Memorandum of Understanding 19071/05/NL/CP

UNIVERSITEIT GENT

FACULTEIT WETENSCHAPPEN

MELiSSA FOOD CHARACTERIZATION: PHASE 1

TECHNICAL NOTE: 98.7

DEFINITION OF THE REQUIREMENTS FOR A PLANT CHARACTERIZATION UNIT

prepared by/*préparé par*	Martin Weihreter
reference/*réference*	Contract number 22070/08/NL/JC
issue/*édition*	7
revision/*révision*	0
date of issue/*date d'édition*	08.12.2010
status/*état*	Final
Document type/*type de document*	Technical Note
Distribution/*distribution*	MELiSSA Consortium, ESA/ESTEC

CONFIDENTIAL DOCUMENT

APPROVAL

Title *titre*	Definition of the requirements for a Plant Characterization Unit	issue 7 *issue*	revision 0 *revision*

author *auteur*	Martin Weihreter Laury Chaerle	date *date*	08.12.2009 – 12.11.2010

Reviewed by		date *date*	
EnginSoft	Matteo Nobili		4.01.2010 – 15.04.2010
ESA	Christel Paillé		
ETH	Erich Windhab		
Sherpa	Jean Brunet Olivier Gerbi		
UBern	Valerie Page		
UBP	Pauline Hezard		
UCL	Muriel Quinet Heather Mclean		
UGent	Dominique Van Der Straeten Laury Chaerle		
UNapoli	Roberta Paradiso		
UoGuelph	Mike Dixon		15.11.2010
	Michael Stasiak		15.11.2010
approved by (UGent)	Dominique Van Der Straeten		15.11.2010

CHANGE LOG

reason for change /*raison du changement*	issue/*issue*	revision/*revision*	date/*date*
Initial document draft	1	0	08.12.2009
Reviewed version	2	0	11.02.2010
Intermediate version for HVAC design	3	0	10.03.2010
Version revised by UoGuelph	4	0	08.04.2010
First version submitted to ESA for approval	5	0	15.04.2010
Second version with ESA comments implemented	6	0	08.07.2010
Final version	7	0	12.11.2010

CHANGE RECORD

Issue: 7 Revision: 0

reason for change/*raison du changement*	page(s)/*page(s)*	paragraph(s)/*paragraph(s)*

TABLE OF CONTENTS

Table of Figures

List of Tables

List of Abbreviations

AC:	Air Conditioning
CFD:	Computational Fluid Dynamics
CS:	Control System
FC:	Food Characterization (project)
FPPS:	Food Production and Preparation System
GUI:	Graphical User Interface
HPC:	Higher Plant Chamber
HPS:	High Pressure Sodium
HVAC:	Heating, Ventilation and Air Conditioning
I/O:	Analog and digital inputs, analog and digital outputs
IP:	Internet Protocol
IR:	Infra Red
LED:	Light Emitting Diode
LSS:	Life Support System
MH:	Metal Halide
MPP:	MELiSSA Pilot Plant
NCER:	Net Carbon Exchange Rate
PAR:	Photosynthetically Active Radiation
PCU:	Plant Characterization Unit
PLC:	Programmable Logic Controller
PPFD:	Photosynthetic Photon Flux Density
PPU:	Plant Production Unit
RH:	Relative Humidity
SCADA:	Supervisory Control And Data Acquisition
VOC:	Volatile Organic Compound
VPD:	Vapor Pressure Deficit
WP:	Work Package

Glossary

Gully:	Also known as trough or gutter. Inclined channel used in hydroponic systems to hold the roots, and where the nutrient solution flows through.
PCU:	An array of three independent chambers “subunits” used to grow plants in separate sealed environments. The three separate subunits are used to achieve statistical reliability through independent parallel repeats by keeping a maximum of flexibility. Several PCUs (composed of three subunits each) will be installed in different laboratories.
PCU subunit:	A single independent plant growth chamber. Three PCU subunits outline one complete PCU as it is installed in a laboratory.

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; TN 98.3.1 Crop cultivar study and selection method; Contract No. 22070/08/NL/JC.

Ref 3 MELiSSA Food Characterization Phase 1; TN 98.3.21 Review of modelling issues related to higher plant metabolism, identification of critical points and proposed method; Contract No. 22070/08/NL/JC.

Ref 4 MELiSSA Food Characterization Phase 1; TN 98.4.12 Test plan and procedures for a preliminary trade-off of the crop cultivar - Update for bench test 2; Contract No. 22070/08/NL/JC.

Ref 5 MELiSSA Food Characterization Phase 1; TN 98.4.21 Cultivar tests I; Contract No. 22070/08/NL/JC.

Ref 6 MELiSSA Food Characterization Phase 1; TN 98.4.31 Cultivar test result evaluation I; Contract No. 22070/08/NL/JC.

Ref 7 MELiSSA Food Characterization Phase1, Technical note: 98.3.22 Chamber Hardware modeling step 1 dry model; Enginsoft: Contract No. 22070/08/NL/JC.

Ref 8 MELiSSA Food Characterization Phase 1; TN 98.3.23 Chamber hardware specification review; Contract No. 22070/08/NL/JC.

Ref 9 MELiSSA Pilot Plant Frame Contract 19445/05/NL/CP - Call Off Order 6: HPC1 installation and start-up; TN 96.8 Requirements for the mapping of HPC1; Enginsoft; Juli 2009; HPC1Mapping_Rev4.doc.

Ref 10 MELiSSA Pilot Plant Frame Contract 19445/05/NL/CP - Call Off Order 6: HPC1 installation and start-up; TN 96.10 Mapping as-run procedures and results; NTE; Doc Nr.: NTE-HPC_HVAC-RP-004.

Ref 11 Spaceflight life support and biospherics; Peter Eckart; Kluwer Academic Pub, Dordrecht Space Technology Library, 1996.

Ref 12 EB-002 - Acid Detergent Fiber in Feeds - Filter Bag Technique (ANKOM200); Department of Environmental Biology University of Guelph.

Ref 13 EB-003 - Acid Detergent Lignin in Feeds - Filter Bag Technique (ANKOM200); Department of Environmental Biology University of Guelph.

Ref 14 Effects of radiation quality, intensity, and duration on photosynthesis and growth; International lighting in controlled environment workshop; Tibbitts T.W. editor. NASA-CP-95-3309 Bugbee B.; 1994; http://ncr101.montana.edu/Light1994Conf/1_5_Bugbee/Bugbee%20text.htm

Ref 15 Night temperature has a minimal effect on respiration and growth in rapidly growing plants; Annals of botany, 94, 155-166; Frantz, J. M., Cometti, N. N., Bugbee, B.; 2004a.

Ref 16 Characterizing the environmental response of a gibberellic acid-deficient rice for use as a model crop. Agron J, 96, 1172-1181. Frantz, J. M., Pinnock, D., Klassen, S., Bugbee, B.; 2004b.

Ref 17 Exploring the limits of crop productivity: Beyond the limits of tipburn in lettuce. Jour. ASHS 129: 331-338; Frantz J., Ritchie G., Cometti N., Robinson J., and Bugbee B.; 2004c.

Ref 18 Plants and microclimate: a quantitative approach to environmental plant physiology. Cambridge university press, Cambridge; Jones H.G.; 1992.

Ref 19 Irradiance levels affect growth parameters and carotenoid pigments in kale and spinach grown in a controlled environment. Physiologia Plantarum 127 (4): 624-631 Lefsrud M.G.; Kopsell D.A.; Kopsell D.E.; Curran-Celentano J.; 2006.

Ref 20 A Data Base of Nutrient Use, Water Use, CO_2 Exchange, and Ethylene Production by Soybeans in a Controlled Environment; R. M. Wheeler, C. L. Mackowiak, B. V. Peterson, J. C. Sager, W. M. Knott; NASA Biomedical Office and Dynamac Corporation, Kennedy Space Center, FL 32899; W. L. Berry, M. R. Sharifi; Biomedical and Environmental Sciences, University of California, Los Angeles, CA 90024; NASA/TM-1998-270903; April 1998.

1 Introduction

WP 7000 defines the detailed requirements for a Plant Characterization Unit (PCU) which will be used to characterize the relative performance of cultivars of the crops selected for food production in a space based Food Production Unit (FPU) within the MELiSSA Food Characterization (FC) project. This WP builds on the chamber hardware specification review (WP 3230) and takes into account objectives derived from the plant metabolic mathematical model (WP 3210), the review of the MELiSSA Pilot Plant (MPP) Higher Plant Chamber (HPC) model (WP 3220), the requirements to food processing and nutritional analyses (WPs 3310 – 3330) and the crop cultivar test evaluation (WP 4300).

WP 7000 is followed by four other WPs to lead to the final design of the PCU. These are:

- WP 8100: Consolidation of specifications for the PCU design.
- WP 8200: Preliminary design of the PCU.
- WP 8300: Study of critical subsystems and selection of most suitable technologies.
- WP 8400: Detailed design of the PCU.

1.1 Naming rules

The hierarchy of the requirement listing in this document is organized in a way to be as close as possible to the logic of the SmarTeam MELiSSA Data Management System. Each requirement obtains a unique identifier which satisfies the syntactic rules given below:

Req.id = <Req level >-<Req.category>-<Req.subcategory>-<Req.number>

Requirement level: e.g. SYS for system level
Requirement category: e.g. FUNC for functional
Requirement subcategory: e.g. PROD for functional requirement “produce crops”
Requirement number: consecutive numbering

All the naming rules ensure that a requirement identifier is unique.

For a preliminary trade-off of the PCU features, each requirement is ranked. Due to planning and financial constraints not all requirements can be met, but are included for future consideration. This ranking will be used to define the final design. Each requirement defined must be accompanied by a ranking value.

Rank 1:	These requirements are critical for the overall functioning of the PCU and the principal scientific objectives. These requirements MUST be met.
Rank 2:	These requirements are not absolutely critical for the overall functioning of the chamber but would allow the achievement of secondary scientific objectives.
Rank 3:	These requirements are targeted towards features that can be considered in future experimental upgrades.

2 PCU system description

2.1 Overall objectives

2.1.1 Grow crops

The PCU will be used to grow a wide range of crops (see chapter 2.3) in hydroponic culture in a closed and controlled environment with artificial lighting. The crops studied will be used in future closed loop Life Support Systems (LSS) for oxygen production, CO_2 fixation, water recycling and food production.

The range of settable environmental parameters must comprehend the optimal conditions for each selected crop. An important factor for the sizing of the chamber is the number of plants needed for a reproducible assessment of plant growth parameters within a single PCU. Obtaining statistically reliable crop growth data (sufficient number of independent repeats) can be achieved by using an array of chambers. As a first guideline one PCU will consist of three separate chambers. In the following text, the term *PCU* always depicts a set of three subunits. If one single chamber is addressed, the term *PCU subunit* is used. Furthermore the biomass production needs per PCU to allow an efficient food processing evaluation and nutritional analysis (see chapter 2.1.2) have to be taken into account.

Other important factors for the PCU design are:

- A highly sealed chamber atmosphere to allow precise calculation of mass balances of carbon, oxygen and water.
- An adaptable illumination system for different crop species, the study of intensity and spectrum influence and the evaluation of new technologies such as LED illumination.
- An HVAC system that will guarantee a narrow envelope of T and RH control values, as imposed by the light system heat load and other external/internal heat and humidity sources.
- A certain level of spatial homogeneity for atmosphere composition, temperature, light and airflow for a statistically valid and reproducible crop development of all plants inside the chamber.
- Online and offline characterization of the gas and liquid phase (online analysis of liquid phase will be limited to EC and pH measurements with the potential to integrate more sophisticated systems (e.g. ion specific) when they become available).
- Systems for non-destructive online monitoring of plant growth (e.g. cameras).
- Ergonomic nutrient solution handling. For some crops, the nutrient solution composition must be changed during production to stimulate the switch to a next physiological stage of growth (e.g. vegetative growth to fruiting). The required drainage and filling ports must be given.

Germination and the seedling stage might be carried out in the PCU depending on the experimental objectives and the used crop. The PCU hardware will however not explicitly consider environmental parameters for these phases as facilities for this purpose are already available (see SYS-FUNC-GRO-2). In the case of external germination, the laboratories infrastructure must provide the seedlings with the necessary quality standards and sizes to be accommodated in the PCU hydroponic system.

In general the PCU shall be used to grow plants throughout the following growth phases:

- growth from a defined plantlet size to maturity
- flowering (if applicable to the crop)
- fruiting (resp. tuberization as applicable to the crop)

The final stage of the plants life cycle, the senescence, might also be carried out in the PCU depending on the experimental objectives. For this stage the same environmental variable range as for the main growth phases (maturation, flowering and fruiting) will be available.

2.1.2 Characterize cultivars

The PCU will be used to characterize several cultivars to be used as food sources in future space exploration. The characterization of crops consists of the analysis of:

- Their physiological response to steady and time variable environmental conditions (including atmosphere temperature, vapor pressure deficit (VPD), light intensity and spectrum, CO_2 atmosphere content, nutrient solution temperature and composition). All these aspects are also addressed in plant modeling and are thus grouped under this point in the following. The measurement protocols for plant modeling are extensive, and some data gathered for this purpose will also be used to assess the overall physiological responses to the environment.
- Their nutritional aspects at different harvest time points (content and quality of carbohydrates, proteins, fats, vitamins, micro and macro elements and antinutritional and pro-nutritional compounds. Potential accumulation of contaminants has to be considered as a parameter for analytical determination (potential factors negatively impacting health such as carcinogens).
- Their processability in view of food preparation and storage processes.
- Their waste (inedible biomass) composition.
- Their resource demands (surface, energy, water etc.). As for the physiological response, the measurements conducted for plant modeling are also used to asses these points.

2.1.3 Validate plant model

One major goal of the PCU is to provide the necessary data to develop and validate a plant model. Ultimately, this physiological model will represent plant growth in response to its environment. The kinetics of plant growth under controlled environment conditions and the dynamic response to changing environmental parameters will be addressed. The model will be based on the elemental mass balance in transient or steady state. The energy balance will be taken into account at plant and PCU subunit level (i.e. metabolic energy and electrical power). The final model will predict the evolution of the following over the plant life cycle, with and without step change of environmental parameters:

- The fresh and dry mass of the whole plant.
- The fresh and dry mass of the edible component.
- The gas and liquid mass fluxes (liquid water and mineral absorption, uptake and release of oxygen, water vapor and carbon dioxide release, etc...).
- As a long term goal, the composition of the different parts (organs root, stem, leaf, fruit, tuber, and edible/inedible) in terms of chemical elements (C, H, O, N, P, S, K, Ca, Mg, Fe) and nutritional compounds (protein, lipid, carbohydrates, etc.) is useful for the plant model itself and for the overall MELiSSA loop mass balance calculations. Since this is a very complex domain, it is not yet clear how far the segregation of the model into different plant subparts will be feasible. Accumulation of certain chemical elements and nutritional compounds in specific plant parts is not yet described for the species involved in this study and will require a lot of basic research. Thus modeling based on empirical data could be envisaged instead.

Plant morphology and development, the influence of the exchange areas and coupling with environmental parameters and the influence of the metabolism are taken into account. The model is built on a simple basis in a first approach. In further steps, more detailed mechanisms are implemented in order to obtain more detailed simulations. The use of empiricism and simplistic phenomenology will be minimized. Explanatory or mechanistic descriptions are favored.

2.1.4 Chamber modeling

The model of the chamber hardware characterizes the fluid dynamic performance of the PCU by investigating and analyzing the air handling loop. Computational Fluid Dynamic (CFD) calculations are the most convenient method to be employed to assess air management in the chamber as they allow an enormous number of virtual measurement probes via simulation. Specific goals of the chamber model are:

- Determine the flow distribution into the air grilles and the plenum.
- Judge the performance of the HVAC system (pressure drops, heat transfer).
- Evaluate the light mapping (spectral bands, intensity).

The physical phenomena taken into account are the convective and diffusive transport of mass via standard Navier Stokes equation and the thermal transport via thermal energy equation and radiation modeling. Hence the CFD equations include the following parameters:

- U, V, W (3 velocity components).
- Pressure.
- Temperature.
- Light intensity.

2.1.5 Test predictive control models

One purpose of developing a physiological plant model is to be able to create a Higher Plant Chamber (HPC) control algorithm based on predictive laws. This predictive control will interconnect the HPC with the MELiSSA loop. Instead of using a black box (empiric) control, physiological laws predict the evolution of the system and hardware parameters are set accordingly. Environmental parameters are thus set dynamically in view of a certain goal. One example would be a dynamic adjustment of CO_2 levels and light intensities depending on the output and input needs of other MELiSSA compartments or setting environmental parameters to obtain a certain amount of food at a certain time.

The MELiSSA Pilot Plant (MPP) comprising all compartments has been built at the University of Barcelona. This pilot plant is the major target for testing these predictive control strategies. The prime target of the PCU is to provide valuable scientific results to move forward with the development of the physiological plant model and to characterize crop performance in view of a life support application. However, to be able to test control strategies on a compartment level, the PCU control system should be flexible enough to accommodate models and to interface with other (virtual) MELiSSA compartments.

2.2 Experimental protocol

This section provides a first overview of the experiments to be performed within the PCU. The level of detail is high enough to allow a correct compilation of requirements and to develop the system design. Detailed experimental protocols will be derived prior to the experimental runs.

2.2.1 Characterize cultivar

As explained in chapter 2.1.1 the characterization of the cultivar relies heavily on post harvest analyses. Some online measurements such as the Net Carbon Exchange Rate (NCER), water consumption/transpiration and oxygen production, primarily used for plant model validation, can also be used to evaluate the overall performance of the plant.

Intermediate biomass sampling possibilities are given only to a limited extent to ensure statistically valid further growth. Post harvest analyses themselves are not considered part of the PCU. The PCU must however deliver the quality and quantity of samples required for these analyses. The overall dimensions of the PCU and thereby the growing area are mainly driven by the required amount of biomass for post harvest analyses. The technical implication of harvesting protocols for further offline analysis are described in chapter 2.2.4.1. The following post harvest analyses are to be performed:

- Nutritional analysis: The edible biomass will be analyzed for nutritional content. The nutritional compounds and chemical elements are thereby characterized and quantified. This is done by destructive measurement after harvest. Optimization of exact harvest times is an important aspect for nutritional composition and processability (see next point). To obtain the evolution of processability and nutritional quality 5 harvest points with a few days to weeks difference are needed towards the end of maturity.

- Food processing tests: The processability of the edible component will be analyzed and the performance of different food processing techniques compared. A focus is thereby set on miniaturizing and integrating food processing equipment. The losses in nutritional content due to processing steps are also taken into account. Sufficient harvest must be available for the full set of nutritional analyses before and after processing. These processing tests will first be performed on commercially available crops. After processing pre-selection and optimization, the hydroponically grown crops will be tested since texture and composition can vary compared to field grown crops. At this stage it is impossible to define minimal harvest requirements for food processing. The currently available testing infrastructure is targeted towards large scale industrial processes. Available experimental milling setups require for example at least 10 kg of grains for processing. These quantities cannot be expected to be grown within the PCU. However, if harvests obtained in bench test setups (the hydroponic growth chambers currently used in the consortium) prove to be of sufficient quality, larger representative harvest quantities could be reached for preliminary processing tests. Last but not least, large industrial processes are not within the scale of a space application. Thus a miniaturization of processing equipment is a major premise.
- Biomass measurements: The produced amount and the quality of different biomass categories will be assessed after harvest. These entail edible and inedible fractions and leaf, stem and root amounts. Besides the total weight (fresh and dry weight) and overall volume (for elements to be stored or further processed) of each category, the chemical composition is also characterized. For the edible biomass these characterization steps imply the above mentioned nutritional analysis and the food processing tests. For inedible biomass this primarily implies the determination of fiber content, including cellulose. It is important to note at this point, that other MELiSSA compartments rely on a proper characterization of waste streams for further degradation. The experimental protocols for fiber analysis are defined in Ref 12 and Ref 13. The amount of dry matter needed for these analyses are very small. Both the acid detergent fiber and the acid detergent lignin tests need only 0.5 grams of dried and grinded biomass. In any PCU design these low inedible biomass yields will be achieved even if several repeats are foreseen. Therefore no design criteria for these parameters are described in more detail in this document. For the sizing of the chamber, harvest requirements concerning edible biomass are an important factor (see chapter 2.3.1).
- Plant architecture: In some cases the progression of plant architecture/geometry over time might be of interest. This includes the overall height of the plant, size of fruit (resp. ears or tubers), the leaf area index (LAI) and possibly branching. The LAI is a dimensionless value defined as the ratio of total one-sided leaf surface of the plants divided by the surface area of the physical growing surface. The overall height of the plant can be measured online with cameras. Branching and LAI however imply destructive sampling.

In the final experimental protocols some of the above described measurements can be combined to avoid several subsequent cultivations if the intermediate harvesting time points can be harmonized. LAI and branching measurements can for example be combined with fresh and dry mass weighing.

2.2.2 *Validate plant model*

The PCU should deliver continuous non destructive measurements of major plant growth parameters and the corresponding environment parameters. A detailed description of online measurements is given in chapter 3.1.3. The main continuous measurements are NCER, evapotranspiration and oxygen production. The environment parameters of interest are:

- Air temperature.
- Total and partial pressures of the main gases (water (VPD), oxygen, carbon dioxide). Other atmospheric hydrocarbons might be of interest at later stages but are not considered for the first steps. Thus no Gas Chromatograph (GC) is implemented directly into the PCU. However sampling ports are available at the correct positions for future extension of the experimental sequence.
- Light intensity and spectral composition.
- Photoperiod.
- Hydroponic solution temperature.
- Nutrient solution pH and Electrical Conductivity (EC).

Besides the online measurements, which can yield a total plant weight increase as a function of time, the evolution of the mass of different plant organs is needed for more advanced plant models taking into account partitioning information. Results of destructive biomass measurements described in chapter 2.2.1 will also be used for the plant model. Experiments may have to be repeated with other sampling intervals since the respective goals are different. The sequential harvest time points for the analyses on nutritional composition and processing of the edible biomass will be in short intervals towards the end of the cultivation. For plant modeling, sequential harvests distributed over the whole growing cycle may be required. As a first estimation 5 intermediate samples are sufficient. If required up to 15 intermediate sampling points can be achieved when harvesting single gullies (15 in total) in just one of the PCU subunits at once. The harvested samples might in this case not be sufficiently large for nutritional analyses but can provide valuable intermediate biomass information for plant model validation. In this case however the statistical reliability is smaller since no triple samplings are taken. Statistical reliability is then only provided by the number of plants in one gully.

2.2.3 *Chamber modeling*

In order to verify the results and fine tune the boundary conditions of the model, the experimental mapping of the PCU must provide the maps of fluid dynamic variables mentioned in chapter 2.1.4.

Moreover, the presence of the plant evaporative load is taken into account by implementing the mass transfer laws of evapotranspiration into the chamber model. Hence to adjust the coefficients of the laws and to test the ability of the model to predict the humidity generated by plants, the mapping of the relative humidity inside the chamber is required.

Within the MELiSSA project a CFD model has been built for the MELiSSA pilot plant (MPP). Up to now, several different models (dry model representing the overall flow properties; wet model taking into account a simplified model of evapotranspiration and O_2/CO_2 mass transfer and a canopy submodel taking into account the plant geometry by applying a simplified porous structure) have been simulated and validated on the HPC1 of the MPP. These will also be used to characterize the fluid dynamic performance of the proposed design of the PCU and provide suggestions on how to improve it prior to construction. The parameters of focus are light, temperature and VPD at plant level and the overall efficiency of flow management. The PCU hardware should provide the possibility to validate those simulations.

2.2.4 Sampling

2.2.4.1 Intermediate biomass samples

For cultivar characterization (chapter 2.1.2) and plant model validation (chapter 2.1.3), biomass samples at different life stages are required to be able to evaluate change in time. Having plants of different life stages in one shared environment might induce unwanted and unquantifiable physiological interactions due to hormones and other substances released to the common atmosphere and nutrient solution. The need for nutrient solution composition changes depending on crop developmental stage also preclude this strategy. Thus all plants must be germinated under the same conditions and inserted into the chamber at the same time.

One possibility is to run several identical cultivations and harvest the whole chamber at different time intervals. This is the simplest method, however it is time consuming and provides large harvest quantities which are not always necessary.

Harvesting plants of one batch at consecutive time points to obtain intermediate samples is also possible. A full cultivation is started, the chamber opened at defined time intervals and plants are sampled. After sampling, the chamber is closed again and the cultivation continues with the remaining plants. Unwanted physiological interactions between plants are not present since all plants contained in one chamber always have the same age. Some online measurements such as the NCER and the transpiration rate will be affected by the opening and the removal of plants. Thus separate experiment runs might be needed for intermediate samplings and online measurements targeted towards mass balances. The control system and the chamber hardware must be resilient enough to balance the sampling interference quickly enough to avoid major physiological responses of the plants e.g. due to atmosphere variation caused by gas exchange with the labs atmosphere or due to thinning of the total foliage.

Intermediate sampling of single plants is not always possible without damaging/disturbing neighboring plants due to root entanglement. To alleviate this, one whole gully can be removed at each sampling point. An empty gully should be placed back to keep the airflow as constant as possible. To avoid long intervention, spare gullies should be available for a rapid replacement. The chamber opening can then be reduced to a few minutes. One full gully is removed and an empty one inserted. For some crops a support structure for the foliage is required to avoid entanglement of plants on neighboring gullies. For larger plants with a thicker canopy the airflow could be changed considerably by the resulting gap. Air will naturally flow where less resistance is present. Thus dead zones could occur within the remaining foliage. The degree of impact will have to be determined through simulations. Deflectors or plant dummies might be needed to keep environmental factors constant.

2.2.4.2 Fluid sampling

At several time points in the experimental protocols sampling of the chamber atmosphere and the nutrient solution will be required. The design of the fluid handling system and the total fluid volumes must take this into account.

2.3 Crop specific design parameters

The main crops are durum wheat, wheat, potato and soybean. Based on literature research and first bench tests 4 cultivars for each crop were selected:

- Durum wheat: Avonlea, Strongfield, Commander, Eurostar.
- Wheat: Fiorina, CH Rubli, Greina, Aletsch.
- Potato: Annabelle, Bintje, Desiree, Innovator.
- Soybean: PR91M10, Regir, Atlantic, Cresir

These cultivars will be analyzed in the PCU after another screening in bench tests. At later stages, other MELiSSA crops can be characterized. These comprise:

- Rice
- Lettuce
- Onion
- Spinach
- Tomato

The PCU is designed with a fairly broad range of environment setpoints and flexible control. An accommodation of the remaining crops will be possible with little modification.

2.3.1 Minimum growing area

The required growing area is driven by the needs for biomass to perform nutritional analyses, processing tests and to quantify mass fractions of edible and inedible biomass. Other analyses such as determination of fiber content and element composition (C, H, N, P, O) to be performed on harvested edible and inedible biomass have far lower quantity requirements (see Tab. 2). Nutritional analyses on PCU grown harvest are crucial. Processing tests can be performed on commercially available harvest for the first tests. At later stages processing tests on hydroponically grown harvest are favorable since the composition (e.g. water content) and texture can vary. Furthermore a second nutritional analysis after the processing and/or storage is required. If processing tests are only done on commercial harvest, smaller quantities of harvest obtained on hydroponic cultures will have to be processed in an analog way to obtain the material for a successive nutritional analysis and to gain certitude on the processing efficiency on hydroponically grown food. Since the PCU will most likely not be capable of providing sufficient harvest for all processing tests, bench test cultivations can also be used.

In chapter 2.1.2 it is specified that for some experiments to determine the optimum harvest time, 5 harvest points with a few days to weeks interval are needed towards the end of maturity for further processing tests and nutritional analyses. The chamber is designed according to these requirements. The experimental protocols for intermediate samplings for plant model validation differ from a technical point of view only in their harvest time points. To avoid long-lasting subsequent cultivations, a staggered harvest is favorable. Therefore the PCU should be sized to provide at least 5 harvests with the required biomass for the analyses. Tab. 2 details the amount of fresh biomass needed for the specific analyses. The requirements for nutritional analysis are taken from Ref 4 and a protocol for a complete nutritional analysis of potato tubers defined by IPL in FC1. An overview of the protocol defined by IPL is given in Tab. 1. The experimental protocols for bread wheat analyses are not yet defined but can be assumed to be similar to durum wheat analyses. The harvest requirements were set to 100 grams to assure sufficient margin compared to the 30 grams required for durum wheat analyses. The large difference in fresh weight requirements for potatoes results from their high water content. For the nutritional analyses requirements the fresh weight is mentioned since the water content is also analyzed in detail. When converting this value to dry weight around 100 grams is obtained which is similar to the dry weights for the other crops.

The requirements for processing tests are still very vague. Since no bench scale equipment is currently available, estimations have been performed based on expert opinion. The values mentioned in Tab. 2 were discussed during several meetings and fixed in the TN 7 review meeting.

The composition (e.g. fiber content) of the inedible biomass does not necessarily need to be measured at several time points. But in any case the inedible biomass produced would also suffice for that. The required amounts for the lignin and fiber content analysis are taken from Ref 12 and Ref 13. The same applies for the element composition of edible and inedible biomass. The quantities required for these analyses are very small compared to the totally produced biomass and even regular intermediate samples will be possible. Tab. 2 summarizes all analyses required on the different biomass fractions and the required amounts of biomass.

Tab. 1 Protocol for nutritional analysis of potatoes as defined by IPL

Potato tuber analysis		3rd revision		2010-01-12	
Analyte		Analysis method (AOAC number if not otherwise stated)	mass of sample needed (DW)	(FW)	
Moisture/ Dry matter		984.25 / 920.151A	**2 g**	**10 g**	
	Ash	923.03	Same sample		
	Na, K	969.23 C	Same sample		
	Ca, Mg, Fe,Zn, Cu, Mn	985.35	Same sample		
	Cl	971.27	2 g	10 g	
Proteins					
	Kjeldahl N	984.13	**1,5 g**	**8 g**	
	Amino acids[1]	Hydrolysis :994.12 HPLC analysis : AccQ-Fluor[2]	1 g	4 g	
Lipids					
	Total (fast & cheap usual method)	ISO1443	**10 g**	**40 g**	
	fatty acids (and total triglycerides)	969.33/996.06	6 g	30 g	
	sterols	994.10	2 g	10 g	
Fibers					
	TDF	985.29	**2 g**	**8 g**	
	resistant starch	2002.02	0,5 g	2 g	
Glucids					
	total, by difference			**0 g**	
	starch	2002.02	1 g	2 g	
	simple sugars	GC method developed in lab	6 g	30 g	
Others …	Vitamins				
	C	EN14130 or *AOAC 984.26*[1]	2 g	10 g	
	B1	942.23	20 g	100 g	
	B5[1]	945.74	2 g	10 g	
	B6[1]	961.15	2 g	10 g	
	B2-B3-B8-B9-B12[1]	vitafast[3]	2 g	10 g	each
	other minerals				
	P	IDF33A [4]	1.5 g	8 g	
	Se	996.16	4 g	20 g	
	Ni, Al, Se and others[1]	990.08 if ICP is available			
	NO_2^-/NO_3^-	968.07	4 g	20 g	
	Solanine, chaconine[1]	997.13	6 g	30 g	
	Anti oxydant activity[1]	ORAC[5]	Still need literature review		
Total		All selected protocols implemented	85.5g / 412g		**100/500**

---

[1] Analytes or methods in italic still need some adaptation work in our lab.

[2] AccQ-Fluor is commercial name for Waters amino acids derivatization / hplc analysis / fluorescence detection http://www.woongki.com/best_product/accqta.htm

[3] Microbiological test by Rbiopharm. No known AOAC method. http://www.r-biopharm.com/

[4] International Diary Federation

[5] Oxygen Radical Absorbance Capacity

Tab. 2 Required amount of biomass in gram fresh weight for each type of analysis

	Bread wheat	Durum wheat	Potato	Soybean
Edible biomass				
Nutritional analysis	100	30	500	60
Processing test	2000	1000	3000	3000
Element composition	max 10	max 10	max 10	max 10
Inedible biomass				
Waste composition test	1	1	1	1
Element composition	max 10	max 10	max 10	max 10

For the initial PCU sizing the yield results of bench tests and other studies are used. This is a worst case estimation since the bench test setups mostly provide less optimal growing conditions. Yield results in the PCU are expected to be superior due to higher range and better control of environmental variables.

For durum wheat, the results of the UoGuelph bench tests are taken. These were performed in closed growth chambers and closely represent yield expectations of the PCU. Both cultivations were performed in technically similar chambers. For the design driving yield, the test with the lowest yield (*Avonlea*) was used to take into account a safe margin of error.

The FC bread wheat bench test were performed at UBern. The results of previously performed bread wheat cultivations in UoGuelph sealed chambers are also taken into account as a comparison. The cultivar used in this previous study is *Norwell*. No major variations in yield are expected for the bread wheat varieties of concern The BT1 results of the UBern bench tests on the *CH rubli* cultivar which matured first yielded maximal 0.42 kg/m^2. On average CH Rubli, Fiorina and Greina yielded 0.40 to 0.41 kg/m2. Greina was limited to 0.3 kg/m2.

These results converge with the results obtained at UoGuelph.

The FC potato bench tests were performed at UGent and UCL. The results of both tests were not satisfactory from a yield point of view due to the experimental protocols applied (too extreme nitrate limitation). Furthermore light levels in both setups are far below the ones which will be achievable in the PCU. Therefore these values are not representative to estimate the potato yields to be expected in the PCU. To estimate these yields (selected value = 2000 g/m^2), a pre-test performed at UGent (2160-2276 g/m^2) and the results of additional hydroponic cultivations carried out by the FC1 consultant HZPC under greenhouse conditions (natural light, all above 2200 g/m^2) are used. These cultivations yielded a much higher harvest compared to the FC bench tests at UGent and UCL. The results of the greenhouse experiments must be applied with caution. Different light intensities and spectrum are measured under natural conditions. The variations in the greenhouse experiments of 2009 and 2008 are explained by the lower incident light flux and a shorter growing period in 2008. The *Innovator* cultivar showed low performance in all cultivations. Depending on the results of a repeat experiment, this cultivar could be replaced for future considerations. The values are only given for the sake of completeness but are not taken into account for the definition of design driving parameters. All cultivations at UGent, UCL and HZPC are based on the same gully system and the same nutrient solution composition. The growing area based on which the yields of UGent and UCL are calculated are worst case estimates. The potatoes were grown sideways and not (as for the other species and HZPC cultivations) on top of the gully lid. The accounted growing area comprises the area of actual plant growth plus the surface taken by the gullies. In the PCU, potatoes will be top-grown. Therefore the respective growing area will shrink and the total yield value increase.

As for the potato bench test experiments, the results of the FC soybean cultivations conducted at UNapoli are not representative for what can be achieved in the PCU due to the experimental protocols applied. For a first estimation Ref 20 is used. The NASA experiment used CO_2 and light levels similar to those which will be available in the PCU and reached a yield of 0.49 kg/m^2 of soybean seeds.

All values given in Tab. 3 are taken from Ref 5 and Ref 2 if not mentioned differently.

Tab. 3 Yield results used for PCU sizing

Species	Cultivar	Location	Chamber	Nr. of plants	Max plant height [cm]	Harvest [g] ****	Growing area [m^2] *****	**Yield [g/m^2]**	Water content [%]	DW yield [g/m^2]	**Design driving fresh yield [g/m^2]**	Inedible dry harvest [g]	**Waste yield [g/m^2]**
Potato	Bintje	UCL	FC BT Walk-in	16	54	546	0.80	683	86.00	96	**2000**	61	76
	Annabelle				52	662	0.80	828	81.00	157		49	61
	Desiree				42	299	0.80	374	83.00	64		104	130
	Innovator				*52*	*283*	*0.80*	*354*	*76.00*	*85*		*36*	*45*
	Bintje	UGent	FC BT Walk-in	16	31	466	0.80	583	75.00	146		33	41
	Annabelle			15	31	511	0.75	681	82.05	122		18	24
	Desiree			16	25	274	0.80	343	75.33	84		40	50
	Innovator			*15*	*26*	*415*	*0.75*	*553*	*73.91*	*144*		*27*	*36*
	Bintje	UGent	Pre-test Walk-in*	6	40	648	0.30	**2160**	78.00	475		69	**231**
	Desiree		Pre-test Walk-in*	7	40	797	0.35	**2276**		501		103	**295**
	Bintje	HZPC	Greenhouse09**	24	73	1984	0.90	**2204**	N/A	N/A		138	**153**
	Desiree		Greenhouse08***	20	N/A	1141	0.75	**1521**	N/A	N/A		77	**103**
			Greenhouse09**	24	89	3998	0.90	**4442**	N/A	N/A		258	**287**
	Annabelle		Greenhouse09**	24	79	4420	0.90	**4911**	84.80	746		234	**260**
			Greenhouse08***	20	N/A	1872	0.75	**2496**	N/A	N/A		104	**139**
	Innovator		*Greenhouse09***	*19*	*25.5*	*663*	*0.71*	*931*	*N/A*	*N/A*		*67*	*93*
			*Greenhouse08****	*20*	*N/A*	*676*	*0.75*	*901*	*N/A*	*N/A*		*52*	*69*
	VanGogh		Greenhouse08***	20	N/A	1774	0.75	**2365**	N/A	N/A		67	**89**
Durum Wheat	Avonlea	UoGuelph	SEC2-Bluebox	N/A	86	2100	5.00	**420**	7.83	387	**420**	N/A	N/A
	Strongfield		SEC2-Bluebox	N/A	84	3800	5.00	**760**	8.17	698		N/A	N/A
Bread Wheat	Norwell	UoGuelph	SEC2-Bluebox	N/A	N/A	2300	5.00	**460**	N/A	N/A	**460**	N/A	N/A
	CH Rubli	UBern	FC BT Walk-in	N/A	85	247,5	0,6	412	E	E		E	E
Soybean	Regir, PR91M10, Atlantic	UNapoli	FC BT Walk-in	N/A	38	N/A	N/A	N/A	N/A	N/A	**486**	N/A	N/A
	cv. McCall	NASA	NASA BPC	N/A	N/A	4860	10.00	**486**	N/A	N/A		N/A	N/A
		******	field grown	N/A	90	N/A	N/A	N/A	N/A	N/A		N/A	N/A

* Growing area per cultivar: 1.5m long x 0.5m wide shelf including gully and side growing foliage; harvest estimate from mixed culture

** Total growing area 2 gullies + trellis system (side illumination)

*** Shorter growing period in 2008

**** Fresh weight for Potato and mature harvest for wheat and soybean varieties (wheat and soybean are mostly dry at harvest)

***** Reference surface areas explained in next chapter

****** Information from a literature study summarized in Ref 2.

N/A Harvest not representative, plant culture with phytopathogenic problems or not measured
E Preliminary estimate on 3 plants + extrapolation – characterization pending
FC BT Walk-in: Walk-in growth chambers used in the Food Characterization project for bench tests. Each partner has his own particular system
SEC2- Bluebox: Closed walk-in growth chambers used at UoGuelph for plant experiments
NASA BPC: Large closed growth chambers used at NASA (BPC = Biomass Production Chamber)

From these values the minimal required growing area can be deduced. The maximal harvest needs from Tab. 2 are divided by the yield estimate given in Tab. 3. The results are presented in Tab. 4.

Tab. 4 Minimum required growing surface

	Bread wheat	Durum wheat	Potato	Soybean
Required surface for one nutr. analysis [m²]	0.22	0.06	0.25	0.12
Required surface for five nutr. analyses [m²]	1.09	0.3	1.25	0.62
Required surface for five nutr. analyses incl. element comp. analysis [m²]	1.20	0.4	**1.275**	0.72
Required surface for one processing test [m²]	4.35	2	1.5	6.17
Required surface for five processing tests [m²]	21.74	10	7.5	30.86
Required surface for five processing tests incl. element comp. analysis [m²]	21.85	10.1	7.525	30.97
Total minimal growing area	**1.275 m²**			

2.3.2 Minimum chamber height

The internal chamber height has to take into account the maximal sizes of all crops and a safety distance to the lamp loft to avoid overheating of the upper plant parts and excessive shading of the lower canopy. The minimal distance between the canopy and the glass will be 20 cm. The maximal sizes of the relevant crops are specified in Tab. 3. Furthermore the height of the gullies must be considered. Assuming a gully height of 10 cm, a maximal plant size of 90 cm and a safety distance of 20 cm, **the total internal chamber height must be at least 1,20 m**.

2.3.3 Atmosphere temperature range

The optimal atmospheric temperature during light and dark periods for FC crop cultivars grown under hydroponic conditions are not readily available in the scientific literature. One goal of the PCU is to determine these. The chosen temperature range should be sufficiently flexible to allow the growth and development of all candidate LSS crops.

Most plants can survive in a temperatures range from above the freezing point to approximately 40 degrees Celsius. However, the exact range depends on the geographical region of origin to which a plant species has adapted. The type of plant assimilation metabolism (in general C3, C4 and CAM) is correlated with the evolutionary adaptation of plant species to their habitat. For each plant species, growth approaches a maximum value over a more restricted temperature range that possibly also depends on growth stage (Ref 18).

Eckart (Ref 11) presented in an overview, derived from former research, five classes of crops based on the maximal growth rate and the required conditions to achieve those rates. The current MELiSSA crops are all C3 plants for which 2 classes were defined:

Class I: The class with the least maximum growth rate (20-30 g/m^{2}day) contains C_3 plants including the MELiSSA crops **potato** and **wheat**.
The optimum temperature range is 15-20°C. The growth range is 5-30°C.

Class II: The second class of C_3 plants with a maximum growth rate of 30-40 g/m^{2}day contains the MELiSSA crops **soybean** and **rice.**
The optimum temperature range is 25-30°C. The growth range is 10-35°C.
Tomato is classified in C3 class I as well as II, indicating the diversity of genotypes among tomato cultivars. Other MELiSSA crops (**onion, table beet, lettuce and spinach**, which are all **C_3** plants) were not mentioned in the table by Eckart (Ref 11).
Based on the paper from Franz et al. (Ref 17), describing optimal growth conditions for **lettuce** (in a hydroponic system), lettuce does not seem to fit in either class I or II. Its optimal growth temperature varied between 25 and 30°C, which corresponds to class II, but its maximum growth rate was only 19 g/m^{2}day, which corresponds more to class I.
Spinach yield in relation to temperature was determined by Lefsrud et al. (Ref 19). In a hydroponic system the maximum fresh weight yield was achieved at 20°C.

Class III: The third class contains C_4 plants (30-60 g/m^{2}day) which are not included in the present MELiSSA crop list (optimum temperature range 30-35°C, millets, sorghum, maize, sugarcane).

Class IV and V: The fourth and fifth classes cover the low temperature range C4 (e.g. also maize) and the CAM plants (pineapple) respectively, which are not relevant for the present choice of crops (optimum temperature range 20-30 and 25-35°C respectively).

Conclusion:
A temperature envelope for optimal growth ranges from 15 to 30°C for C3 species and can be extended to 35 °C when intended to include C4 species. The 15 to 35 °C temperature range includes all temperatures used in FC bench tests during light and dark periods (see Ref 2 and Ref 5).

2.3.4 Atmosphere VPD

As for the temperature, the settable VPD range is defined broad enough to contain the optimal setpoints for each type of crop. In general, the optimal value for plant growth and development is 0.85 kPa. The selectable range is chosen between 0.2 and 1.5 kPa to provide sufficient flexibility in the experimental protocols. The range of 0.2 to 1.5 kPa represents a RH range of 40-90% at a temperature of 20°C. The following table shows the RH for both VPD values at the upper and lower temperature setpoints:

Tab. 5 RH values at the extreme temperature and VPD setpoints

VPD	15°C	35°C
0.2 kPa	88%	96%
1.5 kPa	12%	73%

2.3.5 Nutrient solution temperature

As for the atmosphere temperature no precise nutrient solution temperature range is available in the literature for the relevant crops. However nutrient solution temperature should always be equal or below the atmosphere temperature. This is most critical for potato tuber induction. Therefore the setpoint range for this parameter is 15 to 30°C.

2.3.6 Water consumption per plant per day

The maximal water consumption (including evapotranspiration and gully evaporation) of each crop as determined in plant bench tests is listed in Tab. 6. These values must be used with care since they were obtained at lower light intensities compared to what will be possible in the PCU. Furthermore air velocity and VPD have a high impact on transpiration. The UoGuelph sealed chamber values are a maximum based on evaporation per square meter.

Tab. 6 Maximal total water consumption in bench tests

	Bread wheat	Durum wheat	Potato	Soybean
Water consumption per plant per day (including evapotranspiration and gully evaporation)	50 ml	20 L/m^{2}day	UGent: 63 ml UCL: 125 ml	250 ml
Water consumption per gully	3 liters	N/A	1 liters	3.5 liters
Length of gully	1 m	N/A	1.6 m	0.93 m
Number of plants per gully	60	N/A	16	14

The maximal water consumption will be reflected in the nutrient solution tank and the water reservoir volume. The largest impact of these values on the volumetric design comes into play if condensate is collected rather than returned to the nutrient solution. If condensate from evapotranspiration is recycled back to the nutrient tank, water uptake has less impact on sizing. In all scenarios the reservoirs must be sized to provide at least 3 days of continuous work under maximal load without refilling to overcome week-ends or other work-free days.

2.3.7 Illumination

2.3.7.1 Intensity

Horizontal-leafed species (potato, soybean) light-saturate at lower levels than vertical leafed species (wheat, rice). For **spinach** the potential light saturation point based on fresh weight yield was determined to be 775 µmol/m^{2}s in a hydroponic system (Ref 19). For **wheat** grown at constant 21 °C with elevated CO_2 (1200 ppm), the photosynthetic rate is linearly correlated to light intensity even up to the equivalent of full sunlight (2000 µmol/m^{2}s) (Ref 14). For **rice**, the yield increased with higher photosynthetic photon flux density (PPFD) up to the highest level tested at 1800 µmol/m^{2}s (12h photoperiod; 77.8 mol/m^{2}d) (Ref 16). However in the case of rice the yield efficiency (grams per mole of photons) only increased to 900 µmol/m^{2}s and then slightly decreased at 1800 µmol/m^{2}s.

2.3.7.2 Spectrum

Depending on the plant species, the red/blue and red/far-red ratios are parameters to take into account for optimal growth. UV light will be mostly blocked by a lamping loft barrier, but can be an important parameter, also for nutritional composition.

Growth abnormalities, especially intumescence/oedema are signs of a spectral imbalance. Mitigation possibilities should be foreseen in the lighting system design for future upgradability: provisions for increasing UV, far-red (typically low in artificial illumination settings).

2.3.8 Air velocity

Air velocity has two impacts on the plant growth:

On one side sufficient convective gas exchange must be provided to allow a good mixture of the atmosphere and to avoid stagnating zones within the foliage. A too low air velocity will limit the plant growth by suboptimal mass transfer. Under artificial light condition, the airflow is also important to provide sufficient cooling from the lamps radiative heat load.

On the other side air velocity puts a mechanical stress on the plants structure. Too high air velocities will inhibit optimal growth.

The selected range (up to 0.5 m/s) of air velocity available in the PCU takes into account both factors. More information is found in chapter 4.3.8.

2.4 Definition of levels and surfaces

2.4.1 Leaf level

The leaf level is defined as the maximal fully grown height of all crops measured from the top of the gully lid (see Tab. 3).

Here leaf level is defined as 90 cm from the top of the gully.

2.4.2 Mid canopy level

The mid canopy level is defined as the center of leaf carrying volume of a plant at a fully grown stage. For wheat species the mid canopy level is half the size of the fully grown plant. Actual mid canopy is crop dependent.

Here mid canopy is generally defined as 45 cm from the top of the gully.

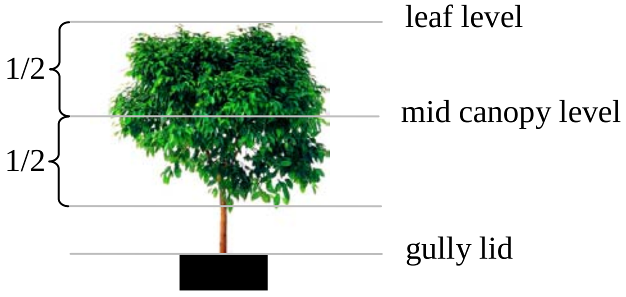

Fig. 1 Leaf and Canopy level

2.4.3 Gully surface

The gully surface area represents the internal bottom surface area of the gully. The surface area is an important consideration in nutrient film layer thickness calculations (root amount and inclination will also have an influence on the holdup and the layer thickness).In airflow design both, the bottom surface and the lid surface of the gully are important considerations as the homogeneity and velocity are closely correlated with these values and the inter gully space.

2.4.4 Growing surface

The growing surface is defined as the area of the growth chamber where foliage is present at any given time of the cultivation in a top down view. The growing area can vary from crop to crop depending on the plant horizontal dimensions and the distance between individuals. At the beginning of plant growth, free space between individuals will be considerable. At later developmental stages the canopy will cover the entire growing surface.

Depending on the size of the chamber, the whole surface area of the chamber can be considered as the growing surface. To avoid entanglement of plants on neighboring gullies (important for intermediate sampling, see chapter 2.2.4.1), plants should be confined in their growth by fences or foils between the gullies (see Fig. 2). It is important to note at this point that this is not necessary for all crops. The risk of foliage entanglement is very low for wheat species but is high for potato and soybean. Thus a fence system is not needed for all crops and experimental protocol and can easily be added to the PCU for specific experiments.

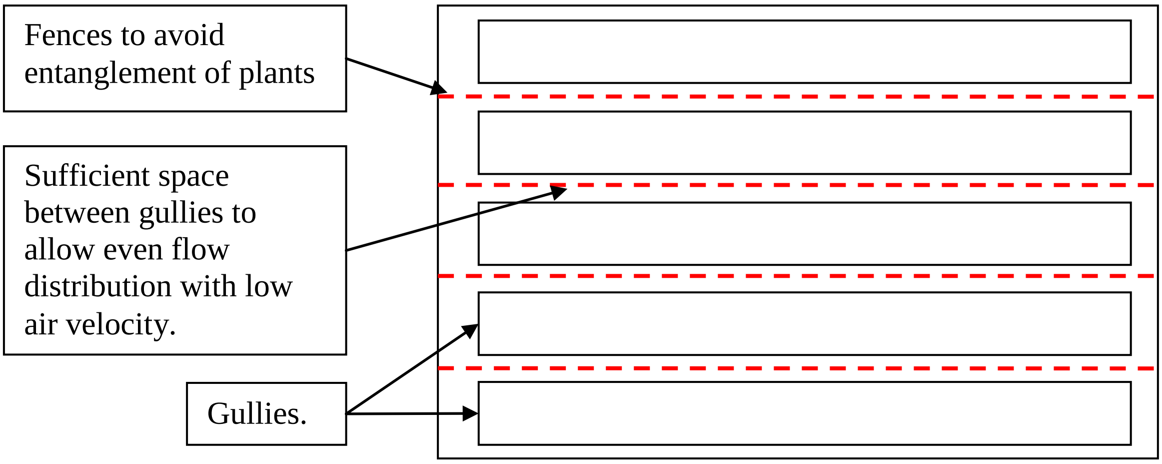

Fig. 2 Schematic of gully arrangement and fences

3 System requirements

3.1 Functional requirements

This section defines the top level functionality requirements. All sub-system requirements are then derived from these functional requirements. This document does not define the detailed experimental protocols needed to obtain the scientific objectives of the PCU. Here only the actual hardware requirements are specified. However several requested experimental protocols were taken as a basis to derive the PCU requirements (see section 2.2). For a better traceability and understanding of these derived functional requirements, the logical structure of the scientific objective is kept.

3.1.1 Grow crops

SYS-FUNC-GRO-1: The PCU shall allow crop growth in a sealed environment in hydroponic culture under artificial illumination.
Rank 1

SYS-FUNC-GRO-2: The PCU shall accommodate pre-germinated plantlets or plants germinated within the chamber.
Rank 1

SYS-FUNC-GRO-3: Post harvest treatment shall be done in separate equipment (not within PCU).
Rank 1

SYS-FUNC-GRO-4: The PCU shall be amenable to batch production.
Rank 1

SYS-FUNC-GRO-5: The PCU shall be capable of providing staggered harvests of single gullies.
Rank 1

SYS-FUNC-GRO-6: The PCU shall be capable of keeping all atmospheric parameters (atmosphere T, VPD and CO_2, O_2, ethylene concentrations) within the boundaries and the homogeneity and stability defined in chapter 4.3.
Rank 1

SYS-FUNC-GRO-7: The PCU shall be capable of keeping all nutrient solution parameters constant (nutrient solution T, pH, EC) within the boundaries defined in chapter 4.1.
Rank 1

SYS-FUNC-GRO-8: The PCU shall be capable of keeping all illumination parameters constant (intensity and spectrum) within the boundaries and the homogeneity defined in chapters 4.2.
Rank 1

SYS-FUNC-GRO-9: The PCU shall be capable of gradual temperature and VPD changes (e.g. continuous rise in T within a defined time period) as defined in chapter 4.3.10.
Rank 1

3.1.2 Characterize cultivars

SYS-FUNC-CHR-1: The PCU shall provide sufficient biomass for the nutritional analysis of the selected cultivars.
Rank 1

SYS-FUNC-CHR-2: The PCU shall provide sufficient biomass for processing tests on the selected cultivars.
Rank 2

SYS-FUNC-CHR-3: The PCU shall provide sufficient biomass for the composition analysis of waste products on the selected cultivars.
Rank 1

The required amounts of biomass are specified in Tab. 2. The equivalent surface areas are defined in Tab. 4.

SYS-FUNC-CHR-4: The PCU shall give the option to harvest 5 sequential samples compliant to SYS-FUNC-CHR-1, SYS-FUNC-CHR-2 and SYS-FUNC-CHR-3 with a few weeks difference toward the end of maturity.
Rank 1

3.1.3 Validate plant model

For development and validation of the plant model, cultures in several different environmental conditions are needed. Only with a set of complete growth cycles at different setpoints (e.g. different atmosphere temperature or CO_2 levels), can the range of valid simulations be extended. Furthermore experiments with changing environmental conditions at different growth stages are needed to analyze the dynamics of plant reaction to changes (e.g. loss of nutrient solution circulation or temperature increase/decrease).
For data processing it is advantageous to have temporally synchronized measurement logs. It is however not absolutely necessary. If measurements of different variables have a slight temporal offset, the log files can be post processed.

SYS-FUNC-PM-1: All measurement logs defined in chapter 3.1.3 with the same measurement frequency shall be synchronized.
Rank 3

The following measuring parameters are needed:

3.1.3.1 CO_2 assimilation

The NCER will be calculated based on the CO_2 chamber atmosphere content and the added amount of CO_2.

SYS-FUNC-PM-2:	The CO_2 content in the chamber atmosphere shall be logged continuously with a frequency of at least 1 per 10 seconds and an accuracy of at least ±10 ppm. Rank 1
SYS-FUNC-PM-3:	The CO_2 measurement shall be representative for the main chamber volume (within main air flow). Rank 1
SYS-FUNC-PM-4:	The added amount of CO_2 to the chamber atmosphere shall be logged continuously with an accuracy of at least ±1% (measurement frequency depending on injection strategy; for continuous injection, a frequency synchronized to the atmosphere CO_2 content measurement is favorable). Rank 1
SYS-FUNC-PM-5:	The NCER shall be calculated and logged continuously with a time increment of at least 5 min and accessible through the HMI. Rank 2

An online calculation is not absolutely necessary. For plant modeling the CO_2 data gathered in the PCU will be post processed. However implementing a preview into the HMI is simple and does not imply large budgets.

Bacterial growth in the nutrient solution can influence the CO_2 mass balance. It is uncertain whether the impact of this mass transfer is relevant for the overall NCER. The general consensus of the FC scientific committee is that the CO_2 contribution from the nutrient solution to the overall mass balance is of low relevance due to the high plant metabolism. Nevertheless the PCU will be designed with a hydroponic system which has the capability to be retrofitted to a closed system to be able to perform mass balances (for CO_2 and other) on the root zone (gullies) separately from the shoot zone (chamber). A proper design of such a system will however require further research, development and testing (see chapters 4.1.4 and 4.1.6).

SYS-FUNC-PM-6:	CO_2 mass transfer between the chamber atmosphere and the nutrient solution shall be quantified (accuracy at least ±10%) and logged with a frequency of at least 1 per 10 seconds. Rank 3

3.1.3.2 Biomass evolution

As described in chapter 2.2.4.1, intermediate samplings are also required for plant modeling purposes. To achieve this, measurement of biomass ratios (edible/inedible) and determination of total foliage surface area is needed at various time intervals. In this case, the required harvest quantity per sample is not necessarily driven by total biomass as it is the case for the characterization objectives. Nevertheless for the sake of simplicity, these are kept the same. Sampling and frequency is dependent on the experiment protocol employed. As for the characterization samplings, complete sampling of one whole gully at each interval is favorable to avoid disturbing neighboring plants. Statistical reliability by the number of sampled individuals is given in any case when the characterization requirements concerning the biomass harvest are met.

For modeling purposes 5 intermediate sampling points are needed. However the sampling intervals defer from the characterization requirements. For plant modeling 5 measurement points distributed over the whole plant life cycle are necessary (in contrary to 5 harvest points with a few weeks interval at the end of maturity for characterization purposes). Thus two separate cultivations are necessary for both measurements. Up to 15 samples will be possible if each PCU subunit is harvested at different time points (3 times 5 gullies).

SYS-FUNC-PM-7: The PCU shall give the option to harvest 5 subsequent samples (i.e. one whole gully in each subunit at once) or 15 subsequent samples (i.e. one gully in one subunit at a time) distributed over the whole plant growth cycle.
Rank 1

3.1.3.3 Online biomass determination

At the current stage the plant model relies on NCER to estimate biomass increase. For a basic model this is sufficient. More complex algorithms might however require both the assimilated CO_2 and the actual biomass increase. To minimize destructive sampling during growth and development, the real weight of the plants during the experiment can be calculated based on the weight of the whole gully system. A tray weighing the whole gully is a simple system with low budget implication. It will not be implemented in the first PCU design. However a weighing setup should be implementable at later stages.

Online biomass weighing is accurate only if the flow in the gully is stable and water holdup due to root growth is quantifiable. A possible solution is the determination of the water holdup both, without roots and after harvest with fully developed root tissue. To obtain water holdup during the experiment, linear or logarithmic interpolation can be used. Furthermore changes in liquid flowrate have to be noted and the dry weight recalibrated. The accuracy of water holdup quantification will be determined in bench tests.

SYS-FUNC-PM-8: The PCU structure shall be capable of being retrofitted with a system for real time gully weighing.
Rank 3

3.1.3.4 Plant transpiration

In a sealed chamber the leaf transpiration is measured at chamber level. Several measurements are required to set up a water balance on the system to calculate transpiration. Evaporation from hydroponic subsystem falsifies the measurement and must therefore be quantified. A simple solution is to measure the evaporation rate by running the chamber without plants prior to the experiment or to measure the baseline evaporation at the beginning of the experiment when the small plantlets were inserted.

SYS-FUNC-PM-9: Each addition of water (also through pH and nutrient stock solutions) to the liquid tank shall be logged with its volume (accuracy at least ±1 ml) and time point.
Rank 1

SYS-FUNC-PM-10: The atmosphere RH shall be logged continuously with a frequency of at least 1 per 10 seconds and an accuracy of at least 5% RH.
Rank 1

SYS-FUNC-PM-11: The VPD measurement shall be representative for the main chamber volume (within main air flow).
Rank 1

SYS-FUNC-PM-12: The amount of water condensed from the atmosphere shall be logged with its volume and time point (e.g. tipping bucket). The overall measurement accuracy shall be at least 5% from the total condensate mass flow.
Rank 1

SYS-FUNC-PM-13: The amount of water added to the atmosphere shall be logged with its volume and time point. The overall measurement accuracy shall be at least 5% from the total water addition mass flow.
Rank 1

Manual removal or addition of water (sampling etc.) from the nutrient solution will not be logged automatically. These have to be noted manually and incorporated into mass balance calculations externally.

3.1.3.5 Oxygen production

SYS-FUNC-PM-14: The O_2 concentration in the chamber's atmosphere shall be measured continuously with a frequency of at least 1 per 10 seconds and a precision of at least 0.1% and an accuracy of ± 1.0%.
Rank 1

SYS-FUNC-PM-15: The O_2 measurement shall be representative for the main chamber volume (within main air flow).
Rank 1

SYS-FUNC-PM-16: The O_2 sensors shall be able to be recalibrated at any time during the growth and development of the crop.
Rank 1

SYS-FUNC-PM-17: The O_2 concentration in the nutrient solution shall be measured continuously with a frequency of at least 1 per 10 seconds and an accuracy of at least ±1% of the oxygen setpoint.
Rank 2

Keeping a precise oxygen setpoint is not required. It is sufficient to keep oxygen permanently below a certain limit. To avoid high concentrations as observed in previous experiments at UoGuelph, an oxygen removal system is needed. Oxygen can either be removed continuously or periodically when reaching a threshold. The tolerable oxygen limits are defined in chapter 4.3.6.2. According to the oxygen removal strategy the removed amounts must be logged periodically or continuously. Despite the fact that the oxygen content in the chamber may vary, an accurate measurement of the total produced oxygen is important.

SYS-FUNC-PM-18: The time and amount of O_2 removed from the chamber atmosphere shall be logged (continuously or periodically according to removal strategy) with an accuracy of at least ±5% of the totally produced oxygen per time.
Rank 1

The chamber level mass balance could also be disturbed by the dissolved oxygen in the added nutrient solution or water. However, since the solubility of oxygen in water is quite low (10 mg/L for fresh water at 1 bar (total pressure of air) and 15°C), the total amount of oxygen added to the chamber from these external sources does not ad considerable amounts to the mass balance (max. 2 grams O_2 for 200 liters of saturated water).

SYS-FUNC-PM-19: All O_2 added from an external source either to the chamber atmosphere or to the nutrient solution (e.g. in a dissolved state in the stock solutions) shall be below 1% of the total oxygen content of the chamber at ambient conditions. If a larger addition cannot be avoided, it shall be quantified with an accuracy of at least ±1%.
Rank 3

The oxygen mass balance is also affected by internal mass transfer between the liquid and the gas phase (e.g. oxygen dissolving from the chamber atmosphere to the nutrient solution due to nutrient solution aeration or bacterial oxygen consumption). As for the CO_2 balance, the general consensus of the FC scientific committee is that the O_2 contribution from the nutrient solution to the overall mass balance is of low relevance. Here as well, sealing of the hydroponic system (see chapters 4.1.4 and 4.1.6) from the chamber atmosphere will allow to establish mass balances.

SYS-FUNC-PM-20: O_2 mass transfer between the chamber atmosphere and the nutrient solution shall be quantified (accuracy at least ±10%) and logged with a frequency of at least 1 per 10 seconds.
Rank 3

3.1.3.6 Ethylene production

SYS-FUNC-PM-21: The PCU shall be equipped with an online ethylene measuring device.
Rank 1

SYS-FUNC-PM-22: The ethylene content in the chambers atmosphere shall be measured on an hourly basis with an accuracy of at least ±1 ppb.
Rank 1

SYS-FUNC-PM-23: The ethylene measurement shall be representative for the main chamber volume (within main air flow).
Rank 1

3.1.3.7 Plant architecture

The plant model may require the evolution of total height of the plants and fruit sizes for future implementation. This point is still unclear and can only be assessed when more detail is known about model development. Destructive measurements will provide a certain amount of data. However continuous measurements could become interesting at later stages.

The height of the plant can be monitored with horizontally oriented cameras. For budget and complexity reasons it is most likely favorable to use an array of fixed cameras instead of one (robotic) moving camera since no high performance cameras are needed (webcam type). To obtain the real height of the plants, the camera is calibrated once and the pictures are post processed by external software. At advanced growth stages it could become difficult to measure each plant separately. Nevertheless, average values for the whole chamber will provide a good estimate. The height measurement system can be retrofitted as these measurements are not absolutely necessary in the near future.

For potatoes a camera system inside the gullies is also needed to monitor tuber growth. To avoid algae growth, NIR LED strips are used within each gully. The LEDs are only turned on for a short period of time while taking pictures (approximately once per day). An array of NIR cameras is placed along the gully lid covering the whole gully bottom surface. Both, the LED array and the camera must be waterproof (splash proof). As gully monitoring is only required for potatoes, the PCU must only provide the necessary interface structure (e.g. cables and connectors). The monitoring system itself will be installed by the partner who is in charge of potato analysis. This system can however also be used for other crops to visualize the root quantity if required.

SYS-FUNC-PM-24: The PCU shall provide the option to install a vertically oriented camera array to measure the overall height of the plants.
Rank 2

3.1.3.8 Leaf area index

The leaf area index cannot be measured online since the total surface of all leaves is needed. Thus destructive sampling is necessary. The leaf area measurements can be done simultaneously with the other biomass measurements described in chapter 3.1.3.2.

3.1.3.9 Atmosphere temperature

SYS-FUNC-PM-25: The chamber air temperature shall be logged continuously with a frequency of at least 1 per 10 seconds and with an accuracy of at least ±0.1°C.
Rank 1

SYS-FUNC-PM-26: The temperature measurement shall be representative for the atmospheric temperature at plant level.
Rank 1

More temperature sensors might be needed for control purposes. This addresses only the scientifically relevant data of temperature at plant level. The requirements for temeperature control are given in chapter 4.3.2.

3.1.3.10 Nutrient solution composition

During some experiments a detailed analysis of the nutrient solution composition is needed to calculate nutrient uptake but may also be valuable to characterize root exudates. A full analysis of the nutrient solution composition may not be needed weekly, but the possibility should be given to address special aspects/problems. The hardware to analyze the samples is not included in the PCU setup. Specific analyzers have to be provided externally.

SYS-FUNC-PM-27: The possibility of weekly sampling of nutrient solution for further composition analysis shall be given.
Rank 1

SYS-FUNC-PM-28: The possibility of sampling up to 1000 ml per sample shall be given.
Rank 1

SYS-FUNC-PM-29: The chamber functioning shall not be affected by the removal of the maximal sampling volume.
Rank 1

Each volume sampled from the nutrient solution is to be taken into account manually for the overall mass balance (see chapter 3.1.3.4).

3.1.3.11 Nutrient solution temperature

SYS-FUNC-PM-30: The nutrient solution temperature shall be logged continuously with a frequency of at least 1 per 10 seconds and a precision of at least 0.1°C and an accuracy of at least ±0.5°C.
Rank 1

SYS-FUNC-PM-31: The nutrient solution temperature measurement shall be representative for the liquid in the gullies.
Rank 1

3.1.3.12 Light properties

Variations in light intensity can affect CO_2 uptake. Therefore a continuous measurement is required. This is not to be confounded with initial homogeneity and intensity measurements for chamber model validation or between experiments. These will require more measurement points at different distances from the lights. The herein described measurements monitor the light quality during an experiment and are thus conducted continuously but only at few representative positions.

SYS-FUNC-PM-32:	Light intensity shall be logged continuously with a frequency of at least 1 per 10 seconds and an accuracy of at least ±10 µmol/m²s. Rank 2
SYS-FUNC-PM-33:	The light intensity measurement shall be representative for two locations (center and border of plant growing area) at leaf level (see chapter 2.4.1). Rank 2

3.1.4 Verify chamber model

As stated in chapter 2.1.4 a CFD model of the PCU will be used to simulate all relevant parameters and to characterize the fluid dynamic performance of the proposed design. The PCU shall be designed flexible enough to accommodate all sensors required for parameter mapping. This mapping is done prior to experimental usage. Thus the sensors do not need to be present during experiments.

The spare ports used for specific experimental protocols can be used for mapping related sensors if not needed for the overall chamber functioning (e.g. camera ports are not necessary for mapping). The ports assigned to fixed chamber sensors (e.g. HVAC pressure sensors) cannot be used for mapping as these sensors are used in parallel to provide input for the mapping activities and to correlate the measured data.

Similar mapping activities have been performed on the MPP. More details on the procedures applied there are available in Ref 9 and Ref 10. For the PCU hardware design, only the number of sensor ports required for the mapping activities must be taken into account. These are specified in the following:

SYS-FUNC-CM-1:	The PCU shall give the possibility to map all parameters to validate the chamber model as defined in Ref 9. Rank 1
SYS-FUNC-CM-2:	The PCU shall provide 5 ports for T/RH sensors for the mapping activities. Rank 1
SYS-FUNC-CM-3:	The PCU shall provide 5 ports for hot wire anemometers for the mapping activities. Rank 1

3.2 Performance requirements

3.2.1 Reproducibility

It was decided to build each PCU composed as a set of three independent chambers together as one set (see Glossary for naming definitions). This gives the advantage of a high degree of flexibility in the system. Three parallel experiments with the same setpoints can be performed to obtain statistical reliability or high harvest quantities. On the other hand three parallel cultivations with different environmental setpoints in each PCU subunit are also possible. Due to the high homogeneity and The number of three was chosen as a compromise between statistical reliability, flexibility and technical complexity.

SYS-PERF-REP-1: Each PCU shall be composed of three separate and independently controlled subunits.
Rank 1

SYS-PERF-REP-2: Each gully shall be sized to contain at least 10 individual plants at full occupation.
Rank 1

SYS-PERF-REP-3: To ensure the statistical reproducibility of the system, the illumination homogeneity requirements defined in chapter 4.2.5 shall be met.
Rank 1

SYS-PERF-REP-4: To ensure the statistical reproducibility of the system, the atmosphere homogeneity requirements defined in chapter 4.3.9 shall be met.
Rank 1

SYS-PERF-REP-5: To ensure the statistical reproducibility of the system, the nutrient solution requirements defined in chapter 4.1.5.2 shall be met.
Rank 1

3.2.2 Condensation

Condensation on cool chamber parts in direct contact with the chamber atmosphere must be minimized for correct water mass balances and hardware protection. The dew point is defined by the RH, T and pressure present at a certain place in the chamber. Condensate collected from the cooling unit shall be quantified as defined in chapter 3.1.3.4. When operating with normal parameters, no surface temperature inside the chamber and the HVAC system (except the cooling coil) shall fall below the dew point.

SYS-PERF-CON-1: Condensation shall only take place in dedicated A/C equipment.
Rank 1

3.2.3 Microbial cleanliness

For the design of the HVAC and nutrient delivery system dead zones and zones with low mass exchange shall be avoided to minimize bacterial growth and fouling.

SYS-PERF-MIC-1:	All parts and volumes in direct or indirect contact with the chamber internal environment (by atmosphere or liquid connection) shall be cleanable and sterilizable. Rank 1
SYS-PERF-MIC-2:	All parts of the PCU which require regular cleaning shall be easily accessible. Rank 1

3.2.4 Response time

SYS-PERF-RESP-1:	The chamber shall be capable of reaching each user defined environmental state from nominal environmental conditions as specified in chapter 3.4 within two hours. Rank 1

For changing internal parameters due to intermediate sampling or door opening the following requirements must be met:

SYS-PERF-RESP-2:	The chamber shall be capable of stabilizing the chamber internal environmental parameters to its previous values within 30 minutes after (short <30 min) user interventions. Rank 1
SYS-PERF-RESP-3:	The response times of the chamber shall be compliant with the dynamic chamber atmosphere adaptation requirements specified in chapter 4.3.10. Rank 1

3.3 Physical requirements

3.3.1 *Mass*

The mass design is relatively flexible since no mobile application is envisaged. It is only limited by the specifications of the laboratory and the delivery approach. The following table lists the mass restrictions of the building floors in which the PCUs will be installed. The primary facilities are at UoGuelph and UGent. Possibly PCUs will also be installed at UNapoli and UBern at later stages. In the case of UBern, the PCU will not be accommodated in the current laboratories due to size restrictions. If an installation at UBern is envisaged, new facilities will be allocated specifically for this purpose. The PCU specifications will then be used as selection criteria. Thus no restrictions on the physical requirements for the PCU are set for UBern. UNapoli could also not deliver the required input. If an installation in UNapoli laboratories is envisaged, an adequate facility will have to be chosen. At UoGuelph the PCUs will be located on the ground floor. Consequently no mass restrictions concerning the floor and elevators are given.

Tab. 7 Load restrictions of the facility building floors

	UGent	UoGuelph
Maximal allowed load in the center of the room [kg/m^2]	500	N/A
Maximal allowed load next to a wall [kg/m^2]	500	N/A

SYS-PHYS-MAS-1: The total PCU weight per ground area including all pieces of equipment and liquids shall be equal to or below 500 kg/m^2.
Rank 1

For transport and delivery to UGent three options are available:

- The PCU subunits (or disassembled parts) are carried up to the 2nd floor with an elevator. The elevator has a mass restriction of **1425 kg**. However to use this elevator, several narrow corridors have to be passed. The dimensions of the corridors and the elevator are given in chapter 3.3.2.2. Furthermore three steps have to be passed to reach the elevator. This could be done with a fork lift.
- The PCU subunits are delivered through a window at the end of the corridor where the laboratory is situated. The transport through the final corridor is easier compared to the elevator scenario since less corners are present and the corridor is wider. However a window has to be unmounted and a crane rented. In this delivery scenario no direct mass restriction is given. A crane rated for the subunits mass will be chosen.
- The PCU could also be inserted through a window in an office in front of the laboratory. This gives the advantage of avoiding a narrow corner which limits the total PCU depth. However the PCU must be tilted which might have an impact on the structural design of the chambers and mass restrictions for delivery.

The delivery scenarios are presented in more detail in the next chapter.
Ongoing renovations at UGent will oblige to move the PCU setups to a different laboratory around 2013. First the PCUs will be installed in the old laboratories in the 2nd floor. A few years later the PCUs will be moved to a newly renovated laboratory on the 6th floor. Unfortunately final construction plans for the new building layout are not yet fixed. Thus the PCU dimensions will have to be submitted to the responsible entity to take into account for the new laboratory layout.

SYS-PHYS-MAS-2: If a delivery through the elevator is chosen, the transportable (packed or structurally supported e.g. wheels or pallet) PCU subunits or the disassembled parts shall have a dry weight equal or below 1425 kg or be delivered in parts with a weight compliant to this value.
Rank 1

For the insertion of the (packed) subunit elements through the window (either tilted or upright), a fork lift or crane will be needed. The packaging and/or the structure of the PCU elements must take this into account

SYS-PHYS-MAS-3: The packaging and/or the structure of the delivered PCU elements shall be stiff enough to avoid irreversible torsion and bending of the PCU elements.
Rank 1

3.3.2 Volume

3.3.2.1 Internal volume

The internal volume is defined by the functional requirements (chapter 3.1). The height of the chamber is determined by the limit of heat load on the plants. Despite the fact that a separate lamp loft is used, the tempered glass will heat up and direct contact must be avoided.

SYS-PHYS-VOL-1: The internal volume shall be sized to comply with all functional requirements.
Rank 1

SYS-PHYS-VOL-2: The free headspace (defined as the distance between the leaf level (see chapter 2.4.1) and the lamping loft glass) shall be at least 20cm for the largest crop at maximal size.
Rank 1

The maximal sizes of each crop as determined in bench tests are listed in Tab. 3.

SYS-PHYS-VOL-3: The growing surface area of the PCU shall be at least 1.56 m^2 large.
Rank 1

The value of 1.56 m^2 results from the minimal value needed to meet the biomass analysis requirements as explained in chapter 2.3.1 (1.25 m^2) plus a 25% margin for subsequent crop testing. Larger values are possible if other factors necessitate this.

3.3.2.2 External volume

The external dimensions are limited by logistic aspects (transport) and the final assembly site (laboratory). In the case of UoGuelph, only the entry door to the laboratory is limiting. This door has a **height of 230 cm and a width of 170 cm**. The laboratory itself and the access route are sufficiently large.

As described above, UBern will have to acquire new premises if a PCU is to be installed. Thus no restrictions are present on this side at the moment. Similarly UNapoli could not give details on local limitations since an installation is not yet sure.

For UGent several logistic limitations are given by the premises. As described earlier, the chambers will first be installed in a laboratory on the 2nd floor. A few years later the laboratory will be moved to a newly renovated laboratory on the 6th floor. As for the mass restrictions no clear statement can be made on the geometrical properties of the new lab. Thus the move to the new labs will have to be planned in the future. No PCU requirements can be set for this case at the moment. In the following the path from the building entrances to the first installation place is detailed for three delivery scenarios:

<u>Delivery with elevator:</u>

1. 3 steps: total 50 cm high and 70 cm deep.
2. Entry door: 155 cm wide, 200 cm high.
3. Elevator: 120 cm wide, 180 cm deep, 200 cm high.
4. Door: 140 cm wide, 200 cm high.
5. Corridor: 110 cm wide.
6. From here on, the same path as for the window entry at the end of the corridor is to be taken (from point 3 on).

SYS-PHYS-VOL-4: If a delivery through the elevator is chosen, the transportable (packed or structurally supported e.g. wheels or pallet) PCU subunits or the disassembled parts must not exceed the following sizes: 200 cm high, 180 cm deep and 110 cm wide.
<u>Rank 1</u>

<u>Delivery through the window at the end of the corridor:</u>

1. Crane to the 2nd floor.
2. Window: 170 cm wide (taking into account the radiator), 240 cm high. The window is flush with the floor. No steps are present once the window is removed. See Fig. 3.
3. Corridor: 160 cm wide.
4. Corner to get into the lab. See Fig. 4.
5. Door into the lab: 115 cm wide, 200 cm high. By removing the upper part of the door, the total height can be increased to 250 cm. See Fig. 5.

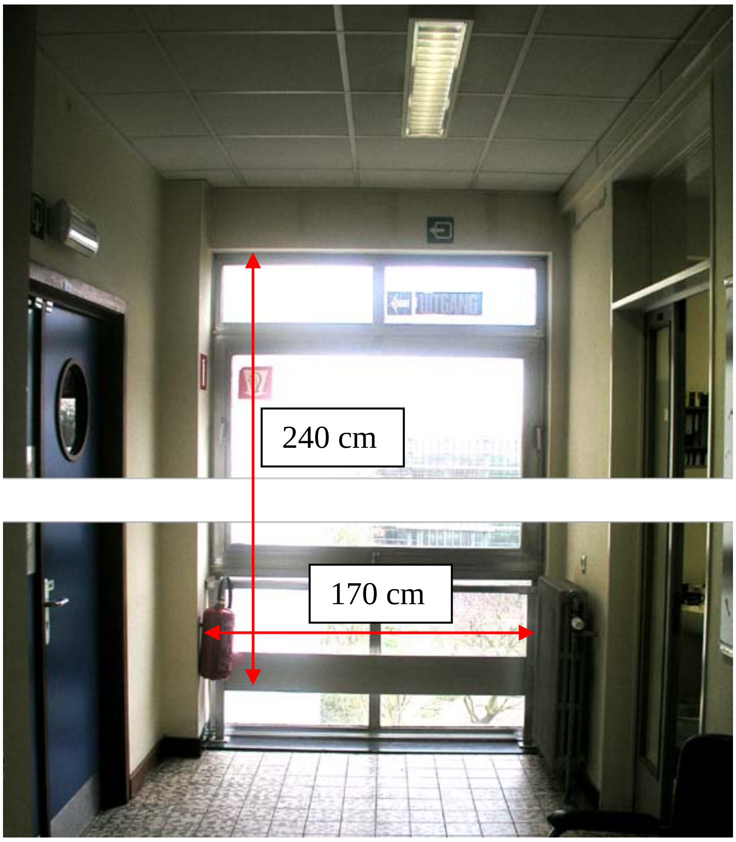

Fig. 3 Access window through the corridor

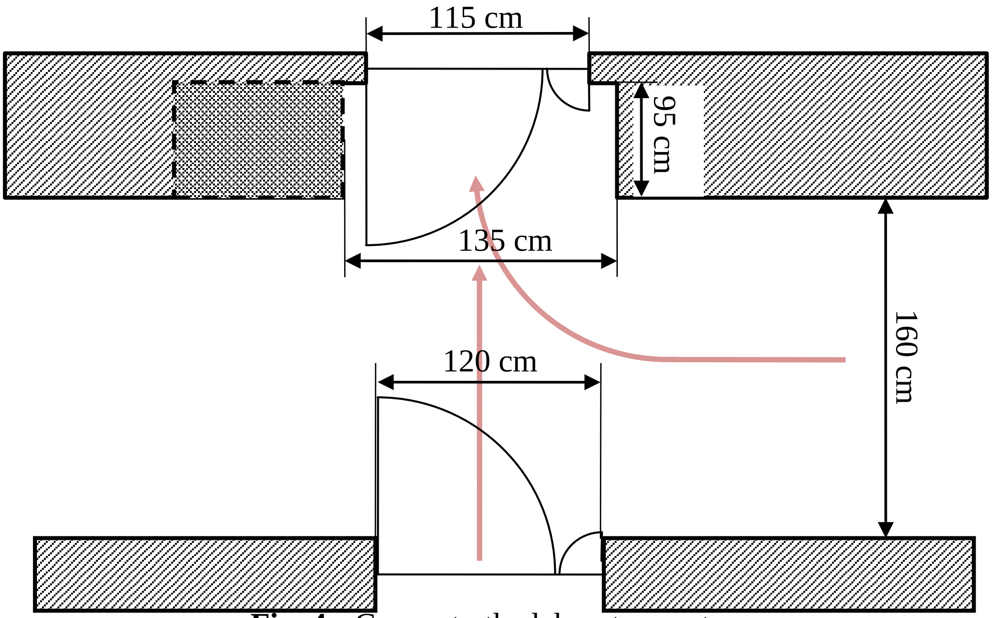

Fig. 4 Corner to the laboratory entry

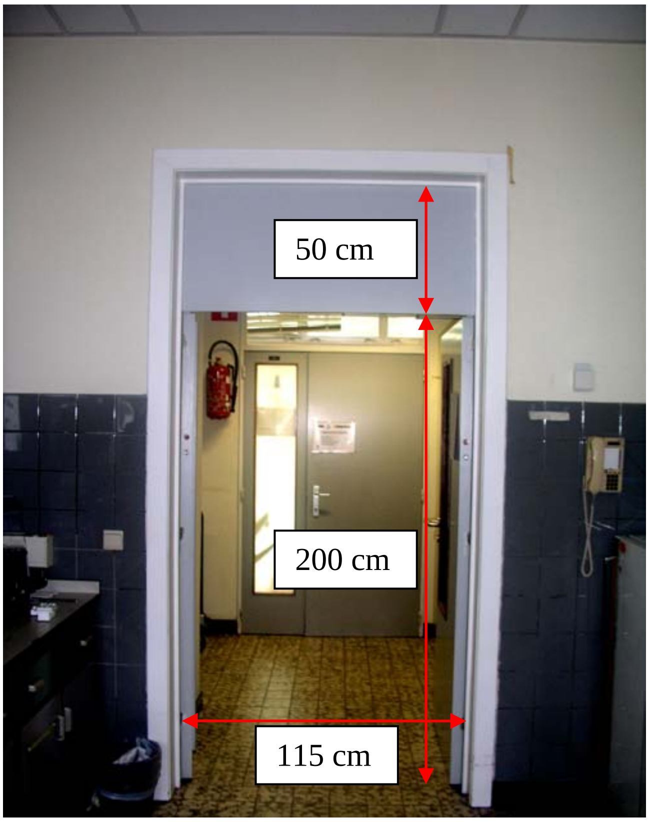

Fig. 5 Door to the lab as seen from inside

The corner to the labs entry is limiting the depth of the PCU subunits. Assuming a width of 110 cm, the maximal depth is 195 cm (taking into account 5 cm margin). The preliminary design of the PCU is 230 cm deep. The dashed square in Fig. 4 represents a fixed wall closet which could be removed by tearing down one wall. The wall is not a supporting structure thus removing is possible without complicated modifications. The PCU subunits can then be inserted in one piece.

SYS-PHYS-VOL-5: If a delivery through the window at the end of the corridor is chosen and the wall closet is removed, the transportable (packed or structurally supported e.g. wheels or pallet) PCU subunits or the disassembled parts shall not exceed the following sizes: 240 cm high, 250 cm deep and 115 cm wide.
Rank 1

SYS-PHYS-VOL-6: If a delivery through the window at the end of the corridor is chosen and the wall closet is not removed, the transportable (packed or structurally supported e.g. wheels or pallet) PCU subunits or the disassembled parts shall not exceed the following sizes: 240 cm high, 195 cm deep and 110 cm wide.
Rank 1

Delivery through the window in the office in front of the laboratory:

1. Crane to the 2nd floor. The dimensions of the window and the building are given in Fig. 6. In front of the building a 2 meters wide flower bed limits the access for the crane. Behind the flower bed a 2 meter wide paved lane is available.
2. The office behind the window is large enough to turn/tilt the PCU subunits in every direction.
3. The office door is 125 cm wide and 206 cm high. If needed the upper part of the door can be removed leaving 55 cm more (261 cm in total). See Fig. 7.
4. The access from the office to the lab is detailed in Fig. 4.

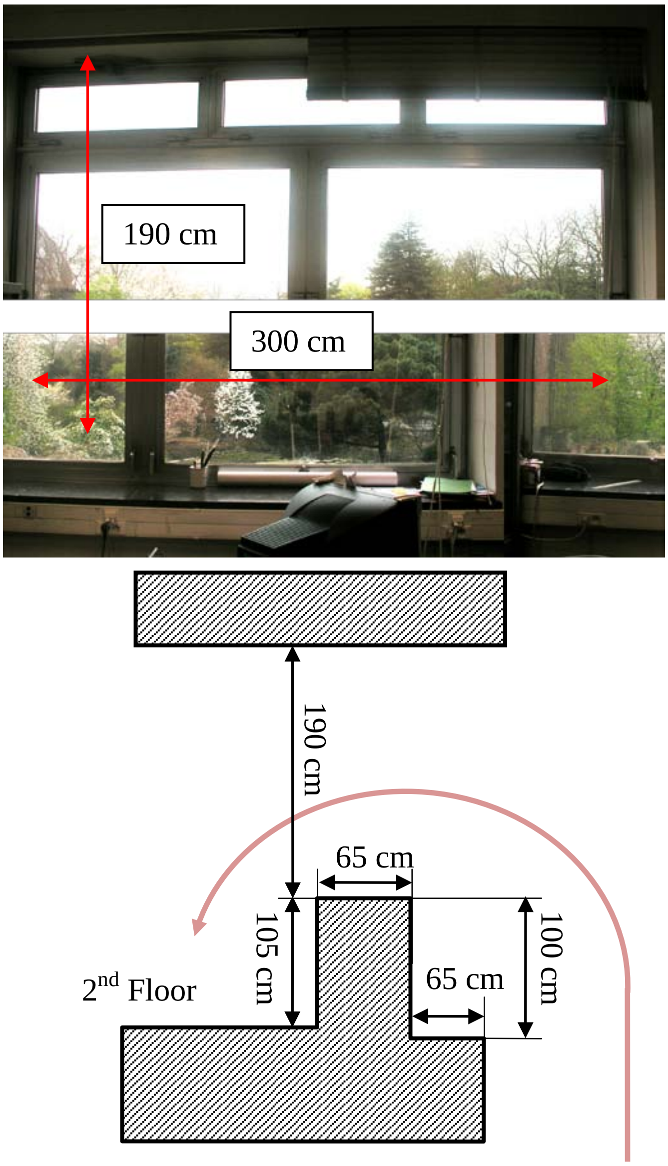

Fig. 6 Access through the window in the office in front of the laboratory

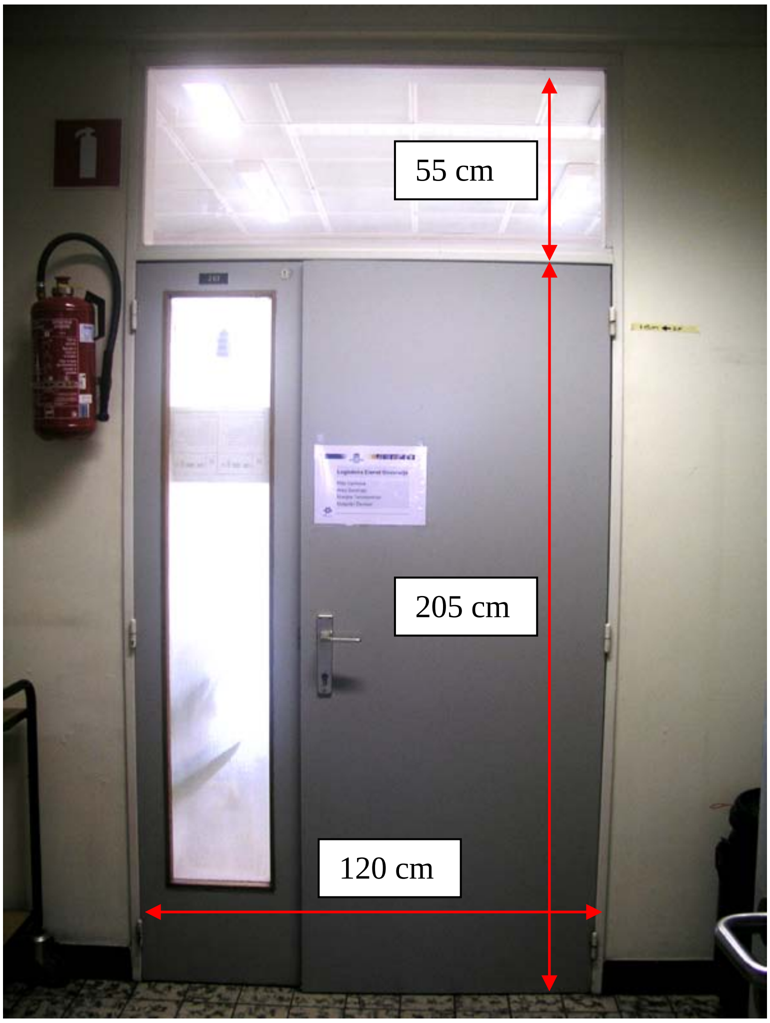

Fig. 7 Door of the office in front of the lab

SYS-PHYS-VOL-7: If a delivery through the window in the office in front of the laboratory is chosen, the transportable (packed or structurally supported e.g. wheels or pallet) PCU subunits or the disassembled parts shall not exceed the following sizes: 260 cm high and 115 cm wide.
Rank 1

Since no corners are to be passed the depth dimension is flexible.

SYS-PHYS-VOL-8: If a delivery through the window in the office in front of the laboratory is chosen, the transportable (packed or structurally supported e.g. wheels or pallet) PCU subunits or the disassembled parts shall be tiltable along the depth axis (axis between front door and rear pane).
Rank 1

Laboratory dimensions:

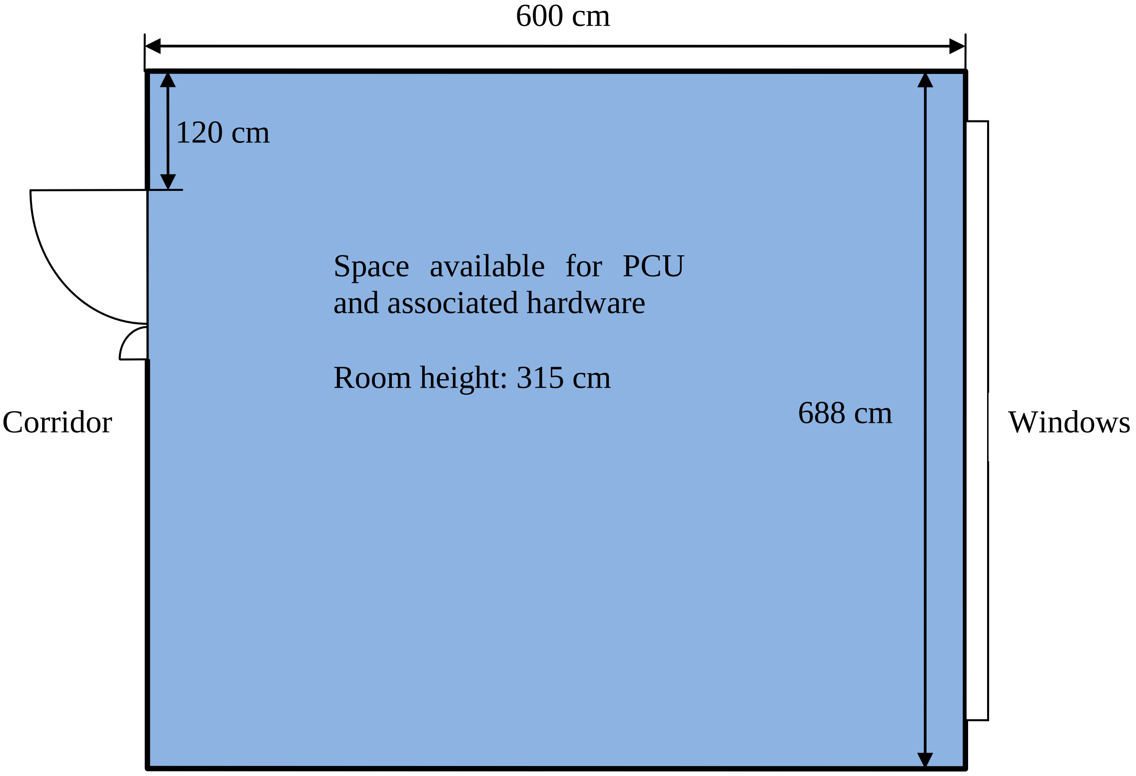

Fig. 8 Layout of the laboratory

3.3.3 Energy

Energy efficiency is an important consideration but does not drive the design. Thus for the upper limit of energy consumption the respective facility limits are given. The following table summarizes the electricity delivery capabilities of each laboratory.

Tab. 8 Power restrictions of the facility buildings

	UGent	UoGuelph
Maximal power/current available in the lab	3 x 20 A 2 x 63 A	30 kW
Supply voltage	660 V 3 Phase	600 V

At the UGent labs three 20 Ampere 3 phase lines with 660 Volt are available. Thus each PCU subunit can be powered with one line. Each 3 phase line can be split into three 220 V lines. This gives three lines of 220 V x 20 A = 4.4 kW. Besides that two 63 A lines are available as spares leaving a large margin for secondary equipment or future expansion.

SYS-PHYS-NRG-1: Each PCU subunit shall not use more than three 220 V lines.
Rank 1
SYS-PHYS-NRG-2: The current drawn from one 220 V line shall not exceed 20 Ampere (4.4 kW).
Rank 1
SYS-PHYS-NRG-3: The current drawn from each line shall be balanced to avoid uneven current drawing from the 3 phase line.
Rank 1

3.3.4 Resource efficiency

Energy efficiency is an important consideration for economic reasons but is not a design driving factor. Thus no requirement is set.
The same applies to other resources such as water. Economic usage is important (e.g. no cooling by a constant water flow) but at this stage no upper levels can be defined.

3.3.5 Limitation of electromagnetic interference

SYS-PHYS-ELI-1: The PCU shall be designed to avoid any internal electromagnetic interferences with negative impact on scientific results and the overall chamber functioning.
Rank 1

3.4 Laboratory environment requirements

The laboratory environmental parameters (RH, T, p) shall be logged continuously for possible failure analysis.

SYS-LENV-PERF-1:	All requirements concerning PCU environmental parameters (chapters 4.1.5.3, 4.3.2, 4.3.3 and 4.3.9) shall be met unless the external (laboratory) temperature fluctuation exceeds ±5°C per hour and/or exceeds the general operating environment condition restrictions. Rank 1

3.4.1 Temperature

SYS-LENV-TEM-1:	The PCU shall be nominal functioning under the nominal temperature conditions in the lab (15-25°C). Rank 1
SYS-LENV-TEM-2:	The PCU shall have an external overheating protection stopping highly dissipative equipment (e.g. illumination) in case of laboratory overheating (e.g. due to AC failure) by keeping a safe mode for plants (continuous nutrient delivery). Rank 1
SYS-LENV-TEM-3:	The laboratory air temperature shall be logged continuously with a frequency of at least 1 per 10 seconds and with a precision of at least ±0.1°C. Rank 2
SYS-LENV-TEM-4:	The external temperature measurement shall be representative for the atmospheric temperature within the lab. Rank 2

3.4.2 Pressure

SYS-LENV-PRS-1:	The PCU shall be nominal functioning under the atmospheric pressure conditions in the lab (78-109 kPa). Rank 1

This requirement only applies to scientific equipment and other devices such as (absolute) pressure sensors and fluid systems. The overall chamber is not affected since the internal pressure of the PCU is always equal to the atmospheric (laboratory) pressure as defined in chapter 4.3.1. According to the European Pressure Equipment Directive 97/23/EC (PED), devices with less than 0.5 bar gauge are not considered as pressurized devices and need therefore no specific safety certification.

No (rapid) pressure changes in the laboratory environment are present (except meteorological effects) thus no requirements concerning the speed of pressure equalization are defined.

SUB-LENV-PRS-2: The absolute pressure in the laboratory shall be logged with a frequency of at least 1 per 10 seconds and an accuracy of at least ±0.1 kPa.
Rank 2

3.4.3 Vapor Pressure Deficit

SYS-LENV-VPD-1: The PCU shall be nominal functioning under the RH conditions in the laboratory (10-75%).
Rank 1

Condensation of laboratory humidity on cool chamber parts in direct contact with the laboratory atmosphere must be avoided. The dew point is defined by the RH, T and the pressure present in the laboratory.

SYS-LENV-VPD-2: The surface temperature of all external parts of the PCU except the chilled water supply line shall be kept above the dew point to avoid condensation.
Rank 1

SYS-LENV-VPD-3: The chilled water supply parts on which condensation will occur shall be positioned to avoid any risk of electric shock or failure due to the condensation.
Rank 1

SYS-LENV-VPD-4: The laboratories RH shall be logged continuously with a frequency of at least 1 per 10 seconds and an accuracy of at least ±5%.
Rank 2

SYS-LENV-VPD-5: The laboratory RH measurement shall be representative for the main laboratory volume.
Rank 2

3.5 Operational requirements

3.5.1 Operational aspects

SYS-OPER-OP-1: The PCU shall have one access door to the main chamber volume.
Rank 1

SYS-OPER-OP-2: The PCU shall have at least one window with a cover for visual inspection of the chamber interior.
Rank 1

The window must be closable by an insulated opaque cover to meet the requirements SUB-ILLU-INT-3 (protection from light during dark periods) and SUB-SHEL-INS-2 (avoid thermal inhomogeneities in the vicinity of the window.

3.5.2 Required resources

3.5.2.1 External resources needed by the PCU

SYS-OPER-RES-1: The PCU shall receive all the required electrical power from the laboratory.
Rank 1

The power interface is defined in chapter 3.6.3.

SYS-OPER-RES-2: The PCU shall receive water for cooling and heating purposes from the laboratory.
Rank 1

The interfaces for cooling and heating water are defined in chapter 3.6.1.

SYS-OPER-RES-3: The PCU tanks shall be filled with water and the nutrient, pH and EC stock solutions prepared in the laboratory.
Rank 1

The tanks for nutrient, pH and EC stock solution as well as the water tank are part of the PCU.

SYS-OPER-RES-4: The PCU shall receive all the required gases (CO_2, optionally O_2 and N_2) from the laboratory.
Rank 1

The interfaces and pressures for the gas supply are defined in chapter 3.6.2.

SYS-OPER-RES-5: The PCU control and monitoring system shall be connected to the laboratory network.
Rank 1

The network interfaces are defined in chapter 3.6.4.

3.5.2.2 Internal PCU resources

The PCU will have externally located reservoirs for nutrient, pH and EC stock solutions. As described in chapter 3.5.2.1, these tanks are considered part of the PCU. Gas bottles and power distribution systems to the PCU are external resources.

3.5.2.3 Consumables

Requirements concerning the consumables are defined under the logistics section (chapter 3.9.4).

3.5.3 Automation degree

SYS-OPER-AUT-1: The following parameters shall be controlled automatically:

- Light cycles.
- Atmosphere control (T, VPD and CO_2).
- Nutrient solution control (T, pH and EC).

Rank 1

SYS-OPER-AUT-2: The PCU shall provide an automatic overheating (light switch off) protection with an associated alarm function.
Rank 1

SYS-OPER-AUT-3: The PCU shall provide an automatic liquid overflow (pump switch off or flow reduction) protection with an associated alarm function.
Rank 1

SYS-OPER-AUT-4: All parameters for plant model validation described in chapter 3.1.3, with exception of the post harvest analyses, shall be logged automatically with the defined data rate.
Rank 1

SYS-OPER-AUT-5: The chamber interior shall be monitored with ordinary cameras and pictures logged with a frequency of at least 1/hour.
Rank 2

These picture logs are primarily used for technical monitoring purposes and failure analysis. Therefore low resolution (web cam type) cameras are sufficient. If the critical areas (e.g. gully outflow) are visible on pictures taken by scientifically relevant cameras (e.g. plant height measurement), separate cameras are not needed.

SYS-OPER-AUT-6: Image processing of scientifically relevant pictures (e.g. plant height measurement and tuber size) shall be done with external software. The PCU shall provide raw images.
Rank 2

3.5.4 Operational modes

3.5.4.1 Automatic (nominal) mode

SYS-OPER-MOD-1: In nominal (automatic) mode the PCU shall perform all nominal tasks as described in this document.
Rank 1

3.5.4.2 Automatic (safe) mode

As mentioned in chapter 3.5.3 the system must also provide an automatic safe mode in case of system failure (e.g. overheating or overflow). This function shall be included in the automatic mode and be switched automatically in case a failure is sensed.

A collective safe mode for all PCU subunits is to be avoided where possible. Individual safe mode operation for each subunit is favorable since the safe mode affects the scientific results (e.g. drought due to pump failure). Thus in case of failure not all results will be jeopardized.

SYS-OPER-MOD-2: Where applicable, each subunit shall switch independently to safe functioning if a failure occurs under automatic mode functioning. The other chambers shall keep the automatic nominal mode.
Rank 1

SYS-OPER-MOD-3: The PCU illumination shall be automatically switched off (or dimmed if possible with illumination system) if temperature inside the chamber at plant level exceeds the set point temperature by 10 degrees.
Rank 1

SYS-OPER-MOD-4: Overflow detectors shall switch off nutrient delivery and associated acid/base/stock addition in case of a detected leak or detected overflow.
Rank 1

SYS-OPER-MOD-5: Audible, visual and email warning systems shall be installed to alert personnel in case of any failure.
Rank 1

3.5.4.3 Maintenance (nominal) mode

Calibration and preventive maintenance needs a specific mode of the control software. Each sensor and actuator must be readable and settable separately. Coupled control laws must be deactivated to be able to work on each element separately.

SYS-OPER-MOD-6: Where applicable, all measurement devices, sensors and actuators (e.g. pumps) shall be calibratable separately.
Rank 1

SYS-OPER-MOD-7: The preventive maintenance mode shall allow sterilization and cleaning procedures as detailed in SYS-PERF-MIC-1 and SYS-PERF-MIC-2 in between experiments.
Rank 1

SYS-OPER-MOD-8: Simple preventive maintenance tasks shall be accomplishable during a running experiment.
Rank 3

3.5.4.4 Maintenance (corrective) mode

SYS-OPER-MOD-9: In case of failure during automatic mode, the automatic safe mode shall be manually switchable to a corrective maintenance mode to allow intervention and failure detection/repair.
Rank 1

SYS-OPER-MOD-10: Where applicable the PCU control shall be capable of sensing reduced performance and warning technical personnel.
Rank 3

3.5.4.5 Off mode

SYS-OPER-MOD-11: In off mode all elements shall be turned off.
Rank 1

3.6 Interface requirements

3.6.1 Liquid interfaces

3.6.1.1 Heating/cooling water ports

Heating and cooling water must be provided by the laboratory. The temperature requirements will largely depend on the temperature setpoints for the chamber atmosphere and the requested response times. Where low temperature set points with fast response times will require lower cooling water temperatures. Currently, only UoGuelph has a centralized heating and cooling supply system. The system currently supplies 16 chambers and has sufficient capacity for expansion. The specifications are given in the following table:

Tab. 9 Heating and cooling water supply at UoGuelph

Cold water temperature range	5-8°C
Source pressure at chiller	8.3 bar (120 psi)
Return pressure at chiller	6 bar (86 psi)
Hot water temperature range	Adaptable; currently set to 50°C
Source pressure at heater	4.1 bar (60 psi)
Return pressure at heater	2.8 bar (40 psi)

The facilities at UGent do not provide building internal heating or cooling water supply. Heating and cooling units will be installed according to the final PCU design. The following requirements are preliminary and primarily targeted towards the chiller and heater installed in the laboratories. The design of the control system (algorithms/parameters) might need slight adaptations for end-location to compensate the different water supply properties (T, p, flowrate).

SYS-INTF-LIQ-1: The pressure of the supplied heating and cooling water shall be between 2 and 10 bars.
Rank 2

SYS-INTF-LIQ-2: The temperature of the heating water shall be user selectable between 40 and 80°C with 1°C increments.
Rank 2

SYS-INTF-LIQ-3: The temperature of the cooling water shall be between 5 and 8°C.
Rank 2

SYS-INTF-LIQ-4: The temperature of the heating and cooling water supply shall not drift or oscillate by more than 0.2°C per hour.
Rank 2

SYS-INTF-LIQ-5: The heating and cooling water inlet and outlet temperature at the heat exchanger shall be logged for possible failure analysis and to increase the performance of the controlling system.
Rank 2

3.6.1.2 Liquid tanks

The stock solution tanks (acid, base, nutrient A and nutrient B solutions) and the distilled water tank are considered part of the PCU. No specific interfaces for filling of the tanks is needed. The stock solutions will be filled manually. The tanks must provide a drainage interface (tap with a hose fitting or similar) which allows a convenient (manual) emptying of the tanks. No liquid must remain in the tank after drainage. All stock solutions and the water tank are stored under ambient conditions. The stock solutions are prepared individually at the labs.

SYS-INTF-LIQ-6:	All tanks shall provide convenient filling and drainage interfaces. Rank 1
SYS-INTF-LIQ-7:	The drainage interfaces shall allow a complete emptying of the tanks. Rank 1

3.6.1.3 Sampling ports

SYS-INTF-LIQ-8:	One sampling port for the nutrient solution shall be provided at a position representative for the main nutrient solution volume. Rank 1

3.6.1.4 Spare ports

SYS-INTF-LIQ-9:	Two spare ports connected to the hydroponic loop shall be provided for representative sampling, addition and fast mixing of liquids, or for future use. Rank 1

3.6.2 Gas interfaces

Each lab has to provide the correct gas bottles and pressure regulators. The PCU provides gas input ports for reduced pressure.

SYS-INTF-GAS-1:	The PCU shall provide one gas input port for each required gas. Rank 1
SYS-INTF-GAS-2:	The laboratory CO_2 supply shall be pressure regulated. Rank 1
SYS-INTF-GAS-3:	Two ports for atmosphere gas sampling shall be provided at a position representative of chamber air composition at mid canopy level. Rank 1
SYS-INTF-GAS-4:	Four spare gas ports useable for gas injection or sampling shall be provided at a position with well mixed atmosphere for future use. Rank 1

3.6.3 Power interfaces

SYS-INTF-EL-1: The PCU shall be powered by 110/220 VAC 50/60 Hz depending on lab location. 220V/50Hz for Europe, 220V or 110V/60Hz for Canada
Rank 1.

SYS-INTF-EL-2: The PCU shall provide 12V power interfaces inside the growth compartment to allow the implementation of LED strips in each gully (for a gully monitoring system).
Rank 1

SYS-INTF-EL-3: The PCU shall provide 5V power interfaces inside the growth compartment to allow the implementation of miniature camera modules for a future monitoring systems.
Rank 1

3.6.4 Data interfaces

The PCU internal functions will be accessible through a Human Machine Interface (HMI) and externally through a network client.

SYS-INTF-DAT-1: The HMI shall be connected to an external Ethernet Network with a static external IP address.
Rank 1

SYS-INTF-DAT-1: The HMI shall provide access to the PLC/HMI internal network through its external Ethernet network.
Rank 1

SYS-INTF-DAT-2: All actuators and sensors shall be accessible to the operator in the HMI.
Rank 1

SYS-INTF-DAT-3: All operator demands (set points and modes) shall be possible from the HMI.
Rank 1

SYS-INTF-DAT-4: The PCU shall provide data interfaces inside the growth compartment to allow the implementation of up to 10 cameras in each gully (for a gully monitoring system).
Rank 1

3.6.5 Control system interfaces

This section defines the top level control system interface requirements. More details on the control system itself are found in the subsystem section in chapter 4.5.

The major goal of the PCU is to produce valuable scientific data for the development of the physiological plant model. Besides that, it would be beneficial to test the developed predictive control algorithms on the PCU itself once the model is sufficiently advanced.

SYS-INTF-CTR-1:	The control system hardware shall be capable of running existing MELiSSA control laws/algorithms. Rank 1
SYS-INTF-CTR-2:	The control system shall be compatible with hardware already installed in the MELiSSA Pilot Plant. Rank 1

3.6.6 Solid interfaces

The solid interfaces mainly consist of inserting and removing gullies into the growth compartments.

SYS-INTF-SOL-1:	The PCU shall provide a convenient system to insert/remove the gullies into the growth compartment. Trolleys to help in this task shall be delivered with the PCU if such a system is not yet available at the end-locations. Rank 1
SYS-INTF-SOL-2:	The hydroponic elements at the rear side of the growth compartment (nutrient solution feed) shall be conveniently accessible for maintenance and flow calibration. Rank 1

3.7 Product assurance requirements

3.7.1 Reliability

SYS-PRAS-REL-1: Construction material in contact with any liquids shall be selected with regards to resistance against corrosion and bio corrosion.
Rank 1

3.7.2 Risk to human

3.7.2.1 Handling, maintenance and operation safety

SYS-PRAS-RSK-1: Risks of electrocution shall be avoided by adequate measures (isolation).
Rank 1

SYS-PRAS-RSK-2: Where risks cannot be excluded, evident signage shall be installed.
Rank 1

SYS-PRAS-RSK-3: Standard red emergency buttons shall be placed on each sub unit at a well reachable position to cut off each subunit from the main power line in an emergency situation.
Rank 1

SYS-PRAS-RSK-4: The emergency buttons shall be placed at a position where accidental pushing is of low risk.
Rank 1

3.8 Human factor requirements

3.8.1 Staff time allocation

The chamber shall have a high level of automation as described in chapter 3.5.3 in order to minimize staff time and improve data reliability. In general, the chamber design should take into account a minimization of maintenance tasks.

3.8.2 Hardware handling

SYS-HUMF-HAN-1:	The gullies shall be accessible from at least one long side when the chamber is opened (e.g. rolling out on tray). Rank 1
SYS-HUMF-HAN-2:	The hydroponic system (with the exception of the gullies) shall be accessible without opening the chamber. Rank 1
SYS-HUMF-HAN-3:	The main electric components (with the exception of the blower motor) shall be accessible without opening the chamber. Rank 1

This allows for efficient emergency intervention. Both the electric and the hydroponic system will be placed underneath the chamber in a separate compartment if possible.

SYS-HUMF-HAN-4:	All sensor ports shall be easily accessible. Rank 1

3.8.3 Human Machine Interface

SYS-HUMF-HMI-1:	A SCADA (Supervisory Control And Data Acquisition) shall be connected to the Programmable Logic Controller (PLC). Rank 1
SYS-HUMF-HMI-2:	The user shall be able to change set points and the operational mode through the HMI. Rank 1
SYS-HUMF-HMI-3:	The user shall be able to choose between: automatic mode, maintenance mode, or off mode for each control loop through the HMI. Rank 1

As described in chapter 3.5.4, several modes of operation are needed for different tasks including calibration and corrective maintenance, degraded (suboptimal) operation, preventive maintenance and nominal (automatic) operation:

SYS-HUMF-HMI-4: The user shall be able to set the parameters of the different modes through the HMI.
Rank 1

SYS-HUMF-HMI-5: The user shall be able to switch to the different modes through the HMI.
Rank 2

Besides the HMI integrated into the PCU remote functionalities are to be implemented:

SYS-HUMF-HMI-6: A remote client shall display user-friendly views to:

- Monitor the PCU (camera and sensor logs).
- Control the PCU.
- Display Alarms.
- Graphing of current and historic data.
- Export data for off-line analysis.
- Change between different operating modes.

Rank 1

SYS-HUMF-HMI-7: The remote client shall have the option to define access rights for each function defined in SYS-HUMF-HMI-6.
Rank 1

SYS-HUMF-HMI-8: The data export functionality shall provide the option to select user defined time steps with a minimum time step equivalent to the log file step size and a maximum time step of 1 hour.
Rank 2

SYS-HUMF-HMI-9: The remote client shall have available internet based remote monitoring.
Rank 3

3.9 Logistic requirements

3.9.1 Transport, delivery and installation

SYS-LOGI-DEL-1: Two sets of PCUs shall be delivered. One set (three subunits) for UGent and one set for UoGuelph.
Rank 1

SYS-LOGI-DEL-2: The subunits shall be delivered in a preassembled state. At the delivery site only final assembly, calibration and testing shall take place. Depending on control system requirements, final panel wiring may take place at each location.
Rank 2

SYS-LOGI-DEL-3: The limitations of the facilities as described in chapter 3.3.2.2 shall be taken into account for the delivery and installation strategy.
Rank 1

Due to the narrow corridors at UGent the packaging and support structures for the delivery through the building must be adapted. Depending on the external dimensions of the final PCU design, a transport without packaging might be needed to fit the PCU subunits through the narrow corridors. A detailed description of the volumetric and mass restrictions of the target facilities is given in chapter 3.3.

3.9.2 Personnel training

SYS-LOGI-TRN-1: A training for the personnel in charge of using/maintaining the PCU shall be held at each end-location.
Rank 1

3.9.3 Maintenance

SYS-LOGI-MTN-1: A maintenance plan, a detailed user manual and sub component documentation (drawings, manuals etc.) shall be delivered with the PCU.
Rank 2

3.9.4 Consumables

SYS-LOGI-CON-1: Equipment consumables (filters, gaskets and substrates) shall be commercially available to Europe and Canada in the correct dimensions and specifications.
Rank 1

Custom made consumable parts should be kept in stock for fast replacement at each location. Spare parts are not included in the initial PCU construction.

SYS-LOGI-CON-2: Spare parts of elements with risk of failure (volume compensation devices, lamps and gaskets) shall be readily available in Europe and Canada or kept in stock.
Rank 1

SYS-LOGI-CON-3: Chemical consumables (nutrient salts, acid solution, base solution) shall be provided by the laboratory.
Rank 1

4 Subsystem requirements

4.1 Hydroponic subsystem

4.1.1 Material choice

SUB-HYDR-MAT-1: All materials in direct contact with the nutrient solutions shall be neutral in their influence on the solution composition (e.g. passivated stainless steel, polypropylene, Teflon, Viton or glass). This applies to the major components. Other materials are allowed if only present in negligible quantities (e.g. components of sensors).
Rank 1

4.1.2 Gullies

SUB-HYDR-GUL-1: The gullies' geometry shall allow substrate-less NFT cultivation and also the usage of substrates (Rockwool) to accommodate wheat, durum wheat, potato and soybean.
Rank 1

SUB-HYDR-GUL-2: The gullies geometry shall be capable of growing wheat, durum wheat, soybean and potato.
Rank 1

SUB-HYDR-GUL-3: The gullies shall be inclinable from 0° (horizontal) to at least 3° (5,2%).
Rank 2

SUB-HYDR-GUL-4: The inclination of the gullies shall be adaptable without opening the plant compartment door.
Rank 3

SUB-HYDR-GUL-5: The gullies' geometrical design shall take into account the effects on the (bottom up) airflow and minimize air jet effects.
Rank 1

SUB-HYDR-GUL-6: For intermediate sampling each gully shall be replaceable from the PCU without shutting down the main hydroponics system.
Rank 1

SUB-HYDR-GUL-7: The design of the gullies shall allow the implementation of one IR LED strip over the whole gully length and 10 cameras per gully to monitor the root/tuber growth inside the gullies.
Rank 1

The gully monitoring system is explained in more detail in chapter 3.1.3.7.

SUB-HYDR-GUL-8: The distance between plant holes in the gullies lid shall be sufficiently long to comply with the length requirements defined in SYS-PHYS-VOL-3.
Rank 1

SUB-HYDR-GUL-9: All crops shall be grown on top of the gullies. All plant holes are located in the gully cover.
Rank 1

Until now potatoes were grown sideways. Thus the plant holes were positioned on the side of the gullies. This was done to be able to access the tubers through the lid. In a closed chamber this is no longer needed. Cameras are used to monitor the tubers. For an easier manipulation, separate lids for each plant would be favorable.

SUB-HYDR-GUL-10: The gully shall have separate lids for each plant.
Rank 3

SUB-HYDR-GUL-11: The gully shall have lids that are adaptable to a variety of crop types.
Rank 2

4.1.3 Nutrient solution delivery

SUB-HYDR-NUT-1: The volumetric flow of the nutrient delivery shall be adjustable between 0 and 10 l/min for one whole subunit (5 gullies).
Rank 1

SUB-HYDR-NUT-2: The volumetric flow to each gully shall be calibratable separately to obtain an equal flow in each gully.
Rank 1

Calibration is done manually once prior to the experiment for each subunit. Automatic calibration is not needed.

SUB-HYDR-NUT-3: The hydroponic solution flowrate into the gullies shall be measured and logged at subunit level.
Rank 1

SUB-HYDR-NUT-4: The design of the PCU shall take into account spare volumes for retrofitting of a clogging resistant flowrate measurement system (at subunit level) in the outflow of the gullies.
Rank 3

A flow rate sensor in the outflow of the gullies (one measurement for all gullies of one subunit together) would allow more precise mass balancing around the root zone. Technically, implementing a flow sensor into the outflow is very difficult as roots will grow down along the tubing and clog sensors, filters or any other system installed in their way. Benchtests and previous hydroponic cultivations in the consortium showed that root growth is a critical issue. Roots were found to grow several meters down into the nutrient solution tank and all attempts at UGent and UGuelph to limit/contain the growth resulted in floodings. For the first design, a sufficiently large tube diameter will be provided to avoid clogging of the outflow. Installation of a flow meter is impossible in the initial design without further root-containment technology development. Thus more research to develop a clogging free system is required which is compatible with the overall scientific objectives and chamber functioning requirements (e.g. no stagnation zones in the nutrient solution loop). The initial design will allow research on this subject and retrofitting of an adequate system.

SUB-HYDR-NUT-5:	The NFT layer thickness shall be monitored with the cameras installed inside the gullies. Rank 3
SUB-HYDR-NUT-6:	The nutrient solution shall be mixed constantly using a pump flow bypass. Rank 1
SUB-HYDR-NUT-7:	Clogging of the gully drain by excessive root growth and subsequent flooding shall be mitigated. Rank 1

Particle filters are not required since they tend to clog with biofilms, causing reductions in flow. Particulates remain in the nutrient solution tank and are removed between experiments during the cleaning process.

4.1.4 Hydroponic system interfaces

To allow quantification of mass transfers between the root and the shoot zone, a sealed gully system is to be implemented into the PCU design. This can however not be implemented from the beginning on as such a system is complex and will require further research and development. Therefore the design shall take into account interfaces to allow a later implementation of a (semi) sealed hydroponic system as it is described in chapter 4.1.6.

SUB-HYDR-IF-1:	The design of the interface between the nutrient solution delivery system and the gullies shall prevent leakage. Rank 1
SUB-HYDR-IF-2:	The design of the interface between the nutrient solution delivery system and the gullies shall be conceived to allow a retrofitting to a closed and/or open hydroponic system as described in chapter 4.1.6. Rank 2
SUB-HYDR-IF-3:	The design of the interface between the gullies and the nutrient solution drainage system shall prevent leakage. Rank 1
SUB-HYDR-IF-4:	The design of the interface between the gullies and the nutrient solution drainage system shall allow a retrofitting to a separated hydroponic system as described in chapter 4.1.6. Rank 2
SUB-HYDR-IF-5:	The nutrient solution delivery (feed) and recovery (drainage) interfaces shall allow convenient intervention for maintenance tasks (quick connect system or similar). Rank 1
SUB-HYDR-IF-6:	Each PCU subunit shall provide a port for nutrient solution sampling at the gully outflow (one common port for all 5 gullies is sufficient) Rank 1

4.1.5 Liquid phase (root zone - plant subsystem)

4.1.5.1 Stock solutions

SUB-HYDR-LIQ-1: The volume of the stock solutions (nutrient, pH and EC solutions) shall be sized to supply the PCU for at least three days without refilling.
Rank 1

SUB-HYDR-LIQ-2: The stock solutions tanks shall be opaque to avoid algae growth.
Rank 1

SUB-HYDR-LIQ-3: The volume of the stock solutions inside the tanks shall be monitored.
Rank 1

SUB-HYDR-LIQ-4: Renewal/exchange of stock solutions shall not compromise the chamber atmosphere.
Rank 1

The requirement defining the volume measurements is defined under SYS-FUNC-PM-9.

4.1.5.2 Nutrient solution

SUB-HYDR-LIQ-5: The liquid level in the nutrient solution tank shall be monitored.
Rank 1

SUB-HYDR-LIQ-6: The nutrient solution shall be replenished automatically from the stock solution tanks.
Rank 1

SUB-HYDR-LIQ-7: Under nominal conditions the nutrient solution tank filling level shall never drop below a safety stock for three days continuous running under maximal consumption.
Rank 2

SUB-HYDR-LIQ-8: The nutrient solution composition (pH, EC) shall be controlled automatically by addition of stock solutions.
Rank 1

SUB-HYDR-LIQ-9: The pH setpoint shall be definable from 4 to 8 with increments of 0.1.
Rank 1

SUB-HYDR-LIQ-10: The accuracy of pH control shall be at least ±0.5.
Rank 1

SUB-HYDR-LIQ-11: The EC setpoint shall be definable from 0 to 3000µS/cm with increments of 1µS/cm.
Rank 1

SUB-HYDR-LIQ-12: The accuracy of EC control shall be at least ±100µS/cm.
Rank 1

4.1.5.3 Temperature setpoint and stability

SUB-HYDR-LIQ-13: The nutrient solution temperature shall be settable from 15 to 30°C with increments of 0.1°C and an accuracy of at least ±1.0°C.
Rank 1

Only nutrient solution cooling is required as the temperature setpoints of the nutrient solution of relevant experimental protocols are always equal or below the atmosphere temperature set points.

SUB-HYDR-LIQ-14: Fluctuations of temperature in the root environment shall not exceed 2°C when all subsystems and external supplies are within operational conditions.
Rank 2

4.1.5.4 Root environment oxygenation

SUB-HYDR-LIQ-15: If oxygenation of the root environment is needed, only internal chamber air shall be used.
Rank 1

4.1.5.5 Renewal of solution

SUB-HYDR-LIQ-16: Renewal of the nutrient solution shall be possible during an experiment run without compromising the chamber air volume.
Rank 1

4.1.5.6 Microbial stability

SUB-HYDR-LIQ-17: The hydroponic system shall provide a possibility to decontaminate the whole liquid loop in case of accidental pathogen infiltration in maintenance mode (between experiments).
Rank 1

SUB-HYDR-LIQ-18: The hydroponic system material choice shall have no detrimental effects on beneficial microflora under nominal conditions.
Rank 1

SUB-HYDR-LIQ-19: The hydroponic system design shall minimize the risk of microbial proliferation by avoiding dead zones in the tubing system.
Rank 1

4.1.6 Gully ventilation proposal

A gully ventilation system using the chamber atmosphere can help to achieve the following:

- Quantification of water evaporation from the hydroponic system (for more precise assessment of the plant transpiration).
- Quantification of root and bacterial oxygen consumption.
- Oxygenation of the nutrient solution (this is not the prime target since a large mass transfer surface is available in the NFT layer).

This would increase the accuracy of the plant modeling. However the level of improvement is not yet known.

The air is pumped from the chamber atmosphere (with a defined composition) flows through the gully and is released again to the chamber.

An oxygen sensor for the nutrient solution can be economized by providing sufficient oxygenation. By saturating the solution, a defined oxygen concentration is created.
The additional hardware needed is:

- One T, RH, O_2 sensor at the air exit of the gully.
- One air pump (aquarium type pump).
- Septa (to seal of the plant stem openings).

The following picture gives an overview of the system functioning. This system is not to be implemented in the chamber from the beginning on. Retrofitting should however be possible.

SUB-HYDR-RET-1:The hydroponic system shall allow the retrofitting to a gully ventilation system as described here. This implies a sealable nutrient solution tank and the appropriate tube connections.
<u>Rank 2</u>

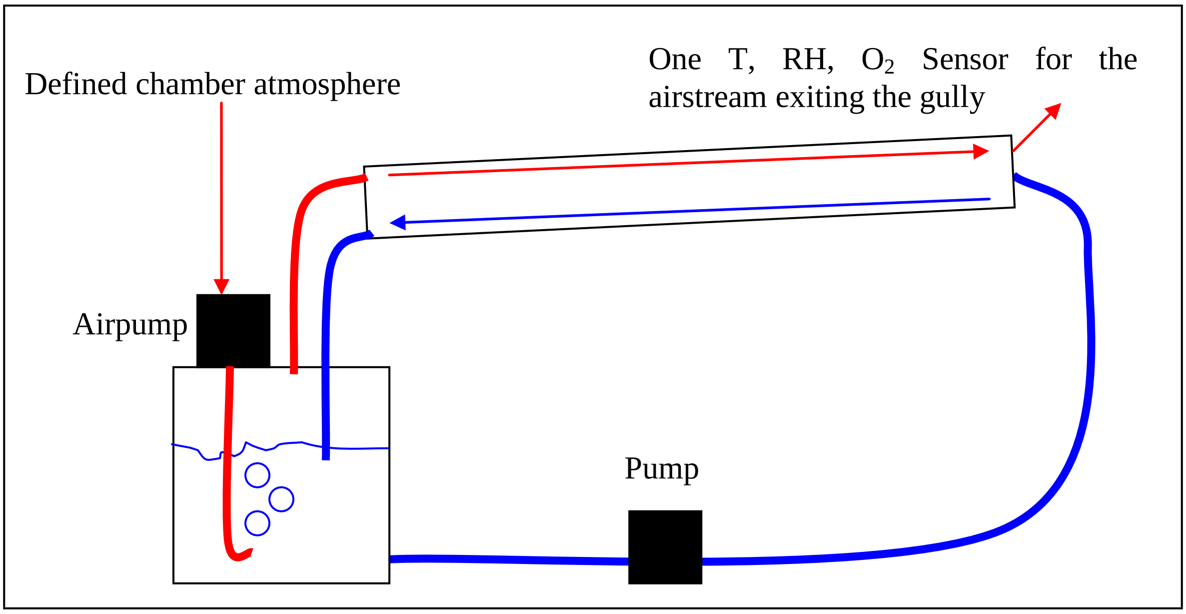

Fig. 9 Gully ventilation system

4.2 Illumination subsystem

4.2.1 Illumination type

SUB-ILLU-TYP-1:	The type of illumination used in the PCU shall be flexible and changeable at a future time. Rank 1

The initial lighting system will consist of HPS lamps with dual ballast which allow the use of either MH or HPS lamps. In later stages the PCU may be retrofitted with LED illumination.

4.2.2 Light spectrum

SUB-ILLU-SPE-1:	The spectral quality required for typical plant growth and development shall be deliverable. Rank 1
SUB-ILLU-SPE-2:	The amount of heat radiation to the chamber compartment shall be kept sufficiently low to avoid negative effects on plants (e.g. adapted illumination or IR filters). Rank 1

4.2.3 Light intensity

SUB-ILLU-INT-1:	The illumination system shall be capable of providing a photon flux density of at least 500 µmol/m²s PAR at mid canopy level. Rank 1
SUB-ILLU-INT-2:	The illumination system shall be dimmable to a minimum of 50 µmol/m²s PAR at mid canopy level. Rank 2

In case of HPS or MH lamps, neutral density screening is used. A minimum of five discrete levels can be obtained in this manner including full irradiation and full darkness. In case of LED illumination electronic dimming (either pulse width modulation or current limitation) is used.

SUB-ILLU-INT-3:	During dark periods the photon flux density shall always be below 0.5 µmol/m²s PAR in the volume occupied by plants. Rank 1

4.2.4 Light production efficiency

For the PCU, a highly efficient light production is not the prime objective. High efficiency is only important for the space based system. At the current state of technology and in view of the foreseeable technological evolution, LEDs or direct sunlight harvest will most likely be the systems with the highest efficiency. Due to the fact that all work performed on the PCU is targeted towards the space system, a focus must be set to characterize the plants under similar conditions. At the current stage LED illumination is not feasible within this frame. Therefore common technology (HPS/MH) will be used for the first illumination systems. This will allow to already gather a lot of valuable data for the above mentioned scientific objectives. The flexibility requirements of the illumination system described in chapter 4.2.1 are sufficient to ensure the feasibility of representative studies. A retrofit to other illumination systems will be possible as technology becomes available. Therefore, no requirements are set for the PCU illumination efficiency.

4.2.5 Illumination homogeneity

SUB-ILLU-HOM-1:	The irradiation during light phases shall be homogeneous in its PAR photon flux density at leaf level over the plant growing area with a max. 25% variation. Rank 2

A mapping (and possibly optimization) of the light homogeneity will be performed after PCU installation. If possible the homogeneity of the light will also be assessed by raytracing simulations. This is especially important if a combination of different light types is used. For simulations of the spectral homogeneity, the distribution of the irradiation flux [W/m^2] is assessed for significant spectral bands in the lamps range. The procedure applied to the simulation of the MPP illumination setup is described in Ref 7. The following values were taken from these simulation settings.

Band 1 (from 380 to 510 nm):	MH lamp contribution is higher compared to one of the HPS lamps.
Band 2 (from 510 to 650 nm):	It is the most energetic band in the visible range. The central regions of the glasses reach values of about 300 [W/m^2] for both types of lamps.
Band 3 (from 650 to 780 nm):	It is a low energy band. The wall irradiation flux distribution is almost the same for both types of lamps.

SUB-ILLU-HOM-2:	The illumination shall be homogeneous in its spectral photon flux density (within the three above mentioned bands) at leaf level over the plant growing area to within ±25% of the maximal value of each band. Rank 2

4.2.6 Lamp cooling

SUB-ILLU-LOF-1: The whole illumination subsystem shall be separated from the main growth chamber environment by a lamp loft.
Rank 1

SUB-ILLU-LOF-2: The lamp loft shall have its own air cooling system separate from the main chamber air conditioning.
Rank 1

SUB-ILLU-LOF-3: The light cooling system shall be deactivatable/changeable to meet the different illumination systems requirements which might be retrofitted at later stages.
Rank 1

SUB-ILLU-LOF-4: The radiative heat transmitted to the plant compartment shall be sufficiently low to avoid detrimental effects on the plants by keeping the chamber ventilation compliant to SUB-CATM-FLO-1 (air flow speed) and by keeping the air temperature within the user selected range.
Rank 1

The radiative heat load must thus be sufficiently low to be balanced with a maximum airspeed of 0.5m/s and the temperature settings defined under chapter 4.3.2.

4.3 HVAC subsystem

4.3.1 Atmosphere pressure

SUB-CATM-PRS-1: The static pressure inside the main growing volume shall be equal to ±2 kPa to the lab atmospheric pressure at all times.
Rank 1

(Dynamic) pressures within the air distribution system do not fall under this requirement.

SUB-CATM-PRS-2: The PCU shall provide a passive pressure compensation device to compensate volume variations caused by gas exchange and thermal expansion.
Rank 1

SUB-CATM-PRS-3: The pressure compensation shall comply with the required gas leak rate defined under chapter 4.4.3.
Rank 1

SUB-CATM-PRS-4: Pressure relief valves shall secure the system from over and under pressure in case of anomalous behavior. The pressure relief valves shall be set to maximum 2 kPa over/under pressure.
Rank 1

SUB-CATM-PRS-5:	Each triggering of the relief valves shall be logged for later failure analysis. Rank 3
SUB-CATM-PRS-6:	The absolute pressure inside the plant compartment shall be logged with a frequency of at least 1 per 10 seconds and an accuracy of at least ±0.1 kPa. Rank 1

4.3.2 Atmosphere temperature

The choice of the range of settable temperature is based on the optimal growth temperature of each crop considered in the Food Characterization project. In chapter 2.3.3 more information on this subject is given.

SUB-CATM-TMP-1:	The chamber atmosphere temperature shall be settable between 15°C and 35°C with 1°C increments for light and dark phases. Rank 1
SUB-CATM-TMP-2:	Up to 30 min after a switch from dark to light phases and vice versa (with a constant temperature setpoint for light and dark phases), the temperature stability shall be ±5°C until a stable state is reached. Rank 1
SUB-CATM-TMP-3:	The temperature stability after the transition phases from dark to light and vice versa shall be ±0.5°C. Rank 1

Scientific protocols might require a temperature change between dark and light phases (e.g. colder atmosphere during dark phase). Requirements to the response time of the temperature control are defined in chapter 4.3.10. For temperature changes within a dark/light phase switch the requirements SUB-CATM-TMP-2, SUB-CATM-TMP-3, SUB-CATM-DYN-1 and SUB-CATM-DYN-2 are valid together. Meaning that a dark/light switch shall be possible within a T change ramp of up to 0.1°C/min with a stability of ±5°C during a period of 30 min after the switch and ±0.5°C 30 min after the transition phase. Fig. 10 exemplifies this. The stability requirements to RH shall also be met during a T change.
SUB-CATM-TMP-3 is valid for steady state conditions (30 min after a switch between light and dark phases) and in case of a dynamic temperature adaptation (SUB-CATM-DYN-1) outside a dark/light switch.

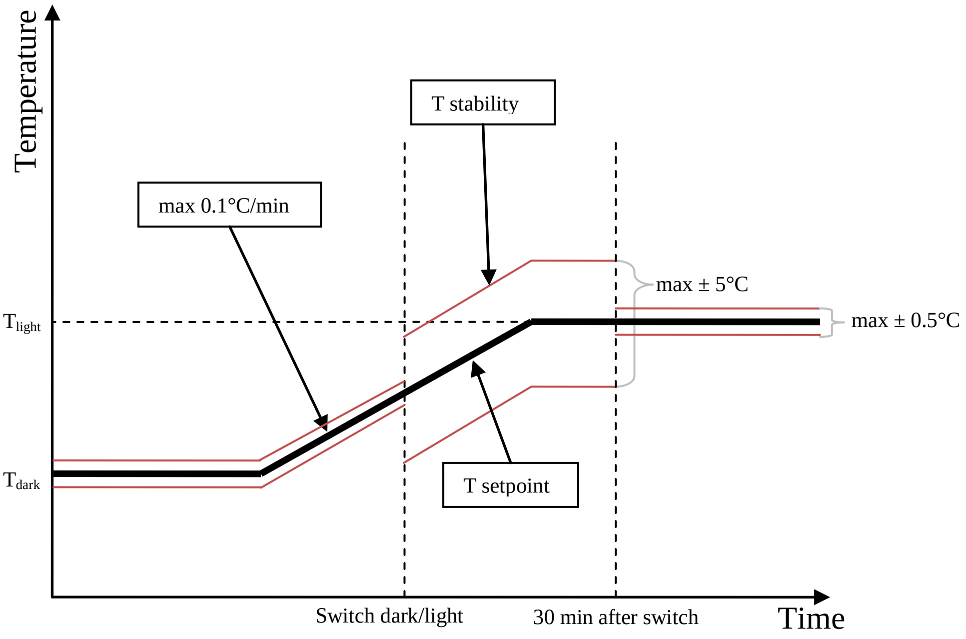

Fig. 10 Control stability for a temperature ramp during a dark/light switch

Temperature measurement requirements are defined in chapter 3.1.3.9.

4.3.3 Atmosphere VPD

SUB-CATM-RH-1:	The chamber atmosphere VPD shall be settable between 0.2 and 1.5 kPa with 0.1 kPa increments during dark and light phases. Rank 1
SUB-CATM-RH-2:	The RH stability shall be ±5%RH during continuous working. Rank 1
SUB-CATM-RH-3:	During the first 30 minutes after the switching from light to dark phases (and vice versa) the RH stability shall be ±20%RH. Rank 1
SUB-CATM-RH-4:	The HMI shall provide the option to define either RH or VPD values. Rank 1
SUB-CATM-RH-5:	The atmosphere control shall be capable of controlling either RH or VPD. Rank 1

This is only of relevance in scenarios where temperature changes or RH/VPD changes are used during an experimental protocol. The RH is defined as the ratio of the partial pressure of water vapor in the mixture to the saturated vapor pressure of water at a given temperature. RH is generally expressed in %.

For plant biology the VPD representation is more convenient. It is defined as the difference (deficit) between the actual partial pressure of water in the air and the saturation partial pressure. It is generally expressed in kPa.

RH measurement requirements are defined in chapter 3.1.3.4.

Analogous to the T stability described in chapter 4.3.2 and 4.3.10, the requirements SUB-CATM-RH-2, SUB-CATM-RH-3, SUB-CATM-DYN-1 and SUB-CATM-DYN-2 are valid together. A dark/light switch shall be possible within a RH change ramp of up to 0.1%RH/min with a stability of ±20%RH during a period of 30 min after the switch and ±5%RH 30 min after the transition phase. The stability requirements to T shall also be met during a RH change.

4.3.4 Material choice

SUB-CATM-MAT-1: All materials in contact with the chamber atmosphere shall be neutral in their outgassing properties (e.g. passivated stainless steel, Teflon, Viton, polypropylene, baked enamel or glass).
Rank 1

SUB-CATM-MAT-2: All hardware parts in direct contact with the condensate shall be made of passivated stainless steel, Teflon, Viton, polypropylene, baked enamel or glass.
Rank 1

4.3.5 Condensate recovery

SUB-CATM-CND-1: If condensate is recovered to the main water tank or the nutrient tank, microbial stability and maintaining correct nutrient solution composition must be ensured while guaranteeing valid water mass balances as requested in chapter 3.1.3.4.
Rank 1

4.3.6 Atmosphere composition

4.3.6.1 CO_2

SUB-CATM-CMP-1: The PCU shall be capable of controlling the CO_2 level in the chamber by addition of pure CO_2.
Rank 1

SUB-CATM-CMP-2: The PCU shall be capable of setting CO_2 concentrations between 350 (approximately atmospheric CO_2 content) and 5000 ppm in the chamber atmosphere with increments of 10 ppm.
Rank 1

The value of 350 ppm is set in this requirement as it is approximately the ambient CO_2 concentration. By reducing the CO_2 feed rate, lower CO_2 concentrations will also be possible if low CO_2 studies are envisaged. CO_2 Measurement requirements are defined in chapter 3.1.3.1.

4.3.6.2 O_2

SUB-CATM-CMP-3: The PCU shall be capable of keeping O_2 level in each subunit permanently below 25%.
Rank 2

O_2 Measurement requirements are defined in chapter 3.1.3.5.

4.3.6.3 Ethylene

SUB-CATM-CMP-4: The PCU shall be capable of keeping ethylene level in the each subunit permanently below 10 ppb.
Rank 1

Keeping ethylene levels permanently below 10 ppb is crucial. If technically possible a user definable upper limit would allow future extension of experimental protocols. This is reflected in the next requirement. If SUB-CATM-CMP-5 is met, SUB-CATM-CMP-4 can be discarded.

SUB-CATM-CMP-5: The PCU shall be capable of keeping ethylene level in each subunit permanently under user defined limits. The limits shall be settable between 10 ppb and 10 ppm with increments of 1 ppb.
Rank 3

Measurement requirements are defined in chapter 3.1.3.6.

4.3.7 Atmosphere quality

VOCs and inhibitory compounds can be monitored by air sampling and external analysis (mass spectrometer). No PCU internal analysis is envisaged.

4.3.8 Airflow

To avoid stress on plants the air speed must be limited. The airflow has two main objectives: Improving the mass transfer in the foliage and cooling the plants from the lamps' heat load. Sufficient mass transfer can be achieved with fairly low flow rates. However a high heat load requires large air recirculation. Thus to avoid wind stress, the illumination system must be designed keeping in mind airflow limits. As a rule of thumb 1 m/s is the upper limit for leaf movement. The PCU temperature control can be achieved in two ways (or by a combination of both):

- Constant air velocity: A constant air velocity is defined and the disturbance variable (external temperature variation, equipment dissipation or illumination) is compensated by controlling the heat exchanger heating/cooling water flow rates. This approach has the advantage of keeping air velocity and thereby mass transfer constant. However temperature gradients can vary in the PCU subunits with fluctuating external influences. Under higher heat loads the temperature gradient will increase. The selectable range of air velocity is limited by the heat load and the allowed temperature gradient in the plant compartment.

- Constant heating/cooling water supply: If the flow rate of the heating and cooling water through the heat exchangers is fixed, the compensation of disturbance variable is done by adapting the air velocity. This approach has the advantage of allowing small temperature gradients in expense of varying air speeds.

The choice of the control strategy will influence the temperature sensor positions in the PCU subunits. The complete air handling system of the PCU will be analyzed using CFD simulations in order to check the efficiency of the system from a fluid dynamic point of view and to optimize sensor positions.

SUB-CATM-FLO-1:	The blower of the HVAC system shall be capable of providing sufficient air velocity (respectively recirculation) to counterbalance the lamps heat load and to provide sufficient mass exchange in the foliage. Rank 1
SUB-CATM-FLO-2:	The average air velocity in the growth compartment shall be below 1 m/s to avoid stress effects on plants. Rank 1
SUB-CATM-FLO-3:	The flow pattern shall be bottom up. Rank 1
SUB-CATM-FLO-4:	The design of the air flow shall avoid any dead zones in the whole internal atmosphere (homogeneous gas distribution and proper mixing). Rank 1

4.3.9 Atmosphere homogeneity

The atmosphere homogeneity will be assessed with CFD simulations before building the PCU. The requirements in this chapter are primarily targeted towards the simulation results. After building a PCU subunit, the actual homogeneity will be mapped and the chamber model verified.

4.3.9.1 Temperature

SUB-CATM-HOM-1:	The temperature in the volume occupied by the plants shall be homogeneous to ±2°C. Rank 1

4.3.9.2 VPD

SUB-CATM-HOM-2:	The RH in the volume occupied by the plants shall be homogeneous to ±5%. Rank 1

4.3.9.3 Flow speed

SUB-CATM-HOM-3:	The flow speed in the volume occupied by the plants shall be homogeneous in its magnitude to ±0.1m/s. Rank 2

4.3.10 Dynamic atmosphere adaptation

SUB-CATM-DYN-1: The temperature control shall be capable of running user defined scenarios of temperature changes within the temperature ranges defined in SUB-CATM-TMP-1 with maximal temperature changes of 0.1°C/min by keeping all other environmental variables constant.
Rank 2

SUB-CATM-DYN-2: The RH control shall be capable of running user defined scenarios of RH changes within the RH ranges defined in SUB-CATM-RH-1 with maximal RH changes of 0.1%RH/min by keeping all other environmental variables constant.
Rank 2

4.4 Chamber shell subsystem

4.4.1 Material choice

SUB-SHEL-MAT-1:	The elements of the PCU subunit shell in contact with the internal atmosphere shall be built with off-gassing neutral materials (e.g. passivated stainless steel, baked enamel and glass). Rank 1
SUB-SHEL-MAT-2:	The internal walls shall be reflective and matt to avoid any hot spots on plants (e.g. beaded stainless steel). Rank 1
SUB-SHEL-MAT-3:	The material choice shall take into account sterilization and cleaning procedures (as defined under SYS-PERF-MIC-1). Rank 1

4.4.2 Insulation

SUB-SHEL-INS-1:	The PCU subunit shell shall be insulated to minimize the influence of the external environment. Rank 1
SUB-SHEL-INS-2:	The window cover shall be sufficiently insulated to avoid thermal non-homogeneity in the vicinity of the window. Rank 1

4.4.3 Leak rate

SUB-SHEL-LEK-1:	The PCU shall have an atmosphere leak rate at or below 5% of the internal volume within 24 hours as measured by passive CO_2 leak testing with a 1000 ppm starting concentration. Rank 1

4.5 Control subsystem

The control system (CS) comprises all the hardware controlling the PCU. In this case the CS is based on a Programmable Logic Controller (PLC). The software used on the CS is called the controller software.

4.5.1 Control system

SUB-CONT-CS-1: The CS shall be interfaced with the PCU for controlling actuators based on sensor and user input.
Rank 1

SUB-CONT-CS-2: All control laws for the PCU shall be implemented in the CS (PLC).
Rank 1

SUB-CONT-CS-3: The CS shall be a Schneider PLC compatible with Quantum PLC as installed in the MPP.
Rank 1

SUB-CONT-CS-4: Each PCU subunit shall have a dedicated stand alone CS with real time operation and control.
Rank 1

SUB-CONT-CS-5: The CS shall be equipped with adequate I/O (analog and digital inputs, analog and digital outputs) cards to be connected to the actuators and sensors.
Rank 1

SUB-CONT-CS-6: The CS shall be user expandable in terms of I/O and additional sensors without additional externally contracted programming requirements.
Rank 1

SUB-CONT-CS-7: 16 additional I/O positions shall be available for each type (digital input, digital output, analog input and analog output) for future expansion.
Rank 1

SUB-CONT-CS-8: All I/O shall be accessible to the PLC through connections between the electrical cabinet and the PLC cabinet.
Rank 1

SUB-CONT-CS-9: An Uninterruptible Power Supply (UPS) system shall be connected to the PLC to prevent power failures.
Rank 1

SUB-CONT-CS-10: Each subunit shall have an autonomous CS with a centralized computer control server and data acquisition and recording (distributed control).
Rank 1

SUB-CONT-CS-11: Additional PCU units shall be implementable without additional externally contracted programming requirements. This applies to the CS as well as to the controller software.
Rank 1

4.5.2 Controller software

SUB-CONT-CR-1: The controller software shall be designed to reach the set points and the temporal and spatial stability previously described.
Rank 1

SUB-CONT-CR-2: An integrated control of environment, irrigation, and nutrient management shall be possible.
Rank 1

SUB-CONT-CR-3: All control parameters shall be accessible and user definable.
Rank 1

SUB-CONT-CR-4: All control algorithms shall be open and documented if needed.
Rank 1

SUB-CONT-CR-5: Sensor parameters shall be user modifiable.
Rank 1

SUB-CONT-CR-6: In accordance with SYS-OPER-OP-**Error! Reference source not found.**, an integrated sensor/actuator failure alarm system with user notification system (auto dialer, email, or other alternative) shall be available.
Rank 1

SUB-CONT-CR-7: All hardware control relays shall be operable manually through the HMI.
Rank 1

SUB-CONT-CR-8: The controller software shall have an automatic data and controller parameter backup function.
Rank 1

SUB-CONT-CR-9: Each control loop shall have 3 modes: *Automatic mode* with setpoint specified by the operator through the HMI including nominal functioning and safe functioning (in case of a failure), *maintenance mode* with all actuators and sensors separately accessible (e.g. for calibration) to the operator through the HMI and *off mode*.
Rank 1

Further details on operational modes are available in chapter 3.5.4.

SUB-CONT-CR-10: Based on the MPP experience and performance, control laws shall be reproduced and/or adapted to the PCU.
Rank 1

4.5.3 User client

SUB-CONT-UC-1:	Software that provides seamless global access to PCU data and control systems shall be installed. Rank 1
SUB-CONT-UC-2:	The PLC shall be configurable and programmable through a remote client. Rank 1
SUB-CONT-UC-3:	Concurrent secure read-only access to all partner systems (individual accounts) shall be available. Rank 1
SUB-CONT-UC-4:	Data recording shall be definable for each parameter with time resolutions previously defined. Rank 1
SUB-CONT-UC-5:	The user client software shall provide data graphing and user friendly data retrieval capabilities. Rank 1
SUB-CONT-UC-6:	Data export to text file with user selectable parameters and time intervals shall be possible. Rank 1

4.5.4 Predictive controlling

A physical control logic based on a predictive physiological plant model is to be implemented at a later stage. For that purpose the following requirements must be met:

SUB-CONT-PRD-1:	The predictive plant model shall be implemented at the HMI level. Rank 3
SUB-CONT-PRD-2:	The HMI shall allow the comparison between the process values and the predictive plant model Rank 3

5 Validation

5.1 Requirements validation

Each requirement shall be validated after the PCU has been installed and calibrated at the target laboratory. Before final design freeze, the requirements related to the CFD simulations shall be validated by the CFD results. Validation of the CFD results will be done once the PCU hardware is fully installed.

5.2 System tests validation

A test plan and the associated procedures will be defined at later stages when the design is more advanced.