Development of a sustainable Green Living Wall design

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Abbreviations

ET0 – Reference evapotranspiration

FC – Field capacity

GS – Growth substrate

IS – Irrigation system

LWM – Living wall module

N - Number of successive datapoint

PH - Porous micro irrigation soaker hose

STD - Standard deviation

WC – Water content

WP – Wilting point

WULCOS - Classifications of Landscape Species

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Introduction

Nowadays, the issue of climate change remains on everyone's mind. It is undeniably the greatest environmental challenge that humanity has ever faced. One of its causes is the growth of urban areas (Kahn, 2009). This growth is mainly due to a natural increase of population but also to the migration of people to urban areas. The reasons for this are better employment rates in the city, better quality of education and thus better life opportunities (Bhatta, 2010). According to the United Nations report (UNFPA, 2007), the urban population will increase to nearly 4,9 billion by 2030, implying urban sprawl. This is a major problem to be avoided. Indeed, it threatens the health, water quality and the environment. Sprawl disrupts ecosystems and fragments the habitats of species. These habitats sometimes become too small to ensure the viability of these endangered species (McKinney, 2008; Bhatta, 2010). In addition, an increase in temperature is also perceived in urban areas compared to the countryside (Oke, 1973). This becomes more pronounced when urban sprawl increases. Indeed, more shaded areas, dark urban pavements that easily absorb solar radiation (McKinney, 2008) and almost absent vegetation contribute to this increase in heat. This increase in heat has an indirect effect on air quality and thus on the health of the population (Bhatta, 2010).

Biodiversity in urban areas must, therefore, be maintained. Indeed, it plays the role of air and water purification (Bolund et al., 1999). From this perspective, urban greening is increasingly being considered. In particular, such vegetation can improve the urban environment by contributing to urban biodiversity, stormwater management, air quality, temperature reduction and the mitigation of the heat island effect (Manso et al., 2015). Several urban developments can be considered: parks, knolls, community gardens, ponds, cemeteries, woods, ... (Thorén, 2000).

However, in most cities, floor space is limited. « Artificial structures » can then be imagined, such as green roofs or green walls (Baudoux, 2018). The construction of green walls is strongly recommended. Indeed, the potential surface cover of green walls is approximately twice the surface cover of green roofs (Manso et al., 2015). Moreover, these walls function as an additional insulating layer to the walls of buildings.

According to Manso et al. (2015), the green wall, also called « vertical garden », is defined as « the common term for all forms of green wall surfaces ». Vegetated walls are separated into two main categories: *green facades* and *living walls.* The former consists of plants climbing or hanging along the wall. The roots develop in a substrate often placed at the bottom of the wall. The latter implies the use of a growth substrate placed along the wall. It can be trays, substrate panels, flexible bags, hydroponic systems, ... This allows for faster growth over large areas with a greater variety of plant species (Manso et al., 2015). Living walls are in full expansion since it fulfils more than the former the services mentioned above. Nevertheless, a lot of research still needs to be done in order to ensure optimal plant growth and thus maximum benefits. An irrigation system (**IS**) is often required. It can be challenging to set up on vertical surfaces. Furthermore, in order to reduce the mass of the system, appropriate growth substrates (**GS**) have to be developed.

This study focuses on the design of a living wall. It must be designed to provide maximum benefits. Nowadays, living walls consume a large amount of energy for the fertigation system and are composed mostly of non-native ornamental plants. The main objective of this study is to propose an alternative to the design, techniques and automation of the IS of a living wall.

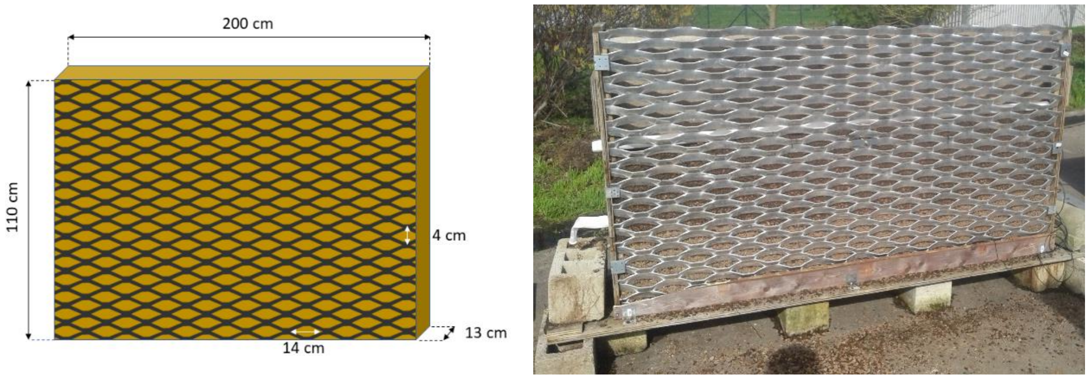
Several sub-objectives are expressed in this report to address the main objective. The first is the implementation of a living wall module (**LWM**). It consists of a relatively small module with an autonomous IS and a continuous GS. The goal is that this standardized module could be duplicated to cover a whole building wall. The design of the LWM implies a wide array of strategical choice. Notability the choice of the IS components, the type of GS, the plant types in order to create a habitat that can strengthen urban ecological networks, their location in the module and the hydraulic techniques used for irrigation, … The watering rate must also be investigated. The second sub-objective is the monitoring of the system. Understanding the measuring principle of the sensors (humidity, radiation, moisture content and temperature) is essential. The design of a measurement scheme and the placement of the sensors in the module must be considered. The programming of the quantities required for irrigation and the automatic recording of data is also fundamental. The last sub-objective concerns the determination of the water needs of the plants, the dose of irrigation to be supplied to them and its automation. Bibliographical research must, therefore, be carried out on the water needs of each species. An irrigation decision algorithm must also be developed. This must be based on the water needs of the plant and according to the technical constraints of the system. A data recording program calculating the indicators necessary for decision making must be written in order to start and stop the irrigation according to the programmed inputs and decision thresholds.

Materials and methods

1. Experimental setup features

Living wall module

In order to develop and test an LWM design, an experimental module will be set up. It is made of a plywood frame closed on one side by a deployed metal sheet (Métal Déployé Belge 200 XL ©). The dimensions and overall look of this module are shown in **Figure 1**.



(a) (b)

Figure 1 : Experimental living wall module *(a) dimensions, (b) overall look*

Location and orientation

The experiment will take place in Gembloux (Wallonia, Belgium). The LWM will be installed on a parking slot (50°33'49.28"N, 4°42'9.00"E). The open side of the module is facing South. **Figure 2** shows its overall location.

Figure 2 – Overall location of the living wall modules [Source: Google maps, 2020]

Growth substrate

The growth substrate that will be used is designed to be relatively lightweight and nevertheless have proprieties homologous to the undeveloped soil found in cracks in rocky cliffs, old walls, ... The presence of 10% of Zinco © and 20% of Pouzzolane ensure relatively high stoniness. The former is natural recycled ceramics enriched in selected minerals. It is used for green roofs and ensures an input of minerals due to its weathering. The latter is a crushed porous volcanic rock (diameter around 2 to 11mm) (Baudoux, 2018). **Table 1** summarizes its composition and physical proprieties.

Table 1 – Composition and physical proprieties of the growth substrate [Source: Baudoux, 2018]

	Fraction [%]	Bulk density [kg/m^3]	Water retention [% $_{\text{dry volume}}$]	pH [-]
Clay pebbles	10	487	50	6 – 7
Zinco ©	10	1 000	40	6.5 - 8
Pouzzolane	60	12 000	10	< 7
Pot soil	20	230 - 390	30	5.5 - 6

Irrigation system setup and components

A micro-irrigation system will be tested in the LWM. A 12 mm diameter *porous soaker hose* (**PH**) (*Gardena* ©) will be used. It is connected with a *Gardena* © hose connector set to a 1 m^3 Rigid IBC tank installed at a height of 3 m on a stackable scaffold storage rack. Irrigation will be triggered with an electric ball valve (12V DC relay controlled, *TAMESON* ©). **Figure 3** shows the general setup of the system. The PH will be inserted in a strained piezometer pipe (in PEHD, 25x32 mm diameter, *Eijkelkamp* ©), **Figure 4(a)**. It will be set up in this way to allow the hose to be taken out of the module for servicing or replacing without taking apart the whole module. The strained piezometer pipe is itself inserted into a geotextile hood. This should diminish the deposition of particles on the PH itself and enhance its lifespan. **Figure 4(b)** shows the hose inserted in the piezometer pipe and **Figure 4(c)** shows the partially filled LWM with two pipes already installed.

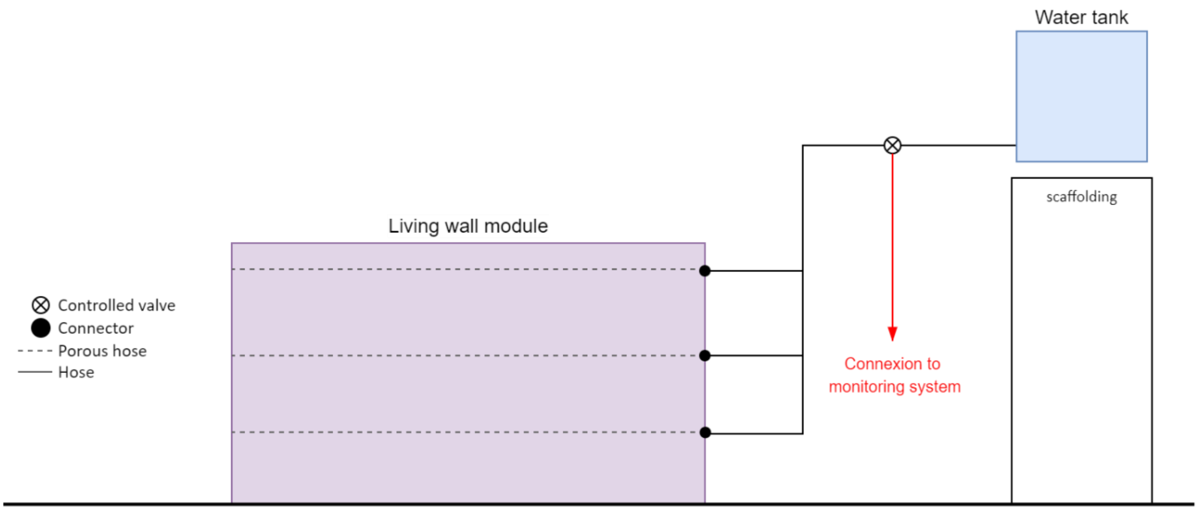


Figure 3 – General set up of the irrigation system

(a) (b) (c)

Figure 4 – Irrigation piping set up *(a) Strained piezometer pipe (Eijkelkamp ©) inserted in a geotextile hood - (b) Porous hose inserted in the piezometer pipe, (c) Piezometer pipe inserted in the partially filled living wall module*

Monitoring

In order to monitor environmental parameters in the LWM, an array of sensors will be set up in and aside from the module. 3 EC_5-$H_2$0 (© *METER* (METER Group, 2020)) capacities probes will be installed to measure volumic water content (**WC**) (METER Group, 2020)) [**Figure 5(b)**]. Their calibration is described in §*Calibrations of the water content probes.* A weather station (**WS**) ATMOS 41 (© *METER* (METER Group, 2020)) [**Figure 5(a)**] will be set next to the LWM. **Table 2** shows the parameters recorded with those sensors that will be exploited as well as their range of measurement, resolution and accuracy.

Table 2 – Monitored environmental parameters, range of measurement, resolution and accuracy
[Source: © METER (METER Group, 2020)]

	Range	Resolution	Approx. accuracy
Water content	0-100% WC	0.001 m^3/m^3	± 0.02 m^3/m^3
Temperature	-50 to 60 °C	0.1 °C	± 0.6 °C
Radiation	0-1750 W/m^2	1 W/m^2	± 5% of measurement
Vapor pressure	0-47 kPa	0.01 kPa	± 0.2 kPa
Wind speed	0-30 m/s	0.01 m/s	3% of measurement
Precipitation	0-400 mm/h	0.017 mm	± 5% of measurement
Relative Humidity	0-100% RH	0.1% RH	± 3% of measurement

(a) (b)

Figure 5 - Environmental parameters monitor sensors *(a) AMOS 41 Weather station, (b) EC$_5$-H$_2$0 capacitive probe*
[Source: © METER (METER Group, 2020)]

Data recorded with those sensors will be processed through an algorithm (coded in Python 2.7). This treatment will be achieved on a virtual server through a *Raspberry Pi* © microcomputer. The whole monitoring setup is presented in **Figure 6.**

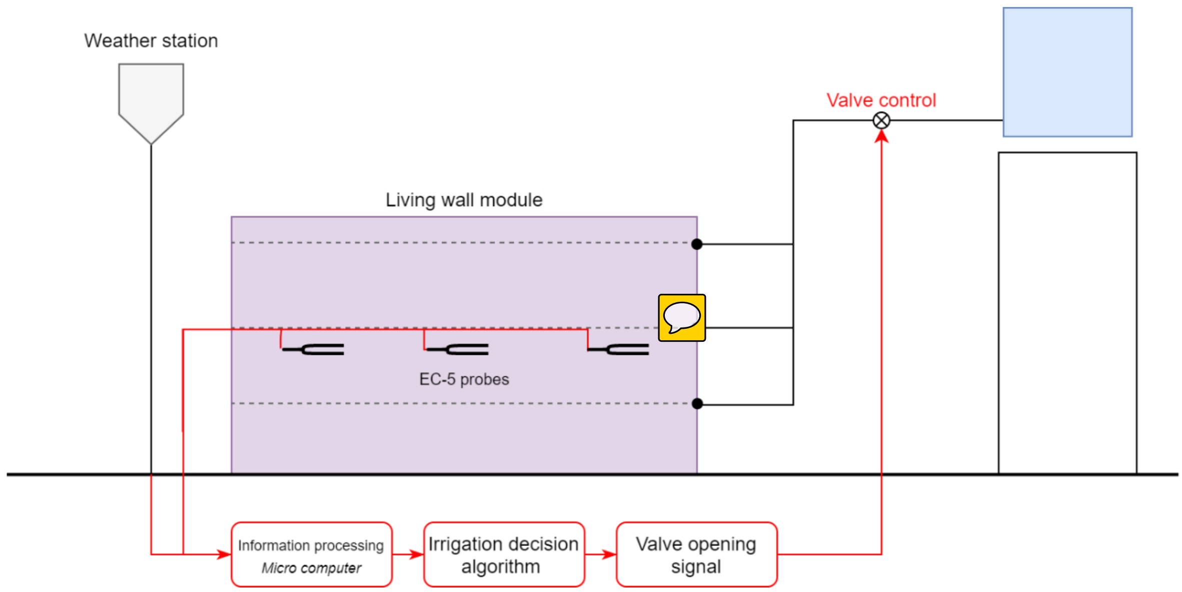


Figure 6 – Monitoring setup

2. Plants selection and installation

In the context of this study, seven different plant species are made available [**Table 3**]. These plants are native to Wallonia and belong to the category of "spontaneously colonized walls" according to the WalEunis classification (Dufrêne et al., 2005). It has been imposed that a minimum of five plants must be chosen. Only some of these species will be selected to be part of the LWM. The selection criteria [**Table 3**] are:

- Water requirements of the species to ensure optimal distribution according to the soil moisture gradient;
- Size of the plant to limit the impact of competition between individuals;
- Recommended exposure to ensure good conditions for plant development;

- The flowering period of the species in order to obtain a spread and varied flowering.

In order to determine the number of plants to install on the LWM, common plant density for each species is taken into account. The overall aestheticism of the module is also taken into account considering the colour of the bloom, the flowering period and the height of the plants at maturity. Besides, an additional constraint is added: a budget limit of 125€.

The location of each plant on the LWM will be determined according to the water needs of each species. Areas expected to have a lower humidity level will accommodate species that need less water to survive over time. These areas are expected to be the ones further away from the PH. Moreover, according to Baudoux (2018), the average water content in the upper parts of the green wall is higher than in the lower parts. The most hydric stress-sensitive plants will be set in the upper part of the LWM. Besides, the recommended exposure for each species will be considered. Plants that need a lot of sunlight will be placed so that they are not shaded by the other plants. Finally, it will be determined if the discharge though the PH is equally distributed (cfr §*Determination of the repartition of the discharge in the drip irrigation system*). If it is not the case, this parameter will also be taken into consideration.

Table 3 shows available plants and their characteristics. The optimal soil moisture for each species is expressed on a scale of 1 to 8 (low to high water need) (Tela Botanica, 2020). Exposition is also expressed on a scale of 1 to 8 (low to high light needs) (Tela Botanica, 2020).

Table 3 – Available plants and their proprieties [Source: Tela Botanica, 2020]

Plants	Exposition	Soil moisture	Height at maturity [cm]	Flowering	Density [plants/m²]
***Asplenium trichomanes* L.** Wall capillary	5	2	6-35	_	9
***Dianthus carthusianorum* L.** Carthusian carnation	7	2	20-50	June-Sept	9
***Geranium sanguineeum* L.** Blood red geranium	5	2	10-40	June-July	6
***Melica ciliata* L.** Ciliate meslin	7	3	30-90	May-July	9
***Origanum vulgare* L.** Common oregano	5	3	30-80	July-Sept	6
***Thymus pulegioides* L.** Thyme faux pouliot	7	1	5-40	July-August	44
***Tragopogon pratensis* L.** Salsify of the meadows	7	3	30-80	May-July	11

3. Irrigation decision algorithm

General structure

On order to ensure a maximum of resilience to the system, the irrigation decision will be based on both data sources (WS and WC probes). The program will be designed to start every day at 6 AM. It is considered to be the best time of the day to do so since it should minimize the possible loss of water through drainage. The program will go through the serial of steps presented bellow then shut off until 6 AM the next day [**Figure 7**]. The detailed flow chart can be found in **Appendix I**.

1. In the first place, WC is checked and if it shows to be below a boundary value, watering will be done.
2. If this condition is fulfilled, irrigation is done based on the estimation of the reference evapotranspiration (ET_0) (cfr §*Reference evapotranspiration computation*) and a coefficient

linked to the plant cover of the module (cfr §*Crop coefficient determination*). ET_0 is computed over the last 24h with the data recorded with the WS.
3. Finally, 2 hours after the end of the irrigation, WC is checked again and if it shows to be too low, an extra watering is processed. The dose is computed based on the WC information from the probe, to bring the WC back to the set boundary value.

The following features will be implemented in the script as well:

- The measured precipitations over the last 24h will be subtracted to the calculated irrigation dose.
- In case of a breakdown of one of the two data sources, thanks to the structure of the algorithm, the still available data (WC or WS) will be used alone to determine the water needs.
- In case of a breakdown of the two data sources, a backup irrigation program will be followed. The dose being computed as 70% of the amount of water necessary to bring the soil from wilting point to field capacity.
- The possible breakdown of one of the sensors will be detected through a data quality check described in the section below.

Data quality check

The data quality check consists of the analysis of the standard deviation of the measures over a certain period of time. This value will be compared to a maximum standard deviation admissible. If the former is higher than this limit, it is considered that the data coming from the sensor is not reliable. This will allow detection of outlier data points and possible jumps in the records. However, this will not allow detection of a blocking or a shutting down of the sensors. The maximum standard deviation admissible will be determined on data recorded during a test period during which no breakout of the monitoring equipment occurs. On this dataset, the standard deviation on a certain number of successive measures (data points available every minute) will be calculated. In order to determine the period necessary to capture the variability of the parameters, the sensibility of the maximum standard deviation to the number of successive data points used for its calculation will be studied. A period that allows the detection of a sufficient degree of variability of the parameters will be retained. Finally, if the quality test is not fulfilled, it will be notified on the irrigation software interface.

Considerations on the algorithm

This algorithm includes an array of strategy choices based on *a priori* knowledge. One of the aims of the study conducted here is to test those and optimize them on a trial and error process. Here is a list of the choices that need to be tested and possibly adapted:

- The algorithm runs every 24h. It might not be the optimum irrigation frequency.
- The WC boundary is set at 70% of the WC at field capacity. It is considered as a satisfying compromise between water use efficiency and probability of hydric stress occurrence.
- The post-irrigation check is realized 2h after the first watering. It is considered sufficient to ensure that the water has spread equally in the module.
- The volume of the backup irrigation program is fixed at 70% of the amount of water necessary to bring the soil from wilting point to field capacity. It is considered as a sufficient security margin.
- The data quality check procedure is based on the assumption that environmental parameters will not vary at a higher rate during the test period.
- The full rainfall height is subtracted to the irrigation dose without taking into account the verticality of the LWM. Ideally, this value should be marked down according to wind direction during the rain.

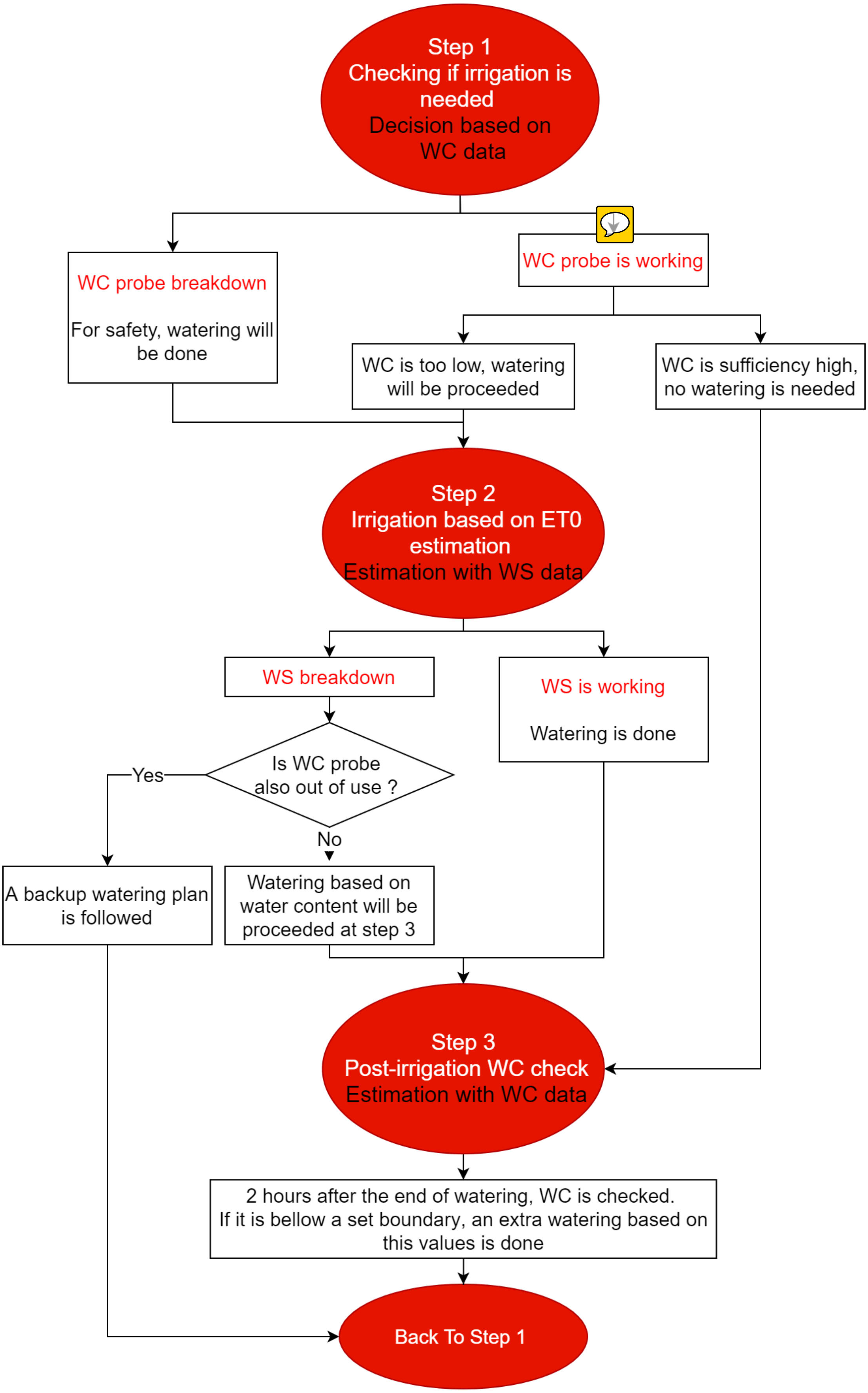


Figure 7 – Structure of the irrigation decision algorithm

4. Reference evapotranspiration computation

In order to determine irrigation doses, ET_0 will be calculated in the decision algorithm. It will be done using the FAO PENMAN-MONTEITH equation, hereunder, on the hourly time scale. ET_0 over the day is computed as the sum of the hourly ET_0 as it has shown to be more accurate (Allen et al., 1998).

$$ET_0 = \frac{0.408\,\Delta(R_n - G) \;+\; \gamma\,\dfrac{37}{T_{hr} + 273}\,u_2(e^0(T_{hr}) - e_a)}{\Delta \;+\; \gamma\,(1 \;+\; 0.34\,u_2)}$$

With:

- ET_0 the reference evapotranspiration (mm.hour^{-1});
- R_n the net radiation at the grass surface (MJ.m^{-2}.hour^{-1});
- G the soil heat flux density (MJ.m^{-2}hour^{-1});
- T_{hr} the mean hourly air temperature (°C);
- Δ the saturation slope vapour pressure curve at T_{hr} (kPa.°C^{-1});
- γ the psychrometric constant (kPa.°C);
- $e^0(T_{hr})$ the saturation vapour pressure at air temperature T_{hr} (kPa);
- e_a the average hourly actual vapour pressure (kPa);
- u_2 the average hourly wind speed (m.s^{-1}).

G will be the neglected here since the absence of contact between the LWM and the soil implies that not heat flux towards the underground is possible. R_n will be approximated to the incoming solar radiation. Canopy reflection, as well as net outgoing longwave radiation, are neglected. This choice is made for the following reasons. On one side, it is highly complex to determine. The albedo of the metal sheet should be taken into account of early stages of growth. Plus, the outgoing radiation occurs not only on the planted side of the LWM but on all, unlike on ground surface. On the other hand, given the relatively high uncertainty on other parameters (notably the crop coefficient and the accuracy of the WC probe calibration), it seems inconsistent to try to reach high accuracy for this factor. Additionally, the incoming solar radiation measured by the WS will be used as it is although it would be necessary to take into account the verticality of the wall and the zenith angle. This simplification will, therefore, be tested but there is no *a priori* guarantee that it will not cause strong over- or under-estimation of the ET_0.

The following parameters are directly received from the WS and do not need further calculation other than an hourly average: solar radiation, air temperature, wind speed, vapour pressure and atmospheric pressure. To calculate the saturation vapour pressure at air temperature, MAGNUS equation hereunder will be used (Alduchov et al., 1995). The saturation slope vapour pressure value is obtained with the derivative of this next equation.

$$e^0(T_{hr}) = \;0.61094\; e^{(17.625\,T_{hr}/\,T_{hr}\,+\,243.04)}$$

The psychrometric constant will be calculated with the next equation (Allen et al., 1998).

$$\gamma \;=\; \frac{C_p P}{\varepsilon\lambda}$$

With:

- γ the psychrometric constant (kPa.°C^{-1});
- P the atmospheric pressure (kPa);
- λ the latent heat of vaporization, 2.45 (MJ.kg^{-1});
- c_p the specific heat at constant pressure, 1.005 10^{-3} at 300 K (MJ.kg^{-1}.°C^{-1});
- ε the ratio molecular weight of water vapour/dry air = 0.622.

5. Crop coefficient determination

The determination of the actual evapotranspiration of the plants (ET_c, mm/day) from the ET_0 parameter requires the determination of a weighing parameter: the crop coefficient K_c (dimensionless) as shown on the equation below.

$$ET_c = K_c \,.\, ET_0$$

The FAO has developed a database of reference K_c for farming crops (Allen et al., 1998). Conversely, for ornamental plants, this type of information is lacking. Furthermore, the combination of a wide variety of plant on a small surface implies a high variability of this parameter over space and time. Hence it will be tried to apply the Water Use Classifications of Landscape Species (WULCOS) method and database developed by Costello et al. (2000). The latter has been developed based on expert work carried out to estimate the water demand of mixed-type urban vegetation, in order to guarantee good growth and an appreciable aesthetic aspect of the plant (Nouri et al., 2013). It consists of the determination of a *Landscape coefficient* (**K_L**) alternative to the K_c. The K_L is equal to the product of three factors allowing the consideration of the complexity of a diversified and stratified plant cover. Here is a description of theses factors (all dimensionless) (Nouri et al., 2013):

The species factor (K_s) – it takes into account the presence of different species. During field observations by experts, four main categories of water demands were created and numerical values were assigned to them, namely very low (< 0.1), low (0.1-0.3), moderate (0.4-0.6) and high (0.7-0.9). In cases where species with different water needs are planted in the same irrigation zone, the species in the highest water-need category determine the K_s value. These parameters can be found in the WULCOS database and vary of one species according to the *ET_0 climatic zone* location (Costello et al., 2000). Since the WULCOS has been developed for California, an equivalence in term of *Californian ET_0 climatic zone* will be determined

The density factor (K_d) – two parameters are taken into account here. The first is the canopy cover, which reflects the presence or rarity of plants and their shade. The second is the vertical height of the vegetation. From immature and sparse vegetation to mature mixed vegetation, three main density classes with values ranging from 0.5 to 1.3 have been defined and correspond to low, medium and high densities (Nouri et al., 2013).

The microclimate factor (K_{mc}) – the microclimate designates different environmental conditions in a given climatic zone. Urban constructions (buildings) can induce shading, which in turn will influence meteorological parameters. This factor is in the range of 0.5 to 1.3, a value that represents how much an area is affected by urban constructions (Nouri et al., 2013).

The combination of those parameters to the ET_0 thanks to the following relation gives an estimation of the real evapotranspiration and thus the irrigation requirement.

$$ET_L = K_L \,.\, ET_0 = K_s \,.\, K_d \,.\, K_{mc} \,.\, ET_0$$

6. Substrate physical proprieties determination

The irrigation will be based upon the water content measured in the substrate of the LWM. More specifically, a water content limit upon which watering will be targeted has to be determined. This will be done considering the water content at field capacity. Richard's chambers experiment at 300 HPa will be conducted to determine this parameter.

7. Calibrations of the water content probes

A calibration will be carried out to determine the relationship (calibration curve) between the output voltage and the WC. Because the output voltage does not only depend on the water content but also on some other soil features, the calibration process must be performed for a particular substrate.

The calibration curve will be built out of four data points. Each being the link between the output voltage of the probe and an actual WC (namely 0, 15, 30 and 100%). For each point, three repetitions will be done and their mean will be considered. Here below are the main steps for the calibration samples preparation:

- A certain amount of GS is passed to the desiccator at 40°C for 48h.
- Dry GS samples are weighted to reach a constant retrieved mass of dry soil (887,3 g).
- Each GS sample is mixed thoroughly with the amount of water required to reach the WC mentioned above.
- The GS samples are inserted in a standardized calibration recipient. The fitted volume is 1013 cm^3. The size and shape of this recipient ensure the presence of a sufficient volume of substrate around the probe.
- To make sure to reach the required soil density and its homogeneity, the recipients are filled up in small portions and possibly packed in order to reach exactly the mentioned volume.

The probes will be inserted in each calibration samples. Thanks to a *CR800 Campbell* © datalogger the probes are submitted to a 2.5 V excitation signal. The probes output voltage signal will be recorded with the same datalogger. For each WC sample, three measures will be realised. The mean of the three repetitions will be linked to the WC of the sample to generate a couple of data points (WC + output voltage) used to draw a calibration curve based on a linear regression of the data points. The obtained equation is the relation that will be used to convert probe output voltage to WC during the experiment.

8. Determination of the discharge proprieties of the drip-irrigation setup

Two important features related to the drip-irrigation setup have to be determined. Firstly, the discharge rate of the PH for a given head. Secondly, the repartition of the water flow in the different parts of the system. The former information is necessary to (1) make sure that the PH allows the discharge of a sufficient amount of water in the LWM. Indeed, the service pressure recommended by the manufacturer is 0.5 to 1 bar and there is no certitude about the workability of the system at a lower pressure (between 0.3 and 0.4 bar in our case). And (2) to program the valve opening time according to the water volume needed. This information is needed because the watering of the LWM is controlled thanks to a single valve located upstream the module. Watering of the three sub-volumes of the module cannot be done separately. The experiments presented in the following two sections will be conducted in order to provide answers to those questions.

Establishment of a discharge-head relation

An experiment will be conducted to ensure that the needed irrigation flow rate is reachable with the order of magnitude of pressure head delivered thanks to the scaffold tank setup. If the condition is not verified, it will be considered to install a pump instead of the scaffold disposal.

A tank is mounted on a scaffold and connected to a pipe itself connected to the PH. The PH is 3.4 m under the top of the scaffold and surrounded by an impermeable pipe which collects water dripping from the PH [**Figure 8**]. The collected water is frequently evacuated to a measurement bucket. After a period of 15 minutes, the amount of collected water is measured and it is, therefore, possible to associate a certain flow rate to the corresponding head. It is possible to set the head at which water injected in the

PH by changing the water level in the tank. This experiment will be done for three different heads: 3.71 m, 3.9 m, 4.05 m.

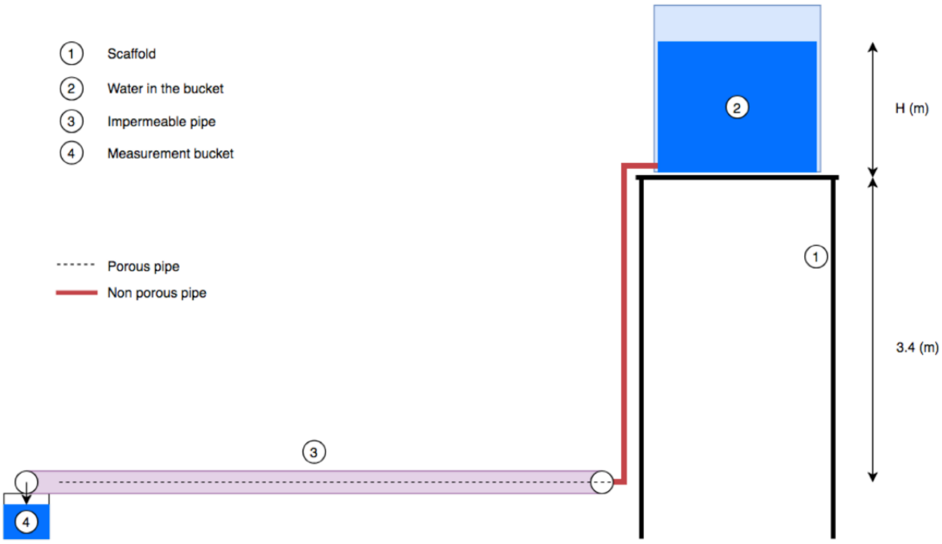


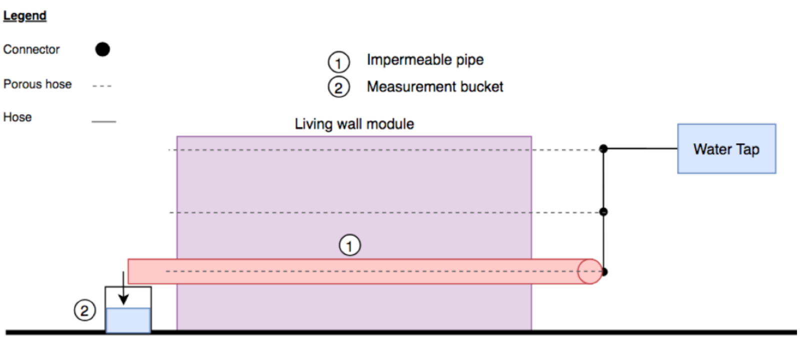
Figure 8 – Setup installed for the determination of a discharge-head relation

Once the flow rates are known for different heads, it will be possible to know if the needed irrigation discharge is reachable in a certain amount of time thanks to the scaffold disposal. An order of magnitude of the needed watering flow rate will be determined based on data available on the software ET_0 (FAO).

Determination of the repartition of the discharge in the drip irrigation system

This second experiment aims to determine the distribution of the discharge within the three PH sections. If the flow rate distribution in the three PH shows not to be homogeneous, the position of the plants on the LWM may be adapted according to their specific water need.

A *fork-shaped* network of three PH (each 2 meter-long) [**Figure 9(b)**] is connected to a water tap (providing around 30m pressure head) with a non-porous hose. This piping network has the same dimensions as what will be installed in the LWM. It is positioned vertically so that the PH is on the same configuration as if they will be in the module. Thanks to a pipe fitted around one of the PH, the water dripping from the PH is collected and frequently evacuated to a measurement bucket [**Figure 9(a)**]. After 2.5 min, the collected water is weighted. It is, therefore, possible to associate a certain flow rate to the corresponding porous pipe of the fork. The operation is repeated two times for each porous pipe.



(a)

(b)

Figure 9 - Setup installed for the determination of the repartition of the discharge

Results

1. Plant selection

Out of the seven available species, six have been selected to be part of LW [**Table 4**– Selected species and number]. In order to decrease the proportion of large plants, *Melica ciliata* L. was not selected. Besides, it has similar characteristics to *Tragopogon pratensis* L., except for the flowering colour. The yellow flowering colour of *Tragopogon pratensis* L. has been preferred to the white of *Melica ciliata* L..

Taking all those elements into consideration, it is decided that a total of 46 plants will be installed on the LW module. The number of individuals per species [**Table 4**– Selected species and number] was determined based on the optimal density of plants per square meter for each species [**Table 3** – Available plants and their proprieties] in order to obtain an equivalent area of occupancy for each species.

Table 4– Selected species and number of plants installed

Plants	Number of plants installed
Asplenium trichomanes L. Wall capillary	8
Dianthus carthusianorum L. Carthusian carnation	11
Geranium sanguineeum L. Blood red geranium	6
Origanum vulgare L. Common oregano	6
Thymus pulegioides L. Thyme faux pouliot	7
Tragopogon pratensis L. Salsify of the meadows	8

The following scheme [**Figure 10**] shows the arrangement of the 46 plants in the plant wall, taking into account sunlight conditions and water requirements. The species with the greatest need for water are installed close to porous pipes. *Thymus pulegioides* L. is placed at the bottom of the LWM where soil moisture will be lowest (Baudoux, 2018). In addition, this species will benefit from the reverberation of heat from the soil. Large plants (*Origanum vulgare* L. and *Trogopogon pratensis* L.) are arranged in such a way as to provide shade only to those plants that accept less exposure.

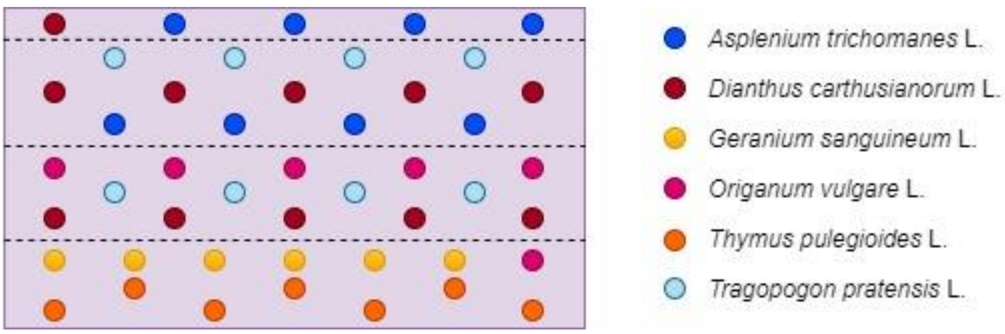


Figure 10 – Pattern of plants distribution on the living wall module

2. Landscape coefficient determination

The density factor (K_d) – it is set to the minimum value of its range (0.5) in the first place. This because the plants installed in the LWM are at an early stage of growth. Plant cover is thus fairly low. It is recommended to update this parameter regularly according to plants development based on a visual examination.

The microclimate factor (K_{mc}) – it has been set to the maximum value of its range (1.3) since the wall is facing South. Nevertheless, it is recommended to adapt this value to the exposition of the module. For a wall facing East or West a much lower value would be used. For a wall facing North, it can be expected that the plants installed would be mosses and lichens. The WULCOS method would therefore not be suitable.

The species factor (K_s) – it has been shown that the Belgian climate is closer the Californian *ET_0 climatic zone* n°1 (San Monica, North Central Coastal). **Figure 11** shows a comparison of the average daily ET_0 over the course of the year. It is seen that the 2 places have very different ET_0 climates in winter but that they are satisfyingly close (10% relative difference) at the period during which the experiment is conducted (May). K_s for this region will thus be considered even though it will be a slight overestimation that will be considered as balanced by the presence of the metal sheet at the surface of the LWM that limits evaporation surface.

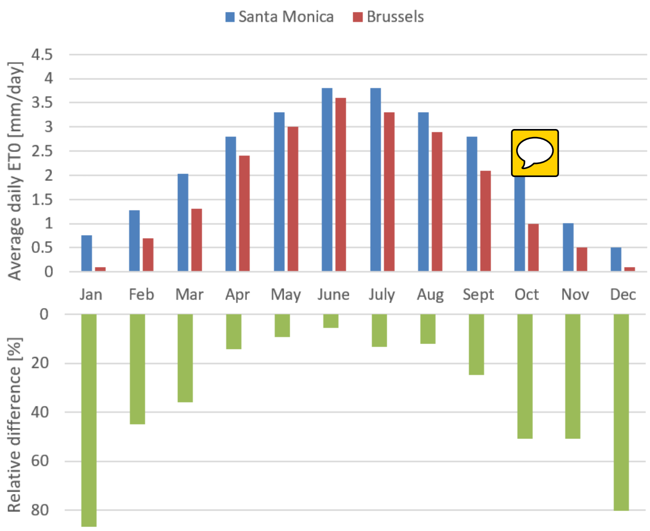


Figure 11 – Comparison of the average daily ET_0 in San Monica (CA) and Brussels (BE)
[Source: Costello et al., 2000 and FAO - ETO Calculator, 2009]

Table 5 shows K_s for the plants installed in the LWM. Data is not available for *Asplenium trichomanes* L. but it is not a critical species in term of water needs [**Table 3** – Available plants and their proprieties]. *Tragopogon pratensis* L. is also not available. Nevertheless, it has been classified in the same Soil moisture requirement class as *Origanum vulgare* L. [**Table 3** – Available plants and their proprieties] which therefore becomes the critical plant for K_s determination. The higher value of its range will be considered in the first place. The landscape coefficient has therefore been set at: $K_L = 0.5 . 1.3 . 0.6 = 0.39$

Table 5 – Water requirements for the installed plants present in the WULCOS database [Source: Costello et al., 2000]

Botanical Name	K_s range
Dianthus spp.	0.4 – 0.6
Geranium spp.	0.4 – 0.6
Origanum spp. and cvs.	0.4 – 0.6
Thymus spp. and cvs.	0.1 – 0.3

3. Growth substrate proprieties determination

Table 6 shows the results of Richard's chambers experiment. Given the volume of the samples (100 cm^3), it can be concluded that water content at field capacity is around 30%. In consequence, the WC boundary would be set at 21% for the GS described above, which represents 70% of the field capacity. Nevertheless, because of technical limitation, the GS described above (cfr §*Growth substrate*) has been mixed with 60% peat rich pot soil. The determination the hydraulic features of this new substrate is based on the experiment of Schindler et al. (2017) on horticultural substrates. From the results of this study on 30 different peat rich pot soils, a range of WC at field capacity and at wilting point have been determined [**Figure 12**].

Table 6– Results of Richard's chambers experiment (volume = 100 cm^3, applied tension = 300 HPa)

Net humid mass after exp.	Net dry mass after exp.
104,1	75,4
97,6	70,2
103,5	73,8
107,1	78,8

The lower value of the range of WC at field capacity (39%) was retained for the new GS. The peat content of the pot soil used for the new GS is not known exactly. Given that is it mixed with 30% of other materials with lower water retention proprieties, it has been considered that this lower value is a reasonable approximation.

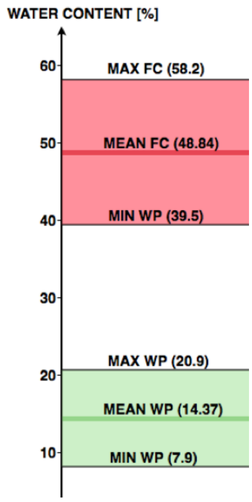


Figure 12 – Average and extremum water content at wilting point and field capacity for an array of peat rich horticultural pot soils [Source: Schindler et al., 2017]

4. Water content probes calibration

The results of the probe calibration process are presented in

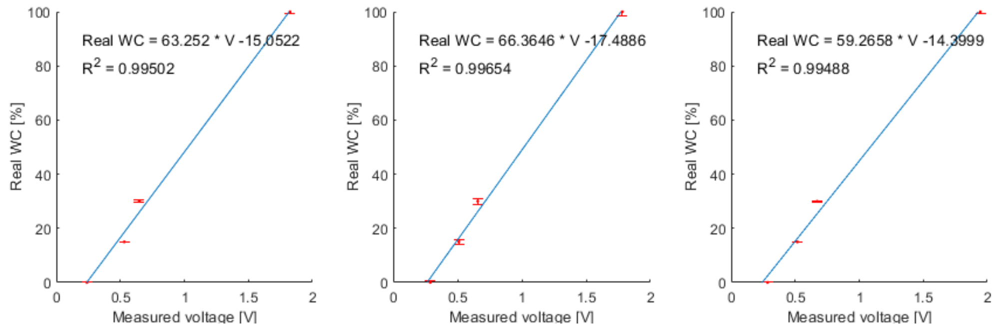


Figure 13. The fitting is acceptable for all calibration curves and the equation should allow determination of the WC during the experiment. However, this calibration curve is only usable for a 2.5 V excitation signal. This setting has shown not to be reachable with the monitoring *micro-computer* setup. The probe has then been used with a 5V excitation signal instead. This, combined with the fact that that initial GS was changed, meant that this calibration was not usable. Furthermore, there is no way to deduct a new calibration relation from the latter since the relation between WC and probe output signal is not strictly proportional to the excitation voltage.

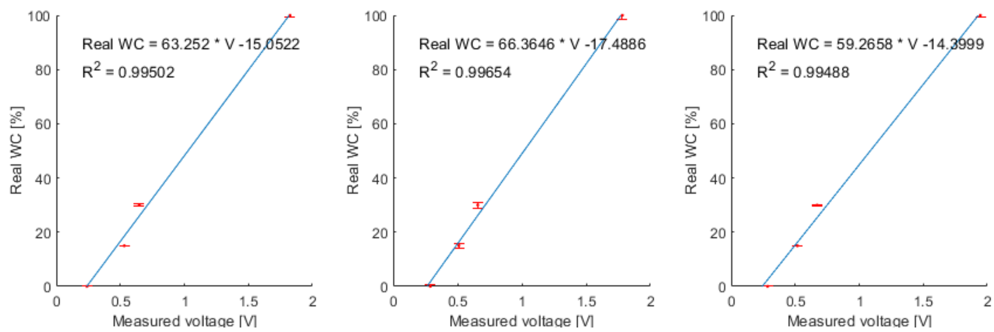


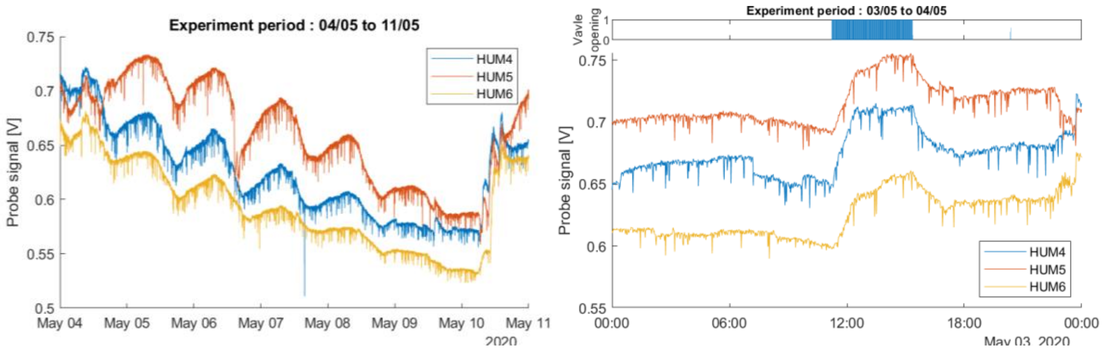
Figure 13 – Calibration curves for a 2.5 V excitation signal

An approximate empirical calibration has therefore been used. It has been based on the observation of the extremums of probe output voltage signal. A period of 6 days without any water input in the LWM (no rain neither watering) was considered to obtain a lower probe signal value. A heavy watering (around 75% of the volume of the LWM was made to bring the GS at saturation [Figure 12**Figure 14**]. The recorded tension extremums were 0.55 and 0.75 V taking the signals of the three probes in account together. The fist value, rounded at 0.5 V, will be considered as the signal of the probe at wilting point. The mean value of the range of WC at wilting point [**Figure 12**] was retained. The latter value should correspond to WC at saturation. It can be seen on **Figure 14(b)** that WC drops shortly after the end of the watering and then stabilises. WC after this stabilitation correspond probably to WC at field capacity. It has been roughly approximated that the 0.75 V signal corresponds to the WC at field capacity (39%) (cfr §*Growth substrate proprieties determination)*,

A simple linear interpolation between those two datapoint couples (0.5V~15% and 0.75V~39%) was done. The resulting calibration equation is shown hereunder.

$$WC\ [\%] = 96 * \text{output signal}\ [V] - 32$$

This relation is a rough approximation, based on the use of the data coming from the three probes altogether and *a priori* approximations. It did not allow the determination of an exact WC but permitted to have an overview of the relative evolution of this parameter. It allowed the appreciation of the overall structure of the irrigation decision algorithm but not a quantitative approach to the choice of the numeric settings.



(a) (b)

Figure 14 – Extremums of water content probe signal

5. Discharge-head relation determination

The results of the experiment are presented in **Table 7**. Unfortunately, due to a lack of time, only three different heads close to each other have been tested and the data points obtained are too close to be extrapolated. It is therefore impossible to obtain a continuous discharge-head relation for the head interval that can possibly be encountered in the LWM. Indeed, with the scaffold set up, the head can vary from 2 m (in the highest PH when the tank is almost empty) to 4 m (in the lowest PH when the tank is full). To obtain a complete discharge-head curve, the experiment should be repeated for a wider range of heads.

Table 7 – Result of the experiment aiming the determination of a discharge-head relation.

Head [m]	Discharge [L/min.m] (per meter of hose)
3.71	0.027
3.9	0.034
4.05	0.040

An order of magnitude of the needed volumes of irrigation for the LWM is estimated thanks to the reference ET_0 data from the software *ET₀* (FAO) for the months of April, May, June and July [**Table 7**]. Those values are based strictly on the ET_0 and do not take into account precipitations either specific plant evapotranspiration proprieties. For a discharge of around 0.035 L/min.m and 6 m of PH in the LWM, the daily water needs evoked in **Table 8** are reachable in less than an hour. The use of this type of PH and the service pressure provided by the scaffold and tank setup is realistic to provide the needed water to the LWM.

Table 8 – Estimated daily water need for the living wall module

Month	Daily water needs [L/day]
April	4.8
May	6
June	7.2
July	6.6

The information about the discharge-head relation is crucial to manage valve opening time for a water level varying over time in the tank. The present experiment has been realised with an alternative setup, not described here, that provides a known discharge.

6. Repartition of the discharge in the drip irrigation system.

The results of the experiment [**Table 9**] witness that the discharge is not equally distributed in the network. Neither is it proportional to the datum of each PH.

Table 9 – Results of the experiment aiming the determination of the repartition of the discharge. Experiment conducted with a typical tap service pressure head (~ 3 bars)

Position of the porous hose	Flow rate [L/hour] Repetition 1	Flow rate [L/hour] Repetition 2	Flow rate [L/hour] Repetition 3	Flow rate [L/hour] Mean
Lower	98.472	95.28	97.512	97.08
Intermediate	53.832	52.632	/	53.23
High	76.872	78.312	/	77.59

In the following lines, it will be tried to estimate head losses in the pipe network in order to determine if the latter is responsible for this difference of discharge. Major head losses are estimated with DARCY–WEISBACH equation:

$$h_{major\ loss} = 4 \cdot C_f \cdot \frac{L}{D} \cdot \frac{v^2}{2\,g}$$

And the minor losses with one of the following 2 relations:

$$\Delta p_{minor\ loss} = 4 \cdot C_f \cdot \frac{L_{equ}}{D} \cdot \frac{v^2}{2g}$$

$$\Delta p_{minor\ loss} = \xi \cdot \frac{v^2}{2g}$$

The following approximations are considered:

- v = 0.5 m/s overestimating the mean discharge as the sum of the discharges in the 3 PH
- L = 3 m the approximate length of the network;

- D = 12 mm the diameter of the PH;
- C_f = 0.02 (after Farshad et al. (2003) for plastic coated pipe);
- L_{equ} = 30.D a typical value for a 90° elbow;
- ξ = 0.5 a typical value for a 90° elbow;

The following losses are computed:

- $h_{major\ loss} \simeq 0.3\ m$
- $h_{minor\ loss} \simeq 0.007$ or $0.03\ m$

Given the approximate 30 m pressure head upstream the experimental network, the head losses cannot explain a difference of discharge of up to 50% between the PHs. It is recommended to conduct further experimentation to determine the actual discharge repartition. It has to be kept in mind that this trial was realized with a pressure head much higher than what will be uncounted in the wall (around 10 times more: ~30 m head instead of ~3 m head with the scaffold disposal). It would be necessary to repeat the experiment with lower service pressure to obtain something applicable to the LWM. Nevertheless, those results show that the discharge is not distributed according to a predictable pattern. For the present experiment, an alternative setup that allows equal repartition of the water flow has been used. This setup is not described here. Furthermore, no adaptation of the position of plant species within the LWM has been done.

7. Program development

Data quality control

Standard deviation over time was computed for a number of successive data points (**N**) ranging from 0 to 100. The data used are the recordings for the month of April. **Figure 15** and **Figure 16(a)** show the results of this calculation. It is seen that for an N value sufficiency high, the maximum deviation is quite stable. It has therefore been considered that an N value of 5 is sufficient to detect abnormal measurements variations in the context of the experiment.

Additionally, the minimum standard deviation has also been observed. For the WS data, and it has shown to be null whatever the N value is. This is due to the fact that the environmental parameters can vary at a very low rate. On the contrary, a minimum standard deviation can be set for WC probes. Indeed, for an N value greater than 4, the minimum deviation is not null [**Figure 16(b)**]. Using this value as a lower limit of acceptance for the WC data quality check would enable the detection of a blocking or a shutting down of the WC sensors. This has not been implemented in the script but it is recommended for future experimentations.

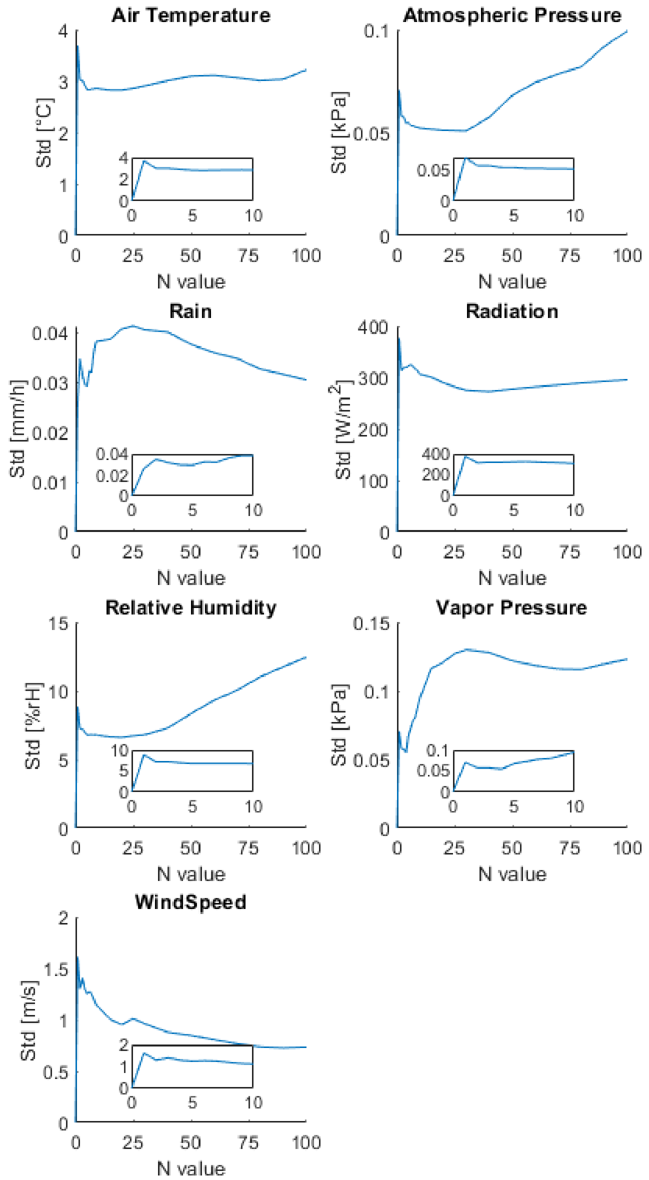


Figure 15 – Evolution of the maximum standard deviation (Std) on WS measures with the number of successive datapoints taken into consideration (N)

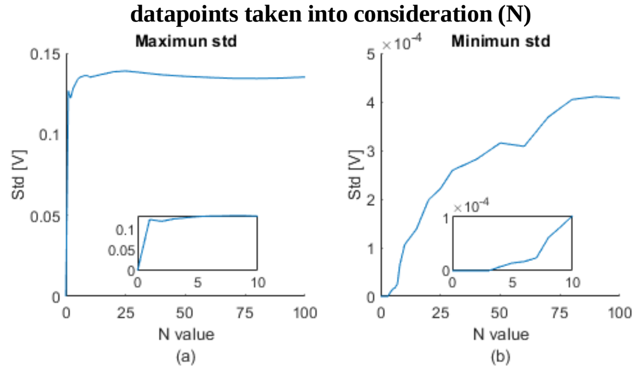


Figure 16 – Evolution of the minimum and maximum standard deviation (Std) on WC measures with the number of successive datapoints taken into consideration (N)

Furthermore, the probability distribution [**Figure 17**] shows that for all parameters but the rain, it is unlikely that the standard deviation on successive datapoints happens to be higher than the maximum deviation computed. A 10% mark-up was nevertheless applied to those values for the data quality check implemented in the script to take in account the possibility that an environmental parameter would evolve at a higher rate than during the test period. It is decided not to carry out data control on the precipitation data. Indeed, the probability distribution of this parameter [**Figure 17**] does not meet the requirements of the quality check. The probability to be close to the maximum standard deviation admissible is too high.

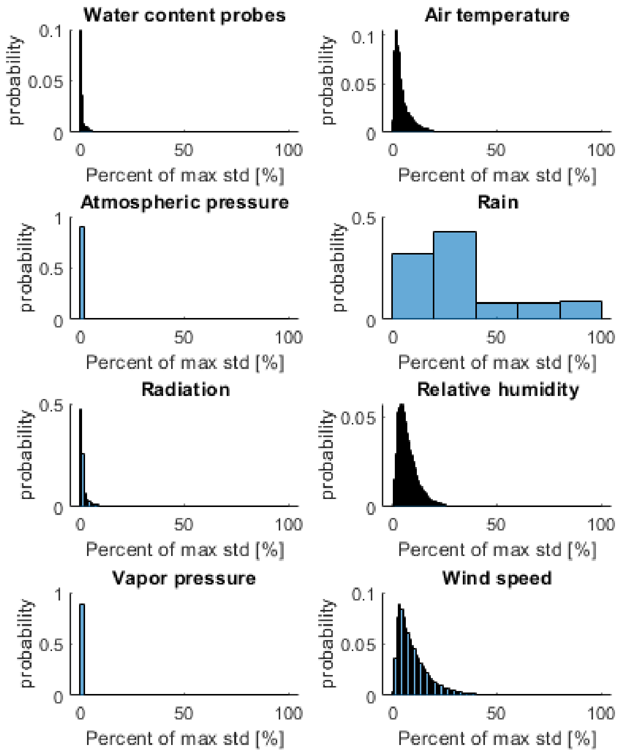


Figure 17 – Probability of occurrence of standard deviation over 5 successive datapoints

Finally, it must be reminded that no procedure has been found in order to detect a blocking or a shutting down of the WS sensor. It is therefore recommended to keep attention on the evolution of the record of those parameters. Those are displayed on a daily basis on the monitoring interface [**Figure 18**

to ease this control. For future experiments, it is also recommended to apply the same method as implemented here for the calculation of the standard deviation of the data coming from the different WC probes. The determination of the deviation of WC measurements over space would enable a more robust quality check of the monitoring of this parameter. This has been implemented in the scrip but the maximum deviation admissible over space was not determined due to a lack of time. This input set has then been left to a relatively high value in the program to ensure that it would not cause a rejection of the WC data.

The overall look of the program interface

Figure 18 shows the appearance of the software interface. This is updated every day to give the user an overview of what is happening in the LWM. It also allows detection of possible breakdowns through a direct notification to the user or by analysing the records displayed. The user is also reminded to verify if the K_L is still up to date.

```
A new day of irrigation management of the WattWall starts
==========================================================
Recorded weather data for the last 24h :
========================================
   * Total radiation was :             22.24  MJ/(m2 day)
   * Mean temperature was :            10.19  degree C
   * Mean vapor pressure was :         0.66  kPa
   * Mean wind speed for was :         0.52  m/s
   * Mean atmospheric pressure was :   95.4  kPa
   * Yesterday it rained :             0.0  mm
   * The ET0 for yesterday was :       5.48  mm

Irrigation decision :
=====================
* Average WC probe signal = 0.59  V
* The water content in the wall today is approximated to 27 %
* Irrigation will start if water content is lower than 30 %
* Irrigation is needed
* The dose of water to apply today is  0.403 L
* The valve will be opened for 16.11  minutes
* This calculation is made for a Kl of  0.7
* If canopy cover has evolved on the module this value might have to be updated
* Irrigation has been programmed

Post-watering check :
=====================

It is now 07:57AM
* Watering has been done 2 hours ago, it will now be checked if extra water is
needed
* Data is being collected over 5 minutes...
* Reliability of the collected data will determined
  Here is the standard deviation over the last 5 minutes for the HUM sensors :
   * HUM4   :   0.001
   * HUM5   :   0.003
   * HUM6   :   0.001
  Here is the standard deviation over space for HUM sensors :
   * HUM456 :   0.051
* The probes are still working
* Post watering check can be processed
* Average WC probe signal = 0.62 V
* Water content is now at 29 %
* This is too low, extra water is needed
* An additional 0.11 L is needed
* The valve will be opened for 4.32 more minutes today
* Extra watering has been programmed
This is it for today, new watering will start tomorrow at 6AM
```

Figure 18 – Display of the irrigation monitoring software interface

Setting up and starting the software

Before launching the program on the server, it is necessary to set an array of parameters specific to the module. This is done in the first lines of the program script (line 15 to 60). It is in shown in **Figure 19.** Among those parameters, the user has the choice to start the program right away to delay the execution to the next morning.

```
##############################################################################
#                            Program settings                                #
##############################################################################
# Please enter the hour at which program is launched on the server :
hour = 16
minute = 25
##############################################################################
# Please specify if you are testing the program & if you want to delay run :
test = False
Delay = True
##############################################################################
# Discharge of the porous hose network Q[L/min] :
Q = 1.5 / 60
##############################################################################
# Calibration parameters :
m_calib = 96
p_calib = - 30
##############################################################################
## QUALITY CHECK
# Number of successive values to consider :
N = 5
# Admissible max std for environmental param :
LIM_Rn = 322.5866
LIM_Thr = 2.8370
LIM_u2 = 1.231
LIM_P = 0.0678
# Admissible max std for WC probes :
LIM_HUM4 = 0.1131
LIM_HUM5 = 0.1340
LIM_HUM6 = 0.1135
LIM_HUM456 = 10
##############################################################################
## IRRIGATION DECISION
# Minimum water content admissible :
Water_Content_Limit = 30
# Crop coefficient
Kl = 0.7
# Waiting time between first irrigation and post-irrig check :
waiting_time = 3600 * 2
# Default irrigation time [seconds] :
default_irrig = 60 * 30
# Dimensions of the pot/module [m2] :
Area = 0.75 * 0.14
# Volume of the pot/module [L] :
Pot_volume = 12.6
##############################################################################
```

Figure 19 – Irrigation monitoring software settings input

Once the program is launched on the server, the user receives confirmation of its execution, a summary of the input settings and the delay planned before the irrigation program starts [**Figure 20**].

```
The script has been loaded successfully at 04:22PM
Irrigation algorithm will start tomorrow at 05:57AM, within 13 hours

Here is the list of all the input setting of the script :
=========================================================

* The discharge of the drip pipe : 0.03 L/min
* The number of successive measures used for data quality check : 5
* The minimum admissible water content : 30 %
* The landscape coefficient Kl 0.7 -
* The delay between first irrigation and post irrigation check :  120 minutes
* The surface of the module : 0.11 m2
* The volume of the module : 12.6 L
* The admissible standard deviation for the sensors over time :
    * HUM4   : 0.11
    * HUM5   : 0.13
    * HUM6   : 0.11
    * Rn     : 322.59
    * Thr    : 2.84
    * u2     : 1.23
    * P      : 0.07
* The admissible standard deviation for the sensors over space :
    * HUM456 : 10.0
```

Figure 20 – Display of the software execution

8. Testing of the program

Figure 21 shows the evolution temperature, WC estimated as well as the valves opening decisions during a period of testing of the program. During this period, the temperatures were slightly increasing so the irrigation doses increased slowly over time. Additionally, WC was fairly high at the beginning of the period. Watering was then not needed before the 5th day. Estimated ET_c was obviously not sufficient since every time irrigation was needed, a second watering was done as well.

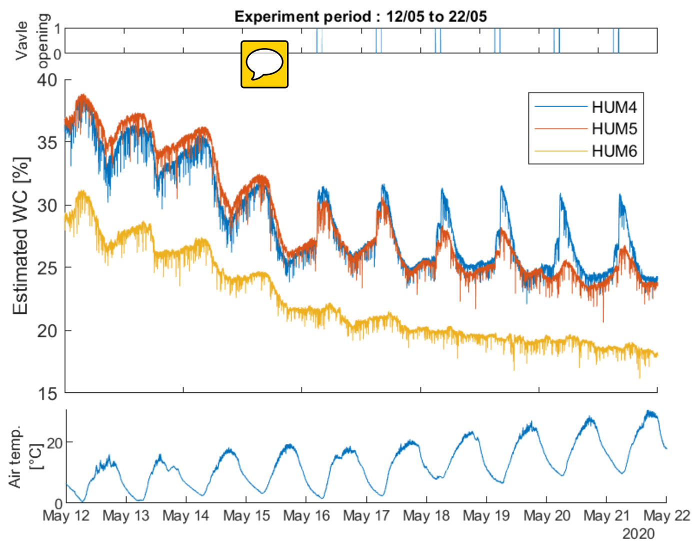


Figure 21 – Temperature, estimated water content and valve opening decisions during a *program testing* trial

Discussion

Irrigation decision algorithm

Firstly, it must be said that the set WC boundary limit and the K_L are the key settings of irrigation doses determination. If the predicted ET_C is high enough, step 2 of the algorithm alone dictates the watering volume. Otherwise, it is mainly the WC boundary limit via the WC data that has the latter decision about watering. Thus, it is the rather arbitrary setting of the K_L parameter that dictates whether the WS or WC data dominates the decision.

Furthermore, the computation of the ET_C relies on two highly uncertain components (ET_0 and K_L) themselves depending on an array of uncertain parameters and approximations. It is therefore questioned if the use of the PENMAN-MONTEITH equation in the first place is suitable. Furthermore, the K_L requires regular update according to plant cover. This is rather inconvenient. It is therefore suggested to consider watering first according to WC data and have the WS data along with the ET_C calculation as a first back up plan and then a pre-planned standard watering as a second back up plan. In this case, calibration of the probes becomes a highly critical point and a lot of attention must be invested in this preparation step. Notably, it is recommended to study the influence of temperature on WC measurements. The vertical South exposition of the LWM makes it highly susceptible to important temperature changes over time and it may lead to WC measurements inconsistency.

Finally, the data quality check implemented is a good starting point but is limited. The possibility that occurs the recording of biased data but varying at a realistic rate is not taken into account. Additionally, no procedure to detect a possible blocking or shutting down of the WS was found. It is suggested to insert additional control check elsewhere in the algorithm. For instance, a control of the calculated irrigation dose could be implemented. It could be set that volumes greater than a certain proportion of the LWM module being computed could be rejected. Also, all the monitored parameters could be confronted with a *range of validity*. This latter would be a range of the real values that the parameter can reach (hardly over ~ 60% for the WC for example).

Irrigation network and setup

Suggestion will be presented below in order to ease the use of LWMs on actual architectural projects. Indeed, on a real situation on a building wall with several LWMs installed one above the other, the distribution of the discharge would be highly unequal if a simple *gravity-fed* micro-irrigation network was installed. It would be necessary to homogenize the pressure head within the network to ensure that water spreads equally in the whole wall.

Several design strategies could be explored. (1) Inject water at a higher pressure in the network and then reducing it at the entry of each PH thanks to a pressure reducer would be a solution. This would nevertheless require to inject pressured water in the network. The simplicity and reliability of a simple *tank-setup* would then be lost. Additionally, this would drive up energy costs which are inconsistent with the sustainability goal. (2) Otherwise, flow measurement devices along with independent controlled valves ahead of each PH would allow independent watering of each sub-module. However, this latter solution implies the use of a large number of electronically piloted devices spread within the building wall. This would decrease the reliability of the whole setup, complexify maintenance and drive up initial costs. (3) The use of the PH for the micro-irrigation forces to reach relatively high service pressures in the pipes. It is therefore suggested to use another type of dripping pipe working at lower service pressures. This may be a solution to keep the system simply *gravity-fed* and still install pressure reducers. This would allow to maintain the reliable, cost and energy-efficient *tank-setup* and obtain equal distribution of the discharge. Additionally, this would suppress the complexity linked to the variation of pressure according to the variation of the water level in the tank. (4) Another solution would be to use a non-porous hose with *pinch* or *barbed* drippers. Those could be unequally distributed within the LWM to balance the inequality of the discharge repartition. This would nevertheless require a finetuning and thus a lot of experimentations to determine exact repartition. But this might allow the use of a decreased number of condoled valves and pressure reducers. The durability of this kind of pipe may, however, be questioned. The risk of clogging is indeed higher than with a PH setup. An intermediate solution may be to alternate PH section with non-porous pipe to tune discharge repartition.

General course of the experiment

A lot of technical limitations have obstructed the good implementation of the initial plans. The exact quantification of the water content in the LWM was impeded. In consequence de appreciation of the efficiency of the algorithm is limited. The experiment was too short to test the efficiency of using strained piezometer pipe to protect the PH. It is recommended to carry out further experimentations about it. This is indeed a cheap solution (around 1 €/m) that may lead to important costs saving in the long run. The appreciation of plant growth was not possible due to this time limitation. It is recommended to try growing the selected plants on the GS independently of the LWM to test their ability to survive in the given conditions. Water needs could also be estimated by watering and weighing the pots on a regular basis. Reach *resource-use* efficiency at low costs, using local plant species and making the modules easily mountable on buildings is a challenge that still requires a lot of research and development. A large panel to technical options is available and further experimentations are strongly needed.

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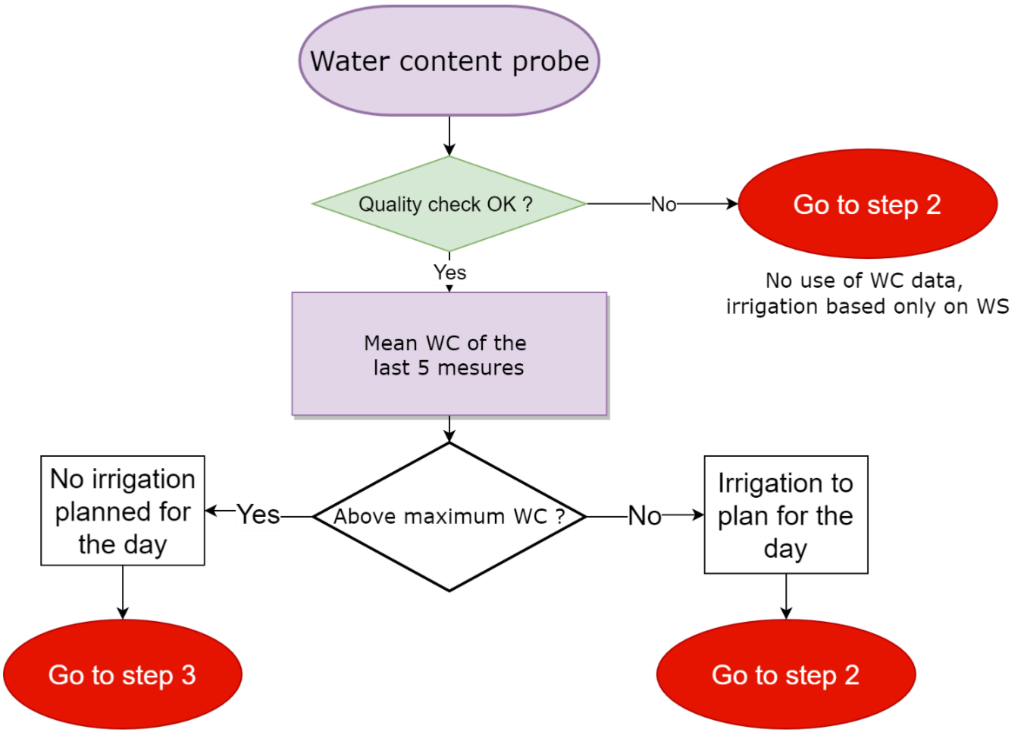
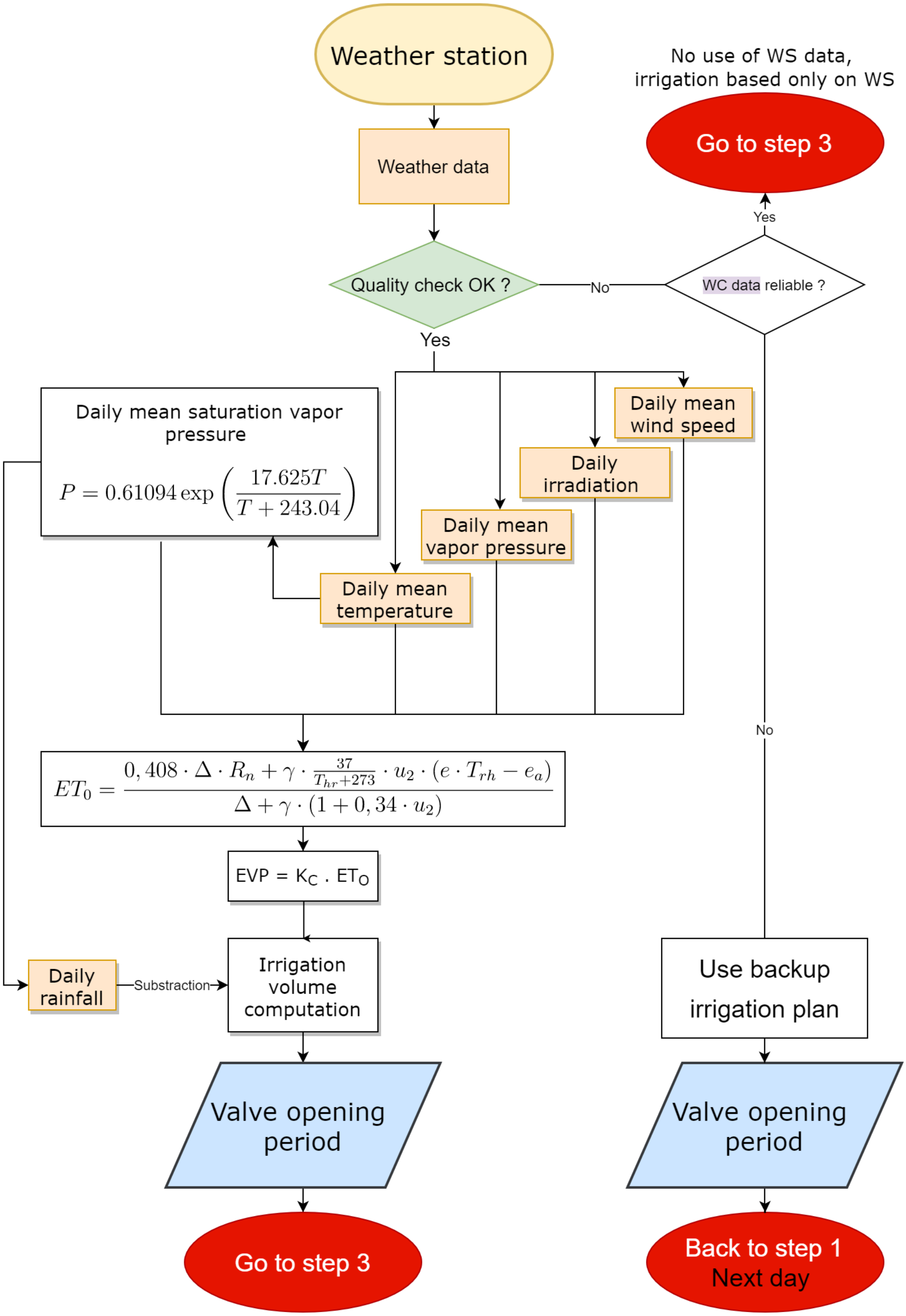
Appendix I – Flow chart of the irrigation decision algorithm

Step 1 of the algorithm



Step 2 of the algorithm



Step 3 of the algorithm