MELiSSA
MICRO-ECOLOGICAL LIFE SUPPORT SYSTEM ALTERNATIVE

2022 MELISSA CONFERENCE
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CREATING A CIRCULAR FUTURE

Designing the MELiSSA Pilot Plant Integration

Gas loop closure between a higher plants chamber and a crew compartment: Requirements, specifications, simulations and hardware design

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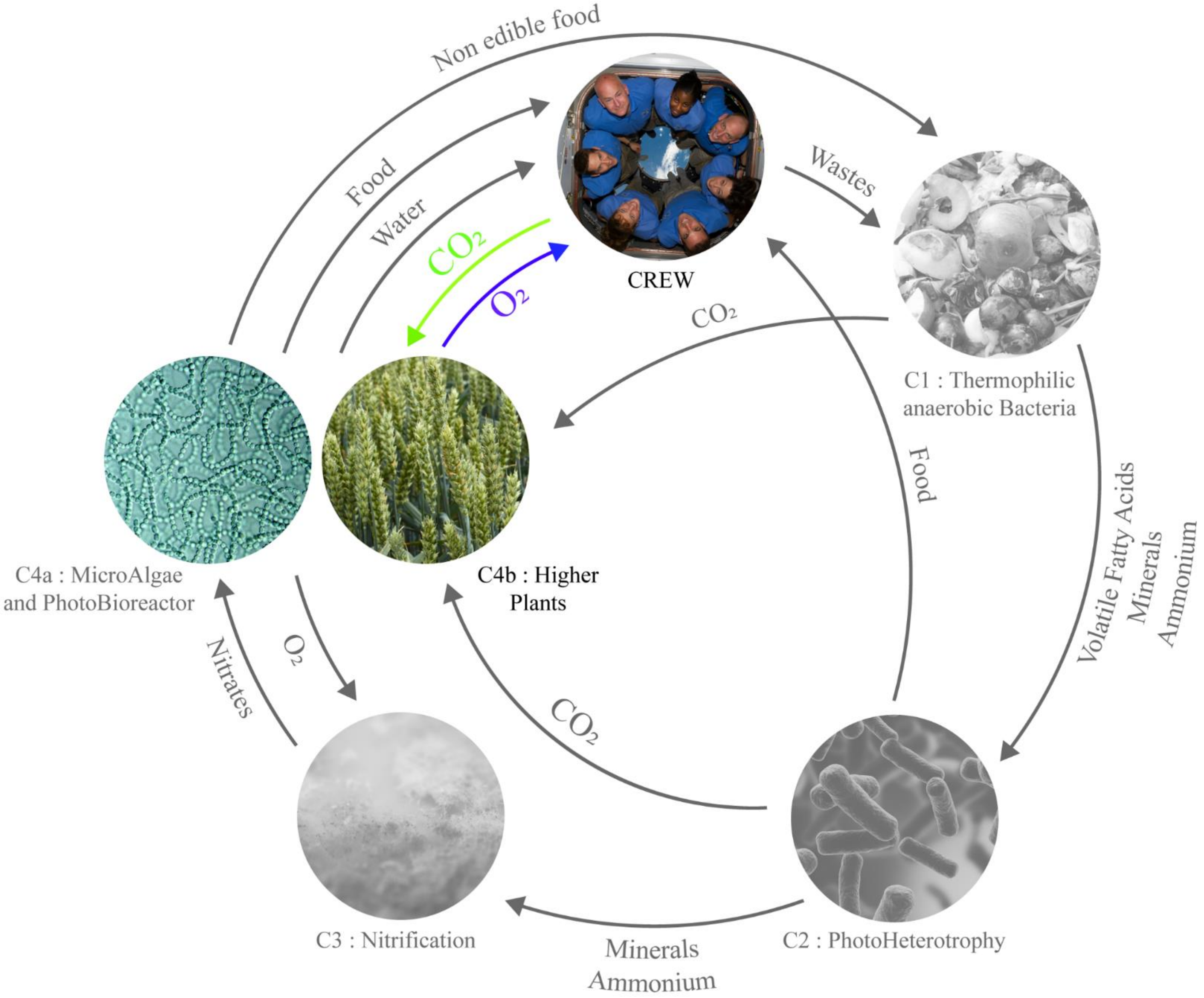
Integration Work Package 2 (WP2)

WP2 consists on the gas loop closure of a higher plants chamber (C4b) and a crew compartment (C5)

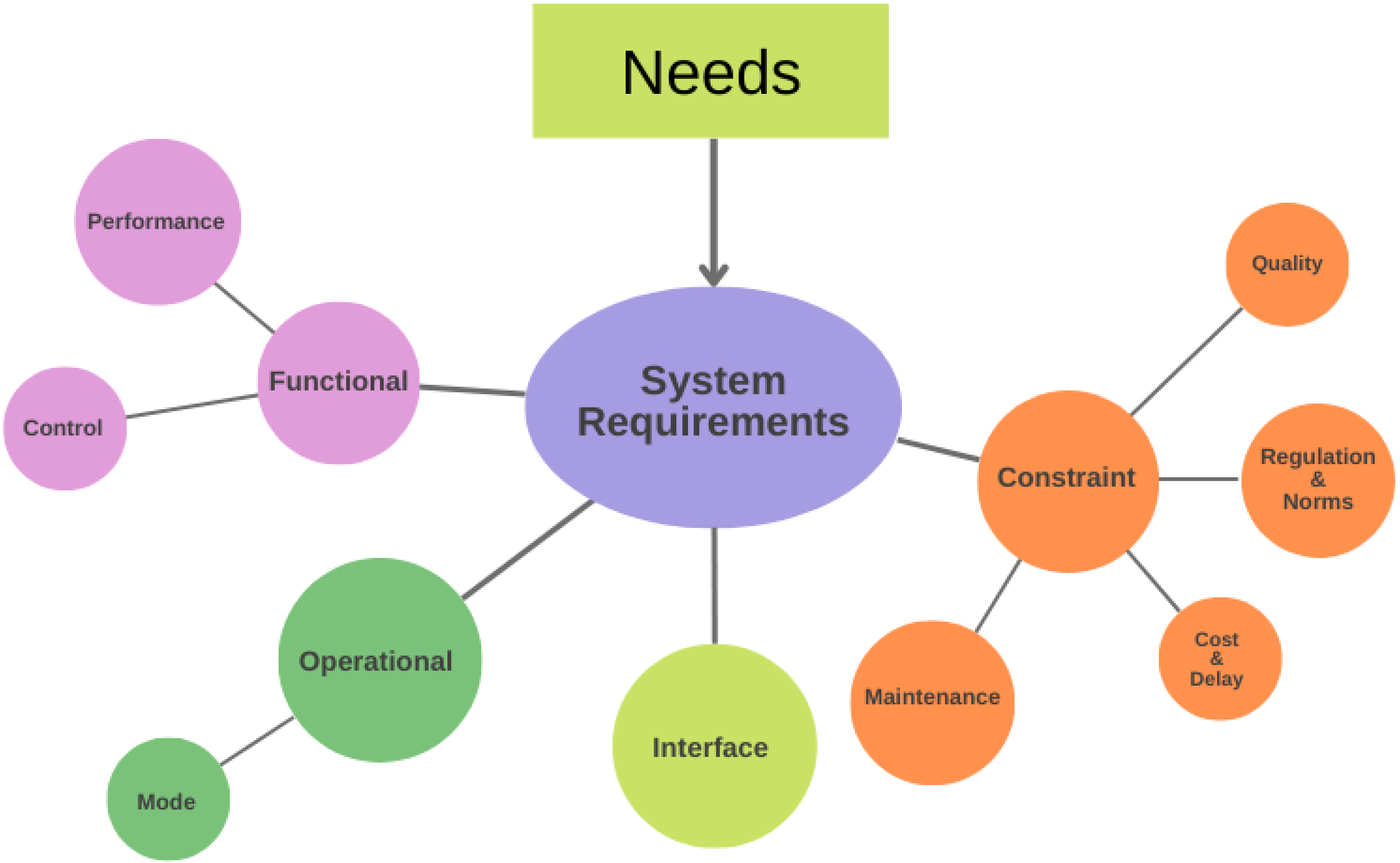
WP2 is a crucial part of a stepwise approach towards the full gas closure of the MELiSSA loop



Systems engineering approach: Requirements Matrix

To address the WP2 design phase properly, a systems engineering approach is followed where needs and systems requirements are carefully considered.

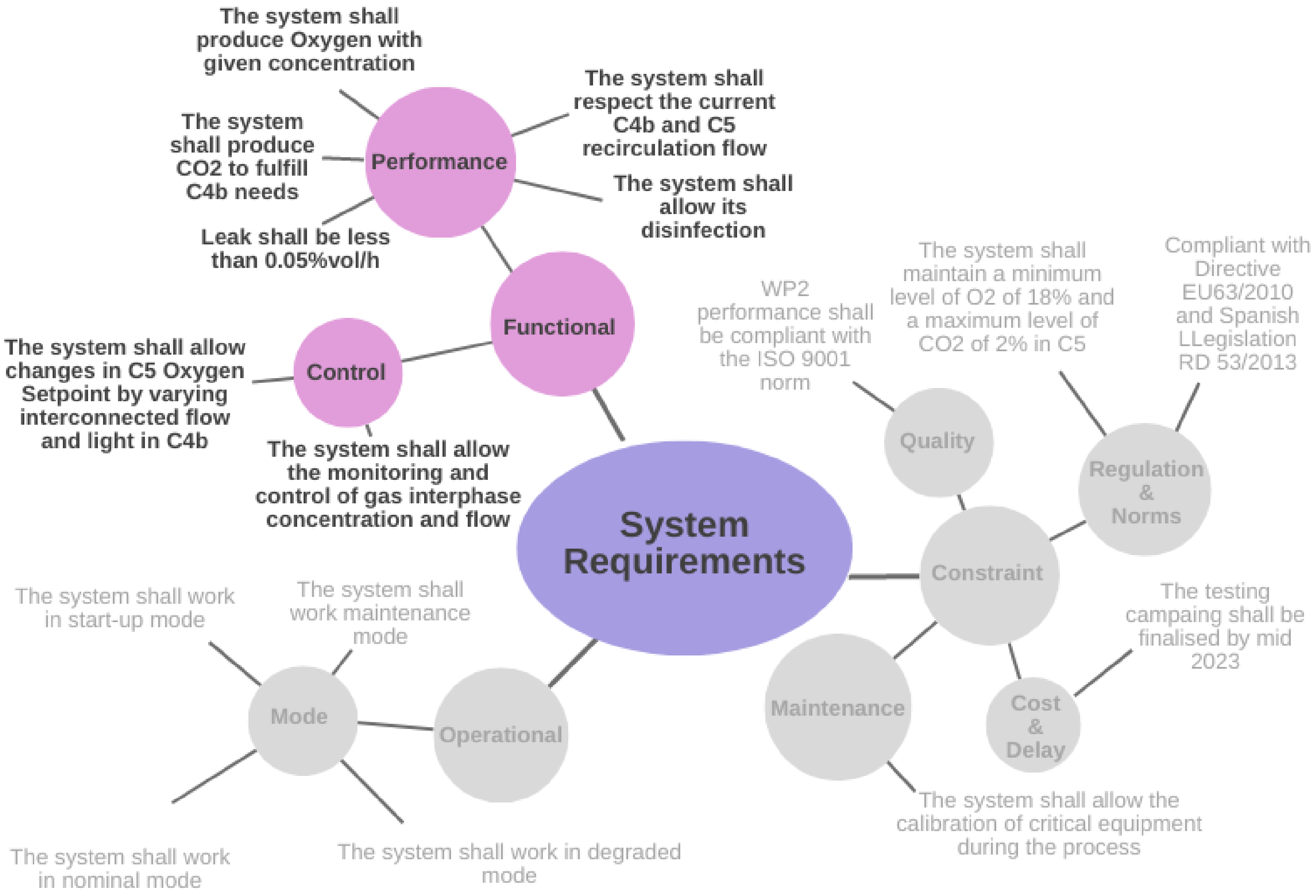
The system requirements include a set of statements of capabilities necessary for the needs to be satisfied



WP2 Requirements Matrix

MAIN NEEDS

1) The system shall collect and connect the gas phases of C4b and C5
2) The system shall deliver gas phases with a required flow
3) The system shall produce more than 90% of oxygen consumed by a given number of crew members
4) The system shall be controlled by the MPP control system
5) The system shall be assessed with ALiSSE criteria



System Requirements

Functional

Performance

The system shall produce Oxygen with given concentration

The system shall produce CO2 to fulfill C4b needs

Leak shall be less than 0.05%vol/h

The system shall respect the current C4b and C5 recirculation flow

The system shall allow its disinfection

Control

The system shall allow changes in C5 Oxygen Setpoint by varying interconnected flow and light in C4b

The system shall allow the monitoring and control of gas interphase concentration and flow

Constraint

Quality

WP2 performance shall be compliant with the ISO 9001 norm

Regulation & Norms

The system shall maintain a minimum level of O2 of 18% and a maximum level of CO2 of 2% in C5

Compliant with Directive EU63/2010 and Spanish LLegislation RD 53/2013

Cost & Delay

The testing campaing shall be finalised by mid 2023

Maintenance

The system shall allow the calibration of critical equipment during the process

Operational

Mode

The system shall work in start-up mode

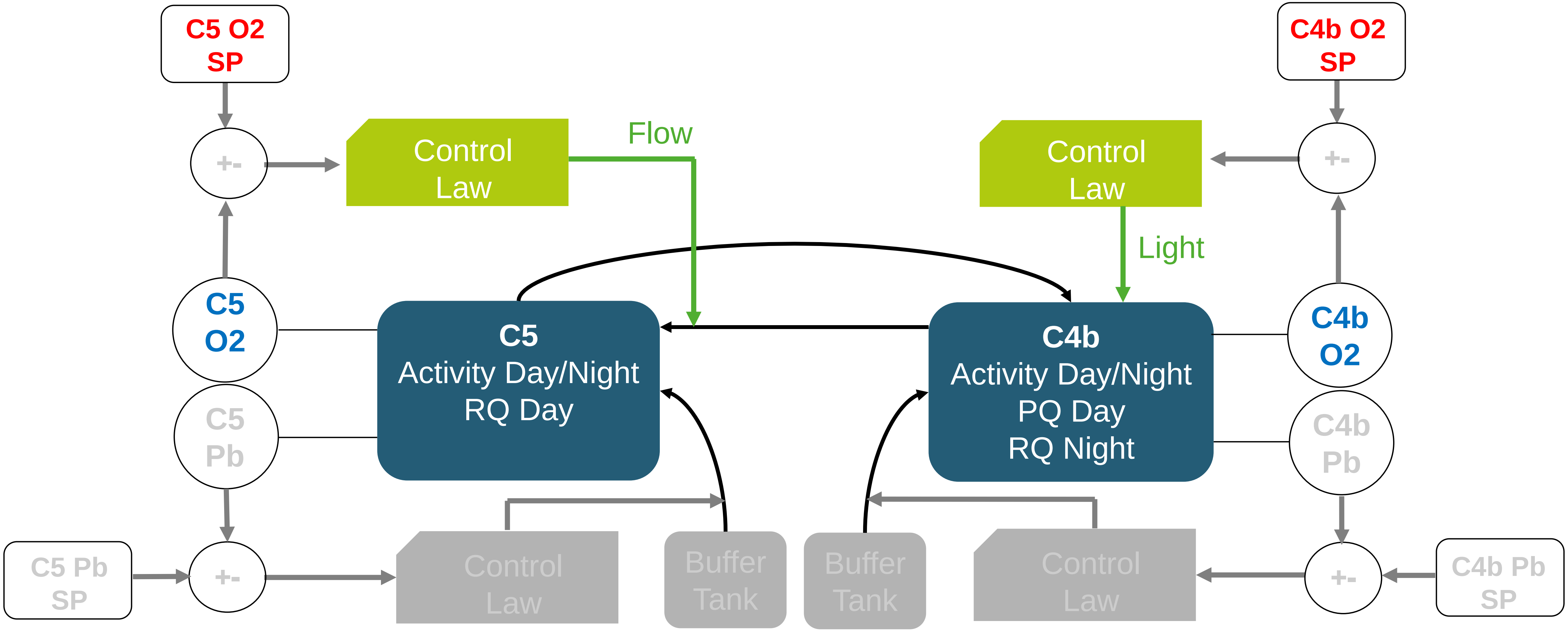
The system shall work maintenance mode

The system shall work in nominal mode

The system shall work in degraded mode

WP2: Basic Design & Control Strategy

Objective: The main objective is **controlling O_2 in C5 at 21%.** This is done by **adjusting the flow from the enriched O_2 gas phase in C4b to C5. C4b gas phase is controlled by adjusting the light intensity.**



C5 O2 SP

+-

Control Law

Flow

Control Law

+-

C4b O2 SP

Light

C5 O2

C5
Activity Day/Night
RQ Day

C4b
Activity Day/Night
PQ Day
RQ Night

C4b O2

C5 Pb

C4b Pb

C5 Pb SP

+-

Control Law

Buffer Tank

Buffer Tank

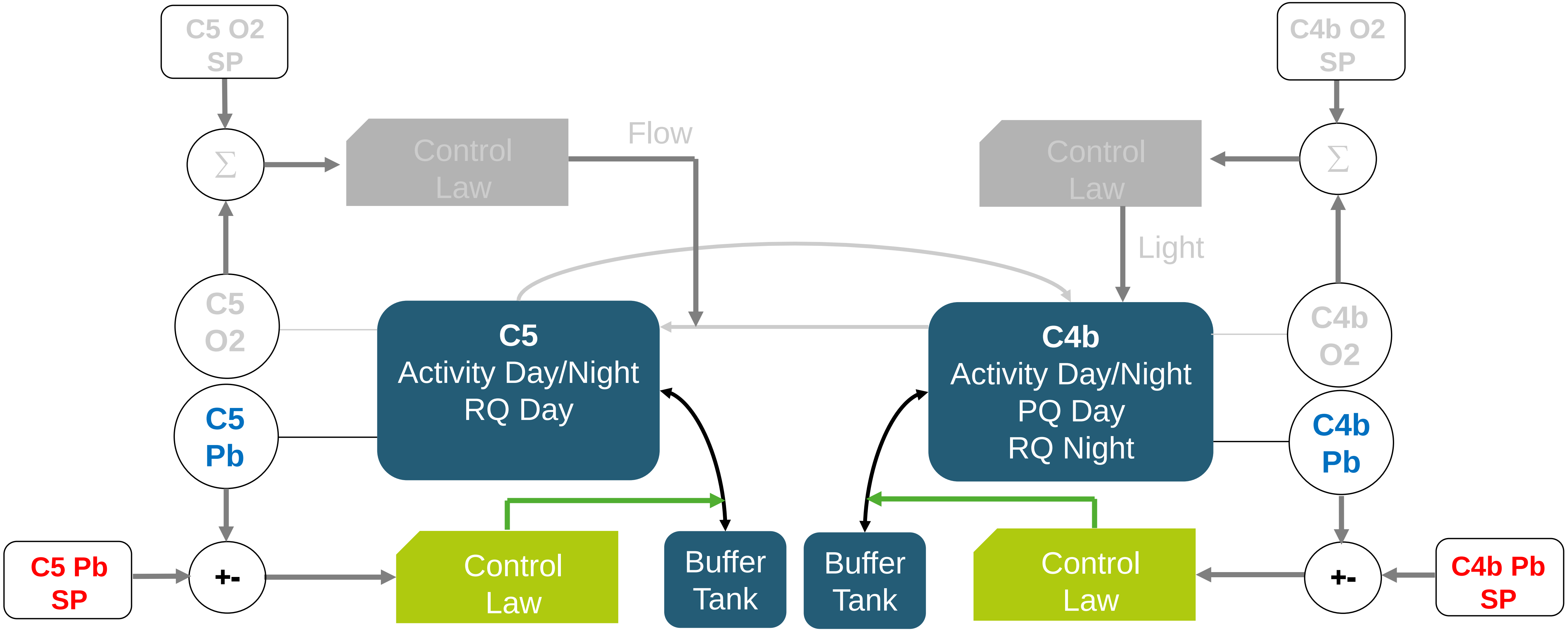
Control Law

+-

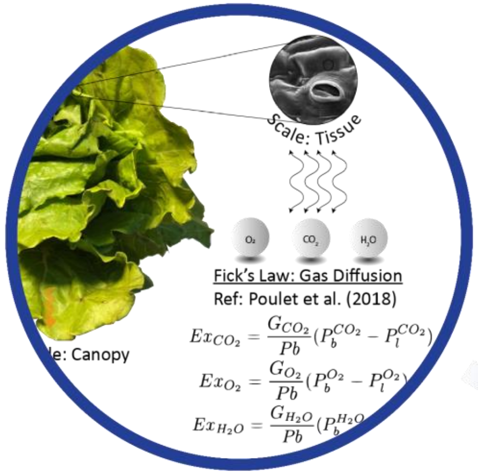
C4b Pb SP

WP2: Basic Design & Control Strategy

Objective: The main objective is **controlling O_2 in C5 at 21%.** This is done by **adjusting the flow from the enriched O_2 gas phase in C4b to C5. C4b gas phase is controlled by adjusting the light intensity.**

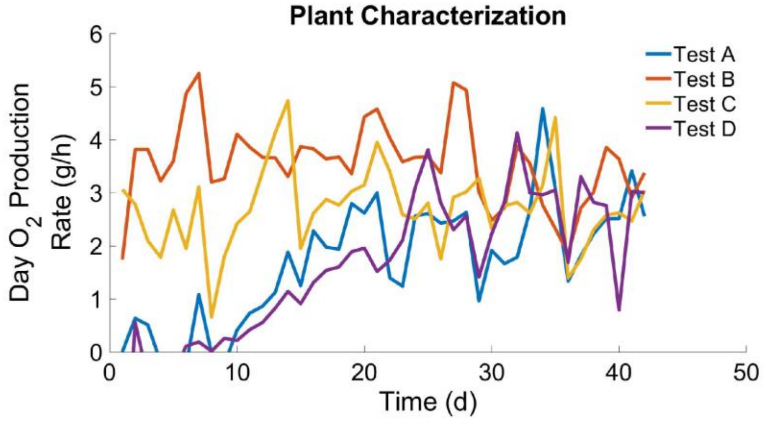


WP2: C4b Required Blocks

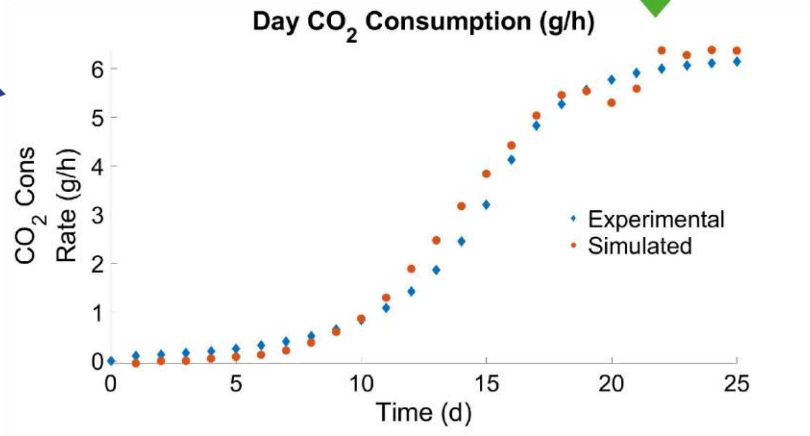


Higher
Plants
Modelling

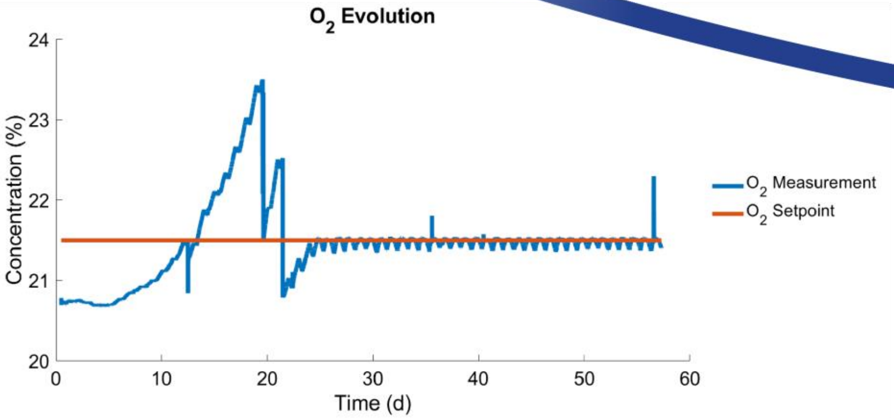
1 Available
Hardware



2 Plant
Characterization



3 Model
Validation

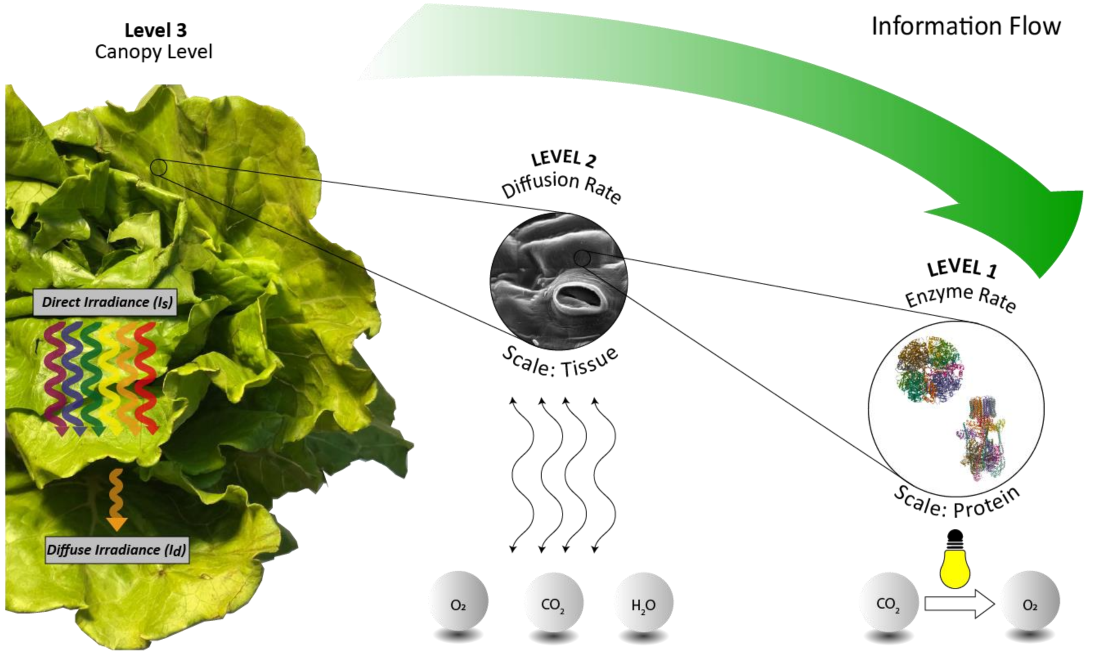


4 Control
Implementation

Integration
C4b-C5

WP2: C4b Model Construction

C4b Required Blocks | C4b Model Construction | C4b Available Hardware | C4b Model Validation | C4b Control Implementation



<u>Canopy Irradiance</u>
Ref: Johnson et al. (2010)
Thronley et al. (1996)

- Canopy effect on irradiance:

$$I_s = kI_u(f_s + (1 - f_s)e^{-kLAI})$$

$$I_d = (1 - f_s)I_u e^{-kLAI}$$

- Canopy effect on irradiated energy:

$$E_{h_s} = I_s NacLAI_s \sum_{i=\lambda_{min}}^{i=\lambda_{max}} \frac{\gamma_i}{\lambda_i}$$

$$E_{h_d} = I_d NacLAI_d \frac{1}{\lambda_{600_{nm}}}$$

<u>Fick's Law: Gas Diffusion</u>
Ref: Poulet et al. (2018)

$$Ex_{CO_2} = \frac{G_{CO_2}}{Pb}(P_b^{CO_2} - P_l^{CO_2})$$

$$Ex_{O_2} = \frac{G_{O_2}}{Pb}(P_b^{O_2} - P_l^{O_2})$$

$$Ex_{H_2O} = \frac{G_{H_2O}}{Pb}(P_b^{H_2O} - P_l^{H_2O})$$

<u>Enzyme kinetics</u>
Ref: Farquhar et al. (1980)

$$F_{LETC} = \frac{(F^{max}_{LETC} + \varphi I_u) -}{2\theta}$$
$$\frac{\sqrt{(F^{max}_{LETC} + \varphi I_u)^2 - 4\varphi\theta I_u F^{max}_{LETC}}}{2\theta}$$

$$V_c = V_{cmax}\frac{(C_l - \Gamma)}{C_l + K_c(1 + \frac{O_l}{K_o})}$$

Main Characteristics of the Model:

- The organization of the model should be structural and funcional
  - In Level 3: Canopy and irradiance
  - In Level 2: Stoma and diffusion
  - In Level 1: Proteins and enzyme kinetics
- The outputs should be dynamically modelled (CO_2, H_2O, O_2)
- When required, statistical approaches may be considered (Leaf area, irradiance decay...)

WP2: C4b Available Hardware

C4b Required Blocks | C4b Model Construction | C4b Available Hardware | C4b Model Validation | C4b Control Implementation

The MELiSSA Pilot Plant Higher Plant Chamber (HPC) is designed to grow higher plants in a hydroponic system, using LED (green, red, far-red and blue) lightning and made by three central modules dedicated to grow vegetables and two airlocks in the laterals dedicated to seed and harvest the plants with a minimum volume loss

HPC Design and Operation characteristics	**Value**	**Units**
HPC Surface	5	m^2
HPC Volume	9.4	m^3
Day/Night Bulk Temperature (T_b) – Controlled	26-20	ºC
Bulk Pressure (P_b) – Controlled	101300+50	Pa
Day/Night Relative Humidity (RH) – Controlled	50-70	%
Day Light Intensity (I_u) – Controlled	130-550	$\mu mol/m^2/s$
External CO_2 concentration (C_i) - Controlled	1000	µmol/mol
Hydroponics pH and EC - Controlled	5.9, 1.9	[], mS

WP2: C4b Model Validation (And Light Control Design)

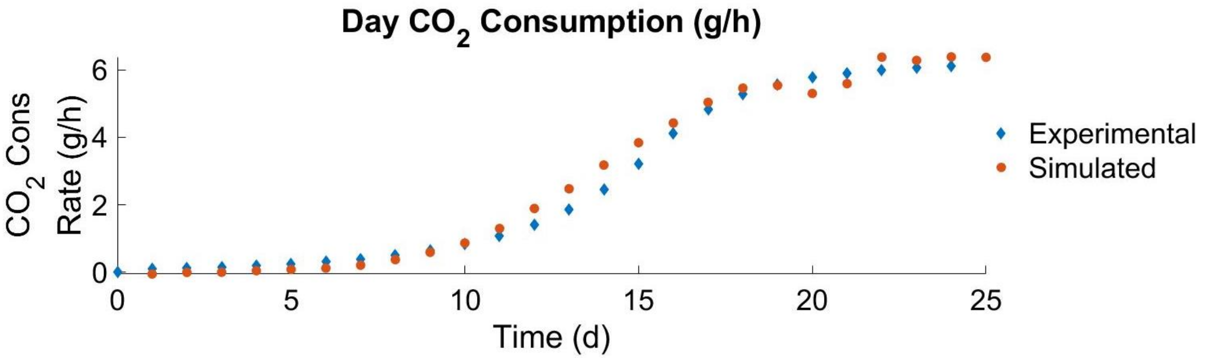
C4b Required Blocks

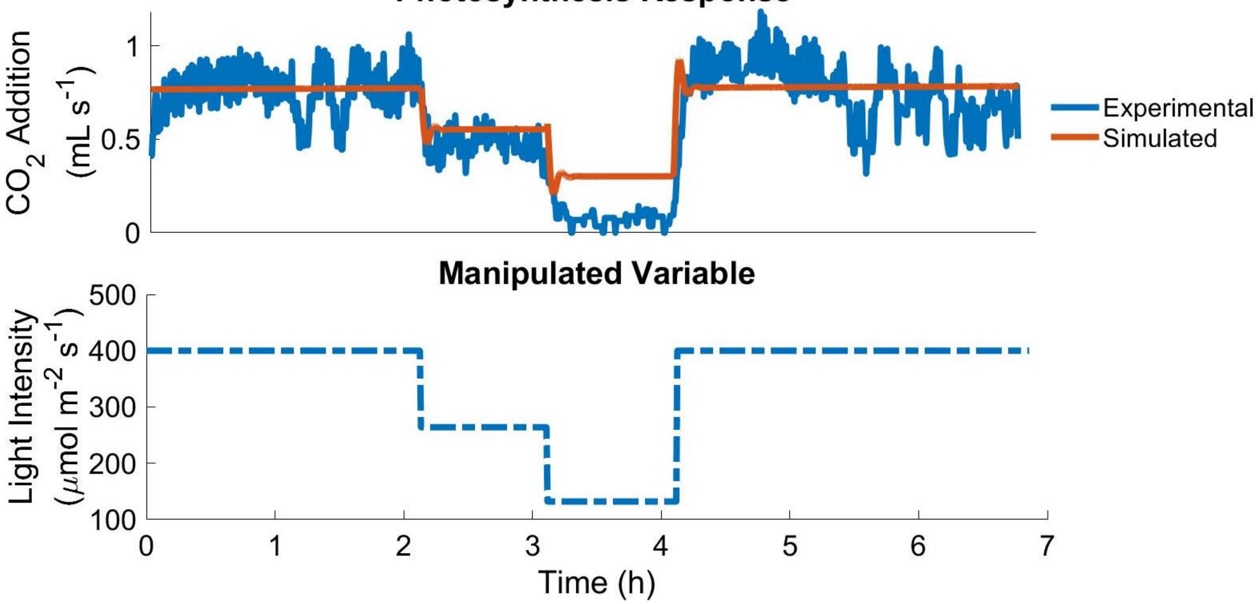
C4b Model Construction

C4b Available Hardware

C4b Model Validation

C4b Control Implementation





Model Validation: Day photosynthetic activity expressed as CO_2 consumption rate demonstrates high model validation

Light Control: Dynamic response of photosynthetic activity to changes in light intensity allows to derive a control law. Such control law can be obtained *empirically* or *model-based (and* even *analitically)*:

$$\tau = 4.8\ h$$

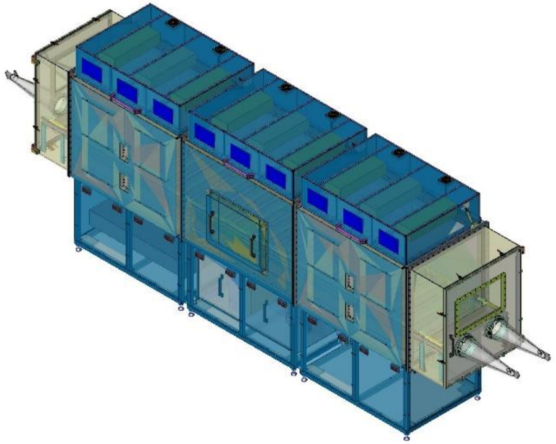
$$K = 1.22 \cdot 10^{-4} \frac{\%\ O_2}{mol\ m^{-2} s^{-1}}$$

WP2: Control Implementation – Experimental Design

C4b Required Blocks | C4b Model Construction | C4b Available Hardware | C4b Model Validation | **C4b Control Implementation**

Test Objective: Adjusting O_2 concentration at 21.5% in C4b by manipulating light intensity and 16h/8h photoperiod

- MPP Higher Plant Chamber **is set to produce up to 2.1 – 2.2 g/h O_2 providing satisfactory biometric quality** *(see Plants Characterisation session 3/3 10:30 by Carolina Arnau et al., for details)*
- N_2 is injected in the chamber to simulate the O_2 consumption of 3 rats (~1.7 g/h)



CO_2 Addition = 0.5 L/h →

N_2 + Air (5% O_2) = 9.5 L/h →

→ *Output* = 10 L/h

O_2 Gain = 1.2 g/h

O_2 Loss = 2.9 g/h

Balance = 1.7 g/h

WP2: C4b Control Implementation - Results

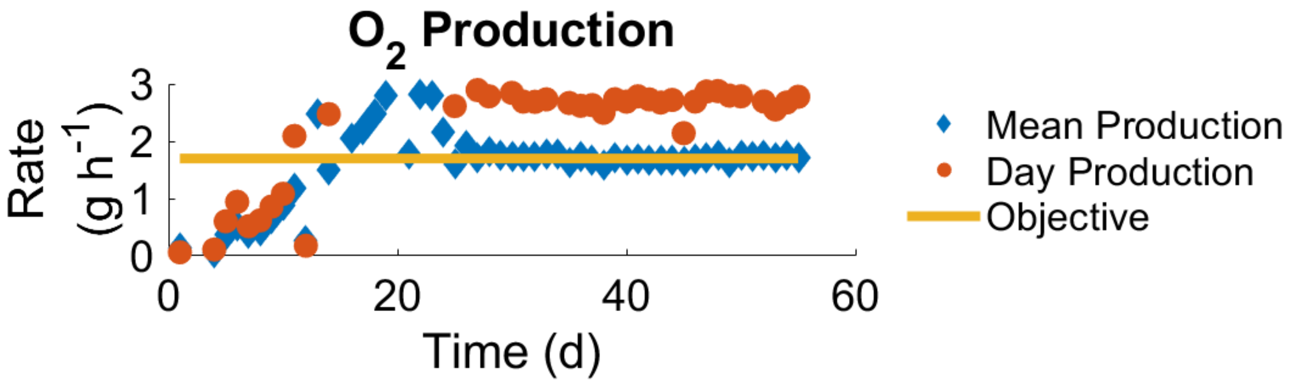
C4b Required Blocks

C4b Model Construction

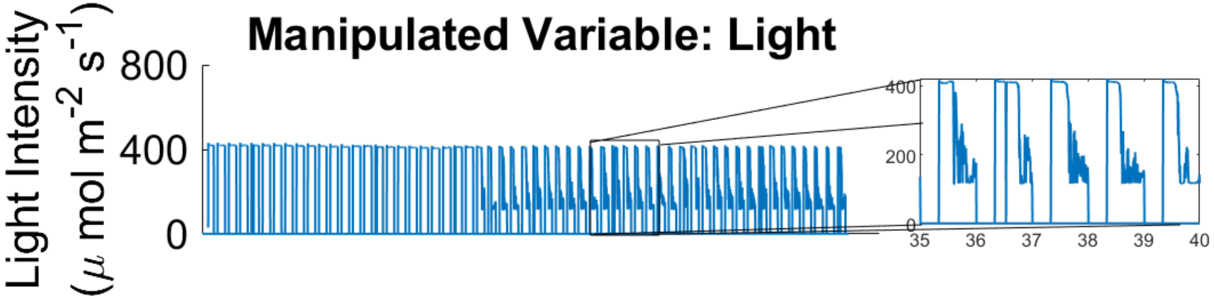
C4b Available Hardware

C4b Model Validation

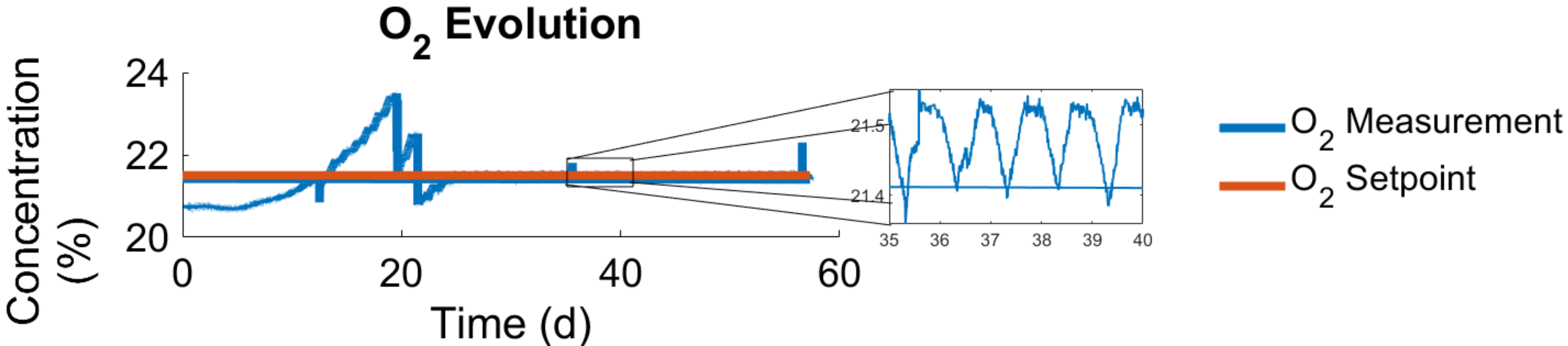
C4b Control Implementation



The expected O_2 **productivity is properly achieved**. Night plant respiration decreases the mean (24-h basis) productivity in relation to day productivity



Light intensity is well adjusted, with saturation after dark photoperiod



O_2 is very well controlled at 21.5%, with minimums achieved during dark respiration

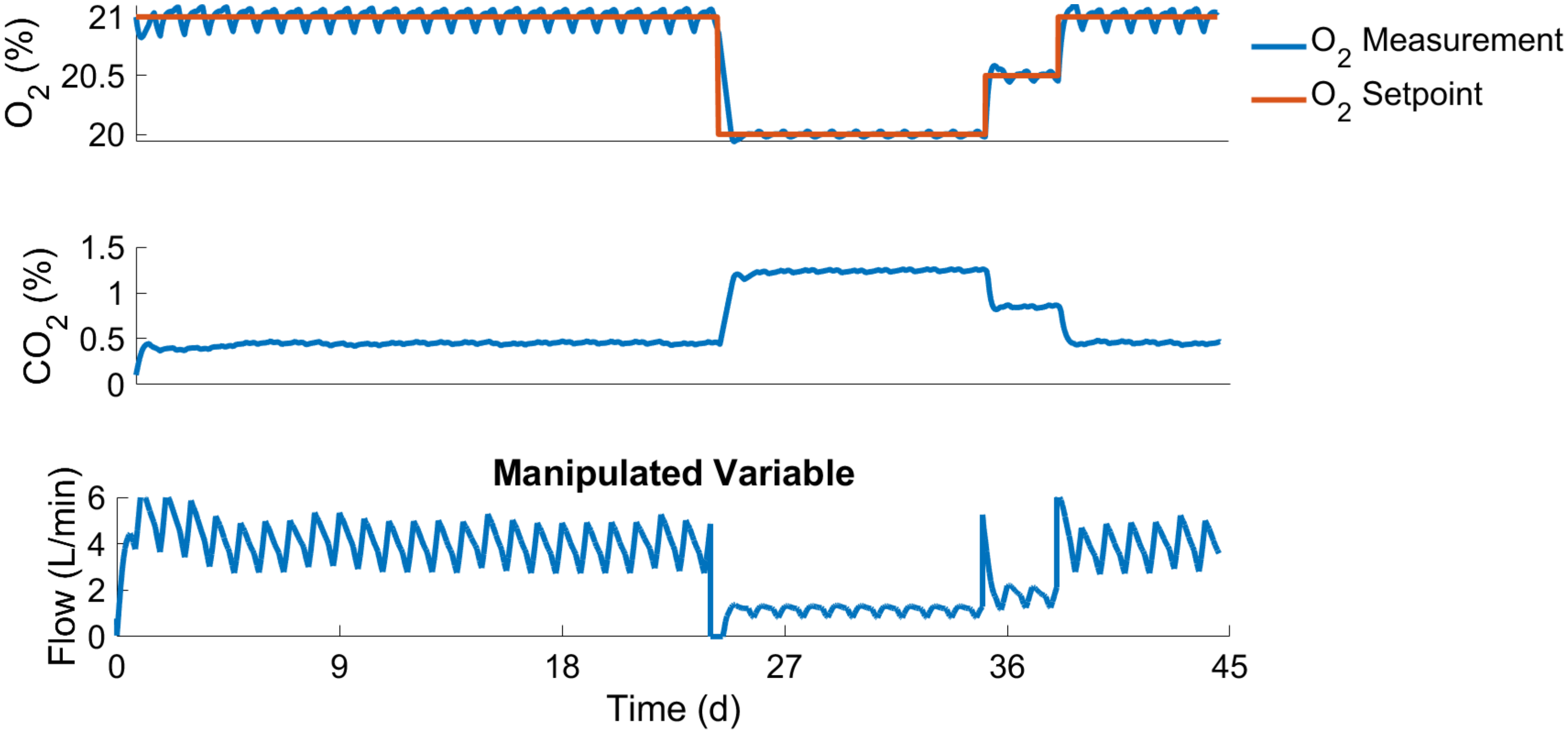
WP2: Simulation C4b – C5 Integration

C5 Dynamics

C5 Operating Conditions	Value
Number of Rats	3
Photoperiod	12h/12h

Controlled Variable: O_2

Manipulated Variable: Flow



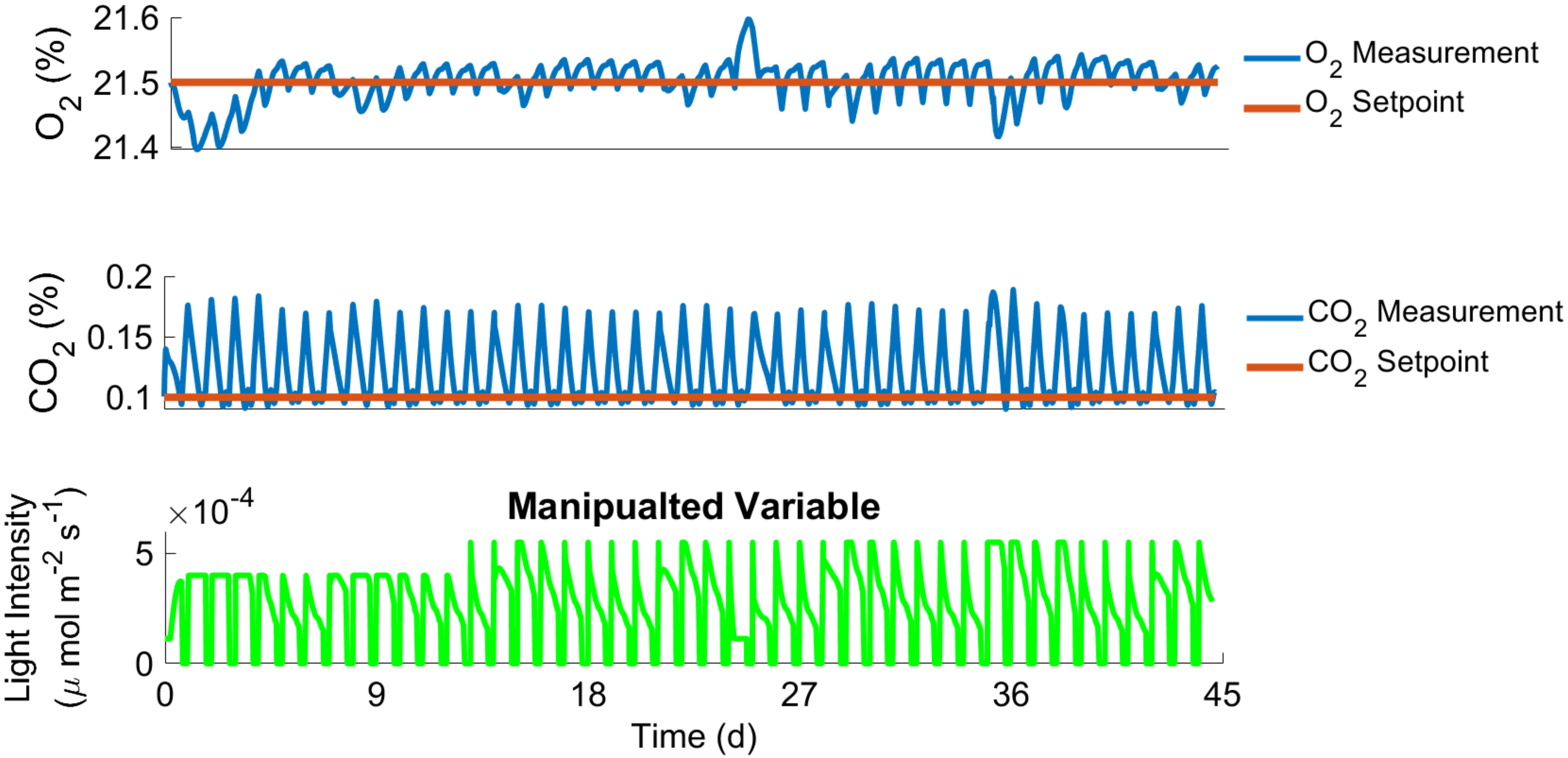
WP2: Simulated C4b – C5 Integration

C4b Dynamics

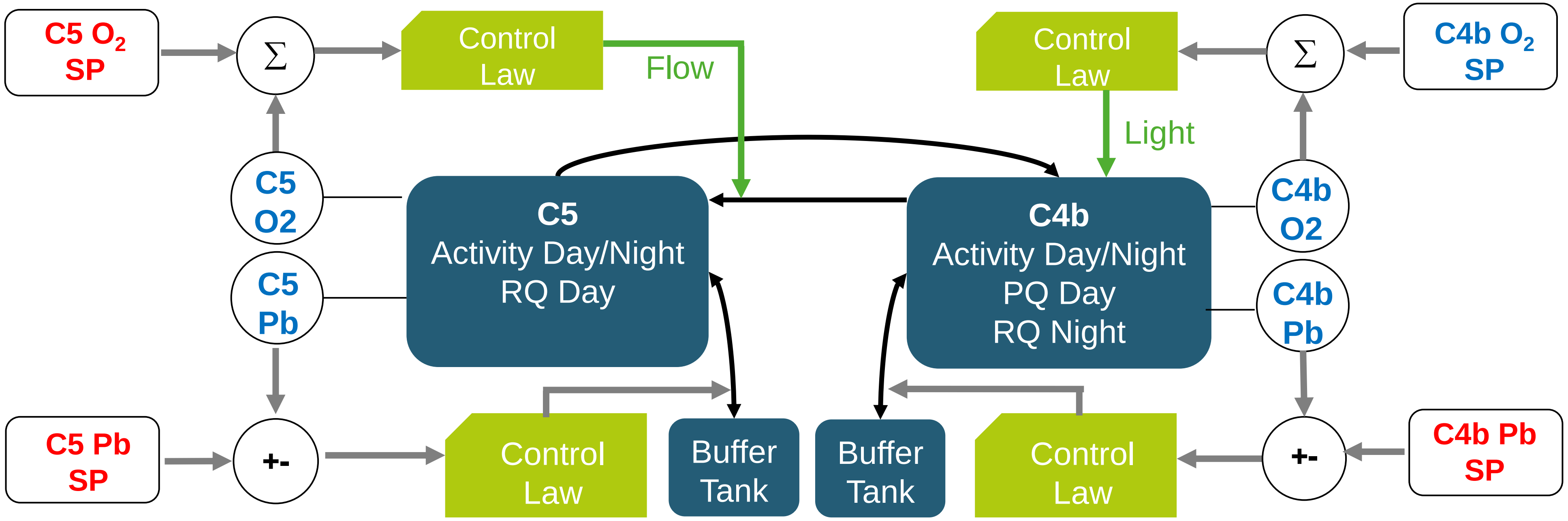
C4b Operating Conditions	Value
Photoperiod	16h/8h
CO_2 SP	0.1%
Light Irradiance boundary	130, 500 µmole $m^{-2}s^{-1}$

Controlled Variable: O_2

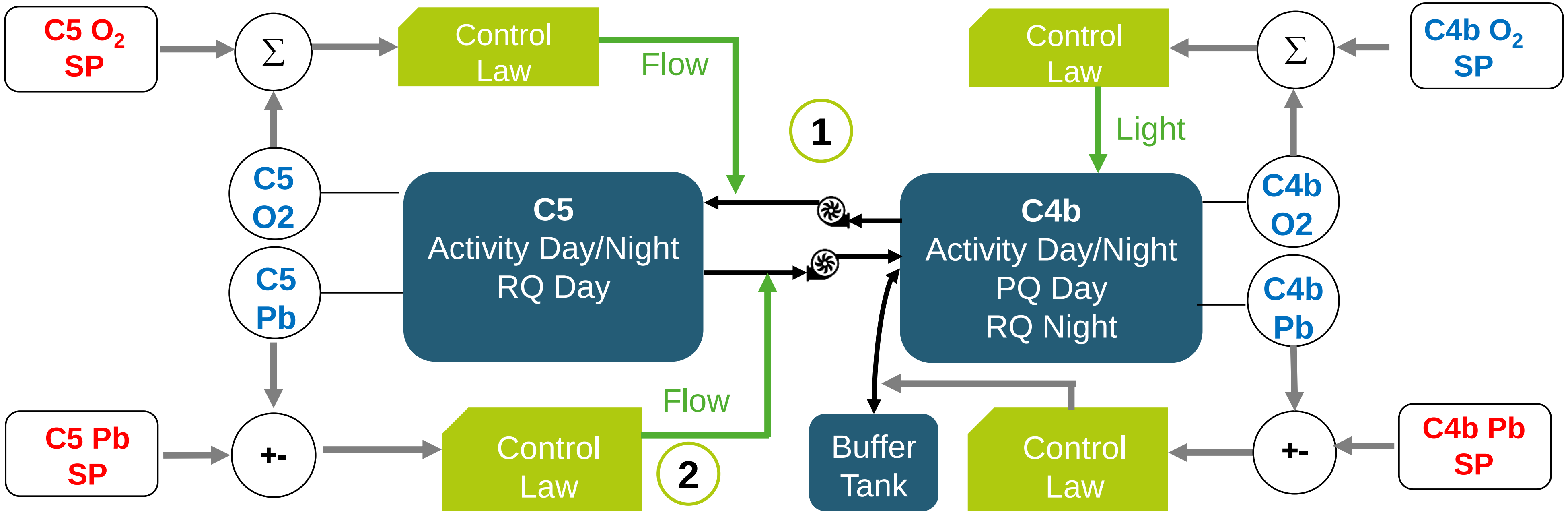
Manipulated Variable: Light



WP2: Process Flow Preliminary Diagram



WP2: Process Flow Final Diagram



C5 O_2 SP

Σ

Control Law

Flow

①

Control Law

Σ

C4b O_2 SP

Light

C5 O2

C5 Pb

C5
Activity Day/Night
RQ Day

C4b
Activity Day/Night
PQ Day
RQ Night

C4b O2

C4b Pb

Flow

C5 Pb SP

+-

Control Law

②

Buffer Tank

Control Law

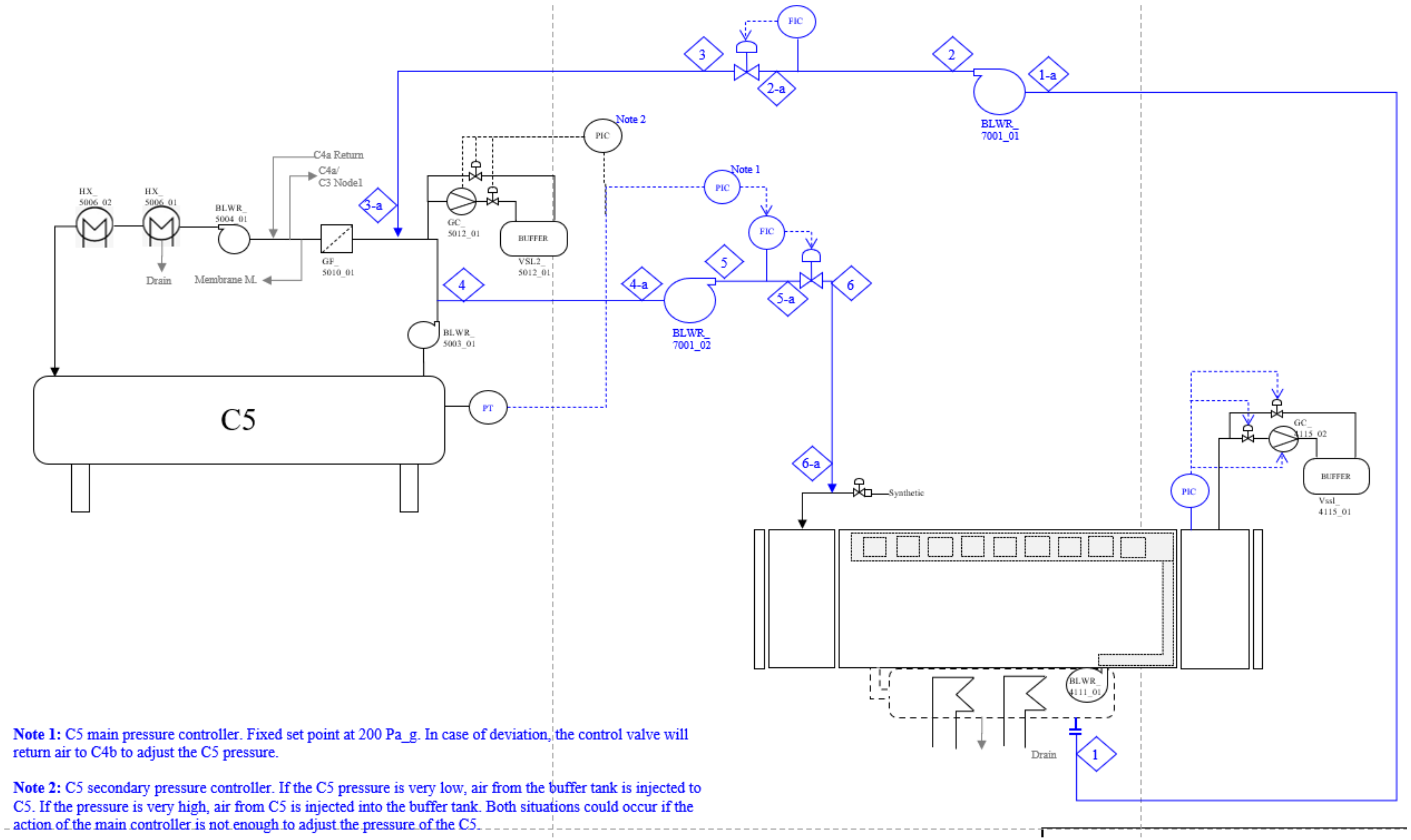
+-

C4b Pb SP

① Low nominal flow (2 mL/min) and low compartment overpressure can be managed by gas buffers

② Error between outbound and return flows may lead to pressure unstability, thus only one buffer tank is used for both compartments and overpressure in C5 is controlled by return flow to C4b

WP2: Detail P&ID and Next Steps



Note 1: C5 main pressure controller. Fixed set point at 200 Pa_g. In case of deviation, the control valve will return air to C4b to adjust the C5 pressure.

Note 2: C5 secondary pressure controller. If the C5 pressure is very low, air from the buffer tank is injected to C5. If the pressure is very high, air from C5 is injected into the buffer tank. Both situations could occur if the action of the main controller is not enough to adjust the pressure of the C5.

Next steps for Integration:

1) HAZOP
2) Final P&ID
3) Manufacturing and installation
4) Site Acceptance Test (SAT), Functional Test (FT)
5) WP2 Integration campaign

THANK YOU.

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