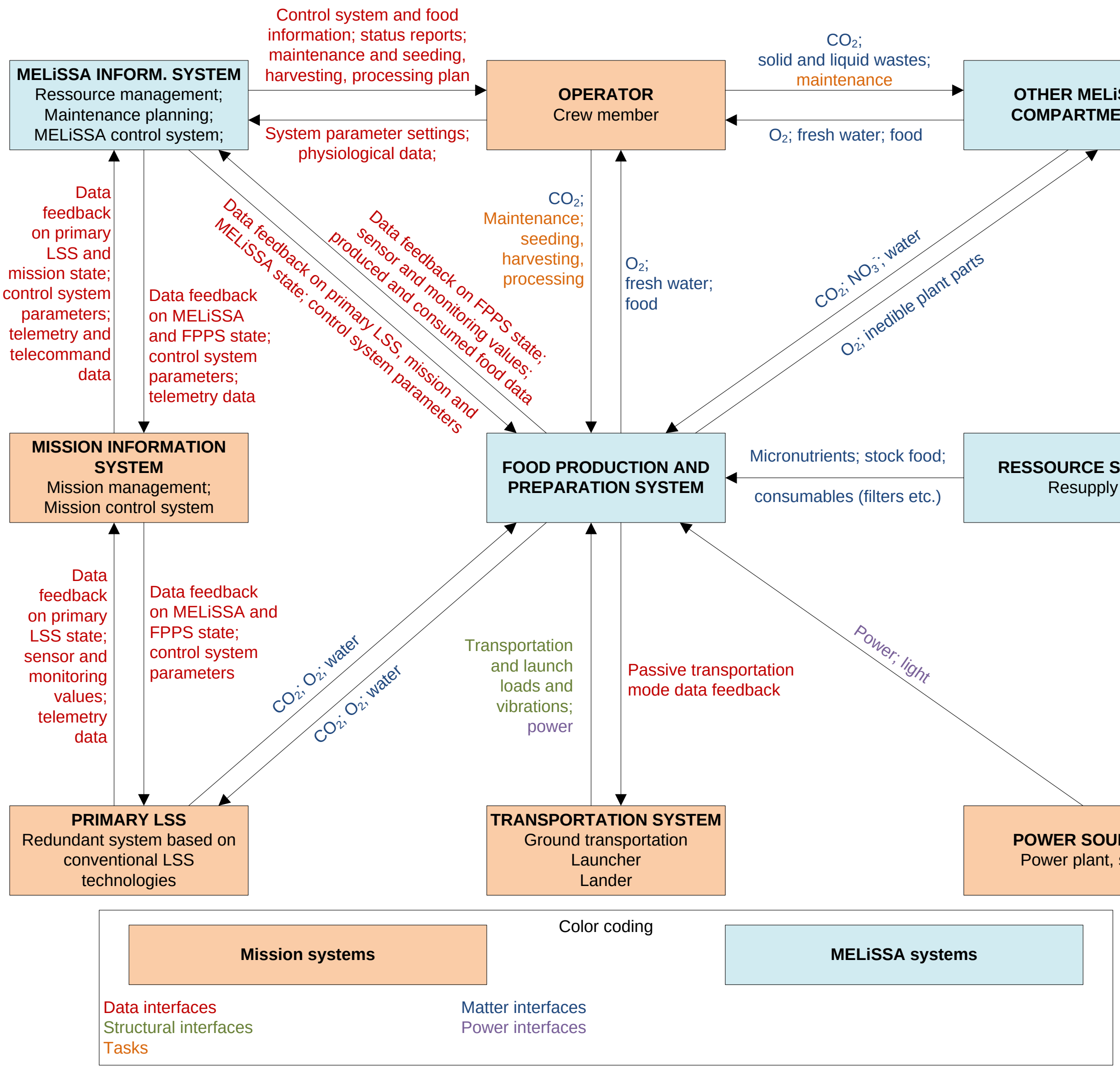

Fig. 1 FPPS context within a closed regenerative life support system

The FPPS is divided into four sub compartments as shown in the following figure. The control system is not categorized as an inherent FPPS sub compartment as it will be integrated at a higher level into the MELiSSA control strategy. It is thus rather to be considered part of a MELiSSA subsystem.

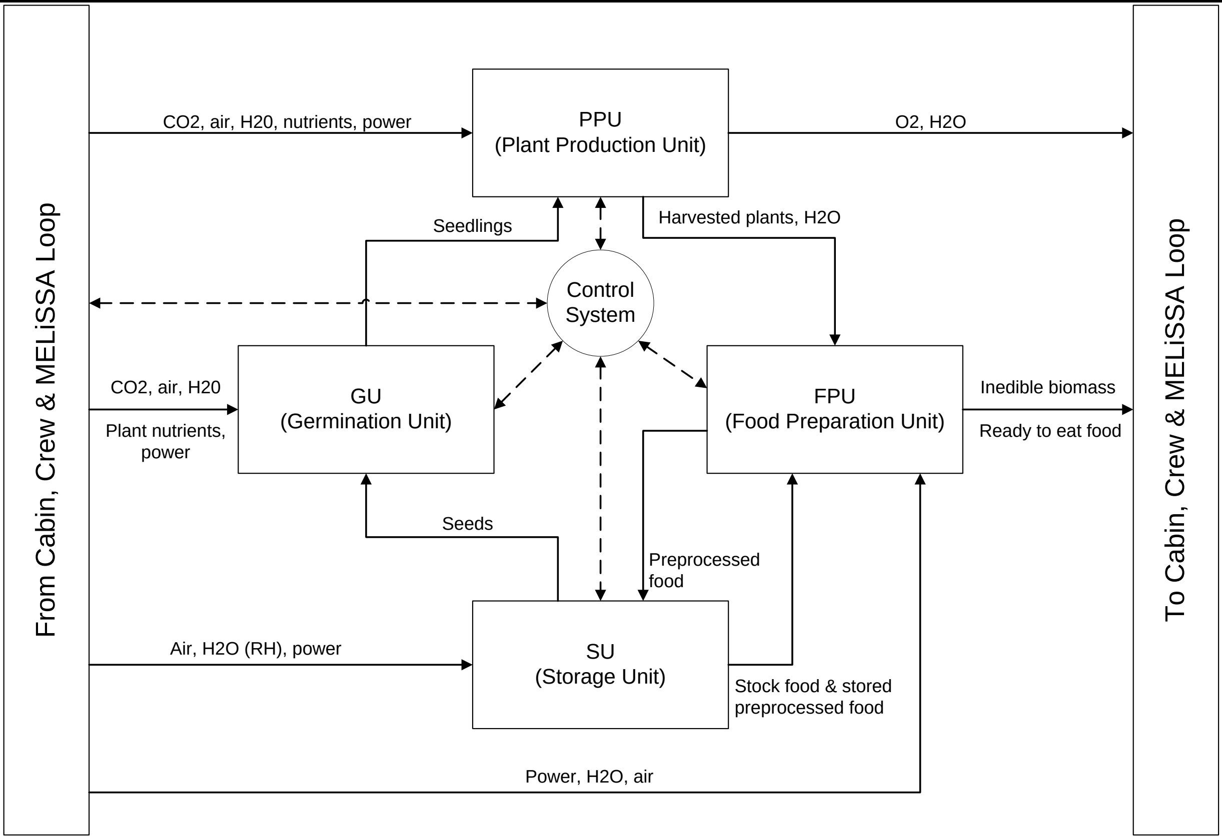

Fig. 2 FPPS sub compartments and interfaces

The sub compartments are further broken down into their subsystems as shown in Fig. 3 to Fig. 6. There the sub compartments are shown in dark blue, subsystems are shown in mid blue and sub-subsystems are marked light blue. Elements which are not yet fixed and which depend on the chosen functional concept are marked orange.

Fig. 7 and Fig. 8 show the Control and Monitoring System (CMS). It has been decided to separate it schematically from the sub compartments as the control system is common to all sub compartments and in fact common to the whole MELiSSA system as an integrated control strategy is targeted. It obviously integrates hardware from all sub compartments (sensors and actuators) but is seen as a discrete subsystem of the MELiSSA loop with interfaces to all sub compartments. To make the view on the CMS more clear, it has schematically been divided into the hardware level and the software/signal level.

In the next chapters the sub compartments and their subsystems are described subsequently. As in some cases several concepts have been listed as options, the subsystem implication of each strategy will be explained to be able to conduct a first selection.

3 Germination Unit (GU)

At this stage it is not yet clear whether the GU and the PPU can be combined into one system. Possibly the seeds can also be germinated inside the PPU with the appropriate hardware. This will have an influence on the required hardware, the logistics approach and on the timing of the cultivation cycles. The similarity between the GU and the PPU are visible by the many parallels in the following chapters.

3.1 Functionality requirements

The GU shall allow the germination of seeds and the rearing of the plantlets to be introduced into the PPU. At this stage it is not yet decided whether batch, staggered or continuous cultivation will be used. Therefore no further detailed requirements can be defined.

3.2 Performance requirements

The plantlets produced in the GU shall be of a size compliant with the PPU requirements (TBD).
The plantlets shall be produced in sufficient quantity (TBD) and frequency (TBD) to comply with the menu cycle and the storage management approach.
The plantlets shall be of sufficient quality compliant with the PPU standards (TBD).

3.3 Physical requirements

3.3.1 Volume and mass

The maximum weight for the whole FPPS is 12 metric tons (Ref 1). The size is limited to 184 m^3 (Ref 1). The mass and volume distribution between the different sub compartments (PPU, FPU, GU, SU) is TBD.

3.3.2 Energy requirements

Both steady state and peak level shall be described. The peak level consumption for the whole FPPS is limited to 142 kW (Ref 1). The ratio between the sub compartments is TBD.

3.3.3 Containment of emissions

3.3.3.1 Vapor, VOCs, dust, particulate matter

The GU shall not emit vapor and VOCs above TBD limits.
Dust and particulate matter are most likely not critical as no emissions are expected. Allowable limits are TBD.

3.3.3.2 Heat/energy dissipation

Heat and other energy dissipation limits will have to be defined based on the base module requirements as the GU will be housed inside an existing module. As a sub compartment with potentially high energy demand (illumination), heat dissipation is a critical issue!

3.3.3.3 Ionizing radiation

No source of ionizing radiation (alpha, beta, gamma radiation, X-rays or neutrons) is expected in the GU.

3.3.3.4 Sound

No excessively high sound levels are expected in the GU. Sound emitting elements will most likely be limited to pumps and fans. Acceptable limits are TBD.

3.4 Environmental requirements

The environmental requirements for the surface transit (accelerations, vibrations, radiation) and the functioning on the extraterrestrial surface (under confined and unconfined conditions) cannot yet be defined as more information on the lunar base, its location and the general functional concept are needed.
The same applies for requirements related to planet protection.
At this stage the level of detail cannot be brought further then what is mentioned in the top level requirements (Ref 2).
As a compartment with permanent presence of living matter for human consumption, radiation shielding will require special attention to avoid/minimize detrimental effects.

3.5 Operational requirements

The implication of the mission phases and duration and the crew size on the operational requirements are not yet certain. First more information is needed on the production strategy and the general functional concept. At this stage only the type of resources needed can be stated. Quantities, frequencies of delivery and qualities can only be stated once the functional concept is more precise.

3.5.1 Required resources

3.5.1.1 Non-MELiSSA resources

The GU will require the following external (non-MELiSSA) resources:

- Energy
- Consumables (substrates, spare parts etc.)
- Micro nutrients

3.5.1.2 MELiSSA resources (non-FPPS)

The GU will require the following external MELiSSA (non-FPPS) resources:

- Water (TBC, could also be recycled from PPU)
- CO_2 (C1, C2 and crew compartment)
- O_2 (TBC, O_2 will be produced in the PPU, and C4a)
- Macro nutrients (e.g. NO_3^- coming from C3)

3.5.1.3 FPPS resources

The GU will require the following resources from other FPPS sub compartments:

- Water (TBC if supplied by the PPU or other MELiSSA compartments)
- O_2 (TBC, O_2 will be produced in the PPU, and C4a)

3.5.1.4 Internal GU resources

At this stage no resources cycled within the GU can be stated.

3.5.2 Automation degree

The requirements to the GU automation are heavily dependent on the functional concept and can therefore not be defined at this stage.

3.5.3 Operational modes

The following operation modes shall be available for the GU:

- Calibration mode
- Routine, nominal operation - Functioning in closed loop system
- Degraded, suboptimal operation mode
- Maintenance operation mode (containing a function for preventive maintenance tasks and for corrective maintenance tasks)

It remains TBD whether the calibration mode and the maintenance mode can be combined.
It is TBD whether it is desirable that the operation modes are settable for the GU independently from the operation modes of the remaining FPPS sub compartments. E.g. to allow maintenance tasks on the GU while the remaining FPPS functions in a nominal mode.

3.5.4 Control system strategy

The GU control shall be integrated in the overall MELiSSA control system. More details remain TBD.

3.6 Interface requirements

3.6.1 Interfaces with the lunar base

At later stages the requirements for data and energy interfaces with the lunar base will have to be defined.
Solid interfaces (racks, connections etc.), liquid interfaces (water, cooling fluids) and gas interfaces (air) to the lunar base can also not be defined at this stage.

3.6.2 Interfaces with the conventional LSS

At this stage there are no specific interfaces envisaged between the GU and the conventional (primary) LSS. This could change once the functional concept and the redundancy strategy becomes clearer. Possibly data interfaces might be required to allow for certain control system and operation mode functions.

3.6.3 Interfaces with other MELiSSA compartments

Interfaces to transfer the resources mentioned in chapter 3.5.1.2 shall be provided. Details remain TBD. Besides this, the requirements for data interfaces will have to be defined at a later stage.

3.6.4 Interfaces with other FPPS sub compartments

At FPPS level, several interfaces are required. The general nature of these interfaces can already be described. Specific information is however still pending:

- Liquid interfaces to the PPU for nutrient solution transfer
- Gas interfaces to the PPU and possibly other compartments for O_2 and CO_2 transfer
- Solid interfaces with the SU for seedlings and the PPU for plantlets
- Data interfaces with all sub compartments for control, storage and cycle management

3.7 Product assurance requirements

Product assurance requirements cannot yet be defined as the reliability (redundancy) strategies and safety (microbial, handling and maintenance) are dependent on a more detailed functional concept.

3.8 Human factor requirements

Requirements to crew time allocation for GU related tasks depend on the functional concept and can therefore not yet be defined. As explained in Ref 3 crew time implication depends heavily on the food production and preparation strategy. In a first scenario, manual seeding and plant transfer are more likely as automated systems require complex mechanisms and imply considerable equipment mass. Requirements related to these activities will have to be defined. In accordance to this Human Machine Interface (HMI) requirements can also not yet be defined.

3.9 Logistics requirements

Logistics requirements concerning the launcher, lunar transit and maintenance (spare part plan) will have to be defined at later stages based on a more detailed functional concept.
The GU will require seeds as a basis for the plant germination. It is not yet defined whether a seed-to-seed or stock seed strategy will be followed. In accordance to this choice resupply related requirements will have to be defined.

3.10 Subsystems

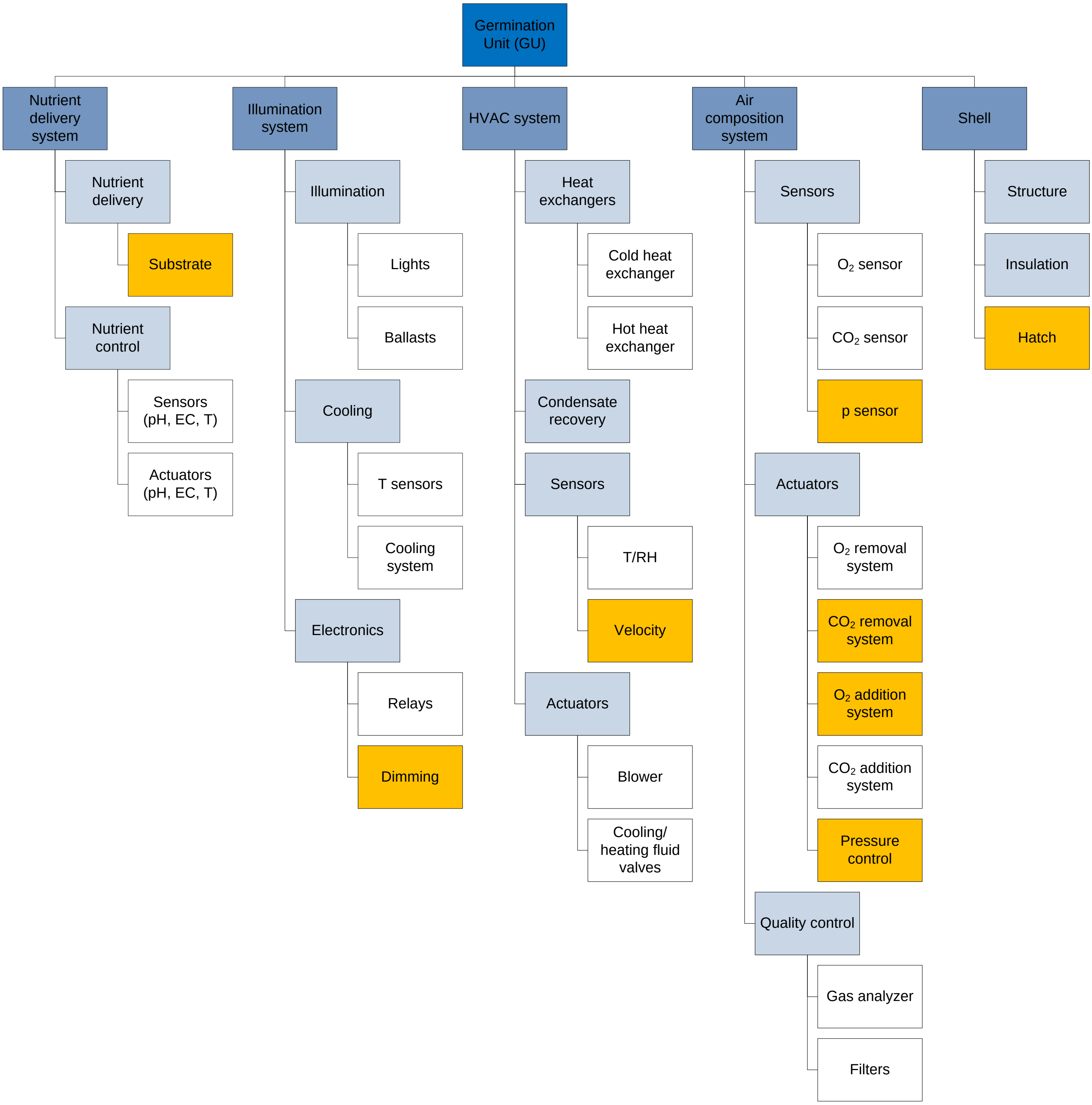

Fig. 3 GU subsystem breakdown (TBD if combined with PPU)

3.10.1 Nutrient delivery system

The nutrient delivery system shall have sufficient capacity to feed the GU with the required (TBD) nutrient solution at all stages of the cultivation.
The nutrient delivery system shall have automatic pH, EC and T control. The necessity of detailed flow and level control is TBD. Safety features such as overflow protection will be necessary, a detailed flow rate control might be unnecessary within certain boundaries.

3.10.2 Illumination system

The illumination system will require automatic light/dark cycle control, overheating protection and synchronization with the overall MELiSSA and FPPS control.

3.10.3 HVAC system

The HVAC system will require automatic T and RH control and possibly control of the air flow rate (resp. air velocity at plant level).

3.10.4 Air composition system

The air composition system will require automatic O_2 and CO_2 level control. Furthermore requirements concerning tolerable VOC levels will have to be defined.

3.10.5 Shell

Requirements to the GU shell and insulation will depend on the lunar base module requirements and the environment it will be installed in.

4 Plant Production Unit (PPU)

4.1 Functionality requirements

The PPU shall enable reproducible production of edible plant material with uniform (margins TBD) and predictable nutritional quality and quantity.
The PPU shall enable reproducible production of water condensate with uniform (margins TBD) and predictable quality and quantity.
The PPU shall enable reproducible production of O_2 within a TBD quantity range.
The PPU shall enable reproducible fixation of CO_2 within a TBD quantity range.
At this stage it is not yet decided whether batch, staggered or continuous cultivation will be used. Therefore no further detailed requirements can be defined.

4.2 Performance requirements

The harvest of each crop shall be produced in sufficient quantity (TBD) and frequency (TBD) to comply with the menu cycle and the storage management approach.
The harvest shall be of sufficient quality compliant with the standards for human nutrition (TBD).

4.3 Physical requirements

4.3.1 Volume and mass

As described in chapter 3.3.1 the volume and mass distribution between the sub compartments is not yet defined.

4.3.2 Energy requirements

As described in chapter 3.3.2 the energy distribution between the sub compartments is not yet defined. The PPU will represent the largest energy consumer in the FPPS due to its artificial illumination (unless direct sunlight harvest is envisaged).

4.3.3 Containment of emissions

The same as for the GU applies. See chapter 3.3.3.

4.4 Environmental requirements

The same as for the GU applies. See chapter 3.4.

4.5 Operational requirements

The implication of the mission phases and duration and the crew size on the operational requirements are not yet certain. First more information is needed on the production strategy and the general functional concept.

4.5.1 Required resources

4.5.1.1 Non-MELiSSA resources

The PPU will require the following external (non-MELiSSA) resources:

- Energy
- Consumables (substrates, spare parts etc.)
- Micro nutrients

4.5.1.2 MELiSSA resources (non-FPPS)

The PPU will require the following external MELiSSA (non-FPPS) resources:

- Water (TBC, the PPU produces water condensate itself, water containing nutrients is produced by C3)
- CO_2 (C1, C2 and crew compartment)
- O_2 (TBC, O_2 will be produced in the PPU, in small amounts by the GU and C4a)
- Macro nutrients (e.g. NO_3^- coming from C3)
- Arthrospira platensis harvest from C4a

4.5.1.3 FPPS resources

The PPU will require the following resources from other FPPS sub compartments:

- Water (TBD by which fraction recycled in the PPU and coming from other MELiSSA compartments)
- O_2 (TBC, O_2 will be produced in the PPU, and C4a)

4.5.1.4 Internal PPU resources

- Water (TBD by which fraction condensate is recycled within the PPU)
- O_2 (TBD, O_2 is produced in the PPU during light phases and is consumed during dark phases; depending on production/uptake rates and volume, active buffering might be needed)
- CO_2 (TBD, CO_2 is consumed in the PPU during light phases and is produced during dark phases; depending on production/uptake rates and volume, active buffering might be needed)

4.5.2 Automation degree

The PPU shall have automated pH, EC and T control for the nutrient solution and T/RH control for the atmosphere. CO_2 and O_2 control will also be needed but at this stage the precision and general functional principle are not yet clear. Simple gas exchange with the other compartments could be sufficient. But most likely active control of O_2 and or CO_2 will be needed.
More detailed requirements to the PPU automation are heavily dependent on the functional concept respectively the production strategy and can therefore not be defined at this stage.

4.5.3 Operational modes

The same as for the GU applies. See chapter 3.5.3.

4.5.4 Control system strategy

The same as for the GU applies. See chapter 3.5.4.

4.6 Interface requirements

4.6.1 Interfaces with the lunar base

At later stages the requirements for data and energy interfaces with the lunar base will have to be defined. The PPU will also interface with the crew compartment for O_2 and water.
Solid interfaces (racks, connections etc.), liquid interfaces (water, cooling fluids) and gas interfaces (air) to the lunar base can also not be defined at this stage.

4.6.2 Interfaces with the conventional LSS

At this stage there are no specific interfaces envisaged between the PPU and the conventional (primary) LSS. This could change once the functional concept and the redundancy strategy becomes clearer. Possibly data interfaces might be required to allow for certain control system and operation mode functions. Interface requirements on the gas and liquid phase are likely to be introduced for redundancy reasons.

4.6.3 Interfaces with other MELiSSA compartments

Interfaces to transfer the resources mentioned in chapter 4.5.1.2 shall be provided. Details remain TBD. Besides this, the requirements for data interfaces will have to be defined at a later stage. The PPU will also interface with the MELiSSA C3 for O_2.

4.6.4 Interfaces with other FPPS sub compartments

At FPPS level, several interfaces are required. The general nature of these interfaces can already be described. Specific information is however still pending:

- Liquid interfaces to the GU for nutrient solution transfer
- Gas interfaces to the GU and possibly other compartments for O_2 and CO_2 transfer
- Solid interfaces with the GU for plantlets
- Solid interface with the FPU and the SU for harvested plants
- Data interfaces with all sub compartments for control, storage and cycle management

4.7 Product assurance requirements

Product assurance requirements cannot yet be defined as the reliability (redundancy) strategies and safety (microbial, handling and maintenance) are dependent on a more detailed functional concept.

4.8 Human factor requirements

Requirements to crew time allocation for PPU related tasks depend on the functional concept and can therefore not yet be defined. As explained in Ref 3 crew time implication depends heavily on the food production and preparation strategy. In a first scenario, manual plant transfer, maintenance and harvest are more likely as automated systems require complex mechanisms and imply considerable equipment mass. Requirements related to these activities will have to be defined. In accordance to this Human Machine Interface (HMI) requirements can also not yet be defined.

4.9 Logistics requirements

Logistics requirements concerning the launcher, lunar transit and maintenance (spare part plan) will have to be defined at later stages based on a more detailed functional concept.
Several issues concerning the logistics approach such as the seed provenance and the menu cycle are still open. In accordance to the final choices resupply related requirements will have to be defined.

4.10 Subsystems

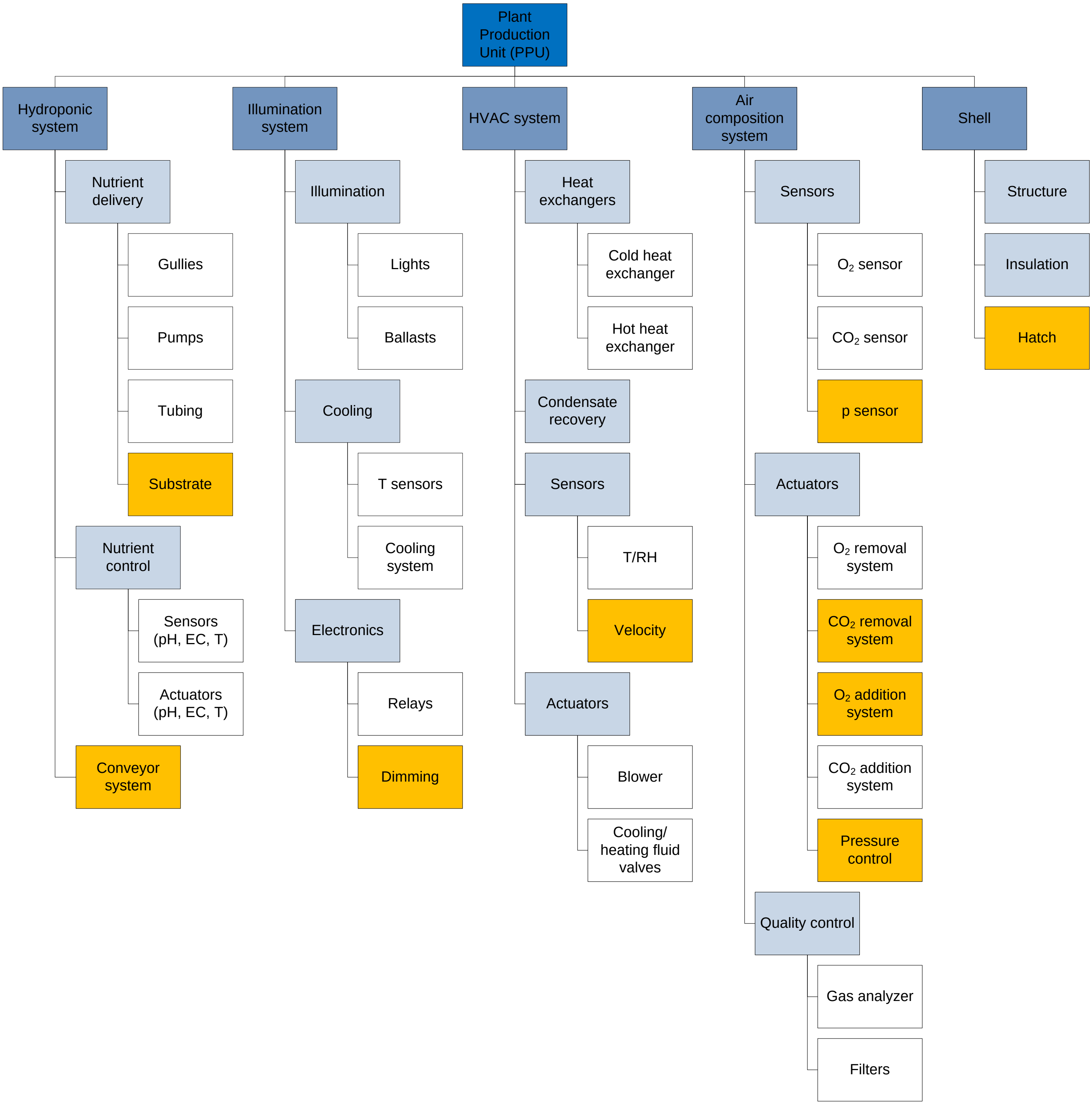

Fig. 4 PPU subsystem breakdown

4.10.1 Nutrient delivery system

The nutrient delivery system shall have sufficient capacity to feed the PPU with the required (TBD) nutrient solution at all stages of the cultivation.
The nutrient delivery system shall have automatic pH, EC and T control. The necessity of detailed flow and level control is TBD. Safety features such as overflow protection will be necessary, a detailed flow rate control might be unnecessary within certain boundaries.
The hydroponic system choice is assessed with emphasis on its applicability in planet surface missions. Microgravity applications are not considered for the first development steps. Adaptation of the respective systems to weightlessness is to be considered at a later stage.
Requirements concerning microbial safety and cleaning maintenance will have to be defined at later stages.

4.10.1.1 Gully requirements

The gullies geometry shall allow substrate less NFT cultivation and also the usage of substrates (Rockwool, TBD). The specific design of gullies for each crop is TBD.
TBD: The inclination of the gullies is to be determined in accordance of the surface gravity (higher inclination for less gravity).

4.10.1.2 Substrate

TBD: The necessity or added value of different growth media types will be determined based on weight, possibilities to sterilize or recycle (e.g. peat–vermiculite, zeolites or arcillite).

4.10.1.3 Nutrient solution delivery

It will have to be determined whether a detail flow rate control is necessary. Furthermore it will have to be determined whether separate systems are used for each crop or whether a combined system is acceptable.

4.10.1.4 Pump requirements

Depending on the liquid handling strategy pump capacity requirements for tank mixing, bypass and oxygenation, will have to be defined in relation to the surface gravity.

4.10.1.5 Liquid phase (root plant subsystem)

Requirements to the liquid phase (T, composition, oxygenation, renewal, purity and microbial stability) will have to be defined based on plant physiological data and scientific experiments.
Considering planetary surface missions with restrictions on mass and energy, reduction of the needed volume of nutrient solution is important. Efficient control of nutrient composition, pH and EC in small volumes is difficult. Requirements on allowable fluctuations in the root environment of the plant and maximum volume will have to be defined.
NO_3^- will be provided by the C3. For other substances (trace elements etc.) it remains TBD whether they are added from a stock or whether they can be recuperated from a MELiSSA process.

For the oxygenation of the root environment no high O_2 concentrations (limits TBD) shall be used for security reasons.
Requirements to solution renewal and disposal/recycling of the old solution will have to be defined.

4.10.2 Illumination system

4.10.2.1 Light spectrum

The whole spectrum needed for plant development (TBD) shall be delivered.
Possibly an adaptation of spectrum and intensity according to growth stadium will be required. This will be determined in future experiments.

4.10.2.2 Light intensity at leaf level

The required light intensity is TBD.

4.10.3 HVAC system

4.10.3.1 Atmosphere pressure

The pressure inside the plant growth chamber shall be equal to the crew compartments to allow easy access and maintenance without hatches and special equipment.

4.10.3.2 Atmosphere temperature

The HVAC system shall be capable of providing the whole range of T required for optimal growth of all crops.

4.10.3.3 Atmosphere RH

The HVAC system shall be capable of providing the whole range of RH (VPD) required for optimal growth of all crops.

4.10.3.4 Condensate recovery

The cooling system shall be made of food grade material wherever contact with condensate is made as the condensate is further used and recycled in the MELiSSA loop.
All elements in contact with the condensate shall be cleanable to avoid and the risk of contamination and unhygienic conditions.
Requirements concerning subsequent filtering and treatment of the condensate are TBD.

4.10.3.5 Atmosphere quality control

VOCs and inhibitory compounds shall be monitored.
If necessary an accumulation of unwanted elements (TBD, e.g. ethylene) shall be avoided (e.g. filters).

4.10.3.6 Atmosphere homogeneity

Tolerable limits for T, RH (VPD) and flow speed homogeneity are TBD.

4.10.3.7 Airflow

The range of airflow for leaf surface gas exchange and cooling is TBD. Possibly requirements to air flow control will be added if future experiments reveal that evapotranspiration can be influenced by air velocity.

4.10.4 Air composition system

The CO_2 levels in the growth compartment shall be low enough to allow human presence without special breathing equipment. Increased CO_2 levels to boost plant growth are possible as long as breathability limits are not breached.

4.10.5 Shell

4.10.5.1 Material choice

The shell materials shall be chosen to avoiding off-gassing of unwanted elements into the growth compartment (e.g. ethylene).

4.10.5.2 Crew access

The PPU shell shall allow crew access at all times without special equipment or access procedures (e.g. pressurized hatch).

4.10.5.3 Depressurization

The PPU shall provide overpressure valves for rapid depressurization events in the base module. More details (e.g. repressurization) remain TBD.

5 Food Processing Unit (FPU)

5.1 Functionality requirements

The FPU shall enable the processing of the raw plant material harvested from the PPU into ready to eat food, storable food elements and waste products.
The FPU shall also enable the elaboration of ready to eat meals using preprocessed (and stored) onboard grown food, stock food and fresh harvest according to the menu cycle plan.
Since at this stage the cultivation strategy (batch vs. continuous) and the menu cycle are not yet defined, no further details can be given.

5.2 Performance requirements

The processing capacity shall comply with the TBD harvest and processing volumes and the temporal availability requirements.
The processing quality shall comply with TBD standards for human consumption.

5.3 Physical requirements

5.3.1 Volume and mass

As described in chapter 3.3.1 the volume and mass distribution between the sub compartments is not yet defined.

5.3.2 Energy requirements

As described in chapter 3.3.2 the energy distribution between the sub compartments is not yet defined.

5.3.3 Containment of emissions

5.3.3.1 Vapor, VOCs, dust, particulate matter

The FPU shall not emit vapor, VOCs and dust above TBD limits to the surrounding environment. Due to the nature of the inherent processes, vapor, VOC and dust will most likely be produced locally inside the FPU (milling, boiling, cooking etc.). Appropriate containment strategies shall be applied. Allowable emission limits are TBD.

5.3.3.2 Heat/energy dissipation

Heat and other energy dissipation limits will have to be defined based on the base module requirements as the FPU elements will be housed inside an existing module. As a sub compartment with potentially high peak energy demands and heat production (oven etc.), heat containment and dissipation is a critical issue.

5.3.3.3 Ionizing radiation
No source of ionizing radiation (alpha, beta, gamma radiation, X-rays or neutrons) is expected in the FPU.

5.3.3.4 Microwave radiation
Possibly microwave radiation will be used in the form of microwave ovens. This remains TBC and associated requirements need to be defined.

5.3.3.5 Sound
Critically high sound levels might occur for certain food processing operations such as milling. Acceptable limits and associated requirements remain TBD.

5.4 Environmental requirements

The same as for the GU applies. See chapter 3.4.

5.5 Operational requirements

The implication of the mission phases and duration and the crew size on the operational requirements are not yet certain. First more information is needed on the production strategy and the general functional concept. At this stage only the type of resources needed can be stated. Quantities, frequencies of delivery and qualities can only be stated once the functional concept is more precise.

5.5.1 Required resources

5.5.1.1 Non-MELiSSA resources
The FPU will require the following external (non-MELiSSA) resources:

- Energy
- Consumables (spare parts etc.)

5.5.1.2 MELiSSA resources (non-FPPS)
The FPU will require the following external MELiSSA (non-FPPS) resources:

- Water (water will be recycled from the FPU, pre-treatment in other MELiSSA equipment is TBD)

5.5.1.3 FPPS resources
The FPU will require the following resources from other FPPS sub compartments:

- Stock food and ingredients stored in the SU

- Fresh plants harvested from the PPU
- Pre-processed and stored food from the SU
- Water (TBD whether directly used from the FPU or if pre-treated with other MELiSSA equipment)

5.5.1.4 Internal FPU resources

Food elements might be treated in several FPU subsystems to reach the final menu. The main product or waste product of one piece of equipment can be the primary matter of another one. More details remain TBD.

5.5.2 Automation degree

Food processing steps shall be automated as far as possible to reduce crew time demands. However the technical complexity is to be kept low to minimize mass and energy needs and the susceptibility to technical failure.

More detailed requirements to the FPU automation depend on the food quantities to process per operation respectively the plant production strategy and can therefore not be defined at this stage. Furthermore the TBD menu plan plays an important role in the processing hardware automation.

5.5.3 Operational modes

As several separate and mostly independent pieces of equipment with manual intervention will be needed (e.g. oven, boiler, mill) the operation mode requirements will most likely be restricted to on/off modes and manual parameter setting. A full integration into the FPPS operation strategy seems unnecessary at this time. This remains TBC.

5.5.4 Control system strategy

As for the operational modes, a full integration of the FPU control into the MELiSSA control loop seems unnecessary at this stage. As every piece of (kitchen) equipment mostly runs individually and manual steps bridge the different processing steps, no integrated predictive control strategy is needed. This remains TBC. Possibly data feedback (quantity and quality) of produced final (or to be stored) products will be needed to improve the MELiSSA control and food management.

5.6 Interface requirements

5.6.1 Interfaces with the lunar base

At later stages the requirements for data and energy interfaces with the lunar base will have to be defined. If PPU condensate treatment is considered to be part of the FPU, it will interface with the respective crew compartments for water.
Solid interfaces (racks, connections etc.), liquid interfaces (water, cooling fluids) and gas interfaces (air) to the lunar base can also not be defined at this stage.

5.6.2 Interfaces with the conventional LSS

At this stage there are no specific interfaces envisaged between the FPU and the conventional (primary) LSS. This could change once the functional concept and the redundancy strategy becomes clearer. Possibly interfaces on the atmosphere will be required to provide crew accessibility and redundancy of the MELiSSA atmosphere management system. Similarly an interface to the primary LSS might be required on the water phase.

5.6.3 Interfaces with other MELiSSA compartments

Interfaces to transfer the resources mentioned in chapter 5.5.1.2 shall be provided. Details remain TBD. Besides this, the requirements for data interfaces will have to be defined at a later stage. The FPU will also interface with the C1 for waste biomass.

5.6.4 Interfaces with other FPPS sub compartments

At FPPS level, several interfaces are required. The general nature of these interfaces can already be described. Specific information is however still pending:

- Liquid interfaces to the PPU for water condensate transfer
- Gas interfaces to the PPU for O_2 and CO_2 transfer (FPU atmosphere for crew accessibility)
- Solid interfaces with the PPU for harvested plants and the SU for preprocessed and stored food.
- Data interfaces with all sub compartments for control, storage and cycle management

5.7 Product assurance requirements

Product assurance requirements cannot yet be defined as the reliability (redundancy) strategies and safety (microbial, handling and maintenance) are dependent on a more detailed functional concept.

5.8 Human factor requirements

Requirements to crew time allocation for FPU related tasks depend on the functional concept (particularly the plant cultivation strategy) and can therefore not yet be defined. As explained in Ref 3 crew time implication depends heavily on the food production and preparation strategy. In a first scenario, manual processing using partially automated systems (e.g. electric mill) are more likely as fully automated systems require complex mechanisms and imply considerable equipment mass. Requirements related to these activities will have to be defined. In accordance to this Human Machine Interface (HMI) requirements can also not yet be defined.

5.9 Logistics requirements

Logistics requirements concerning the launcher, lunar transit and maintenance (spare part plan) will have to be defined at later stages based on a more detailed functional concept.
The FPU will require stock food to complete the dishes. For a moon base regular resupply missions can be envisaged for the delivery of food produced on earth. The frequency of these cargo missions will also have an impact on the requirements for spare parts and a maintenance plan.

5.10 Subsystems

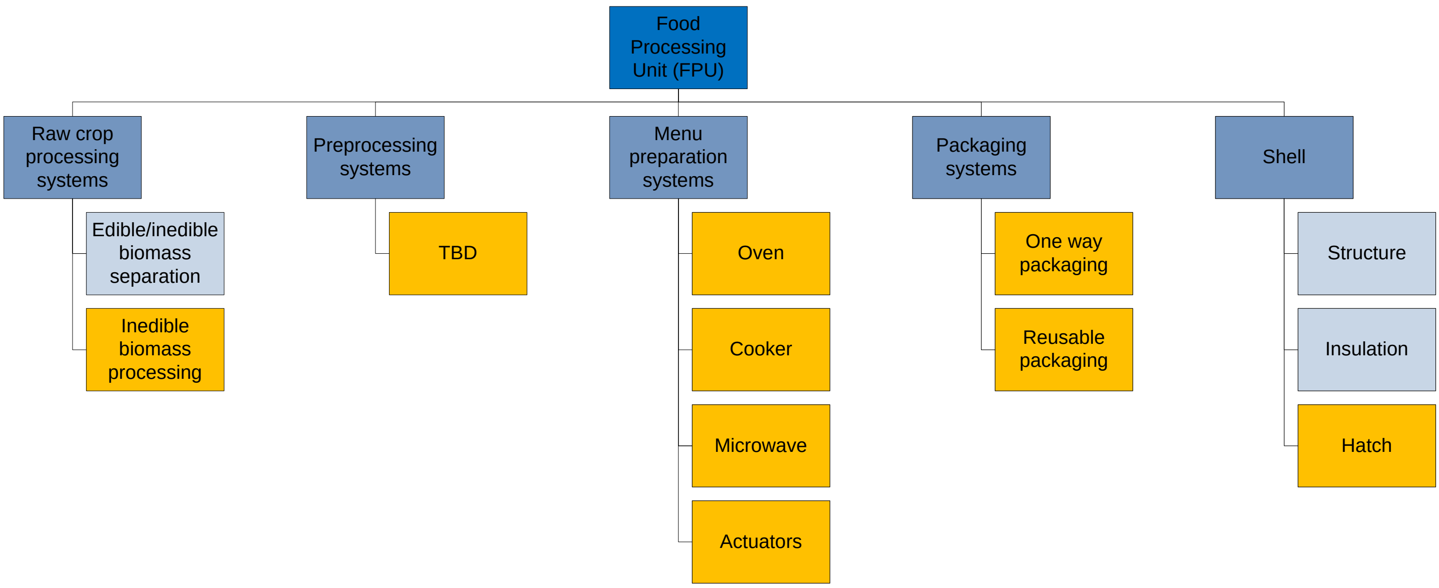

Fig. 5 FPU subsystem breakdown

In general no detailed subsystem description and requirements can be provided at this stage. As a first iteration step, the basic nature of processing steps and their respective requirements are listed.

5.10.1 Raw crop processing systems

At the beginning of the food processing chain stands the separation of the edible biomass from the waste products as produced by the PPU. Roots, stems and leaves will have to be separated from the edible parts (fruits, tubers, grains etc.). The FPU shall provide the infrastructure to accomplish these tasks. Details remain TBD.

5.10.2 Preprocessing systems

After separation of the inedible plant parts, the edible parts can either be prepared into ready to eat food or be processed into intermediate food products for short or long-term storage in the SU. The FPU shall provide the infrastructure to accomplish these tasks. Details remain TBD.
For batch production scenarios, large quantities will have to be processed in long time intervals. For continuous production scenarios, smaller quantities have to be processed in short time intervals (daily).

5.10.3 Menu preparation systems

The stored and preprocessed food elements, the freshly harvested edible plant parts and/or the stock food will be combined into ready to eat meals. The FPU shall provide the infrastructure to accomplish these tasks. Details remain TBD.

5.10.4 Packaging systems

Preprocessed food elements might need packaging for short or long-term storage in the SU. The FPU shall provide the infrastructure to accomplish these tasks. Details remain TBD.

5.10.5 Shell

The actual FPU will most likely be composed of several racks/equipments placed in an already present galley and/or a processing module. The FPU will imply regular human intervention (food processing, meal preparation), thus it will have to be placed in a module rated for regular human presence. Containment of emissions (see chapter 5.3.3.1) is preferably to be applied at equipment level to avoid large scale sub compartment containment requirements.

6 Storage Unit (SU)

6.1 Functionality requirements

The SU shall allow the storage of fresh food, preprocessed food and stock food brought from earth.

6.2 Performance requirements

The food storage unit shall provide sufficient storage volume to compensate harvest and consumption fluctuations and to provide a safety stock (TBD).
The storage conditions shall ensure sufficient (TBD) food stability over a TBD period of time compliant with the menu cycle and the food production strategy.

6.3 Physical requirements

6.3.1 Volume and mass

As described in chapter 3.3.1 the volume and mass distribution between the sub compartments is not yet defined. Considering the large stock food amounts required for a long term mission (60% dry weight of the total food needs), the volume requirements of the SU are expected to be an important fraction of the total FPPS volume. A similar conclusion can be drawn for the mass. However, the largest fraction of the SU mass will be represented by the stored food, not by the hardware mass. Further details remain TBD.

6.3.2 Energy requirements

As described in chapter 3.3.2 the energy distribution between the sub compartments is not yet defined.

6.3.3 Containment of emissions

6.3.3.1 Vapor, VOCs, dust, particulate matter

The SU shall not emit vapor and VOCs above TBD limits.
Dust and particulate matter are most likely not critical as no emissions are expected. Allowable limits are TBD.

6.3.3.2 Heat/energy dissipation

Due to the volume required for stock food elements, a complete module with appropriate environment control (e.g. walk-in refrigerator) is more likely to be the solution of choice than storage racks installed in a module with ambient environmental conditions. Thus heat and energy dissipation requirements might have to be defined at module level. If smaller rack-like storage facilities turn out to be of a higher overall efficiency, heat and energy dissipation requirements will be defined at equipment level to comply with the module requirements. To be able to go further with the requirement definition, more details on the required storage conditions and volumes for each food element are needed.

6.3.3.3 Ionizing radiation

No source of ionizing radiation (alpha, beta, gamma radiation, X-rays or neutrons) is expected in the SU.

6.3.3.4 Sound

No excessively high sound levels are expected in the SU. Sound emitting elements will most likely be limited to pumps, chillers and fans. Acceptable limits are TBD.

6.4 Environmental requirements

The same as for the GU applies. See chapter 3.4.

As some food elements will reside for long periods in the SU, shielding from space radiation must be sufficient to avoid food deterioration over prolonged periods. Further details remain TBD.

6.5 Operational requirements

The implication of the mission phases and duration and the crew size on the operational requirements are not yet certain. First more information is needed on the production strategy and the general functional concept. At this stage only the type of resources needed can be stated. Quantities, frequencies of delivery and qualities can only be stated once the functional concept is more precise.

6.5.1 Required resources

6.5.1.1 Non-MELiSSA resources

The SU will require the following external (non-MELiSSA) resources:

- Energy
- Consumables (spare parts etc.)

6.5.1.2 MELiSSA resources (non-FPPS)

The SU will require the following external MELiSSA (non-FPPS) resources:

- CO_2 (C1, C2 and crew compartment, might be required to provide protective (antioxidant) atmosphere at equipment level)
- O_2 (TBC, O_2 will be produced in the PPU, and C4a)

- Other gases (e.g. N_2 for atmosphere control)
- Processed food based on Arthrospira platensis (C4a)

6.5.1.3 FPPS resources

The SU will require the following resources from other FPPS sub compartments:

- pre-processed and fresh food from FPU
- O_2 (TBC, O_2 will be produced in the PPU, and C4a)

6.5.1.4 Internal SU resources

At this stage no resources cycled within the SU can be stated.

6.5.2 Automation degree

No mechanical (robotic) automation is envisaged within the SU. Automatic functionalities will be atmosphere control (T, RH, composition) and an inventory management system (e.g. bar code based database system). Detailed requirements remain TBD.

6.5.3 Operational modes

As the SU does not imply complex sensor/actuator control loops (e.g. compared to the PPU) and no integrated predictive control is required, the operation mode requirements will most likely be restricted to on/off modes and manual parameter setting (e.g. fridge temperature). A full integration into the FPPS operation strategy seems unnecessary at this time. This remains TBC.

6.5.4 Control system strategy

As for the operational modes, a full integration of the SU control into the MELiSSA control loop seems unnecessary at this stage. As only simple applications such as temperature control with a fixed setpoint are required, no integrated predictive control strategy is needed. This remains TBC.
For the food management system data feedback on quantity and quality of stored products will be needed to improve the MELiSSA control and food management.

6.6 Interface requirements

6.6.1 Interfaces with the lunar base

At later stages the requirements for data and energy interfaces with the lunar base will have to be defined.
Solid interfaces (racks, connections etc.), liquid interfaces (water, cooling fluids) and gas interfaces (air) to the lunar base can also not be defined at this stage.

6.6.2 Interfaces with the conventional LSS

As the SU will contain large amounts of conventional stock food, it can largely be considered as part of the conventional LSS. Depending on the storage requirements for the on board grown food, specific storage elements can be added to the storage room for the conventional food. As storage condition and volume requirements are not yet clear, no further details can be elaborated at this stage.

6.6.3 Interfaces with other MELiSSA compartments

Interfaces to transfer the resources mentioned in chapter 6.5.1.2 shall be provided. Details remain TBD. Besides this, the requirements for data interfaces will have to be defined at a later stage.

6.6.4 Interfaces with other FPPS sub compartments

At FPPS level, several interfaces are required. The general nature of these interfaces can already be described. Specific information is however still pending:

- Gas interfaces to the PPU for O_2 and CO_2 transfer (for atmosphere management)
- Solid interfaces with the FPU for preprocessed and fresh food.
- Data interfaces with all sub compartments for control, storage and cycle management

6.7 Product assurance requirements

Product assurance requirements cannot yet be defined as the reliability (redundancy) strategies and safety (microbial, handling and maintenance) are dependent on a more detailed functional concept.

6.8 Human factor requirements

The SU will most likely depend on human intervention and manual inventory management. An automated (robotic) inventory management system is unlikely to be efficient in a small scale application (6 member crew) as it is envisaged for a lunar mission. Requirements to crew time allocation for SU related tasks depend on the functional concept (particularly the plant cultivation and processing strategy) and can therefore not yet be defined. Requirements related to these activities will have to be defined. In accordance to this Human Machine Interface (HMI) requirements can also not yet be defined.

6.9 Logistics requirements

Logistics requirements concerning the launcher, lunar transit and maintenance (spare part plan) will have to be defined at later stages based on a more detailed functional concept.
The SU will contain a large fraction of stock food to complete the dishes. For a moon base regular resupply missions can be envisaged for the delivery of food produced on earth. The frequency of these cargo missions will have a major influence on the size requirements of the system.

6.10 Subsystems

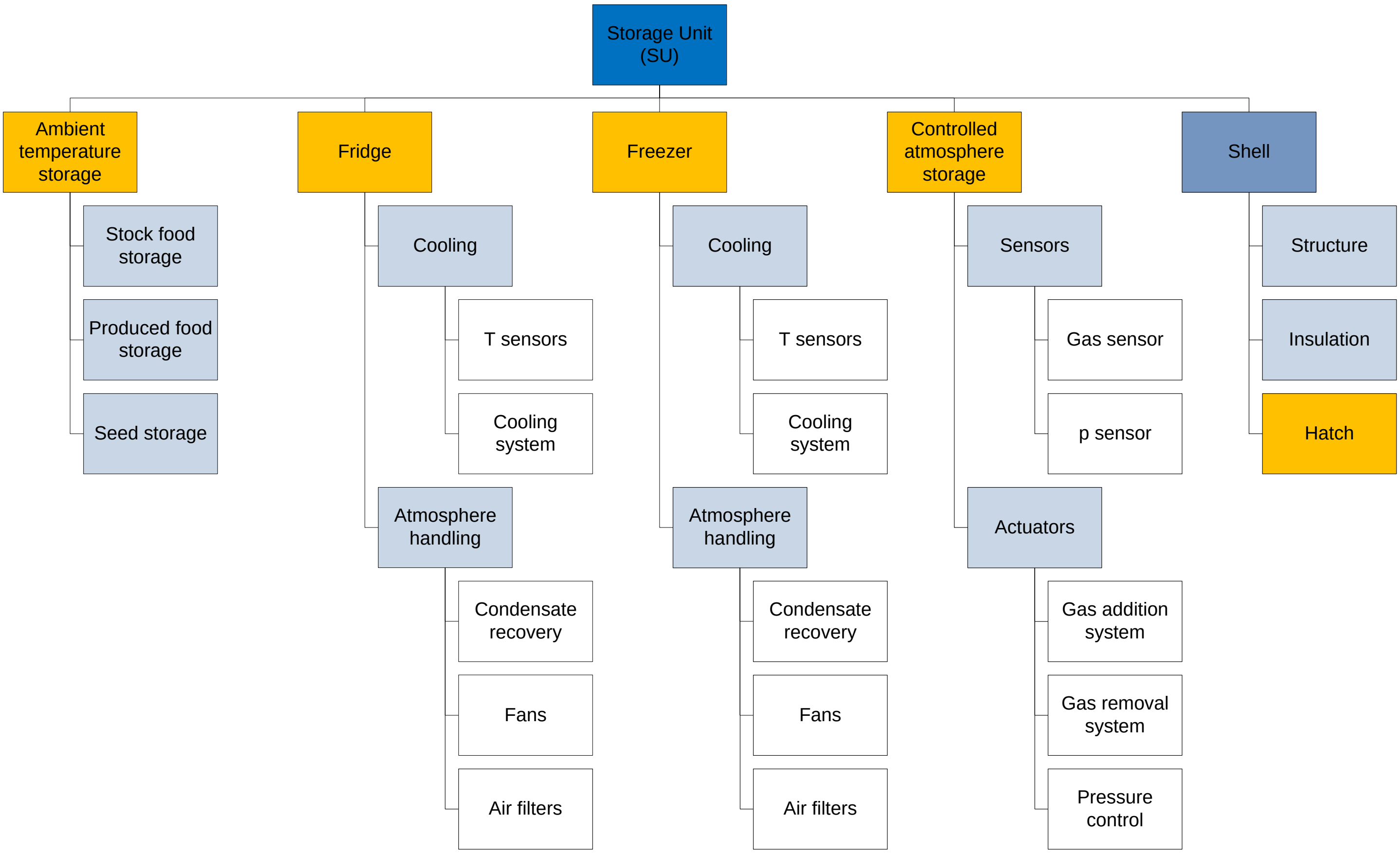

Fig. 6 SU subsystem breakdown

At this stage no detailed assessment of subsystem requirements is possible. Therefore a list of common systems used on earth is listed to give an overview of possible sub systems.

6.10.1 Ambient temperature storage

Ambient temperature storage is the least complex and energy demanding storage technique. It can however only be applied to a limited range of products.

6.10.2 Fridge and Freezer

Cold temperature storage is the most common storage technique on earth. This will most likely play an important role in the SU. Optimal temperature setpoints are not yet clear.

6.10.3 Controlled atmosphere storage

Storage under a protective atmosphere (e.g. pure Nitrogen) is also common on earth for industrial applications. If the necessary resources are available this could turn out to be an advantageous technique in terms of energy consumption and maximal storage duration.

6.10.4 Shell

As described in chapter 6.3.3.2, a module level walk-in storage is a likely solution to store most of the products. Therefore the shell requirements are probable to be defined at module level. If smaller rack like storage elements turn out to be more efficient than one large volume, the requirements to the SU (elements) shell will be defined at equipment level.

7 Control and Monitoring System (CMS)

In principle controlling and monitoring are two separate functionalities of the FPPS. However as these functionalities have many commonalities on the hardware level (e.g. sensors, and HMI) they are summarized in one chapter at this stage.

7.1 Functionality requirements

All CMS requirements are still preliminary and subjected to changes as the knowhow on the behavior of the system and technical possibilities improve. The following functional requirements represent the ideal scenario. The possibility to modulate all mentioned control and output parameters remains TBC.
The CMS shall be designed to adapt the PPU and GU atmosphere parameters (T, RH, composition, air velocity) in accordance to the plants actual needs and the required output for a specific timeframe (O_2, H_2O, edible biomass) by means of predictive controlling.
The CMS shall be designed to adapt the PPU and GU nutrient solution parameters (T, pH, EC, composition) in accordance to the plants actual needs and the required output for a specific timeframe (O_2, H_2O, edible biomass) by means of predictive controlling.
The CMS shall be designed to adapt the PPU and GU Illumination cycles (duration, intensity, spectrum) in accordance to the plants actual needs and the required output for a specific timeframe (O_2, H_2O, edible biomass) by means of predictive controlling.
The CMS shall be designed to provide the crew an optimized seeding and harvesting time plan to obtain the required output for a specific timeframe (O_2, H_2O, edible biomass) by means of predictive modeling of the system.

The CMS shall provide access to all sensor data (logging and temporal availability TBD) and control system actions to the crew and ground personnel.
The CMS shall warn the crew and ground personnel for regular and corrective maintenance tasks.
The CMS shall provide alarm functions in case of system failure and/or reduced performance to the crew and ground personnel.

7.2 Performance requirements

The CMS shall be capable of reaching the targets defined by the functions mentioned in chapter 7.1 with a TBD precision and accuracy.
The required quality and quantity of products remain TBD.

7.3 Physical requirements

7.3.1 Volume and mass

As described in chapter 3.3.1 the volume and mass distribution between the sub compartments is not yet defined.
The CMS is composed to a large fraction of elements belonging to other subsystems (e.g. sensors and actuators are part of the subsystem they act in). Only the intrinsic CMS elements (controllers, processors, HMI etc.) will be counted into the CMS mass budget.

7.3.2 Energy requirements

As described in chapter 3.3.2 the energy distribution between the sub compartments is not yet defined.
The energy consumption of the sensors and actuators is accounted for in the budgets of the surrounding subsystem.

7.3.3 Containment of emissions

7.3.3.1 Vapor, VOCs, dust, particulate matter

The CMS shall not emit any vapor, VOCs, dust or particulate matter.
The CMS are not expected to release any vapor, VOCs, dust or particulate matter.

7.3.3.2 Heat/energy dissipation

The requirements to the energy dissipation of the electrically active CMS systems remain TBD.

7.3.3.3 Radiation

The CMS shall not emit any ionizing radiation.
No source of ionizing radiation (alpha, beta, gamma radiation, X-rays or neutrons) is expected in the CMS.

7.3.3.4 Sound

The CMS shall not emit sounds above a TBD limit.
The CMS is not expected to be a source of critically high sound levels.

7.4 Environmental requirements

The environmental requirements for the surface transit (accelerations, vibrations, radiation) and the functioning on the extraterrestrial surface (under confined and unconfined conditions) cannot yet be defined as more information on the lunar base, its location and the general functional concept are needed. For the electric components of the CMS, radiation could become critical. Failure proof system design or shielding shall be applied to avoid any failure or reduced performance.
No critical points or specific requirements are expected to emerge for the CMS in terms of planet protection.

7.5 Operational requirements

At this stage only the type of resources needed can be stated.

7.5.1 Required resources

7.5.1.1 Non-MELiSSA resources

The CMS will require the following external (non-MELiSSA) resources:

- Energy
- Spare parts
- Data input on general base state and from sensors (TBD).

7.5.1.2 MELiSSA resources (non-FPPS)

The CMS will require the following external MELiSSA (non-FPPS) resources:

- Data feedback from other MELiSSA compartments (TBD)

7.5.1.3 FPPS resources

The CMS will require the following resources from other FPPS sub compartments:

- Data feedback from other FPPS sub compartments

7.5.1.4 Internal CMS resources

At this stage no internal resources can be stated.

7.5.2 Automation degree

The CMS shall work fully automated in nominal mode with the option of having user intervention. More details remain TBD.

7.5.3 Operational modes

The following operation modes shall be available for the CMS:

- Calibration mode
- Routine, nominal operation - Functioning in closed loop system
- Degraded, suboptimal operation mode
- Maintenance operation mode (containing a function for preventive maintenance tasks and for corrective maintenance tasks)

It remains TBD whether the calibration mode and the maintenance mode can be combined.

7.6 Interface requirements

7.6.1 Interfaces with the lunar base

At later stages the requirements for data and energy interfaces with the lunar base will have to be defined.

Solid interfaces (racks, connections etc.) can also not be defined at this stage. No liquid interfaces (water, cooling fluids) and gas interfaces (air) to the lunar base are expected for the CMS.

7.6.2 Interfaces with the conventional LSS

Possibly data interfaces with the conventional LSS might be required to allow for certain control system and operation mode functions. Further details remain TBD.

7.6.3 Interfaces with other MELiSSA compartments

As the CSM will be integrated in the top level MELiSSA predictive control system, several interfaces will have to be defined at later stages. These interfaces will mainly be on software level. Further details remain TBD.

7.6.4 Interfaces with other FPPS sub compartments

At FPPS level, several data interfaces are required. As for the MELiSSA interfaces, further details are pending as the general CMS concept is not yet finalized.

7.7 Product assurance requirements

Product assurance requirements cannot yet be defined as the reliability (redundancy) strategies are dependent on a more detailed FPPS functional concept and a more detailed MELiSSA control concept.
No microbial safety issues are expected in direct relation with the CMS. Handling and maintenance requirements will have to be defined at a later stage.

7.8 Human factor requirements

Requirements to crew time allocation for CMS related tasks (maintenance, monitoring) are not yet clear and can therefore not yet be defined. Monitoring requirements will also depend on the automation degree on the other sub compartments and subsystems.
Human Machine Interface (HMI) requirements can also not yet be defined as they depend on the functional range of the HMI.

7.9 Logistics requirements

Logistics requirements concerning the launcher, lunar transit and maintenance (spare part plan) will have to be defined at later stages.

7.10 Subsystems

As a first step the general subsystem breakdown is presented. Due to the lack of a detailed functional concept (for the FPPS in general and the CMS), detailed requirements are not yet determined. In the following the hardware and the software/signal level of the CMS will be discussed separately.

7.10.1 Hardware level

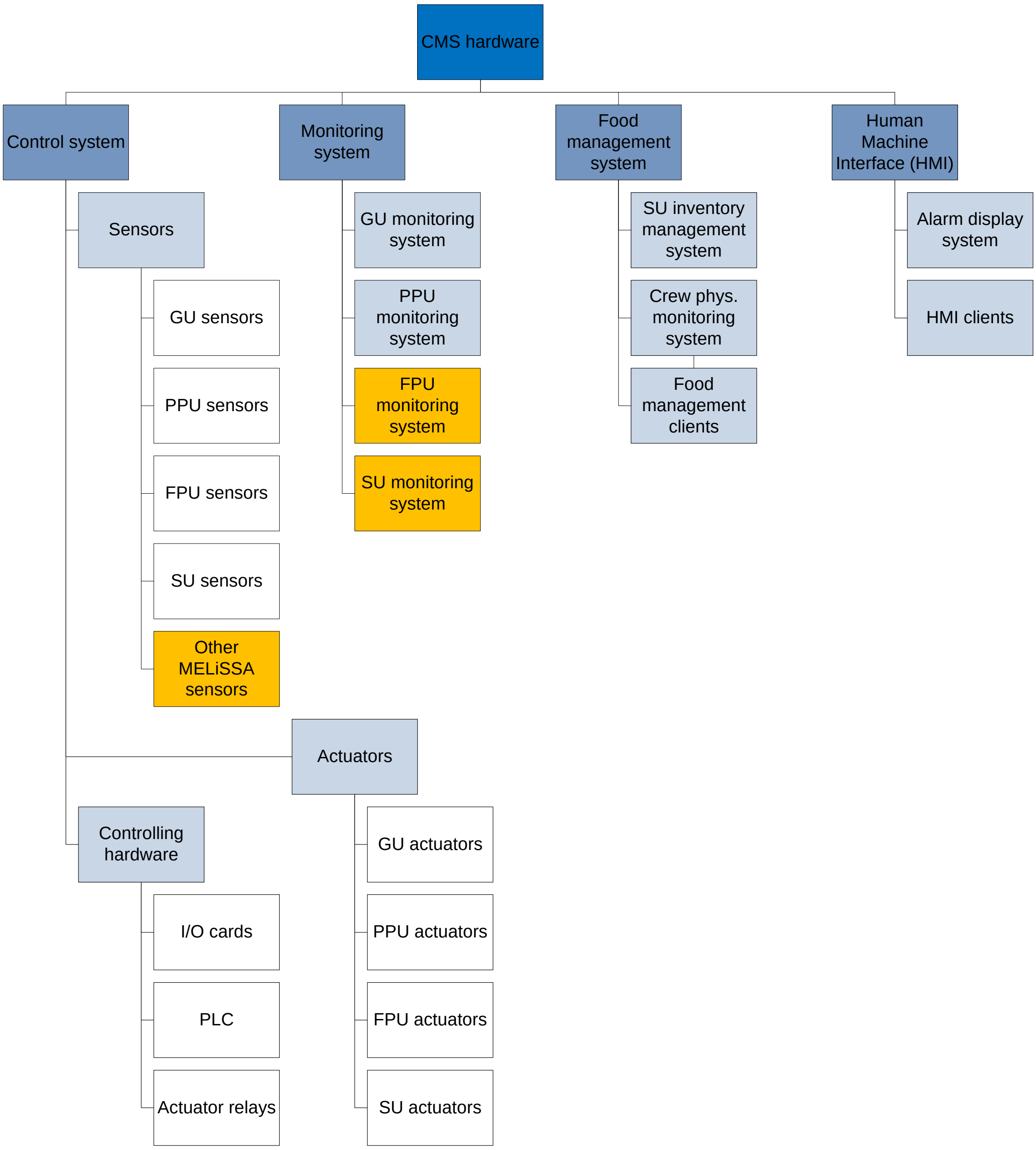

Fig. 7 CMS hardware level subsystems

7.10.1.1 Control system

The term control system describes all hardware used to process sensor signals, to provide the logic controlling (processor) and to trigger actuators. In general these will be I/O cards, Programmable Logic Controllers (PLC), actuator relays and the associated electronics. The detailed CSM structure and the requirement of each sub-sub-system remains TBD.

In principle the sensors and actuators can also be counted as part of the control system. For the ease of energy and mass budgeting these are however counted as part of their respective surrounding sub systems.

7.10.1.2 Monitoring system

The monitoring system has as aim to provide the crew and ground personnel with real time and stored data in a convenient way. The monitoring system has no direct influence on the controlling of the system. It remains TBD in how far the monitoring system is separated from the control system and the HMI in terms of hardware. Monitoring systems will certainly be required for the GU and the PPU. Whether monitoring is necessary in the FPU and the SU and on which scale remains TBD.

7.10.1.3 Food management system

The food management system has as a goal to provide input to the GU/PPU control, manage the food inventory and to provide a guideline for the menu cycle. The hardware components of the food management system are limited to an inventory tracking system in the SU (e.g. barcode system) and computers to treat and visualize data and hardware to monitor the crews physiological state. It remains TBD whether the crew monitoring system is part of MELiSSA as it will most likely already be available in the basic configuration (without the MELiSSA loop) of a lunar base. In that case interfaces and/or structured data input systems are required.

7.10.1.4 Human Machine Interface (HMI)

The HMI is the interface between the CMS and the crew (respectively the ground personnel). It provides a graphical user interface to access and visualize data and to set control parameters and operation modes. The HMI will most likely also provide a TBD alarm visualization system across the lunar base.

7.10.2 *Software and signal levels*

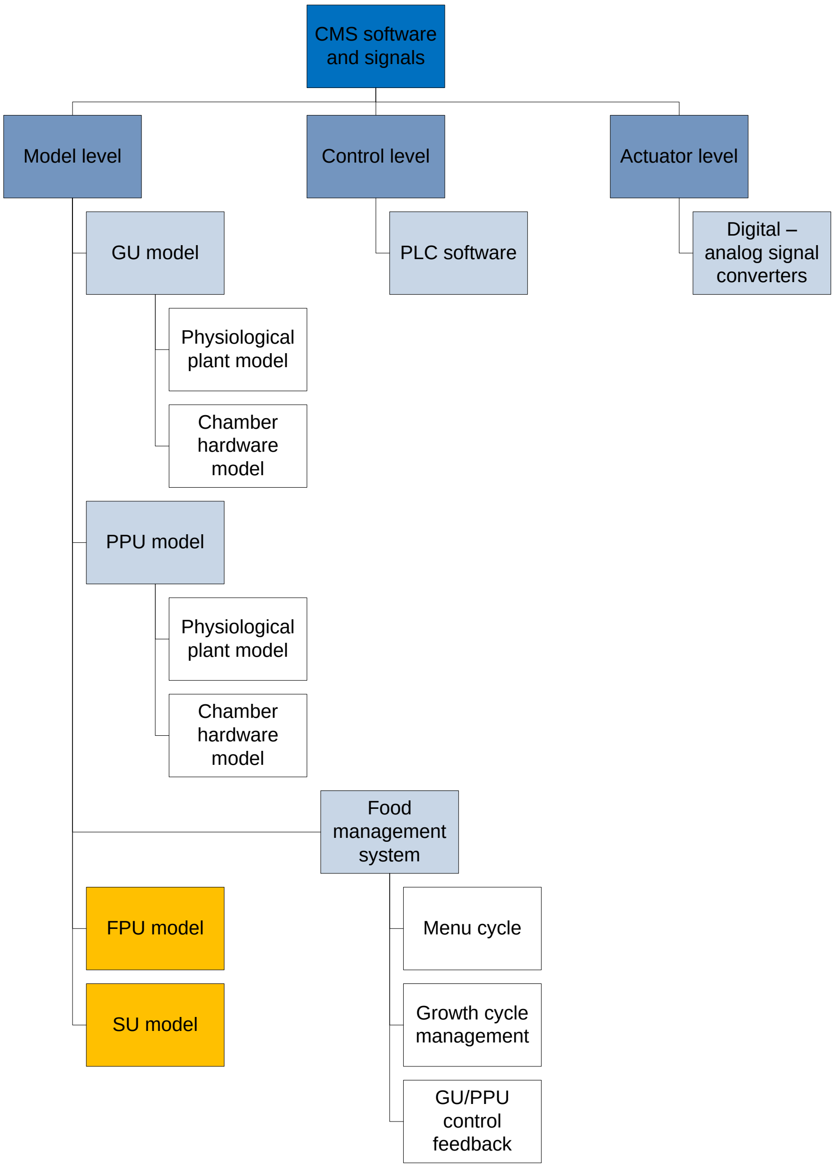

Fig. 8 CMS software & signal level

7.10.2.1 Model level

The model level represents the top level of the MELiSSA control loop. Models of each MELiSSA compartment (and sub compartment) work together to adjust control parameters dynamically in the view of a certain goal (e.g. a certain amount of harvest at a given time). The FPPS model will be integrated into the MELiSSA model. Therefore several interface requirements at hardware and software level will have to be defined. The FPPS model will consist of models for the GU and the PPU, a food management system and possibly models for the FPU and SU.

The GU and PPU models will consist of plant physiological and chamber hardware models. The FPU model will represent the transformation process in terms of nutritional losses, property changes and waste product generation. This information will be used for the food management system and the MELiSSA waste treatment compartments. The SU model will predict food quality, deterioration and property changes due to storage. This information will also serve to improve the food management system performance. Detailed requirements for all models remain TBD.
The food management system also uses predictive process modeling together with GU, PPU, FPU and SU model inputs, the SU inventory and the physiological status of each crew member to provide a (flexible) menu cycle and to guide the GU/PPU control and growth cycles.

7.10.2.2 Control level

The control level is where the actual controlling takes place. Control system setpoints provided by the model level are treated and the required actions are transmitted to the actuator level. The control level software is usually implemented into a PLC.

7.10.2.3 Actuator level

At actuator level the control level commands to the actuators are transformed from digital signals to analog signals. At this level pure signal processing and hardware action becomes blurred.