Experimental evaluation of thermal behaviour in green roofs

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Abstract

Currently, one of the main concerns in the construction is how to become more sustainable and energetically efficient. The use of green roofs can improve these aspects due to countless advantages in roof, buildings and city levels, particularly the soil and vegetation capacity to protect the building from extreme temperatures and to restrict heat fluxes.

The aim of this study is to evaluate experimentally the thermal behaviour of green roofs in two case studies during Winter and Summer. In the first one, two interior rooms with different thermal envelopes were analysed and the behaviour of the green roof was compared to an area with concrete flags. The capacity to smooth temperatures and decrease the temperature range through soil layers was observed. Inside the rooms the superficial temperatures of the structural elements under the green area are higher than the zone with concrete flags and the thermal envelope also causes different behaviours. In the second case study the behaviour of two vegetation types in a green roof was compared. The main differences are in the exterior zone, where the soil with groundcover presented higher exterior superficial temperatures than the zone with higher vegetation.

In the end, thermal transmittance was also calculated in both case studies through methods that uses temperatures and heat fluxes data from the experimental campaigns and from the roof material properties.

Keywords: green roof, thermal behaviour, thermal monitoring, thermal performance, thermal transmittance

1 Introduction

The energetic efficiency of the buildings is currently a major concern in the construction area. More researches have been done and, later on, constructive solutions that minimize heat losses through its envelope have been used. One example of these solutions are the green roofs that have become more popular in the Southern Europe, characterized for the Mediterranean climate. However, its study is still scarce, particularly in Portugal.

This type of roofs has innumerous benefits, not only for the building but also at larger scale. Green roofs help to mitigate the urban heat island effect through evapotranspiration processes that absorb atmospheric pollutants (Sfakianaki et al., 2009). Other benefit in larger scale is that this type of roofs helps to reduce stormwater runoff, which depends of the soil thickness, type of vegetation and duration and intensity of precipitation (Henry et. al., 2012). Thermal comfort, less energetic consumption, acoustic comfort, increase of thermal inertia, reduction of solar absorbance are examples of benefits for the buildings (Fioretti et al., 2010).

The vegetation helps the roof from the solar exposition through shadow effect and, with the evapotranspiration process, produces a cooling effect in the substrate, reducing surface temperatures. So, the vegetation absorbs and dissipates a large amount of heat, reducing the thermal load through the soil and decreasing the heat flux that goes into the building. As a consequence, the energetic needs for cooling/heating and temperatures fluctuations during the day decrease (He and Jim, 2010; Niachou et al., 2001; Fioretti et al., 2010; Santamouris et al., 2007). The energetic consumption is mainly influenced by thermal properties of the soil (thermal conductivity, heat capacity) and its thickness, the characteristics of the plant cover (Leaf area index – LAI -, the orientation and shape of the leaves) and meteorological conditions (Czemiel Berndtsson et. al, 2009; Schweitzer and Erell, 2014).

In this context, it is relevant to evaluate the thermal behaviour of this type of solution, particularly in the Mediterranean climate – Portugal included – where the studies are still scarce.

The principal aim of this study is to evaluate the thermal behaviour of green roofs in the Mediterranean climate.

To proceed with the analysis of the thermal behaviour two case studies were chosen – *Fundação Calouste Gulbenkian* and *ETAR de Alcântara* – both in Lisbon. The main objectives of this study are: evaluate the thermal behaviour of green roofs during the Winter and Summer; compare the thermal behaviour in a green roof with groundcover and with concrete flags; analyse the influence of different species of vegetation in terms of temperatures and heat fluxes through the roof; analyse the impact of the thermal envelope of some rooms and the air-conditioning system in the temperatures and heat fluxes through the roof; identify the principal parameters that influence the roof behaviour; estimate the u-value of the case studies green roofs through three methods.

2 Green Roofs

There are three types of green roofs, which depend of the thickness of the soil and the maintenance costs (Henry et al., 2012; Wark et al., 2003): extensive, semi-intensive and intensive. Currently, extensive roofs are the most common. This type of roof is characterized by having a thin layer of soil (between 10 and 15cm), having one or two types of vegetation. It requires low maintenance and is less expensive. An intensive roof has a deep layer of soil (more than 20cm), has different types of vegetation (such plants, shrubs and trees) and requires a lot of maintenance. The semi-intensive roofs have both characteristics from extensive and intensive roofs.

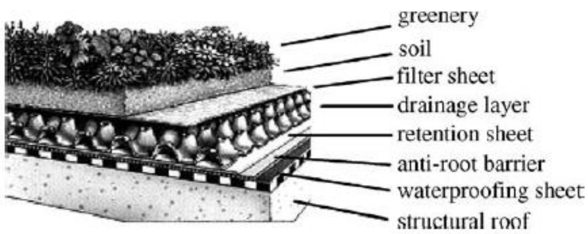

Figure 1 – The different layers of a green roof (Lazzarin, 2005).

Green roofs have different layers, indicated in Figure 1, which have each one its function. The waterproof sheet protects the roof slab and the anti-root barrier prevents the damage of the structure. The drainage layer recreates the natural environment for vegetation growing, drainages the excess water that is accumulated and also accumulates water for dry periods while the filter sheet stops the finest particles of the soil, letting the water pass. The soil that is used has low volumetric mass (800-900kg/m^3) and it is enriched with minerals (Lazzarin et al., 2005). The thickness of the soil varies according to the type of roof and it is normally between 10cm and 50cm. The vegetation type can be as different as groundcover or shrubs. It can also be ornamental plants and trees, although they will need more maintenance.

2.1 Experimental studies

Over the years, knowledge about green roofs has been deepened in some countries and regions with different climates through experimental campaigns and simulation models. It was remarkable, in studies about cold climates (Liu, 2004; Lanham, 2007; Sailor et al., 2008; Pierre et al., 2010; Sailor et al., 2011), tropical climates (Wong et al., 2003; He and Jim, 2010; Feng et al., 2010; Lin et al., 2013; Dvorak and Volder 2013) and Mediterranean climates (Niachou et al., 2001; Lazzarin et al., 2006; Santamouris et al., 2007; Sfakianaki et al., 2009; Fioretti et al., 2010; Schweitzer and Erell 2014; Ouldboukhitine et al., 2014), the huge influence that vegetation characteristics (such LAI density, water consumption, growing power) and soil properties (moisture saturation levels, soil composition) have during Summer, when the temperatures decreases through evapotranspiration of the plants, and in Winter, when a large amount of heat load is stored, moderating temperature fluctuations.

In the cold climates was also observed that during Winter, the thermal insulation has an essential role, while in tropical climates, by having a high level of relative moisture, the green roofs are also efficient without the irrigation needs, particularly in days without precipitation. In the Mediterranean area, in hot Summer regions, was also observed the need of taking additional measures to increase the passive cooling and, during raining period, the benefits of green roofs about stormwater were also observed.

3 Case study 1 - *Gulbenkian*

The first case study was in *Fundação Calouste Gulbenkian*, in Lisbon, and it is characterized as a service building. The experimental campaign was realized in three different places: Rehearsal room, green roof and technical sound room.

The rehearsal room, with an area of 184.5m^2, has three walls that can be considered adiabatic and one that has glazed area of 52% of its total area (34.4m^2) and it is in contact with the exterior, where occur heat losses. The other place where heat losses occur is through the roof. This room has a suspended ceiling (0.20m gap air) and has four beam fair-faced concrete (h=0.70m). The room has also an air-conditioning system that works every day from 8h00 to 18h00, which setpoint temperature is 22ºC.

The green roof is located above the rehearsal room and has a 0.20m concrete slab with, a drainage layer with gravel, a filter sheet and a 0.25m height soil that is covered with groundcover or concrete flags. The irrigation is manual and occurs every Monday, Wednesday and Friday during two periods of 30 minutes in the morning.

The technical sound room, with an area of 3m^2, is fully adiabatic except for the roof addressed. This room has also a suspended ceiling with a maximum of 1.30m gap air. The air-conditioning system works the most of the times between 8h00 and 18h00 and its setpoint temperature is 20ºC. The green roof of the technical sound roof is similar to the rehearsal room roof.

3.1 Parameters monitored and instrumentation

The experimental campaign during the Winter of 2013 was made through 9 days with the objective of simulating Lisbon climate.

- start: 21st January 2013 at 10h40;
- end: 30th January 2013 at 19h30.

The physical parameters measured in the rehearsal room and green roof are presented in Table 1 and in Figures 2 to 5. The instrumentations used are indicated in Table 2.

Table 1 - Physical parameters measured in the rehearsal room and in the green roof.

	Name	Description	Unit
Rehearsal room	TA1/TA2	Slab interior surface temperature (below the concrete flags area)	ºC
	TA3/TA4	Slab interior surface temperature (below the vegetation area)	ºC
	TA5/TA6	Beam interior surface temperature (below the concrete flags area)	ºC
	TA7/TA8	Beam interior surface temperature (below the vegetation area	ºC
	TA9/TA10	Air temperature inside the gap air in the rehearsal room	ºC
	TA11/TA 12 /TA13	Air temperature inside the rehearsal room	ºC
	Flux A1	Slab heat flux below the vegetation area	W/m^2
	Flux A2	Slab heat flux below the concrete flags area	W/m^2
	Flux A3	Beam heat flux below the vegetation area	W/m^2
	HR A	Relative humidity inside the rehearsal room	%
Green Roof	TB1	Concrete flag surface exterior temperature above the slab area	ºC
	TB2	Soil surface temperature in vegetation area	ºC
	TB3	Soil temperature (h=11.5cm) in the vegetation area (above slab area)	ºC
	TB4	Soil temperature (h=23cm) in the vegetation area (above slab area)	ºC
	TB5	Concrete flag surface exterior temperature above the beam area	ºC
	TB6	Soil surface temperature in vegetation area (above slab beam area)	ºC
	TB7	Soil temperature (h=13cm) in the vegetation area (above beam area)	ºC
	TB8	Soil temperature (h=26cm) in the vegetation area (above beam area)	ºC
	TB9/TB10	Exterior air temperature	ºC
	RS B1	Solar radiation in vertical plan normal to facade with Southwest orientation	W/m^2
	HR B	Relative humidity of the exterior ambient	%

Table 2 – Set of instrumentation used in the experimental session.

Area	Instrumentation		Parameters
A – Rehearsal Room	Data Logger (Campbell) +	Thermocouples - T	TA1 to TA12
		Heat flux sensor	Flux A1 to A3
	Tinytag (thermometer-psychronometer)		TA13 and HR A
B – Green Roof	Data Logger (Delta-T) +	Thermocouples - T	TB1 to TB9
		Pyranometer	RS B1
	Tinytag (thermometer-psychronometer)		TB10 and HR B

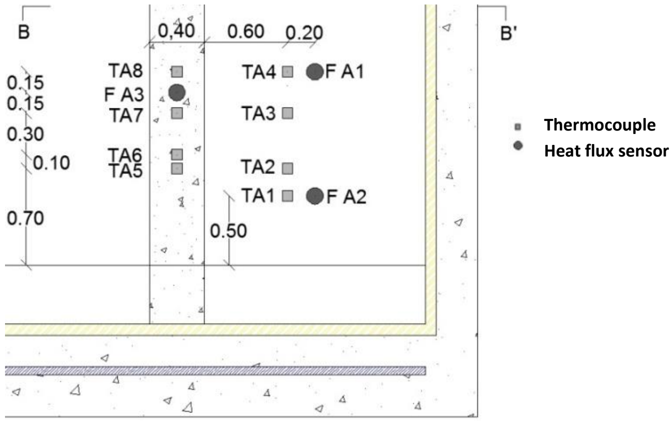

Figure 2 – Location of the instrumentation and parameters monitored in the rehearsal room (interior view).

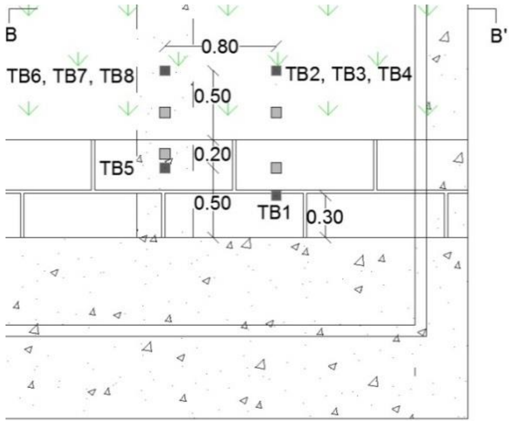

Figure 3 - Location of the instrumentation and parameters monitored in the green roof (exterior).

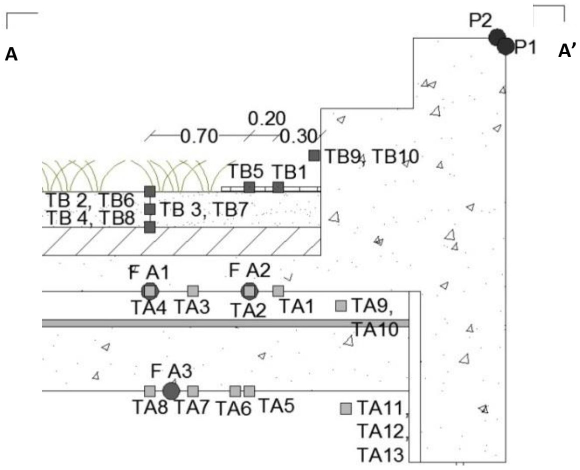

Figure 4 - Location of the instrumentation and parameters monitored in the rehearsal room (cut AA').

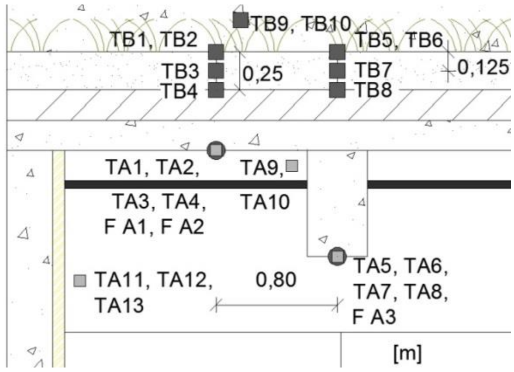

Figure 5 - Location of the instrumentation and parameters monitored in the rehearsal room (cut BB').

The physical parameters measured in the rehearsal room and green roof are presented in Table 3 and in Figures 6 to 7. The instrumentations used are indicated in Table 4.

Table 3 - Physical parameters measured in the technical sound room.

Name	Description	Unit
TC1/TC2	Slab interior surface temperature (below the vegetation area)	ºC
TC3/TC4	Beam interior surface temperature (below the vegetation area)	ºC
TC5/TC7	Air temperature inside the gap air in the technical sound room	ºC
TC6	Air temperature inside the technical sound room	ºC
Flux C	Slab heat flux below the vegetation area	W/m^2
HR C	Relative humidity inside the gap air in the technical sound room	%

Table 4 - Set of instrumentation used in the experimental session.

Area	Instrumentation		Parameters
C- Technical Sound Room	Data Logger (Data Taker) +	Thermocouples - T	TC1 to TC6
		Heat flux sensor	Flux C
	(thermometer-psychronometer)		TB7 and HR C

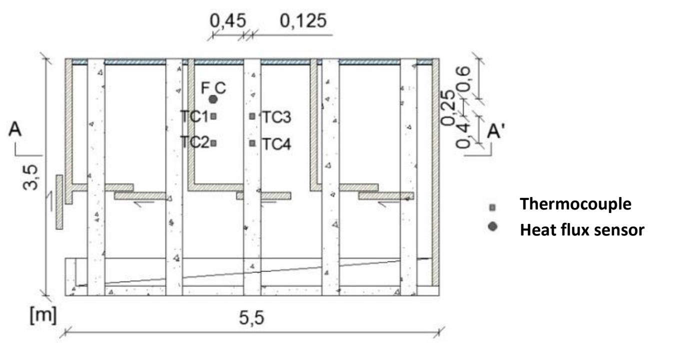

Figure 6 – Location of the instrumentation and parameters monitored in the technical sound room (interior).

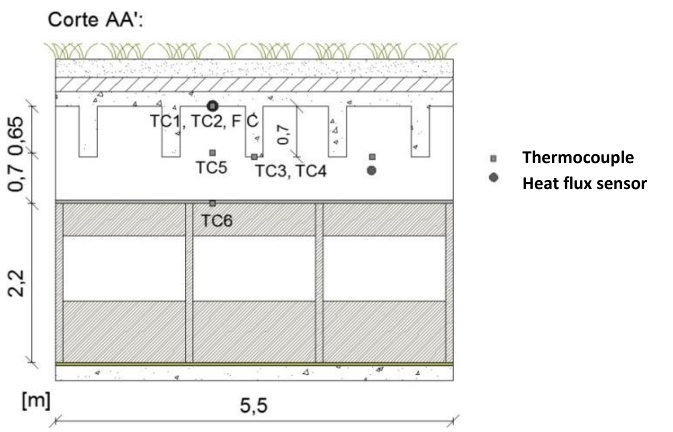

Figure 7 – Location of the instrumentation and parameters monitored in the technical sound room.

The measurements were taken every 1-minute period. Their average values were registered every 10-minute period.

3.2 Experimental results (Winter)

Due to the large amount of data, the results presented are from two defined days which represent the extreme climatic conditions from Winter in terms of exterior air temperature and solar radiation. During this experimental campaign the days chosen were Cooler Day (CD+ - the day with less average exterior air temperature) and the Less Solar Radiation Day (SRD- - the day with less average solar radiation).

The CD+ was in 28th January 2013 (9.7ºC and $36.4W/m^2$) and the SRD- was in 24th January 2013 (12.54ºC and $14.9W/m^2$). The results are shown in Figures 8 to 14.

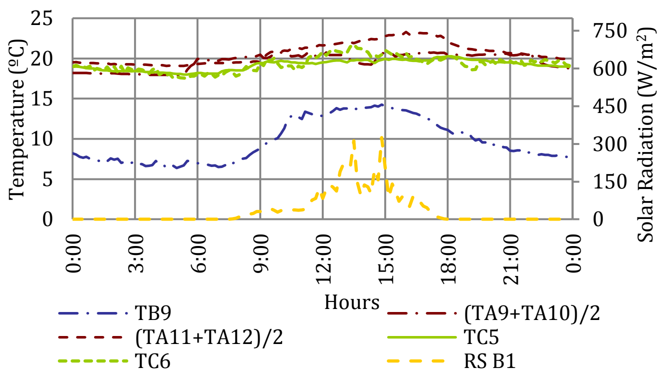

Figure 8 – Solar radiation and exterior and interior air temperatures in the rehearsal room and in the technical sound room, in *Gulbenkian*, during CD+ - 28th January 2013.

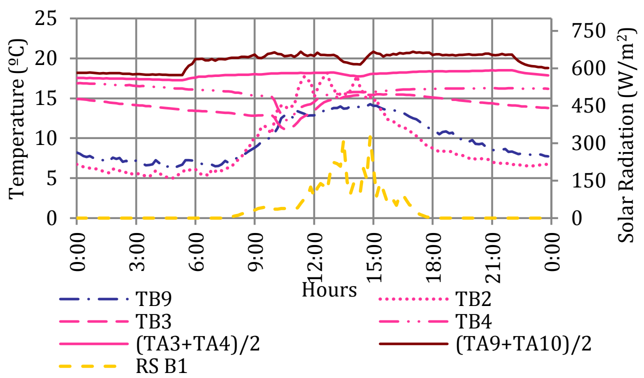

Figure 9 – Solar radiation and temperatures in the vegetation area (slab area) in the rehearsal room, in *Gulbenkian*, during CD+ - 28th January 2013.

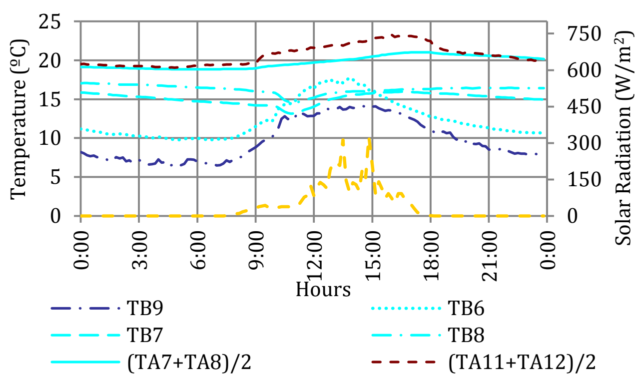

Figure 10 - Solar radiation and temperatures in the vegetation area (beam area) in the rehearsal room, in *Gulbenkian*, during CD+ - 28th January 2013.

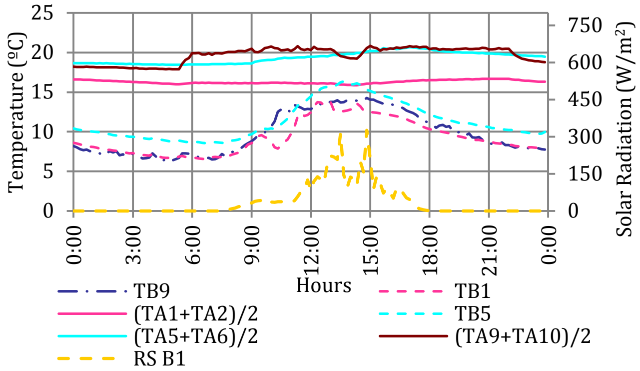

Figure 11 - Solar radiation and temperatures in the concrete flags area (beam and slab area) in the rehearsal room, in *Gulbenkian*, during CD+ - 28th January 2013.

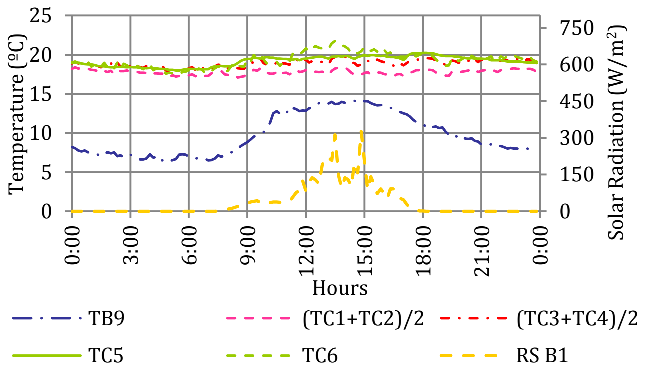

Figure 12 - Solar radiation and temperatures in the vegetation area (beam and slab area) in the technical sound room, in *Gulbenkian*, during CD+ - 28th January 2013.

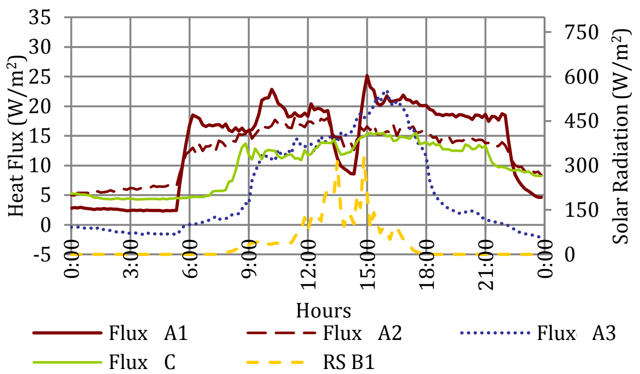

Figure 13 – Solar radiation and heat fluxes measured in both of the rooms, in *Gulbenkian*, during CD+ - 28th January 2013.

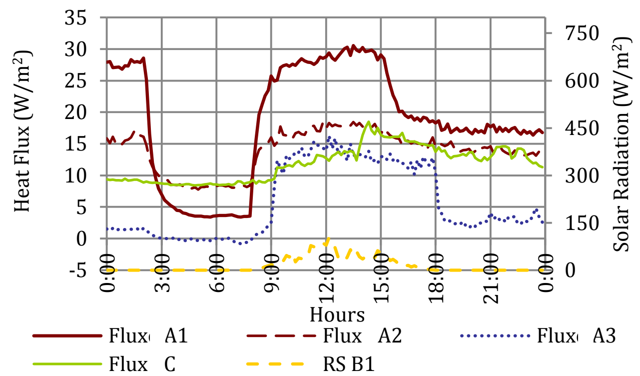

Figure 14 - Solar radiation and heat fluxes measured in both of the rooms, in *Gulbenkian*, during SRD- - 24th January 2013.

3.3 Principal conclusions

After the analysis of the Winter experimental campaign it was possible to verify some of the benefits from green roofs, particularly:

- the influence of the soil moisture and the evapotranspiration from the vegetation: it was possible to verify that the soil is very susceptible to exterior air temperature, particularly when the soil has moisture due to rain, making the surface temperature of the soil decrease and, consequently, the soil conductibility increases. During this period, the heat fluxes also reduced;
- lower thermal fluctuations in the green roof: it was possible to see that the thermal amplitude of the soil decreased along the substrate while its temperature increased. This shows the high thermal inertia of the green roof;
- the performance of the green roof is superior to the part that has soil and concrete flags: it was possible to observe that the concrete flags are less susceptible to exterior air temperatures than the groundcover during the Winter, once the surface temperature of the concrete flags had less thermal amplitudes;
- energetic efficiency: the heat fluxes analysis shown in the slab area, were higher below the vegetation area than below the concrete flags area. This behaviour is related to the evapotranspiration and the shading effect from the vegetation, since these effects can reduce the soil temperature, particularly at the surface. It was also possible to verify that in the rehearsal room the interior surface temperatures from the slab and beam below the vegetation area were higher than the interior surface temperature of the slab below the concrete flags area.

As a final remark, inside of both rooms, beams surface temperatures were higher than slabs surface temperatures. This effect was expected because the concrete thickness influences the thermal resistance from the structural elements.

4 Case study 2 – *ETAR*

The second case study was in *ETAR de Alcântara*, also in Lisbon and the part of the building where the experimental campaigns where taken is characterized by being an office building. The experimental campaign was realized in a support room inside a conference room.

The support room, with an area of 7.96m^2, has one door that connects the conference room, which is almost of the time semi-open. The conference room, with an area of 90.35m^2, has three walls that can be considered adiabatic and one that is a glazed facade, where occur heat losses. The major heat losses occur from the roof slab to the air space in the suspended ceiling, from this space to the interior of the support room and from the conference room to the interior of the support room. The air gap from the suspended ceiling is 1.23m to 2.45m height. The conference room also has an air-conditioning system that works every work-day from 7h00 to 19h00, which setpoint temperature is 22ºC +/- 1ºC. The green roof is located above the conference and support rooms and has a 0.20m concrete slab, waterproofing sheet, anti-root barrier, a drainage layer with varying thickness of lightweight gravel (0.40m to 0m), a filter sheet and a 0.65m soil thickness that is covered with two different plants. The zone 1 is covered with *Calluna Vulgaris* (groundcover) and the zone 2 has *Juniperus horizontalis* (highter plant) and they are separated by a metallic wall of 0.40 high.

4.1 Physical parameters and instrumentation

In ETAR there were two experimental campaigns, one during Winter and other during Summer:

i) Winter campaign (17 days)[1]:
   - start: 26th February 2013 at 19h00;
   - end: 18th March 2013 at 11h00.

ii) Summer campaign (23 days):
   - start: 8th June 2013 at 15h50;
   - end: 2nd July 2013 at 11h00.

The physical parameters measured in the support room and green roof are presented in Table 5 and in Figures 15 to 17. The instrumentations used are indicated in Table 6.

Table 5 - Physical parameters measured in the support and in the green roof.

	Name	Description	Unit
Support room	TA1	Air temperature inside the gap air	ºC
	TA2	Air temperature inside the support room	ºC
	TA3	Slab interior surface temperature (below the vegetation area 1)	ºC
	TA4	Slab interior surface temperature (below the vegetation area 2)	ºC
	Flux A1	Slab heat flux below the vegetation area 1	W/m^2
	Flux A2	Slab heat flux below the vegetation area 2	W/m^2
	HR A	Relative humidity inside the support room	%
Green Roof	TB1/TB8	Exterior air temperature	ºC
	TB2	Soil surface temperature in vegetation area 1	ºC
	TB3	Soil temperature (h=32.5cm) in the vegetation area 1	ºC
	TB4	Soil temperature (h=65cm) in the vegetation area 1	ºC
	TB5	Soil surface temperature in vegetation area 2	ºC
	TB6	Soil temperature (h=32.5cm) in the vegetation area 2	ºC
	TB7	Soil temperature (h=65cm) in the vegetation area 2	ºC
	RS B1	Solar radiation in vertical plan normal to facade with West orientation	W/m^2
	RS B2	Solar radiation in horizontal plan	W/m^2
	HR B	Relative humidity of the exterior ambient	%
	C.R.	Cumulative rainfall	mm/day

Table 6 - Set of instrumentation used in the experimental sessions.

Area	Instrumentation		Parameters
A – Support Room	Data Logger (Campbell) +	Thermocouples - T	TA1 to TA4
		Heat flux sensor	Flux A1 and A2
	Rotronic (thermometer-psychronometer)		TA5 and HR A
B – Green Roof	Data Logger (Delta-T) +	Thermocouples - T	TB1 to TB7
		Pyranometer	RS B1 and RS B2
	Tinytag (thermometer-psychronometer)		TB8 and HR B
	Udometer		Cumulative rainfall

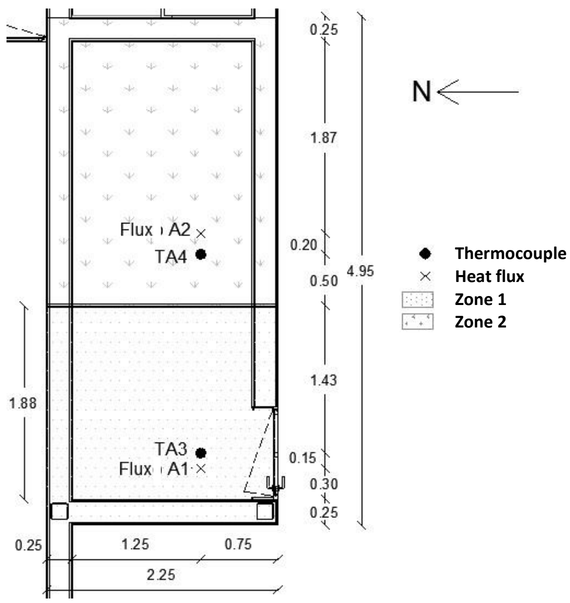

Figure 15 - Location of the instrumentation and parameters monitored in the support room.

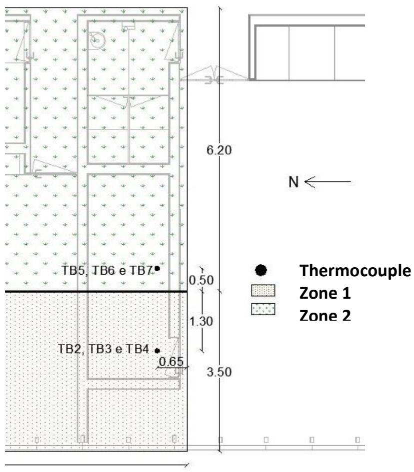

Figure 16 - Location of the instrumentation and parameters monitored in the green roof.

[1] Due to some technical problems with the Data Logger Campbell Scientific the physical parameters were not monitored between 10h50 of 6th March 2013 and 16h50 of 8th March 2013.

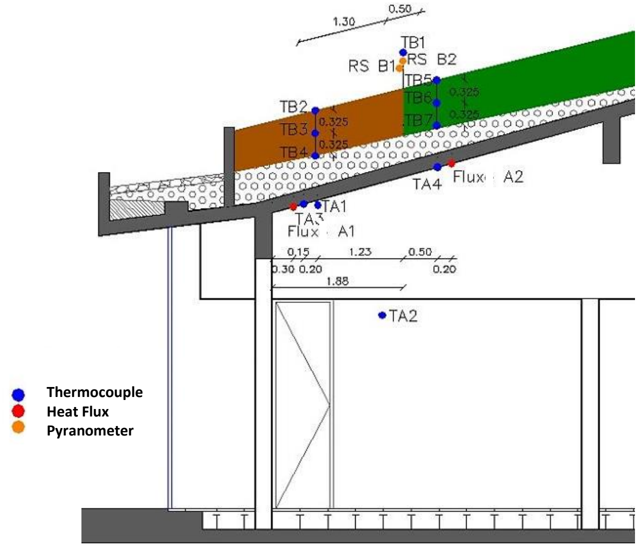

Figure 17 - Location of the instrumentation and parameters monitored in the support room and green roof.

The measurements were taken every 1-minute period. Their average values were registered every 10-minute period.

4.2 Experimental results

4.2.1 Experimental results from Winter

In this experimental campaign there were also a lot of data and like in *Gulbenkian*, two days where chosen (CD+ and SR-). Those days represent the extreme climatic conditions from Winter, in terms of exterior air temperature and solar radiation.

The CD+ was in 27th February 2013 (8.8ºC, 22.3W/m², in vertical plan, and 187.0W/m², in horizontal plan) and the SRD- was in 4th March 2013 (12.4ºC and 8.96W/m², in vertical plan, and 10.7W/m², in horizontal plan).

The results are shown in Figures 18 to 22.

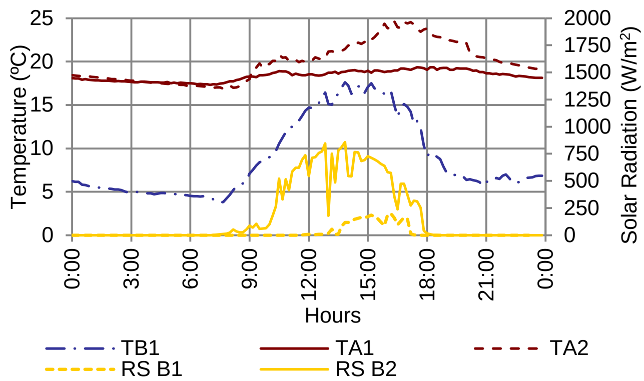

Figure 18 – Solar radiation and exterior and interior air temperatures in the support room, in *ETAR*, during CD+ - 27th February 2013.

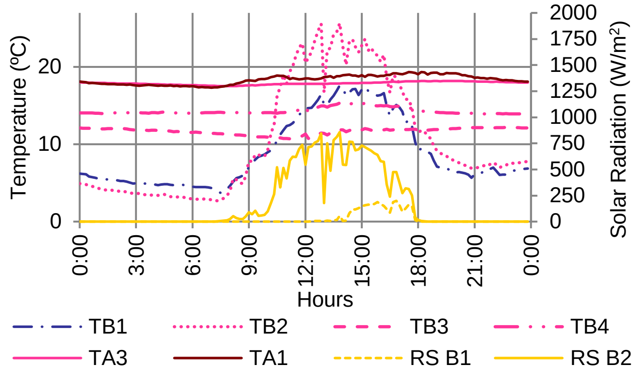

Figure 19 - Solar radiation and temperatures in the vegetation area 1 in the support room, in *ETAR*, during CD+ - 27th February 2013.

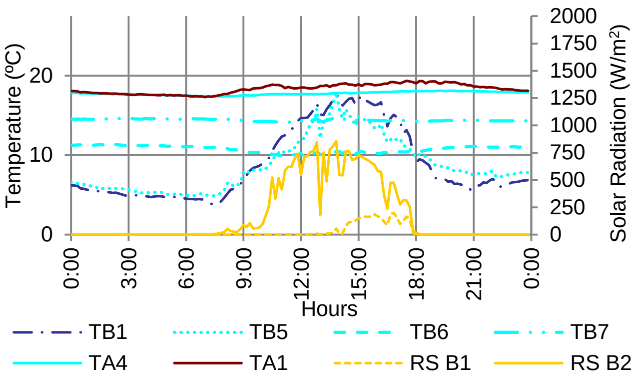

Figure 20 - Solar radiation and temperatures in the vegetation area 2 in the support room, in *ETAR*, during CD+ - 27th February 2013.

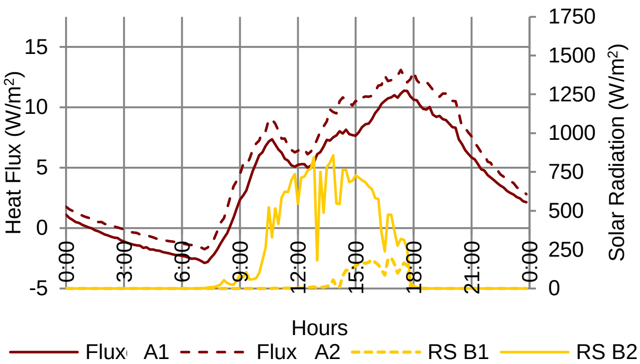

Figure 21 – Solar radiation and heat fluxes measured in the slab surface below both vegetation areas, in *ETAR*, during CD+ - 27th February 2013.

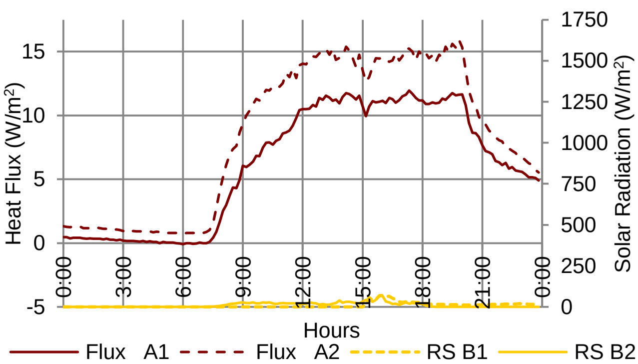

Figure 22 - Solar radiation and heat fluxes measured in the slab surface below both vegetation areas, in *ETAR*, during SRD- - 4th March 2013.

4.2.2 Experimental results from Summer

During this experimental campaign the two days chosen were Hotter Day (HD+ - the day with more average exterior air temperature) and the More Solar Radiation Day (SRD+ - the day with more average solar radiation).

The HD+ was in 25th June 2013 (26.5ºC, 184.2W/m^2, in vertical plan, and 312.3W/m^2, in horizontal plan) and the SRD+ was in 14th June 2013 (19.7ºC and 198.1W/m^2, in vertical plan, and 361.0W/m^2, in horizontal plan).

The results are shown in Figures 23 to 272.

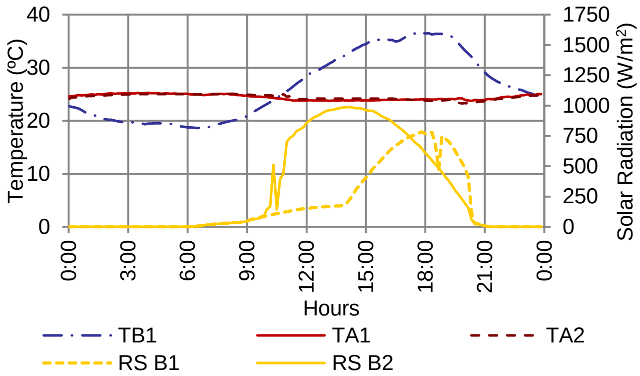

Figure 23 – Solar radiation and exterior and interior air temperatures in the support room, in *ETAR*, during HD+ - 25th June 2013.

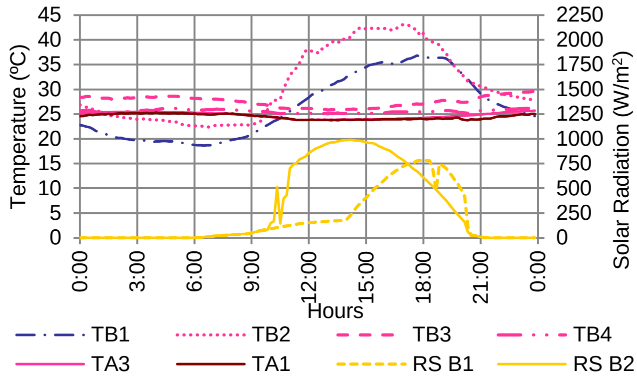

Figure 24 - Solar radiation and temperatures in the vegetation area 1 in the support room, in *ETAR*, in *ETAR*, during HD+ - 25th June 2013.

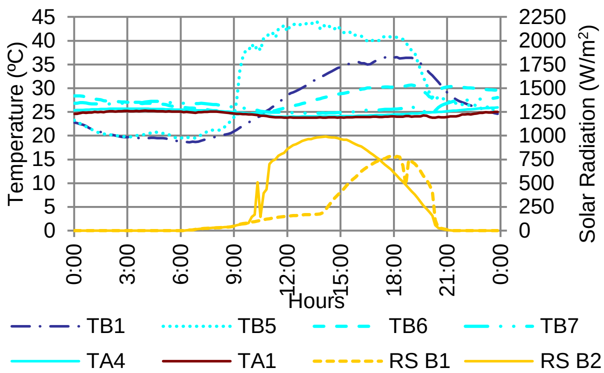

Figure 25 - Solar radiation and temperatures in the vegetation area 2 in the support room, in *ETAR*, during HD+ - 25th June 2013.

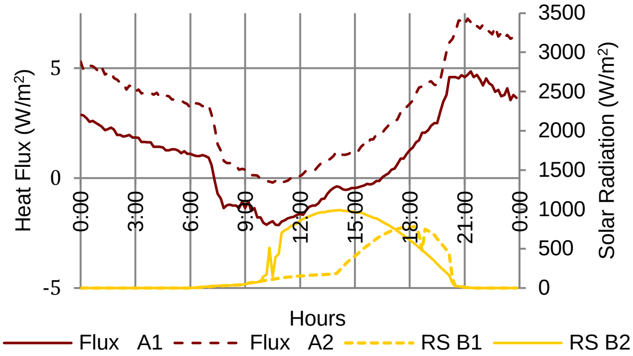

Figure 26 – Solar radiation and heat fluxes measured in the slab surface below both vegetation areas, in *ETAR*, during HD+ - 25th June 2013.

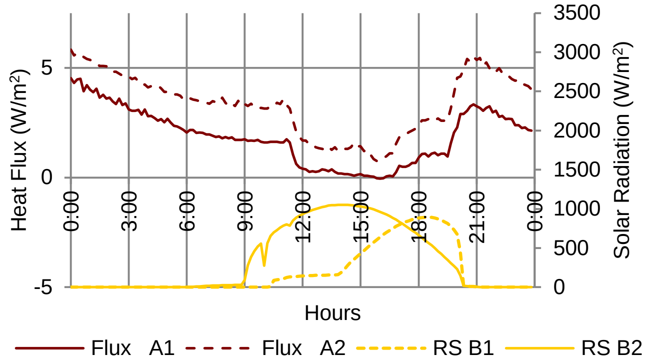

Figure 27 – Solar radiation and heat fluxes measured in the slab surface below both vegetation areas, in *ETAR*, during SRD+ - 14th June 2013.

4.3 Principal conclusions

In this case study, a green roof with two different vegetation types were compared (zone 1 with groundcover and zone 2 with higher vegetation). So, it was possible to verify some benefits from green roofs, particularly:

- The influence of the soil moisture and the evapotranspiration from vegetation: as it was seen in *Gulbenkian*, the influence of the soil moisture was observed, particularly during Winter campaign due to rainfall, and the surface soil temperatures, in both zones, were close to air exterior temperature (comparing CD+ and SRD-). Evapotranspiration effect of the vegetation were observed in zone 2 also during Winter, where the temperatures of the soil (on the surface and in the layer with h=32.5cm) were lower than the temperatures in zone 1;
- Lower thermal fluctuations in the green roof: the soil was able to lower the temperatures in both experimental campaigns, which had increased during Winter and reduced in Summer;
- Shading effect: vegetation from zone 2 has protected the soil, during Winter, and it surface temperatures were lower than the ones in the surface of zone 1 and exterior air. During Summer this effect was seen when the solar radiation in vertical plan started to get higher values because the shading in zone 2 increased and the surface temperature of zone 2 started to lower, due to the metal wall that separated both zones.

As a final remark, inside the support room the slab surface temperatures below the two zones were praticly the same and the heat fluxes below zone 1 were lower than the ones in zone 2.

5 U-Value estimation

After getting the experimental data from both case studies, a study was carried out to estimate the thermal transmittance coefficient (U-Value). This section presents the methodology to estimate (U-Value).

The U-value measures the thermal transmittance originated by the three mechanisms of heat transfer (conduction, convection and radiation) and describes the rate of heat through a square metre of a construction element (1).

$$U = \frac{1}{R_{si}+R_{se}+\sum\frac{e}{\lambda}} \quad \left[{}^{W}/_{m^2 ºC}\right] \qquad (1)$$

where:

- U - thermal transmittance coefficient [W/m^2.°C];
- R_{si} - interior surface thermal resistance [m^2.°C/W];
- R_{se} - exterior surface thermal resistance [m^2.°C/W];
- E - thickness of the material [m];
- λ - thermal conductivity coefficient of the material [W/m.°C].

Methods to estimate U-Value:

A. Method 1 (Progressive average method – exterior and interior air temperatures):

This method is described in EN ISO 9869:1994, and it consists on calculating the conductance by using, for each instant, average values calculated in all the previous instants, instead of flux and temperature instant values (2).

$$U = \frac{\sum_0^{i-t} Qi}{\sum_0^{i-t} Ti_i - \sum_0^{i-t} Te_i} \quad \left[{}^{W}/_{m^2 ºC}\right] \qquad (2)$$

where:

- Q - heat flux [W/m^2.°C];
- T_i - interior air temperature [°C];
- T_e - exterior air temperature [°C].

B. Method 2 (Progressive average method – exterior and interior surface temperatures):

This second method is an alternative, according to EN ISO 9869:1994, to method 1 because instead of using air temperatures, the thermal transmittance coefficient relates heat flux and surface temperatures (interior and exterior) and their surface thermal resistances (3).

$$U = \frac{1}{\frac{\sum_0^{i-t} Tsi_i - \sum_0^{i-t} Tse_i}{\sum_0^{i-t} Qi} + R_{se} + R_{si}} \quad \left[{}^{W}/_{m^2 ºC}\right] \qquad (3)$$

where:

- Q - heat flux [W/m^2.°C];
- T_i - interior air temperature [°C];
- T_e - exterior air temperature [°C];
- R_{si} - interior surface thermal resistance [m^2.°C/W];
- R_{se} - exterior surface thermal resistance [m^2.°C/W].

The exterior and interior surface thermal resistance can be seen in Table 7.

Table 7 – Surface thermal resistances (*RCCTE*).

Direction of heat flow (vertical)	R_{se} (m^2.ºC/W)	R_{si} (m^2.ºC/W)
Upwards	0,04	0,10
Downwards	0,04	0,17

C. Method 3 (Thermal resistances through different materials)

This method uses expression 1 to calculate the U-Value. It is necessary to calculate all the thermal resistances of the different materials used in the roof. It is also needed to know all the materials and their thicknesses and see, through ITE-50, the thermal conductivity coefficient of all the materials.

5.1 Case study 1 – *Gulbenkian*

All the materials of the green roof in *Gulbenkian*, thermal conductivity coefficients and thicknesses are listed in Table 8.

Table 8 – Parameters used in method 3 in *Gulbenkian*.

Material	λ (ITE-50)	λ_{chosen}	e (m)	R_i (m^2.ºC/W)
Concrete Slab	2,3	2,3	0,20	0,087
Gravel	2,0	2,0	0,10	0,050
Soil	Sand - 2,0 Clay - 1,5	1,75	0,25	0,143

In Table 9 are presented all the U-Value estimations that were obtained using the three methods and in Figure 28 is represented a chart with the results from method 1 and 2.

Table 9 - Results from the three methods in *Gulbenkian*.

Method	U (W/m^2.ºC)	Standard-Deviation
1	1,713	0,293
2	1,674	0,375
3	2,382	-

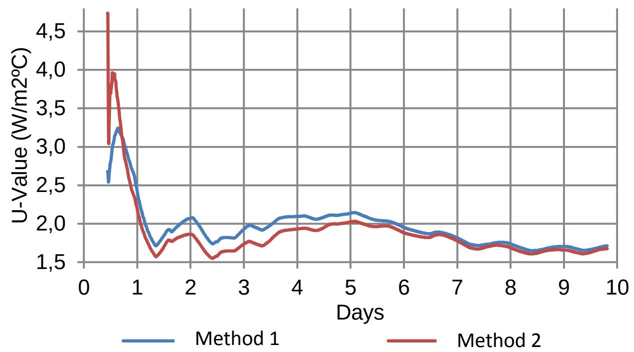

Figure 28 - U-Value estimation using method 1 and 2 in *Gulbenkian*.

5.2 Case study 2 – *ETAR*

All the materials of the green roof in *ETAR*, thermal conductivity coefficients and thicknesses are listed in Table 10.

Table 10 - Parameters used in method 3 in *ETAR*.

Material	λ (ITE-50)	λ_{chosen}	e (m)		R_i (m^2.ºC/W)
Concrete slab	2,3	2,3	0,20		0,087
Lightweight gravel	-	0,11*	0,25 - 0,50	0,38	3,409
Soil	Sand - 2,0 Clay - 1,5	1,75	0,65		0,371

*This value was taken from a catalog (Weber).

In Table 11 are presented all the U-Value estimations that were obtained using the three methods and in Figure 29 is represented a chart with the results from method 1 and 2 in both zones of vegetation.

Table 11 - Results from the three methods in *ETAR*.

Method	Zone	U (W/m^2.ºC)		Standard-Deviation	
		Day 0 - 8	Day 10-20	Day 0 - 8	Day 10-20
1	Zone 1	0,592	0,320	0,138	0,193
	Zone 2	0,763	0,399	0,130	0,231
2	Zone 1	0,720	0,395	0,139	0,266
	Zone 2	0,932	0,611	0,155	0,272
3		0,250		-	

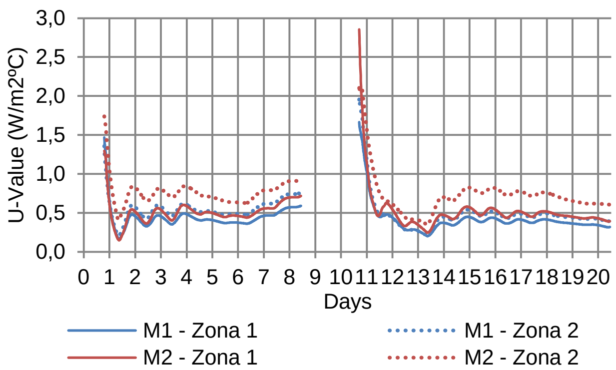

Figure 29- U-Value estimation using method 1 and 2 in both zones of vegetation in *ETAR*.

5.3 Principal conclusions

In the first study case, in Gulbenkian, the method 1 had estimated a U-value higher than method 2 in spite of, at the end of the experimental data from Winter campaign, both of the values had converged to an average value. In ETAR, the U-values estimation by method 2 were higher than method 1 and these values hadn't converged to the same value neither the value had stabilized.

In the third method it was shown the importance of defining correctly all the materials that constitute the roof and also their characteristics, being difficult to specify precisely the thermal conductibility coefficient through ITE-50. In both study cases just the layers that were thicker were considered in the calculation of U-value, which results in an inaccurate and different value from the other two methods value.

6 Conclusions

This study consisted in experimental evaluation of the thermal behaviour of green roofs. In the first study the *Gulbenkian's* green roof which had groundcover was compared to the concrete flags above the soil. In the second study case it was analysed the *ETAR's* green roof covered with two different species of vegetation – one with groundcover and other that was higher.

After the experimental data from the two case studies were collected and analysed it was possible to verify similar behaviours between the green roof in *Gulbenkian* and *ETAR*.

The influence of the soil moisture and the evapotranspiration were observed, especially during Winter due to rainfall, when the surface soil temperatures had decreased and, consequently the thermal conductivity had increased, reducing the heat fluxes. The shading effect was detected just in *ETAR*, and resulted in lower surface temperature in zone 2 than in zone 1. This can be explained because in zone 2 the vegetation was higher.

Other important conclusion was that the thermal fluctuations had decreased through soil depth. The soil smoothed the temperatures from the surface to the deeper layer monitored, protecting the roof from lower temperatures in Winter and from higher temperatures in Summer.

In *Gulbenkian* was compared the behaviour of the vegetation and the concrete flags zones. The results show that the area below the vegetation zone had higher heat fluxes than the area below concrete flags. The energetic efficiency is connected to the soil moisture, the evapotranspiration and the shading effect from vegetation, which decrease the soil surface temperature and, consequently, reduce the temperature variation between the soil surface and the slab interior surface, reducing the heat flux.

Finally, the U-value from the *Gulbenkian's* and *ETAR's* green roofs was estimated by three methods.

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