U.Porto Journal of Engineering, 9:2 (2023) 16-99
ISSN 2183-6493
DOI: 10.24840/2183-6493_009-002_001949

Received: 28 November, 2022
Revised: 07 February, 2023
Published: 19 April, 2023

Reflexions on an ENVI-met operation-methodology case study

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Abstract

An ENVI-met-operating methodology is case-studied aiming at contributing to the experience-exchange in ENVI-met's applied-to-practice operation and providing its developers with feedback.

The operating methodology is explained in detail as being applied – in an earlier research partnership with a city council's urban-projects division – on an actual urban-street-requalification project.

Daytime and night-time pedestrian-thermal-comfort impact of different intervention scenarios – differing both in soil-cover types and/or street-trees numbers and arrangements – were assessed and compared during a significant heat-wave event.

The results seem to reveal a significant ENVI-met limitation on modelling green pergolas – open-wire-trellis overhang covered with climber plants.

Author Keywords. ENVI-met Methodology, Green Pergola, Research Design Tool, Urban Greening, Urban Thermal Comfort.

Type: Research Article

1. Introduction

It is considered that the implementation of scientific-climate-sensitive-urban-design knowledge is still hesitant and limited to few cities (Jänicke, Milošević, and Manavvi 2021; Parsaee et al. 2019; Wong, Jusuf, and Tan 2011; Webb 2017). This is understood to be due to, among other factors, the complexity, extent and expertise requirement of this field (Bherwani, Singh, and Kumar 2020). This is where the numerical-model simulators can play a relevant role in translating such knowledge into a user-friendly interface operable by common practitioners and decision-makers (Gabriele Lobaccaro et al. 2021; Liu et al. 2021; Jänicke, Milošević, and Manavvi 2021; Erell 2008).

Within these numerical-model simulators and at the micro-scale, ENVI-met (Bruse and Fleer 1998) is one of the most widely used and evaluated software (Toparlar et al. 2017; Tsoka, Tsikaloudaki, and Theodosiou 2018) and already counts with a great number of case studies focusing on urban-greening thermal-comfort impact (Jänicke, Milošević, and Manavvi 2021; Liu et al. 2021; Lai et al. 2019). Nevertheless, most of these case studies are intangible (G. Lobaccaro and Acero 2015; Peter J. Crank et al. 2018) – based on either idealized or 'typical' environments –, strictly academic (Sorbona 2021; Cortesão et al. 2016; Lee, Mayer, and Chen 2016; Taleghani 2018) – neither involving or collaborating with practice, such as local governments and planners – and/or omit some relevant details on the adopted ENVI-met configuration settings (Lee and Mayer 2018; Jamei et al. 2019). While case-studying in detail a tangible and practice-involving ENVI-met-operating methodology, the present paper aims at filling the gap in literature on ENVI-met operation, contributing to the experience-exchange in this software's applied-to-practice procedure and providing its developers with feedback.

2. Study's background

The ENVI-met-operating methodology case-studied in the present research is a result of an earlier urban-planning Master's Dissertation that, developed within the Faculties of Architecture and Engineering of the University of Porto and in partnership with Porto City Council's Municipal-Urban-Projects Division, trialled ENVI-met as a design tool in one of the Division's urban-street-requalification projects in Porto, Portugal (Barnstorf 2022). Such urban-street-requalification project – part of a wider council-led-urban-street-requalification programme called 'Rua Direita' (GO-Porto 2022; CMP 2018) – involved a near-total reconstruction of street infrastructures (A.C.C. Moreira 2021) and hence, represented a precious street-tree-introduction opportunity.

The mentioned Dissertation focused on predicting and assessing the impact of different street-tree-introduction scenarios as a support to the project's decision-making process. The analysis was restricted to its impacts on pedestrian-thermal-comfort, specifically during heat-wave events. For clarity, Physiological Equivalent Temperature (PET) (Höppe 1999) was selected as the parameter to be assessed at two distinct moments-of-analysis – one at daytime and another at night-time. Beyond comparing the original-council-proposal scenario – 'Scenario-1' – against the 'Existing', two additional scenarios – 'Scenario-2' and 'Scenario-3' – were forward to test a possible improvement to 'Scenario-1' thermal behaviour.

While the 'Existing' did not include street-trees, 'Scenario-1' – beyond surface-materiality differences – introduced ten small-spheric trees – *Prunus cerasifera* J. F. Ehrch. cv. *"Pissardii"*. 'Scenario-2' was a slight variation from *1*'s while selecting another much taller but equally-small tree species – *Fagus sylvatica* L. cv. *"Dawyck Purple"*. 'Scenario-3' further greened *2*'s with the addition of five identical trees and a green pergola – an open-steel-wire-trellis overhang covered with vine-like plants.

2.1. Method

The present introduction section is followed by a literature review section that, given the current literature gap in ENVI-met operation-methodology case studies already mentioned above, outlines the currently most diverse and challenging discussions on ENVI-met's operationality in the context of urban-greening studies.

The following case study section details every aspect and step of the featured ENVI-met-operating methodology. It is sub-divided into three parts: field survey, configuration and analysis.

It is then followed by a section discussing the results, singling out the issues we have come across and reflecting on its possible causes and impacts. Finally, a last section with final remarks and future studies recommendations.

It should be noted that, for clarity, the exact terms used in ENVI-met environment are used – such terms are identified in-between single quotation marks. Furthermore, this study includes 19 Appendices – *A-S* – as supplement, including an overall glimpse of our ENVI-met's understanding (**Appendix R**), which serves as reference and might be particularly helpful for those not familiar with the software.

3. Literature review

Within ENVI-met operation-methodology discussions in the context of urban-greening thermal-comfort-impact studies, tree-modulation and model-validation aspects appear to be the most diverse and challenging (Liu et al. 2021).

4. Tree modulation

ENVI-met models trees as three-dimensional (3D) objects – '3D Plants' – in 'Albero' where, apart from defining its 3D shape, several of its properties – physiological, mechanic, etc. – are set (ENVI-met 2020). Following ENVI-met's version 5 launch, there are now two methods of tree shaping (Bruse 2021). The initial method would require a direct and block-by-block assemblage or the use of the 'Add rotation plant…' tool – similar to a lathe. The Leaf Area Density (LAD) value could be individually attributed or, when using 'Add rotation plant…' tool, as a whole. The recently added tree shaping method turns to 'Lindenmayer Algorithmic System' ('L-system') (Lindenmayer and Prusinkiewicz 1990) as an input coding for the tree's shape and up to each individual leaf. This is then converted into ENVI-met's parallelepipedal format – including the LAD differentiation between grid cells. In the context of urban greening, tree behaviour is often at the study's core and, given ENVI-met 3D parallelepipedal rigidity contrast against a tree's 'random' morphology and organic properties, issues regarding the tree's modulation/configuration are often discussed (Liu et al. 2021; Lam et al. 2021; Jamei et al. 2019; Shinzato et al. 2019). One can conclude that there is still a degree of uncertainty on how to adequately model/configure a tree or a group of them.

Although ENVI-met allows the differentiation of many tree properties, most studies simplify them due to limitations of time and instruments. Within these, some only consider one typical representing tree while others include several (Liu et al. 2021). Four approaches for acquiring tree properties can be distinguished: citing the literature (Altunkasa and Uslu 2020; Morakinyo and Lam 2016), measuring representing trees (Gatto et al. 2020; Aboelata 2020), parameterizing in accordance with tree physical characteristics (Morakinyo et al. 2020; Liu, Zheng, and Zhao 2018) and resorting to existing tree models in Envi-met's 'System Database' (Antoniadis, Katsoulas, and Kittas 2018; Rahul, Mukherjee, and Sood 2020). As for on-site measurements, three parameters seem to attract attention: leaf albedo, Leaf Area Index (LAI) and LAD distribution (Liu et al. 2021). Leaf albedo has been measured either through a spectrophotometer (Liu, Zheng, and Zhao 2018) or resorting to two albedometer (Fahmy et al. 2017). LAI acquisition has been done either through hemispheric photographs using a fisheye-lens-equipped camera (Morakinyo et al. 2018; Wang et al. 2015), scanner (Katsoulas et al. 2017) or plant canopy analyser (Fahmy et al. 2018). The LAD distribution is considered to be difficult to measure accurately but Lalic and Mihailovic's empirical formula claims to be able to estimate it from a given LAI and tree height (Lalic and Mihailovic 2004; Liu et al. 2021). The retrieval of both LAI and LAD has also been explored using airborne Light Detection and Ranging – also termed as airborne laser scanning (Lin and West 2016). Liu et al. (2021), suggest that, at least, the LAI and tree height values should be acquired from field measurements in order to consider what the authors consider to be the parameters with the most significant impact.

4.1. Model validation

Despite ENVI-met's robust physical foundation (Huttner 2012), it still cannot fully simulate reality as it uses 'approximations' (Yang et al. 2019; Liu et al. 2021). The specific case of tree simulation is, as mentioned above, particularly challenging. Therefore, model validation is essential to assess reliability of simulation results and avoid misjudgement (Liu et al. 2021; Peter J Crank et al. 2020).

Model validation is done through the comparison of one or more meteorological variables at a single moment or during a period of time of actual field measurements against corresponding simulation results. This can be translated into one or more statistical metrics which indicate 'how reliable' the model is (Shinzato et al. 2019; Lam et al. 2021; Liu et al. 2021; Jamei et al. 2019). Air temperature is a commonly used meteorological variable for validation, followed by relative humidity and mean radiant temperature (Liu et al. 2021). In contrary, PET, a commonly used variable in urban-comfort studies, is seldom used as comparing parameter for model validation (Liu et al. 2021; Lam et al. 2021). The coefficient of determination R^2 is commonly used as statistical metric, followed by the Root Mean Square Error, the Index of Agreement and the Mean Absolute Error (Liu et al. 2021).

The deviations between field-measured and simulation-resulting values in studies focused in green-and-blue infrastructures can be due to, as summarized in Liu et al. (2021) review, three broad reasons: ENVI-met limitations; modelling assumptions; unsystematic errors from experimental operations. Lam et al. (2021) suggest that all analysed meteorological parameters in a given study should be individually validated against field measurements – being particularly relevant when dealing with indexes such as PET. When validating, Liu et al. (2021) suggest including, at least, one radiation-related or ventilation-related variable and combining two or more statistical metrics.

5. Case study

For clarity, three stages are distinguished to describe the ENVI-met-operating methodology: field survey (6), configuration (6.2) and analysis (6.2.12). The field-survey stage is particularly relevant when the object of study is an actual environment – tangible. One must carefully observe the site and systematically characterize it onto a plan-referenced database. The configuration stage includes all the necessary steps, within the ENVI-met system, until the simulation run. At last, the analysis stage regards the arrangement of the simulation-resulting data by resort to further software within the ENVI-met system.

6. Field survey

6.1.1. Defining 'Model Domain'

As the aim of the Mater's Dissertation study was to test different interventions' scenarios upon a defined 'Intervention Area' of a street-canyon's public space (Barnstorf 2022), the modelled elements were limited to those within and in the immediate vicinity of the 'Intervention Area' except for the case of 'Soil Profiles' which, as a principle, are limited to the 'Intervention Area' and are only differentiated in its immediate vicinity if it is a natural soil – such as a vegetable garden. As for the 'Model Domain', it is rotated by 10° off the North grid in order to follow the prevailing street orientation and ensure a smaller domain for quicker processing times. The limits of the 'Model Domain' were determined as a result of model inspections in 'Spaces' – using the 'model inspector…' tool. The preliminary 'Model Domain' limits ensured, as recommended, a clearance off the 'Buildings' of at least their height. However, when inspecting it in 'Spaces' – using the 'model inspector…' tool – some needed adjustments were identified and implemented. The resulting 'Model Domain' plan dimensions were 381 x 172 m (**Figure 1**).

Figure 1: 'Model Domain' and to-be-modelled 'Buildings'
Source: adapted from 'Google Earth' and Porto City Council

6.1.2. Updating plan

When comparing the available *DWG*-format survey plans against 'Google Earth', it was clear that these were outdated and needed to be updated. A site visit was done to specify which of the elements to be modelled were outdated in order to better target a search on Council's documentation regarding their eventual development approvals or construction certificates. Relevant documentation was found regarding most of the outdated elements, including dimensions, heights/elevations, alignments and materials. However, no documentation was found for some outdated elements. In these cases, known information on adjacent structures based on site observations, Council's documentation and 'Google Earth' were extrapolated. Furthermore, most of the buildings in the plan lacked the location of its roof-ridge lines and other details, their update was mostly based on 'Google Earth' extrapolation and measurements which, beyond locating ridge lines and such, allowed to estimate several heights and elevations. At last, benefiting from the recently surveyed plans – provided by Council's Division –, a more accurate update was undertaken on the location of kerb lines and other pavement transitions within the 'Intervention Area'.

The following parts describe the method used for the actual field survey and are organized in three categories: 'Buildings and Single Walls', 'Soil Profiles and Simple Plants' and '3D Plants'. Each element was attributed a plan-referenced code as shown in **Table 1** and further detailed in the following parts. **Figure 2** provides an overview of the corresponding reference plan – full size and further information can be found in **Appendix A**.

ID	**Urban Surface Element Type**		
01 →	'Buildings'		
m01 →	'Single Walls'		
a01 →	'3D Plants'		
	'Soil Profiles and Simple Plants'		
	cover	natural or built	irrigated
A1	grassed	natural	yes
A2	vegetable garden	natural	yes
B0	bare	natural	no
B1	grassed	natural	no
C	11 cm cobblestone	built	no
D	concrete	built	no
E	tarmac	built	no

Table 1: Field-survey-database-ID-coding logic

Figure 2: Field-survey-reference plan Source: adapted from Porto City Council

6.1.3.'Buildings and Single Walls'

Each ´Buildings' was attributed a two-digit number (**Table 1**) and, when it included more than one significant roofing material, additional single-capital letters to specify its subdivisions – such is the case in 'Buildings' *5* and *34*. To simplify the model, in time spent both modelling and processing, only one wall material and one roof material for each 'Buildings' and/or 'Buildings' subdivision was considered. The material to be considered was the most prevalent.

The specification of the materials included the type of construction and its external face albedo. To determine the albedo of each surface, one resorted to a picture-based mobile app – *Albedo v.1.1* – which, using a grey card as reference, is able to calculate the albedo value (Apple 2022; MISC-LAB s.d.).

Regarding the type of construction, no access to all the buildings' construction details was available and, even if it was, that would be time-consuming and still not ensure that to be faithful to what was actually built. One had to rely on one's architecture expertise and deduce how the great majority of buildings were built. For the cases of roofs and other parts out of reach or sight, the challenge was even greater.

Based on field observation and 'Google Earth', one could distinguish traditional buildings from more recent ones. Traditional construction in Porto includes external stone walls, either exposed, rendered or cladded with tiles, and timber framed terracotta tiled roofs. More recent construction includes concrete structure with brick walls, either rendered or cladded with tiles, and a formed concrete roof substrate cladded with terracotta, fibre cement or metal roofing sheets. However, some traditional buildings have clearly been refurbished, which resulted in the introduction of some modern construction techniques. **Table 2** provides an overview of some of the established assumptions.

Location	**Description**		**Thickness in cm**
Wall substrate	Traditional stone walls		40 (45, if apparent)
	Modern brick walls		30
	Modern concrete walls		20
ETICS	Rendered	Cement render	2
		Insulation - polystyrene	6
	Stone cladded	Stone cladding	2
		Insulation - polystyrene	6
	Traditional framing	Insulation - rockwool	5

Location	Description		Thickness in cm
Roof substrate + insulation	Modern structure	Timber board substrate	2
		Insulation - polystyrene	6
		Concrete slab substrate	20
Simple roofing	Single sheeting		0.3
	'Sandwich' sheet	Aluminium	0.3
		Insulation - polystyrene	6
		Aluminium	0.3
Terraces	All	Floor tiles finish	0.6
		Concrete slab substrate	20

Table 2: Examples of some construction assumptions

Each wall selected to be modelled as a 'Single Walls' was attributed a two-digit number prefixed by the letter *m* (**Table 1**). Similar to 'Buildings', only the most prominent materials were considered and its albedo measured. However, measurements regarding the wall height and thickness were also collected.

Appendix B provides a full list of surveyed 'Buildings and Single Walls' including a description of its considered materiality, location, plan-referenced ID and albedo value.

6.1.4. 'Soil Profiles and Simple Plants'

By means of field observations and mostly 'Google Earth', one managed to delineate and ID code the 'Soil-Cover Types' shown in **Table 1**.

During the site visit, the picture-based albedo calculation was conducted for one or more samples of each of the three 'built' 'Soil-Covers Types'. Additionally, the sandy-joint thickness between the cobblestones was measured in order to estimate the plan fraction for stone and sand – this is relevant to better configure the semi-pervious behaviour of a traditional cobblestone pavement. As for the distinction between 'non-' and 'irrigated' within 'natural' 'Soil-Covers Types', one considered 'irrigated' when it was clear that the field was maintained, such as a home garden or a vegetable garden.

Appendix C lists the considered 'Soil-Cover Types' by plan-referenced ID and indicates their soil-surface albedo value.

6.1.5. '3D Plants'

Similar to the 'Single Walls', each tree selected to be modelled was attributed a two-digit number but prefixed by the letter *a* (**Table 1**). A site visit supported by 'Google Earth' was the mean to confirm their location and estimate their size and botanical species. The two trees, we had visual access to – *a01* and *a03* –, were easily identified as *Camellia japonica*. However, one was unable to identify the third tree, as there was no clear view of it. One had to estimate their size using 'Google Earth' measuring tools – *a01* and *a02* – or through a naked eye estimation – *a03* – when it wasn't shown in 'Google Earth'.

Appendix D lists the three surveyed '3D Plants' by plan-referenced ID and indicates their considered canopy dimensions.

6.2. Configuration

6.2.1. 'Wall/Roof Materials'

All new 'Wall/Roof Materials' database-ID begin with *MA* followed by two letters specific of the type of material and two more digits to differentiate between different albedos or other particularities. Furthermore, an extensive online search was conducted to inform each material's properties settings. Apart from the materials needed to translate the existing buildings and walls, a steel-wire trellis of a green pergola proposed in 'Scenario-3' needed to be translated into 'Wall/Roof Materials' language. The wires were established to be 4 mm thick and to be crossing twice in one direction and once perpendicularly to the first two – considering a 1 x 1 m area –, from which a fraction of 0.006 of 'steel' – *0100ST* from 'System Database' – and 0.994 of 'Air' – *0100O2* from the 'System Database' – were calculated.

For clarity, all used 'Wall/Roof Materials' information are organised into two separate but complementary tables (**Appendices E** and **F**). **Appendix E** lists all 'Wall/Roof Materials' alphabetically by their database-ID and only indicates the input-setting-differing values. For example, although a given black-painted wall has the same emissivity value as another given white-painted wall, their albedo value is different. Therefore, their albedo value is here considered an input-setting-differing value. The remaining input settings, that are common to each type of material – such as concrete or aluminium –, are listed in **Appendix F** where further information on the assumptions taken is provided.

6.2.2. 'Soil Materials'

All new 'Soil Materials' database-ID begin with *TR* except for the one case of cobblestone 'Soil Materials' – *CUBO11*. Apart from the cobblestone surface that, due to its semi-pervious character, needed to be created, transitional 'Soil Materials' were also needed to better translate, into the fixed depth layering logic of 'Soil Profiles', the standard construction layering for the three-class concrete pavements and cobblestone pavement which had been provided by the City Council.

For example, if one overlays the 'Soil Profiles' layering framework (**Figure 4**) onto the standard cobblestones' construction detail (**Figure 3**), one notices that the 'Soil Materials' to be assigned between the depth of 10 and 20 cm must translate 1 cm of 'cobblestone', 4 cm of 'sand bed' and 5 cm of 'gravel'.

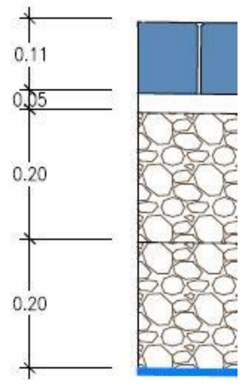

Figure 3: Section of the City Council's standard cobblestone construction detail
Source: Porto City Council

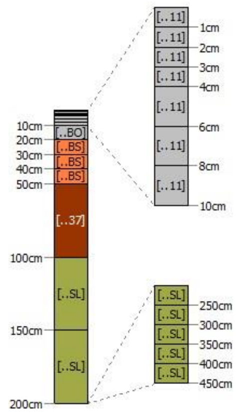

Figure 4: ENVI-met's 'Soil Profiles' layering frameworkSource:
'DB Manager'

Both the transitional and cobblestone 'Soil Materials' were translated using a combination of fractions of different 'Soil Materials' into one. Picking up from the example above, as the soil layer is 10 cm deep: 1 cm of ‘cobblestone’ is a fraction of 0.1; 4 cm of ‘sand bed’ is 0.4; 5 cm of ‘gravel’ is 0.5.

The ‘Soil Materials’ used as reference for ‘sand bed’ and ‘gravel’ were, respectively, the ‘Sand’ and ‘Smashed brick’ from ‘System Database’. As for the ‘cobblestone’, the same proportion as defined for the cobblestone-surface ‘Soil Materials’ – *CUBO11* – was used which, in its turn, is composed of ‘Sandy Clay Loam’ and ‘Granite’, from ‘System Database’, at a fraction of 0.284 and 0.716, respectively.

Appendix G indicates all input settings for each ‘Soil Materials’ and their composing fractions.

6.2.3. ‘Simple Plants’

There was no need to create further ‘Simple Plants’. **Appendix C** indicates which ‘System’ database-ID ‘Simple Plants’ were attributed in relation to ‘Soil-Cover Type’.

6.2.4. ‘Wall/Roof Constructions’

The first two digits of all new ‘Wall/Roof Constructions’ database-ID refer to its substrate material, the following two digits refer to the finish material and the last two digits are to distinguish the finish’s albedo or other characteristics. However, in the case of a distinct material in-between the inside and outside layers, such as insulation, the second digit is the one to reflect it – a stone wall with rendered ETICS is then coded as *PIRE*--. Apart from the thickness and the three-layered composition, the default input settings as shown in **Table 3** were kept.

‘Parameter’	**‘Value’**
‘Possible Usage’	‘Wall or Roof’
‘Roughness Length’	0.02000
‘Can be greened’	‘True’
‘Additional Value 1’	0.00000
‘Additional Value 2’	0.00000

Table 3: ‘Wall/Roof Constructions’ default input settings

Beyond the ‘Wall/Roof Constructions’ that translate the existing buildings, one resorted to ‘Wall/Roof Constructions’ to model the green pergola’s ‘wall’ and ‘roof’ because horizontal ‘Single Walls’ don’t have the option to allow ‘Greenings’, which was the study’s main goal. In configuration terms, the green pergola was assumed to be a building which had walls entirely made of air and a roof translating a steel-wire trellis – as described in 6.2.1. For the steel-wire trellis, the purposely created ‘Wall/Roof Materials’ was attributed to the three layers and ensured that the resulting thickness was 4 mm – the established thickness for the steel wires. As for the ‘walls of air’, ‘Air’ – *0100O2* from the ‘System Database’ – was attributed to all three layers. The simulator was expected to consider ‘Air’ as a seamless continuity between the external and internal air beyond these walls and roof – as is the case of a green pergola in reality. **Appendix H** provides a full list of all new ‘Wall/Roof Constructions’ and their respective composition and total thickness.

6.2.5. ‘Single Walls’

All new ‘Single Walls’ database-ID begin with *SW*, are followed by two digits that refer to its material and the last two referring to its albedo or other differentiation. When, for instances, a stone wall was rendered and painted, as ‘Single Walls’ only includes a single layer of ‘Wall/Roof Materials’, is considered as stone and only its albedo value reflects the painted finish. Apart from the selected ‘Wall/Roof Materials’ and resulting thickness values, the same default value of 0.02 for their aerodynamic roughness length setting was attributed. **Appendix I** provides a full list of all new ‘Single Walls’ and their respective composing material, total thickness and aerodynamic roughness length.

6.2.6. 'Greenings'

Although the existing buildings did not include any 'Greenings', one required to create a single type for a green pergola trialled in 'Scenario-3'. As the intention was to represent a climbing plant onto a wire trellis, the substrate was excluded. From 'System Database' list of 'default Greenings without air gap', a copy of 'only green' – *01NAFG* – was made and only edited its input settings for LAI and 'Leaf Angle Distribution'.

The LAI was set to 1.2 instead of 1.5. It was considered that a LAI of 1.5, with 0.3 m thickness, resulted in a very high LAD of 5.0 and believed that a resulting LAD of 4.0 – of a 1.2 LAI – would be more realistic. Note that the system's default high LAD conifer tree – *01ALDL* – has a LAD of 2.3 and some of the recently added trees to the 'System Database', modelled using the 'L-system' that claims to be more realistic, very rarely display a resulting LAD over 2.0. It was assumed that climbing plants on a wire trellis would present a higher LAD than that of trees and decided to find a half term. Considering that the resulting LAI had to be over 1.0 in order to ensure a proper shade – less than 1.0 would mean open spots –, a LAI of 1.2 was defined – which also resulted in a reduced LAD of 4.0. The leaf angle distribution is a 0-to-1-gradient value representing the leaves' surface angle in relation to the façade or roof – 0 stands for parallel (0°), while 1 stands for perpendicular (90°). This value was set to 0.2, instead of the 0.5, because one considered that, being on a roof, the leaves would favour a more horizontal pitch. The attributed database-ID was *RAMADA*.

6.2.7. 'Soil Profiles'

All new 'Soil Profiles' database-ID begin with *PV*, are followed by two digits that refer to its finish material and the last two digits are used to differentiate when required – as it happens for the concrete pavements that have three variations. Following the creation of the transitional 'Soil Materials', as mentioned in 6.2.2, the make-up of the 'Soil Profiles' was straightforward. The chosen default soil was 'Sandy Loam' from 'System Database'. Any pedological or geological particularity that may be present in the study area's subsoil has been ignored. Apart from albedo, emissivity and whether it is irrigated, the default input settings shown in **Table 4** were kept.

'Parameter'	***'Value'***
'*z*0 Roughness Length'	*0.01000*
'Water: Mixing Coefficient'	*0.00100*
'Water: Turbidity/Extinction'	*2.10000*

Table 4: 'Soil Profiles' default input settings

Appendix J presents all used 'Soil Profiles' and indicates their vertical-profile arrangement and additional input settings.

6.2.8. '3D Plants'

Despite the recent introduction of the 'Quantified Structural Model' for tree 'construction', we decided to resort to the older 'Grid Based Model' for creating the trees we needed. The 'L-system', although promising, revealed to require a time-consuming familiarity to its coding logic in order to achieve the desirable tree shapes and further research into each species' trunk, twigs and leaves articulation's logic. Given the challenge, that is still being widely discussed in literature, on modulation of trees, one considered to be safer to stick to the 'Grid Based Model'.

The existing trees, considered in the field survey, were built upon 'LAD high' 'New Deciduous Tree' from 'System Database'. Although two of the three existing trees were identified as *Camelia japonica* which is a dense-perennial tree – hence, not deciduous –, one understood that its 'Albero' 'Leaf type' could only be considered as 'Decidous Leafs' as one considered that it could be neither ‘Conifer Leafs’ nor ‘Grass-like Leafs’ – as it was the alternative. For instances, a ‘System Database’ palm tree’s – *01PLDL* – ‘Leaf type’ is pre-set as ‘Decidous Leafs’, which is definitely not the case in reality. Hence, one considered that a *Camelia japonica* could be translated into ‘Albero’ as a tree with ‘Decidous Leafs’ that only did not lose its leaves during winter. Just as the palm tree example from the ‘System Database’. The ‘LAD high’ was chosen considering the typical and observed high leaf density of this specie’s canopy.

As for the two types of proposed trees, it was considered their adult-canopy size indicated by Moreira (2008, 94 and 176) and ‘built’ them upon the ‘System Database’ ‘New Deciduous Tree’ default input settings. Apart from their canopy size, their LAD values was also edited. In this case, aiming at benefiting from the improved ‘Quantified Structural Model’ trees recently added to the ‘System Database’, one defined the value of LAD, for each of the two types of trees, as the average-LAD value of a ‘System Database’ ‘Quantified Structural Model’ tree of a similar species. For the case of ‘Scenario-1’ *Prunus cerasifera*, which is a wild cherry tree, ‘Wild Cherry “Plena” (young)’ – *010140* from the ‘System Database’ – was used, which resulted an averaged LAD of 0.27. For the case of ‘Scenario-2’ and *3*’s *Fagus sylvatica*, which is a beech tree, ‘Common Beech (young)’ – *010440* from the ‘System Database’ – was used, which resulted an averaged LAD of 0.38.

One resorted to the ‘Add rotation plant…’ tool to shape the trees’ canopies. Apart from canopy and root shape and LAD values, the input settings shown in **Table 5** were kept.

‘Basic Plant Physiology’	
‘CO2 fixation type’	*‘C3-Plant’*
‘Leaf type’	*‘Decidous Leafs*
‘Foliage Shortwave Albedo’	*0.18’*
‘Foliage Shortwave Transmittance’	*0.30*
‘Isoprene Capacity’	*12.00*
‘Leaf Weight (g/m^2)’	*100.00*
‘Plant Biomechanics’	
‘Density of Wood (kg/m^3)’	*690.00*
‘Young Modulus E (GPa)’	*8.77*
‘Fraction Young E to Shear G’	*0.1200*
‘Modulus of Rupture – Straight Segment (MPa)’	*65.00*
‘Modulus of Rupture – Branch Connection (MPa)’	*45.00*

Table 5: ‘3D Plants’ default input settings

Appendix D indicates each ‘3D Plants’ considered canopy and root dimensions and attributed LAD and RAD values.

6.2.9.‘Model Area Files’

The Figures below (**Figures 5-8**) provide a plan overview of the different ‘Model Area Files’ included in this study – full size image and further information can be found in **Appendices K**, **L**, **M** and **N**.

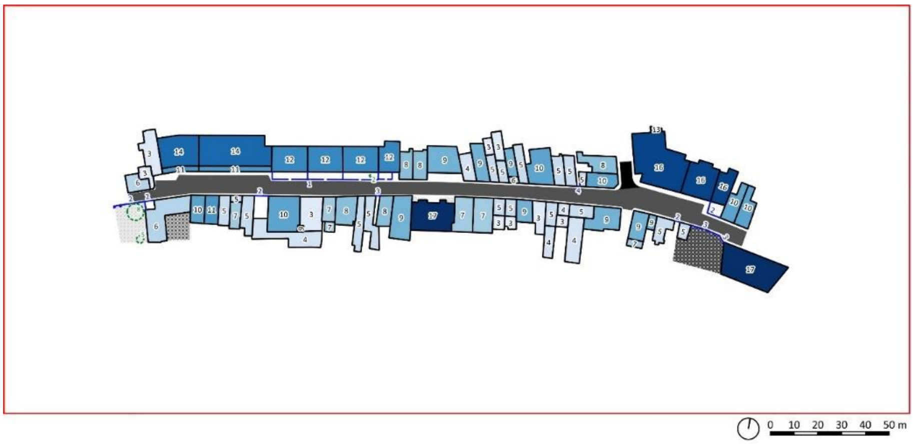

Figure 5: ‘Existing’ planSource: adapted from Porto City Council

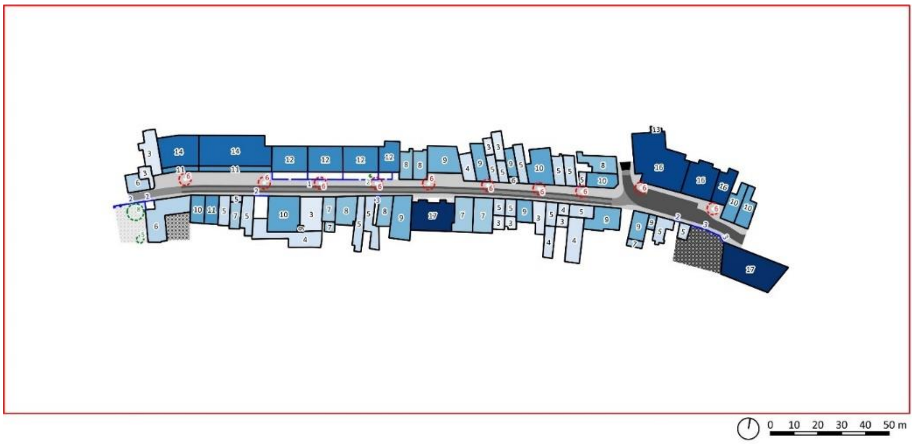

Figure 6: ‘Scenario-1’ planSource: adapted from Porto City Council

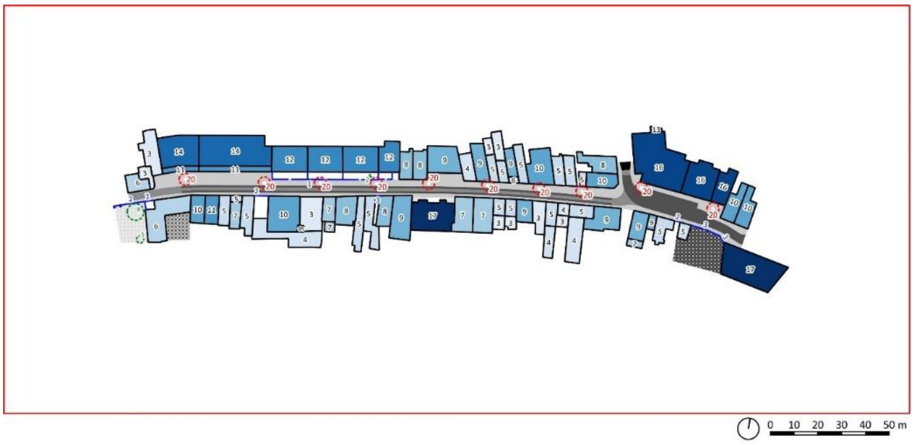

Figure 7: ‘Scenario-2’ planSource: adapted from Porto City Council

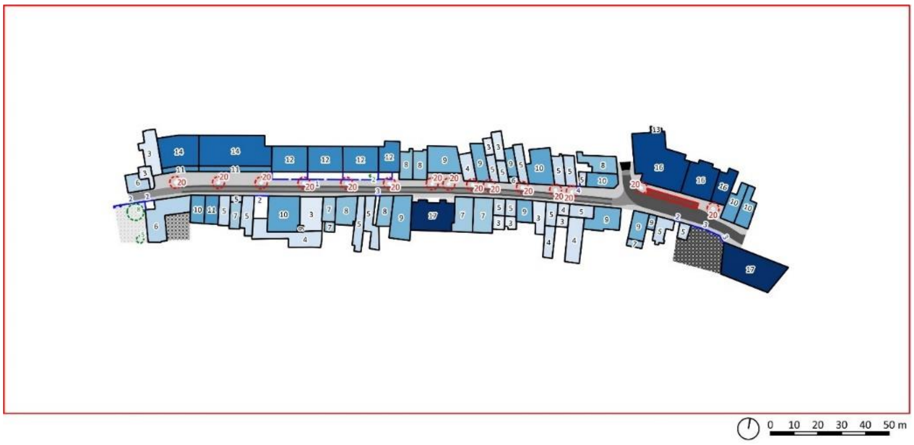

Figure 8: ‘Scenario-3’ planSource: adapted from Porto City Council

Following the import of the *DWG*-format plans – the design software used in the project was ‘AutoCAD’ –, the geolocation and 3D/2D modulation in ‘SketchUp Pro 2022’ (**Figure 10**) and its conversion into ‘Spaces’ *INX* format (**Figure 11**) through the plugin ‘Envimet-inx v2.0.1’, a grid cell size of 2 x 2 x 2 m was established. This was found to be the best balance to ensure both short-processing times and adequate spatial resolution.

Figure 9: simulated aerial view over intervention area due west

Source: ‘Google Earth’

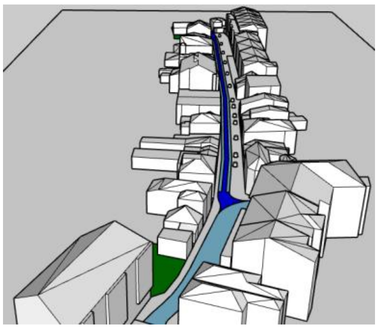

Figure 10: ‘Scenario-3’ 3D model visualization in ‘SketchUp Pro 2022’

Source: adapted from Porto City Council and ‘Google Earth’

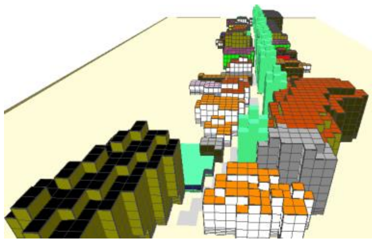

Figure 11: ‘Scenario-3’ 3D model visualization in ENVI-met’s ‘Spaces’ v5.0.3

Source: adapted from Porto City Council and ‘Google Earth’

Table 6, below, indicates ‘Model Area File’ further properties.

‘Model location’	
‘Location on earth’	
‘Latitude (º, +N, -S)’	41.17
‘Longitude (º, -O, +E)’	-8.64
‘Reference time zone’	
‘Name’	CET / GMT +1
‘Reference longitude’	-15.00
‘Model geometry’	
‘Size of grid cell (in meter)’	dx= 2 / dy= 2 / dz= 2
‘Model dimensions (in grid cells)’	x: 192 / y: 87 / z: 20
‘Model rotation out of grid north’	-10.00
‘Number of nesting grids’	0
‘Method of vertical grid generation’	
‘dz of lowest grid box is split into 5 sub cells’	yes
‘Telescoping?’	yes
‘Telescoping factor (%)’	8.00
‘Start telescoping after height (m)’	20.00
‘Geometric check’	

‘Min. distance between buildings and model border’	26 grids (52 m)
‘Height of 3D model top’	51.29 m
‘Highest point building + DEM’	17 m
‘Difference model top to highest point’	34.29 m
‘Georeference’	
‘Co-ordinate of lower left grid’	x: 530445.44 / y: 4557184.50

Table 6: ‘Model Area File’ general properties

6.2.10. ‘Forcing File’

One resorted to IPMA’s – *Instituto Português do Mar e da Atmosfera*, the Portuguese Institute of Sea and Atmosphere – website features to identify a period of time occurring a significant heat-wave in Porto. A nationwide heat-wave period was found between the July 7th and July 18th of 2006 which, at the time, could have been considered the most significant July heat-wave ever recorded since 1941. The duration of this heat-wave in the region of Porto was between 8 and 9 days and with a maximum deviation from the average maximum air temperature of +11.8 °C on the 14th (IPMA 2006).

IPMA’s meteorological records for the period between the 1st and the 19th of July of 2006 were requested. From these was selected a 48-hour period which included the hottest day, the following night and the previous day and night – from 6:00 on the 13th of July to 6:00 on the 15th of July 2006 (**Figure 12**).

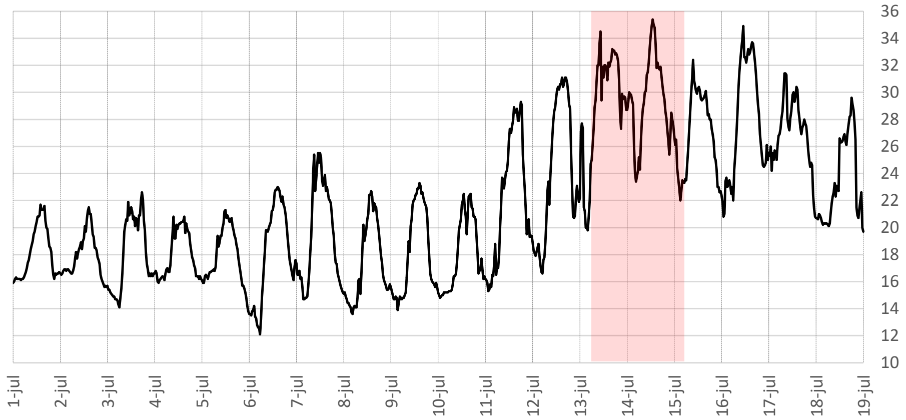

Figure 12: Air-temperature record in ‘Porto/Pedras Rubras’ meteorological station between 1.07.2006 and 19.07.2006. Simulated period shown hatched
Source: IPMA

A 48-hour simulation run was set to allow the ‘Model Area File’ to adjust to the meteorological ‘forcing’ during the first 24 hours. Therefore, only the last 24 hours were to be considered for analysis.

The provided IPMA’s data offered a ten-minute interval between measurements which suited the mandatory 30-minute interval required for the ‘Forcing File’. Nevertheless, despite the extra parameters provided – such as the maximum instantaneous windspeed –, there was insufficient data regarding radiation or cloud cover (**Table 7**) – in the absence of data regarding longwave and direct shortwave radiation, it is not possible to complete the three radiation fields. Therefore, when importing the *CSV*-format weather data into ‘Forcing Manager’, those fields were left as *0* and set to ‘Do not force radiation/clouds’. Based on the geolocation, time, date and all the inputted ‘forcing’ parameters, ENVI-met can automatically calculate the radiation (ENVI-met 2022b).

IPMA's data (every 10 minutes)		**'Forcing File'** (every 30 minutes)	
Parameter	**Format/Units**	**Parameter**	**Format/Units**
Year	YYYY	'Date'	DD.MM.YYYY
Month	MM		
Day	DD		
Hour	HH	'Time'	HH:MM:SS
Minute	MM		
Total Global Radiation	KJ/m^2	'Direct shortwave radiation'	W/m^2
		'Low altitude clouds cover'	0-8
		'Diffused shortwave radiation'	W/m^2
		'Medium altitude clouds cover'	0-8
-	-	'Longwave radiation'	W/m^2
		'High altitude clouds cover'	0-8
Average air temperature	°C	'Absolute air temperature'	K
Maximum air temperature	°C	-	-
Minimum air temperature	°C	-	-
Average relative humidity	%	'Relative Humidity'	%
Maximum relative humidity	%	-	-
Minimum relative humidity	%	-	-
Average windspeed	m/s	'Windspeed'	m/s
Maximum instantaneous windspeed	m/s	-	-
Average wind direction	°	'Wind direction'	°
Maximum wind direction	°	-	-
Precipitation	mm	'Precipitation '	mm

Table 7: Comparison between IPMA's weather data and 'Forcing File' requirements
Source: IPMA and Envi-met 'Forcing Manager'

Additionally, one ensured the wind-speed field to be at least 1 m/s and the wind-direction field to never vary more than 90° in 30 minutes (ENVI-met 2022a).

6.2.11. 'Simulation File'

Apart from the general settings shown below (**Table 8**), it should be clarified that, from all 'Optional Sections', only the 'Radiation Section' was configured and that the use of multi core CPU for parallel computing was enabled. Each scenario simulation took over 50 hours to be processed and produced about 20 Gb of data.

‘general setting’	
‘start date’	*13.07.2006*
‘start time’	*06:00*
‘total simulation time’	*48h*
‘meteorology’	
‘full forcing’	
‘force wind?’	*yes*
‘force air temperature?’	*yes*
‘force radiation/clouds?’	*no*
‘force relative humidity?’	*yes*
‘force precipitation?’	*yes*
‘minimum interval for updating the wind inflow’	*30 s*
‘alternate cloud cover (when not full forced)’	
‘cloud cover of low clouds (0-8)’	*0*
‘cloud cover of medium clouds (0-8)’	*0*
‘cloud cover of high clouds (0-8)’	*0*
‘radiation settings’	
‘ray tracing and IVS height cap’	
‘raytracing precision’	*‘lower resolution’*
‘use height cap for adjusting raytracing (and IVS) precision?’	*yes*
‘height cap in meters above ground below which higher precision is used’	*5*
‘use IVS module?’	*yes*
‘resolution for height segment angles’	*‘low (30º)’*
‘resolution for azimuthal segment angles’	*‘low (30º)’*
‘mean radiant temperature calculation method and minimum longwave radiation cap’	
‘mean radiant temperature calculation method’	*‘common six-directional approach’*
‘human projection factor’	*‘VDI (rayman, SURM)’*
‘advanced canopy radiation module and solar adjustment factor’	
‘use advanced canopy radiation transfer (ACRT) module?’	*yes*
‘update interval for view factor calculation for the ACRT module in days’	*10*
‘adjustment factor for solar radiation’	*1.00*

Table 8: configuration settings of the ‘Simulation File’

6.2.12. Analysis

As the study’s aim was to assess and compare the impact of each intervention scenarios on the pedestrian thermal comfort and illustrate the results in a clear way, the following was established:

- Only one parameter is to be used for comparison. The PET index was adopted.
- Only consider values at a plane 1.4m off the ground – ‘k-level’ *3*.

- Only consider two moments – daytime and night-time. Moments with the highest air temperature but also low wind speed were preferred – 13:00 and 1:00 (**Figure 13**).
- The resulting PETs are to be displayed as a consistent gradient of colours on plan as per corresponding grade of thermal perception by human beings or, when mapping differences of PET between scenarios, between dark red for warmer and purple for colder.

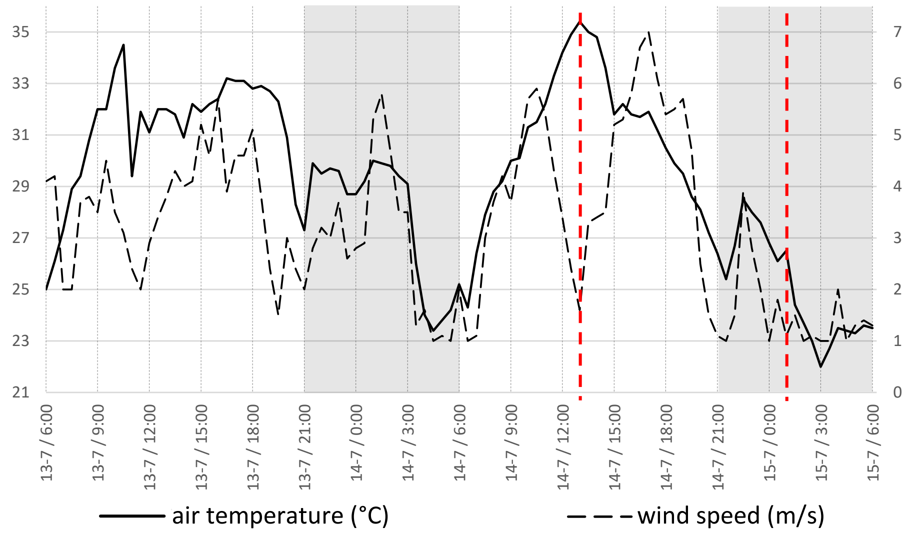

Figure 13: Air-temperature and wind-speed record in 'Porto/Pedras Rubras' weather station between 13.07.2006 and 15.07.2006

Analysed moments indicated in dashed red

Source: IPMA

6.2.13. 'BIO-met'

PET values are not included in the resulting data from a simulation however, the parameters necessary for its calculation are. 'BIO-met' can calculate them. Although the time for calculating all PET values is much less than that for the simulation, it can still take a long time and require further memory space. 'BIO-met' allows the option to only calculate the values within or up to a specified height plane – 'k-level' – and/or within a custom timeframe. Hence, the calculation was limited to 'k-level' *3* plane and at 13:00 and 1:00. The 'personal parameters' used for the calculation were the default as shown in **Table 9**.

'Body parameters'	
'age of person'	*35 years*
'gender'	*male*
'weight'	*75.00 kg*
'height'	*1.75 m*
'surface area (DuBois-area)'	*1.91 m^2*
'Clothing parameters'	
'static clothing insulation'	*0.90 clo*
'Person's metabolism'	
'total metabolic rate'	*164.49 W (=86.21 W/m^2)*
'(met)'	*1.48*

Table 9: Default 'Personal parameters' for PET calculation

6.2.14. 'Leonardo'

At first, one produced the plans illustrating the daytime- and night-time-resulting PETs for the 'Existing' and the other three 'Scenarios'. In order to provide a cross-plans-reading consistency and a closer correspondence with the ranges of PET for the different grades of 'thermal perception by human beings' and 'physiological stress on human beings', a custom 'Datalayer Legend' (**Table 10**) was created.

As the simulation-resulting-PET values' range was between 9.12 and 56.80 °C (**Appendix O**), the 'First value in legend' was set to 9.00 °C. Additionally, as the considered PET ranges are not constant – sometimes at a 5 °C interval other times 6 °C – and given the 47.68 °C range of PET values, the 'Number of colors/classes' was set to 20 and the 'Step size/Class width' to 2.00 which allowed to distinguish most of the thermal perception and physiological stress grades – with the only exception between 'slightly cool' and 'comfortable' – and a maximum value of above 47 °C – well into the last grades of perception and stress. **Table 10** provides an overview of this customed 'Datalayer Legend'.

Legend class's approximate colour	Legend class (°C)	PET (°C)	'Thermal perception'	'Physiological stress'
light blue	9-11		'cool'	'moderate cold stress'
	11-13			
		13		
very light blue	13-15		'slightly cool'	'slight cold stress'
	15-17			
	17-19	18		
white	19-21		'comfortable'	'no thermal stress'
very light yellow	21-23			
		23		
	23-25			
light yellow	25-27		'slightly warm'	'slight heat stress'
	27-29			
		29		
yellow	29-31		'warm'	'moderate heat stress'
	31-33			
	33-35			
		35		
orange	35-37		'hot'	'strong heat stress'
	37-39			
	39-41			
		41		
red	41-43		'very hot'	'extreme heat stress'
	43-45			
	45-47			
purple	47-49			

Table 10: Customed 'Datalayer Legend' correspondence with range of the thermal index PET for different grades of 'thermal perception by human beings' and 'physiological stress on human beings'Source: adapted from Matzarakis et al., (1999)

Eight plans were produced (**Figure 14** and **Figure 15**). One for every two moments of analysis – daytime and night-time – and for all four 'Model Area Files' – 'Existing' and 'Scenarios' *1*, *2* and *3*. These plans can be found full-sized in **Appendix O**.

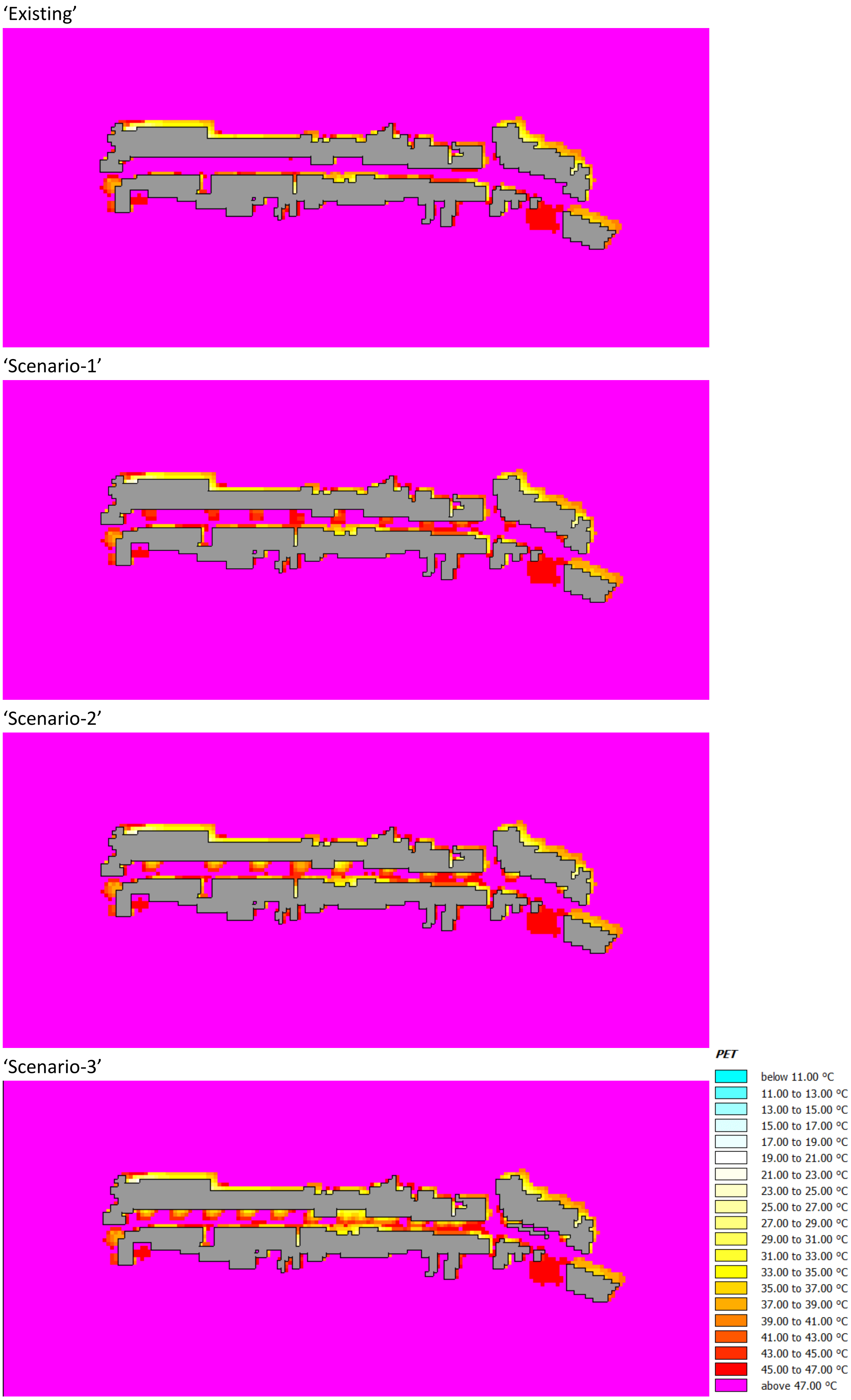

Figure 14: Daytime-simulation resulting PET

Figure 15: Night-time-simulation resulting PET

Secondly, one produced the plans comparing the three ‘Scenarios’ against the ‘Existing’ at both moments – daytime and night-time. As the variations are much more expressive at daytime – between -21.12 and +5.68 °C – than at night-time – between -2.24 and +1.84 °C –, a ‘Datalayer Legend’ was customed for each moment. For the daytime, one noticed that the positive variations higher than 1.00 °C were restricted to very few grid cells in ‘Scenario-3’ comparison and that the negative-differences beyond the -17.00 °C were also restricted to few grid cells in ‘Scenario-2’ and *3*’s comparisons. Therefore, the ‘Number of colors/classes’ was kept to 20 but adjusted the ‘Step size/Class width’ to 1.00 and the ‘First value in legend’ to -18.00 in order to provide higher resolution to the most frequent values – this is especially relevant at the positive-negative interface (**Figure 16**).

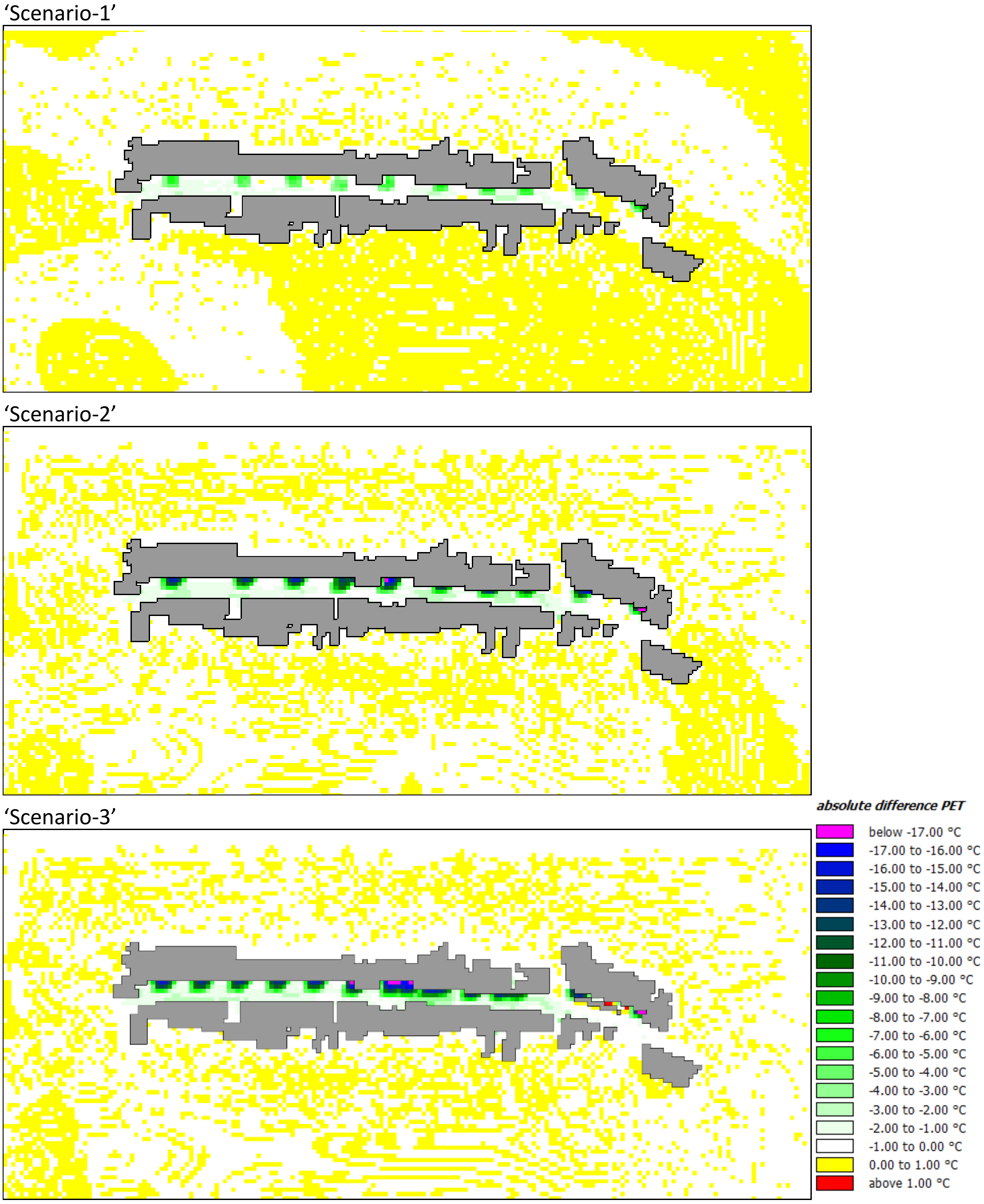

Figure 16: Daytime comparison – ‘Scenarios’ vs ‘Existing’

For the night-time, given the much smaller range of values, the ‘Step size/Class width’ and ‘Number of colors/classes’ were reduced to 0.25 and 18, respectively, and the ‘First value in legend’ adjusted to -2.50 (**Figure 17**). The six resulting plans can be found full-sized in **Appendix P.**

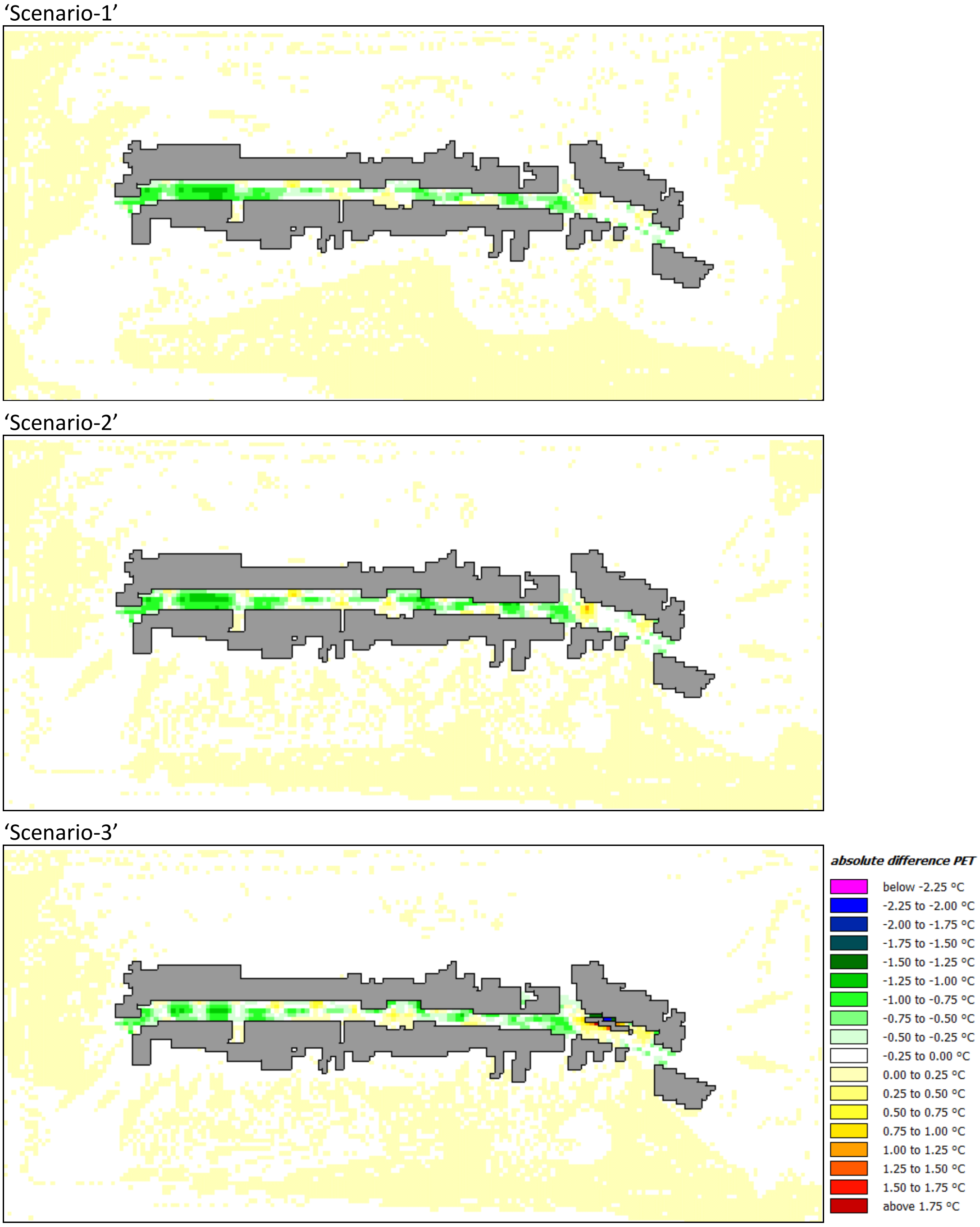

Figure 17: Night-time comparison – ‘Scenarios’ vs ‘Existing’

At last, one produced some plans with the comparison between ‘Scenarios’. One compared ‘Scenario-2’ with ‘Scenario-1’, ‘Scenario-3’ with ‘Scenario-2’ and ‘Scenario-3’ with ‘Scenario-1’. For night-time, the range of values were equally small and so the same ‘Datalayer Legend’ settings were kept as in the comparisons against the ‘Existing’ (**Figure 18**).

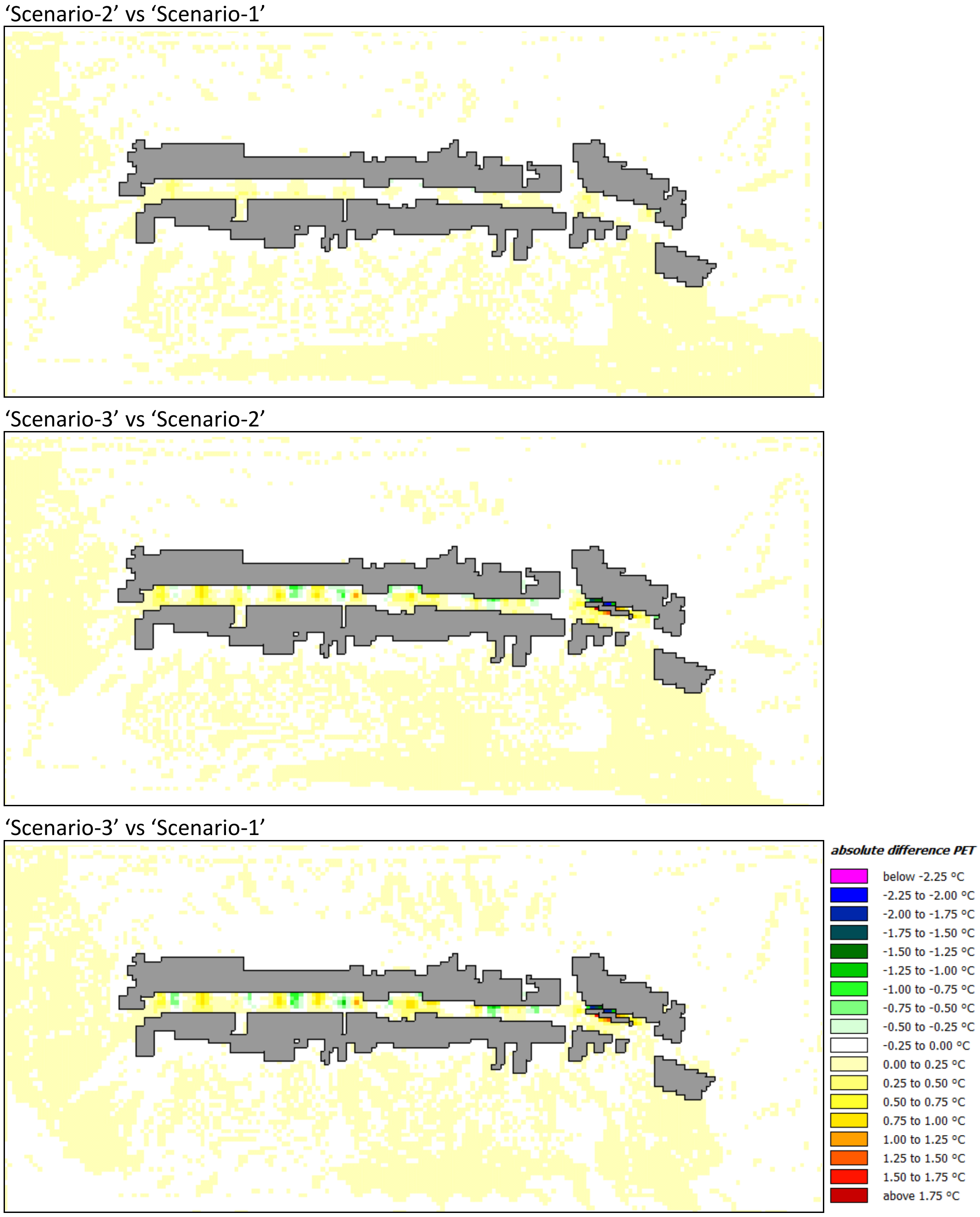

Figure 18: Night-time comparison between 'Scenarios'

As for daytime, the range of values was high – between -19.92 and +12.87 °C – and one found a balance setting the 'Step size/Class width' to 1.50, the 'First value in legend' to -21.00 and the 'Number of colors/classes' to 20 (**Figure 19**). The six resulting plans can be found full-sized in **Appendix Q.**

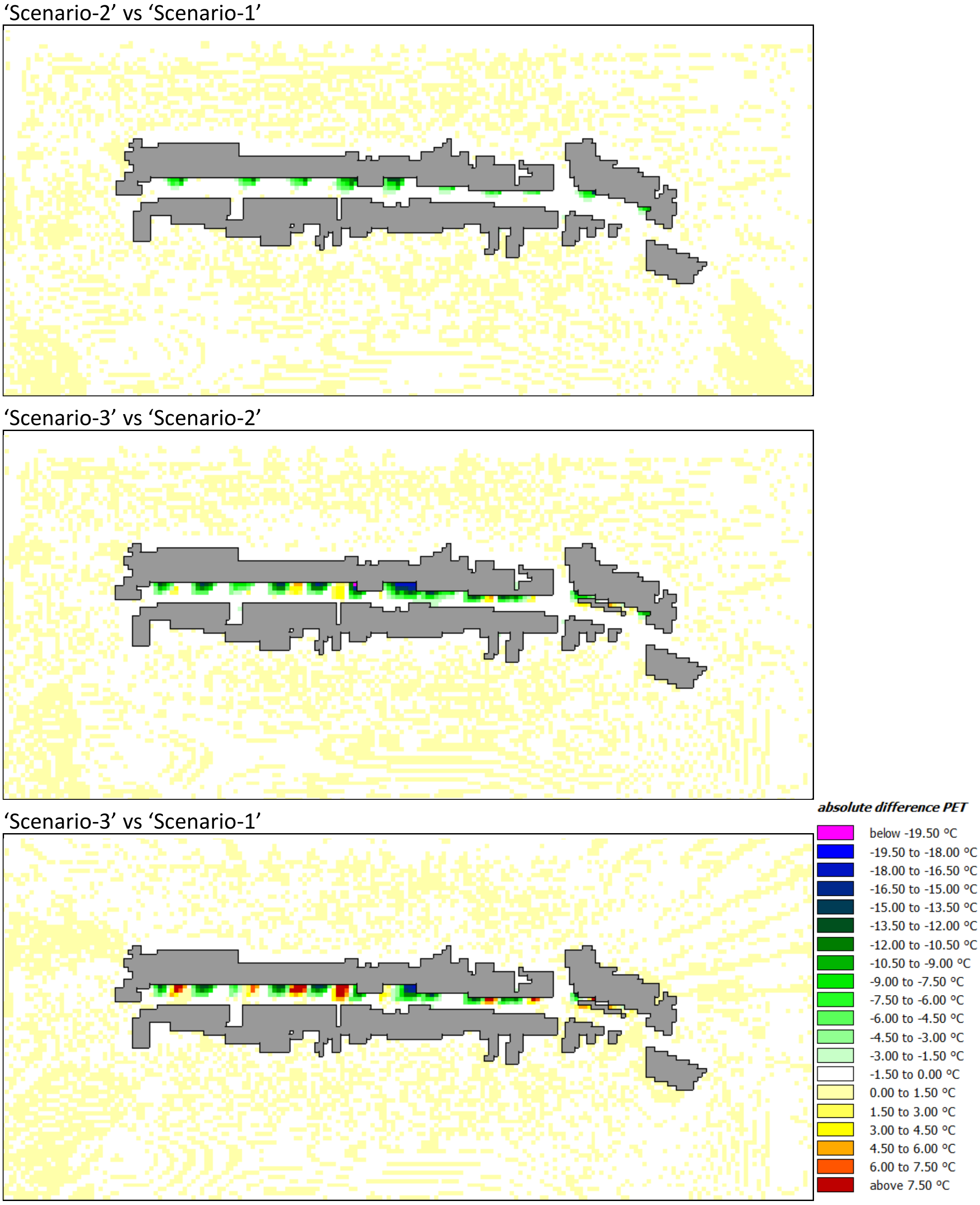

Figure 19: Daytime comparison between 'Scenarios'

Table 11, below, provides an overview of the different customed 'Datalayer Legend' settings employed.

Type of plan	Moment	'First value in legend'	'Step size/Class width'	'Number of colors/classes'
simulation-resulting PET (**Table 10**)	both (**Figure 14** and **Figure 15**)	9.00	2.00	20
comparison: scenarios vs existing	daytime (**Figure 16**)	-18.00	1.00	20
	night-time (**Figure 17**)	-2.50	0.25	18
comparison between scenarios	daytime (**Figure 19**)	-21.00	1.50	20
	night-time (**Figure 18**)	-2.50	0.25	18

Table 11: Overview of the customed 'Datalayer Legend' settings

7. Discussion of results

Four operational/methodological issues while using ENVI-met V5.0.2 have been identified: long simulation-processing times; possible limitation on green-pergola modulation; unexpectedly mild night-time results; possible limitations of dichotomous soil-irrigation settings.Simulation-processing times is an often-reported issue in literature (Jamei et al. 2019; Jänicke, Milošević, and Manavvi 2021; Mirzaei and Haghighat 2010) and is still a major obstacle for an exponential increase in simulation-runs that could compare the enormous number of possible combinations of settings and modulation approaches. For instances, in a previous attempt – using the same computer as in the present-study (**Table 12**) – to run a much bigger and complex model (**Figure 20**) on a much more intensive simulation setting (**Table 13**), the system estimated to take over a year to conclude processing – a single model-run. Hence, the present-study's simulations were simplified but, each model-run still took over 50 hours.

Computer specifications	
CPU	Intel Core i7-8700 CPU @ 3.20 GHz
GPU	Intel UHD Graphics 630
Installed RAM	16 GB
System type	64-bit operating system, x64-based processor
Operating system	Windows 11 Pro / version 22H2

Table 12: Specifications of the computer used to run the simulations

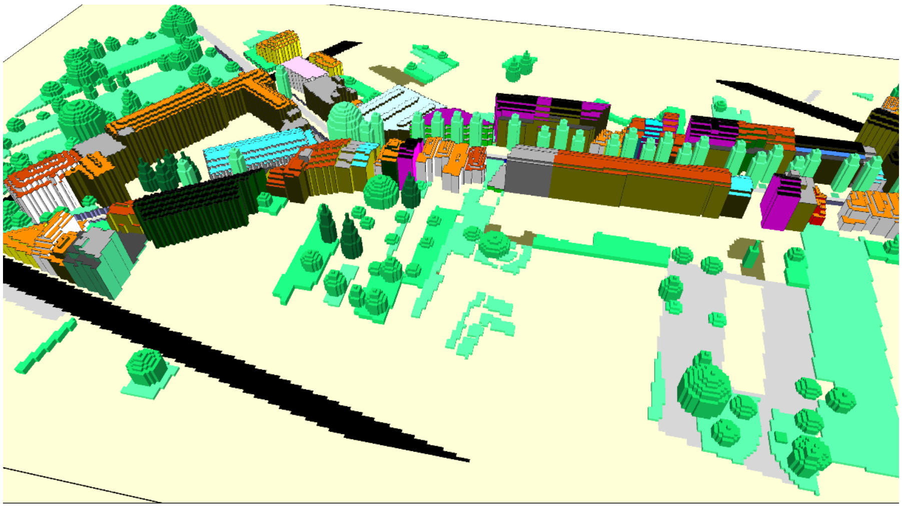

Figure 20: 3D visualization of a much more complex model in ENVI-met's 'Spaces' v5.0.3
'Grid cell size': 1 x 1 x 1 m
'Model dimensions': 308 x 531 x 36 grid cells
Source: adapted from 'Google Earth' and Porto City Council

'general setting'	
'total simulation time'	*360h*
'radiation settings'	
'ray tracing and IVS height cap'	
'raytracing precision'	*'finer resolution'*
'use height cap for adjusting raytracing (and IVS) precision?'	*yes*
'height cap in meters above ground below which higher precision is used'	*5*
'use IVS module?'	*yes*
'resolution for height segment angles'	*'medium (15º)'*
'resolution for azimuthal segment angles'	*'medium (15º)'*

Table 13: Differing settings of the simulation file used on a previous attempt

The results around the green pergola in 'Scenario-3' are counter-intuitive. For instances, the space between it and the northern building is where, by far, the most significant positive-difference in a daytime-existing comparison is predicted – up to 5.68 while the maximum positive-difference predicted for both other 'Scenarios' is 0.60 (**Figure 16**). Overall, this green pergola appears to worsen the thermal comfort in its immediate vicinity – at its western end, there is a significant negative-difference which we attribute to the presence of the tree also present in 'Scenario-2'. Why would a green pergola with clearance to all buildings worsens the daytime-pedestrian-thermal comfort? As for the night-time-existing-comparison results (**Figure 17**), it is curious to note that, while its southern side predicts the strongest positive-difference of all 'Scenarios' – up to 1.84 against 0.66 and 1.07 in 'Scenario-1' and *2*'s, respectively –, its northern side predicts the strongest negative – down to -2.24 against -1.10 and -1.15 in 'Scenario-1' and *2*'s, respectively. Perhaps the clearest evidence is revealed in 'Scenario-3' comparison with 'Scenario-2' as, in this part of the model, they are only distinguishable by the presence or absence of the green pergola. Daytime comparison reveals a predominance of positive-differences, except for a surprisingly strong negative-difference at its western end – where both 'Scenarios' share the same tree (**Figure 19**). Night-time comparison indicates that the most significant differences, in the whole 'Model Domain', are located around the green pergola. Even more than those in areas that differ in the presence or absence of a tree – up to 1.70 and down to -2.00 around the green pergola against up to 1.25 and down to -1.25 in the rest of the 'Model Domain' (**Figure 18**).

These unexpected results around the green pergola may be due to how it was modelled. Note that, in order to be able to include vegetation over it, this was modelled as a building – using 'Wall/Roof Constructions' –, instead of a horizontal 'Single Walls' (6.2.4 and 6.2.1). Perhaps, its 'walls of air' and steel-wire-trellis' roof are not permeable to the air flow and do trap the volume of air within its roof, walls and the whole inside-building's volume – such as a transparent bouncy castle. Nevertheless, testing an alternate green-pergola modulation approach is required to adequately conclude whether it is a software limitation.

As for the overall night-time results (**Figure 15**), these seem surprisingly mild – the great majority of which being within the range of the 'comfortable thermal perception' and the 'no thermal physiological stress' grades (**Table 10**) –, particularly when considering the apparently hot conditions for that moment (**Table 14**).

Parameter	Value
Date	15.07.2006
Time	01:00
Absolute air temperature	299.7 K (26.55 °C)
Relative Humidity	47 %
Windspeed	1.1 m/s
Wind direction	183 °
Precipitation	0.0 mm

Table 14: Input meteorological data for the night-time-analysis moment

Source: IPMA

Without a proper model validation, one cannot be sure whether these results are faithful to reality. Having said that, if the results are accurate, it appears to suggest that an unusually hot night for Porto standards isn't necessarily perceived as 'uncomfortable'. It does depend on what is the Porto-July-night's standard.

In the one hand, if this is the case and given that this specific month in the Porto region revealed a mortality and respiratory-morbidity excess – respectively, 52% and 49 % (Monteiro et al. 2013) – which may have partially been due to high night-time-temperatures (Murage, Hajat, and Kovats 2017), an outdoors' 'comfortable' or 'no-stress' grade may not have been enough to avoid the negative impacts on people's health indoors – considering that people sleep indoors.

In the other hand, if the results are inaccurate, this can possibly be due to the mean-radiant-temperature values used to calculate PET which, given the absence of shortwave-radiation during night-time, are restricted to the longwave-radiation values. This longwave radiation is intimately related with the objects' properties and the amount of heat these have absorbed which, in its turn, might very well be dependent on the heat-exposure-time length (Oke et al. 2017) and/or the materials' own thermal properties configuration. Note that the simulation only ran for 48 hours and materials, such as stone, can take a very long time to warm up and cool down – depending on its thermal properties. Perhaps, the simulated temperature of most objects at the moment of analysis was significantly lower than those that would have actually been in reality and, therefore, resulted in the overall reduction of the longwave-radiation intensity and the PET's values and spatial-differentiation. Given the model being a street canyon, another explanation might be related to ventilation parameters – windspeed and wind direction – which, beyond windspeed being one of the parameters considered in PET, can intensify the objects' cooling rate.

At last, an observation should be noted regarding the dichotomous soil-irrigation settings. Although this present study is not particularly focused on the soil's water content and the overall water cycle, the availability of water to vegetations does impact the plants' capacity/efficiency on cooling and the soil's water content does influence the soil's climatic behaviour (Broadbent et al. 2018). Furthermore, recent forecasts and observations suggest a rise in duration, frequency and intensity of heat waves together with its increasing association with droughts (IPMA 2022; CMP 2016). The true-false irrigation setting seems to disregard irrigation rates and only cover whether to ensure vegetation's access to water (ENVI-met 2019). For instances, a garden's automatic-irrigation system in a drought scenario may not provide adequate watering to ensure all plants' unrestricted access to water – it may depend, beyond other factors, on the irrigation rate and frequency. How would ENVI-met distinguish soil's different irrigation regimes in a drought-scenario simulation?

8. Final remarks

Although current ENVI-met still requires some effort to accurately configure and validate (Shinzato et al. 2019; Jamei et al. 2019; Liu et al. 2021; Lam et al. 2021), this study confirms the possibility to adopt it as a design tool, as it can integrate, with relative ease, a CAD-format-work environment that, apparently, is still common at design stages.

Green-pergola-modulation trial reveals a possible significant ENVI-met limitation. Night-time mild-looking results may indicate a modulation-error and/or that 'comfortable' outdoors' thermal conditions do not ensure 'healthy' indoors conditions. It is then observed that ENVI-met appears not to differentiate soil-irrigation rates.

The major limitation of this study is its non-validated model which imposes prudence when interpreting results – as the night-time-results discussion shows. Nevertheless, other here-described observations, such as those regarding processing times, soil-irrigation settings and green-pergola modulation, are much less susceptible to model-validation uncertainty and therefore, objective.

Future studies should, at least, include some sort of model-validation in order to reduce uncertainty. Longer simulations may also clarify some reservations and better reveal eventual impacts of the dichotomous soil-irrigation setting. Running an alternative to 'Scenario-3' substituting the green pergola with a horizontal 'Single Walls' should help confirm our hypothesis regarding the counter-intuitive results around the green pergola.

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Appendix A: Field Survey Reference Plan

Source: adapted from Porto City Council

Appendix B: Field Survey - Buildings and Single Walls – Wall/Roof Constructions and Single Walls correspondence

Field Survey					Wall/Roof Constructions (Appendix H) / Single Walls (Appendix I)							
					Composition (Appendices E and F)							
					Outside		Middle		Inside			
plan-referenced ID (Appendix A)		location	description	Albedo - α	Database-ID	Thickness (m)	Database-ID	Thickness (m)	Database-ID	Thickness (m)	Database-ID	Thickness (m)
m01		wall	**white painted stone** / height: 1.82 m (considered 2 m for ENVI-met)	0.29	MAPE29	0.3					**SWPE29**	0.3
1		façade	stone + **white painted render**	1	MARE95	0.02	MAPE95	0.2	MAPE95	0.2	**PERE95**	0.42
		roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
2		façade	stone + **white painted render**	1	MARE95	0.02	MAPE95	0.2	MAPE95	0.2	**PERE95**	0.42
		roof	**concrete** (assuming α = soil cover I)	**0.19**	MABE95	0.07	MABE95	0.07	MABE95	0.07	**BEBE19**	0.21
3		façade	brick + **grey painted render**	0.32	MARE32	0.02	0100B1	0.15	0100B1	0.15	**TJRE32**	0.32
		roof	**steel** (assuming α = 0100ST of System DB)	**0.8**	MAAC80	0	MAAC80	0	MAAC80	0	**ACAC80**	0
m02		wall	**stone** / height: 2.4 m (considered 2 m for ENVI-met)	0.47	MAPE47	0.3					**SWPE47**	0.3
4		wall	concrete + 6cm insulation + **stone** (assuming α = m02)	**0.47**	MARE47	0.3	MAIPIP	0.06	MABE95	0.2	**BIPE47**	0.56
		volume	concrete + 6cm insulation + **brown tile cladding**	0.15	MAAZ15	0.01	MAIPIP	0.06	MABE19	0.2	**BIAZ15**	0.27
5	A	façade	brick + 6 cm insulation + **yellow painted render**	0.9	MARE90	0.02	MAIPIP	0.06	0100B1	0.3	**TIRE90**	0.38
		terrace	concrete + **floor tiles** (assuming α = soil cover I)	**0.19**	MAAZ19	0.01	MABE95	0.1	MABE95	0.1	**BEAZ19**	0.21
	B	façade	brick + **yellow painted render**	0.7	MARE70	0.02	0100B1	0.15	0100B1	0.15	**TJRE70**	0.32
		terrace	concrete + **floor tiles** (assuming α = soil cover I)	**0.19**	MAAZ19	0.01	MABE95	0.1	MABE95	0.1	**BEAZ19**	0.21
	C	party wall	brick + air + **white coated steel**	0.97	MARE90	0.02	MAIPIP	0.06	0100B1	0.3	**TIRE90**	0.38
		roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MAAC95	0	010002.	0.02	0100B1	0.3	**TAAC95**	0.32
	D	façade	brick + **yellow painted render**	0.7	MARE70	0.02	0100B1	0.15	0100B1	0.15	**TJRE70**	0.32
		roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MAAC95	0	010002.	0.02	0100B1	0.3	**TAAC95**	0.32
6		façade	stone + **white painted render**	0.83	MARE83	0.02	MAPE95	0.2	MAPE95	0.2	**PERE83**	0.42
		roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
7		façade	stone + **grey painted render**	0.65	MARE65	0.02	MAPE95	0.2	MAPE95	0.2	**PERE65**	0.42
		roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
8		façade	brick + 6 cm insulation + **yellow painted render**	0.96	MARE95	0.02	MAIPIP	0.06	0100B1	0.3	**TIRE95**	0.38
		roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
9		façade	bricks + **orange tile cladding**	0.5	MAAZ50	0.01	0100B1	0.15	0100B1	0.15	**TJAZ50**	0.31

	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
10	façade	bricks + **orange tile cladding** (assuming α = façade 9)	**0.5**	MAAZ50	0.01	0100B1	0.15	0100B1	0.15	**TJAZ50**	0.31
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
m03	fence	**iron** / height: 2.3 m (considered 2 m for ENVI-met)	0.14	MAFE14	0					**SWFE14**	0
11	façade	bricks + **grey painted render**	0.32	MARE32	0.02	0100B1	0.15	0100B1	0.15	**TJRE32**	0.32
	roof	**steel** (assuming α = 0100ST of System DB)	**0.8**	MAAC80	0	MAAC80	0	MAAC80	0	**ACAC80**	0
12	façade	stone + **green tile cladding**	0.23	MAAZ23	0.01	MAPE95	0.2	MAPE95	0.2	**PEAZ23**	0.41
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
13	façade	brick + 6 cm insulation + **yellow painted render**	0.92	MARE92	0.02	MAIPIP	0.06	0100B1	0.3	**TIRE92**	0.38
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
14	façade	stone + **yellow painted render**	0.91	MARE91	0.02	MAPE95	0.2	MAPE95	0.2	**PERE91**	0.42
	roof	concrete + **asphaltic membrane** (assuming α = 0,10)	**0.1**	MATA10	0	MABE95	0.1	MABE95	0.1	**BETA10**	0.2
m04	wall	**stone** / height: 0.95 m (considered 1 m for ENVI-met)	0.11	MAPE11	0.3					**SWPE11**	0.3
15	façade	stone + **rose painted render**	0.93	MARE93	0.02	MAPE95	0.2	MAPE95	0.2	**PERE93**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
16	façade	brick + 6 cm insulation + **grey painted render**	0.48	MARE48	0.02	MAIPIP	0.06	0100B1	0.3	**TIRE48**	0.38
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
17	façade	bricks + **green painted render**	0.97	MARE95	0.02	0100B1	0.15	0100B1	0.15	**TJRE95**	0.32
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
18	façade	stone + **grey painted render**	0.49	MARE49	0.02	MAPE95	0.2	MAPE95	0.2	**PERE49**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
m05	wall	**white painted concrete blocks** / height: matching façade 18 (considered 3 m for ENVI-met)	0.54	MABB54	0.2					**SWBB54**	0.2
19	façade	bricks + **rose painted render**	0.94	MARE94	0.02	0100B1	0.15	0100B1	0.15	**TJRE94**	0.32
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
20	façade	bricks + **red tile cladding**	0.44	MAAZ44	0.01	0100B1	0.15	0100B1	0.15	**TJAZ44**	0.31
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
21	façade	stone + **white painted render**	0.85	MARE85	0.02	MAPE95	0.2	MAPE95	0.2	**PERE85**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
22	façade	bricks + **yellow painted render**	0.94	MARE94	0.02	0100B1	0.15	0100B1	0.15	**TJRE94**	0.32

		roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
23		façade	stone + **white painted render**	1	MARE95	0.02	MAPE95	0.2	MAPE95	0.2	**PERE95**	0.42
		roof	aluminium + 6 cm insulation + **terracota colour coated aluminium (**assuming α = 0100R2 of System DB)	**0.5**	MAAL50	0	MAIPIP	0.06	MAAL50	0	**AIAL50**	0.07
24		façade	stone + **green painted render**	0.58	MARE58	0.02	MAPE95	0.2	MAPE95	0.2	**PERE58**	0.42
		roof	aluminium + 6 cm insulation + **terracota colour coated aluminium (**assuming α = 0100R2 of System DB)	**0.5**	MAAL50	0	MAIPIP	0.06	MAAL50	0	**AIAL50**	0.07
25		façade	bricks + **beige tile cladding**	0.58	MAAZ58	0.01	0100B1	0.15	0100B1	0.15	**TJAZ58**	0.31
		roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
26		façade	brick + 6 cm insulation + **beige painted render**	0.91	MARE91	0.02	MAIPIP	0.06	0100B1	0.3	**TIRE91**	0.38
		roof	concrete + 6 cm insulation + **pebblestone** (assuming α = soil cover I)	**0.19**	MAPE19	0.02	MAIPIP	0.06	MABE19	0.2	**BIPE19**	0.28
27		façade	brick + 6 cm insulation + **beige painted render**	0.96	MARE95	0.02	MAIPIP	0.06	0100B1	0.3	**TIRE95**	0.38
		roof	concrete + 6 cm insulation + **pebblestone** (assuming α = soil cover I)	**0.19**	MAPE19	0.02	MAIPIP	0.06	MABE19	0.2	**BIPE19**	0.28
28		façade	stone + **terracota cladding**	0.16	MABA16	0.01	MAPE95	0.2	MAPE95	0.2	**PEBA16**	0.41
		roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
29		façade	bricks + **white painted render**	1	MARE95	0.02	0100B1	0.15	0100B1	0.15	**TJRE95**	0.32
		roof	concrete + 6 cm insulation + **pebblestone** (assuming α = soil cover I)	**0.19**	MAPE19	0.02	MAIPIP	0.06	MABE19	0.2	**BIPE19**	0.28
30		façade	stone + **white painted render**	1	MARE95	0.02	MAPE95	0.2	MAPE95	0.2	**PERE95**	0.42
		roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.19**	MAFCFC	0	MAILIL	0.05	MAMA67	0.02	**MIFCFC**	0.07
31		façade	stone + **white painted render**	1	MARE95	0.02	MAPE95	0.2	MAPE95	0.2	**PERE95**	0.42
		roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.19**	MAFCFC	0	MAILIL	0.05	MAMA67	0.02	**MIFCFC**	0.07
32		façade	stone + **white painted render**	1	MARE95	0.02	MAPE95	0.2	MAPE95	0.2	**PERE95**	0.42
		roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
33		façade	stone + **yellow painted render**	0.8	MARE80	0.02	MAPE95	0.2	MAPE95	0.2	**PERE80**	0.42
		roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
34	A	façade	bricks + **white painted render**	0.87	MARE87	0.02	0100B1	0.15	0100B1	0.15	**TJRE87**	0.32
		terrace	concrete + **floor tiles** (assuming α = soil cover I)	**0.19**	MAAZ19	0.01	MABE95	0.1	MABE95	0.1	**BEAZ19**	0.21
	B	party wall	stone + air + **steel** (assuming α = 0100ST of System DB)	**0.8**	MAAC80	0	010002.	0.02	MAPE95	0.4	**PAAC80**	0.42
		roof	concrete + 6 cm insulation + **fibre cement** (assuming α = soil cover I)	**0.19**	MAFCFC	0	MAIPIP	0.06	MABE19	0.2	**BIFCFC**	0.26
35		façade	stone + **tile cladding**	0.52	MAAZ52	0.01	MAPE95	0.2	MAPE95	0.2	**PEAZ52**	0.41
		roof	2 cm timber board + 5 cm rockwool + **fibre cement** (assuming α = soil cover I)	**0.19**	MAFCFC	0	MAILIL	0.05	MAMA67	0.02	**MIFCFC**	0.07
36		façade	stone + **yellow painted render**	0.67	MARE67	0.02	MAPE95	0.2	MAPE95	0.2	**PERE67**	0.42

	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
37	façade	stone + **yellow painted render** (assuming α = façade 36)	**0.67**	MARE67	0.02	MAPE95	0.2	MAPE95	0.2	**PERE67**	0.42
	roof	**concrete** (assuming α = soil cover I)	**0.19**	MABE95	0.07	MABE95	0.07	MABE95	0.07	**BEBE19**	0.21
38	façade	bricks + **yellow painted render**	0.72	MARE72	0.02	0100B1	0.15	0100B1	0.15	**TJRE72**	0.32
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
39	façade	bricks + **yellow painted render**	0.81	MARE81	0.02	0100B1	0.15	0100B1	0.15	**TJRE81**	0.32
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
40	façade	stone + **grey painted render**	0.49	MARE49	0.02	MAPE95	0.2	MAPE95	0.2	**PERE49**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
41	fachada	stone + **grey painted render** (assuming α = façade 40)	**0.49**	MARE49	0.02	MAPE95	0.2	MAPE95	0.2	**PERE49**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
m06	wall	**grey painted stone** (assuming α = façade 40) / height: match façade 41 (considered 4 m for ENVI-met)	**0.49**	MAPE49	0.3					**SWPE49**	0.3
42	façade	stone + **yellow painted render**	0.64	MARE64	0.02	MAPE95	0.2	MAPE95	0.2	**PERE64**	0.42
	roof	2 cm timber board + 5 cm rockwool + **fibre cement** (assuming α = soil cover I)	**0.19**	MAFCFC	0	MAILIL	0.05	MAMA67	0.02	**MIFCFC**	0.07
43	façade	stone + **white painted render**	0.9	MARE90	0.02	MAPE95	0.2	MAPE95	0.2	**PERE90**	0.42
	roof	2 cm timber board + 5 cm rockwool + **fibre cement** (assuming α = soil cover I)	**0.19**	MAFCFC	0	MAILIL	0.05	MAMA67	0.02	**MIFCFC**	0.07
44	façade	stone + **rose painted render**	0.2	MARE20	0.02	MAPE95	0.2	MAPE95	0.2	**PERE20**	0.42
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
45	façade	stone + **beige painted render**	0.29	MARE29	0.02	MAPE95	0.2	MAPE95	0.2	**PERE29**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
46		**UNDER CONSTRUCTION**									0
47	façade	bricks + **beige painted render** (assuming α = façade 05 A)	**0.9**	MARE90	0.02	0100B1	0.15	0100B1	0.15	**TJRE90**	0.32
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
48	façade	stone + **grey painted render**	0.56	MARE56	0.02	MAPE95	0.2	MAPE95	0.2	**PERE56**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
49	façade	stone + **rose painted render**	0.53	MARE53	0.02	MAPE95	0.2	MAPE95	0.2	**PERE53**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
m07	wall	**rose painted stone** / height: 2.3 m (considered 2 m for ENVI-met)	0.53	MAPE53	0.3					**SWPE53**	0.3

50	façade	bricks + **yellow painted render**	0.86	MARE86	0.02	0100B1	0.15	0100B1	0.15	**TJRE86**	0.32
	roof	**concrete** (assuming α = soil cover I)	**0.19**	MABE95	0.07	MABE95	0.07	MABE95	0.07	**BEBE19**	0.21
m08	wall	**grey painted stone** / height: 3.2 m (considered 3 m for ENVI-met)	0.59	MAPE59	0.3					**SWPE59**	0.3
51	façade	bricks + **tile cladding** (assuming α = façade 20)	**0.49**	MAAZ49	0.01	0100B1	0.15	0100B1	0.15	**TJAZ49**	0.31
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAIPIP	0.06	MABE19	0.2	**BIBA50**	0.31
52		**UNDER CONSTRUCTION**									0
m09	construction fence	**timber board** / height: 2 m	0.41	MAMA41	0.03					**SWMA41**	0.03
53	façade	stone + **grey painted render**	0.37	MARE37	0.02	MAPE95	0.2	MAPE95	0.2	**PERE37**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
54	façade	stone + **rose painted render**	0.7	MARE70	0.02	MAPE95	0.2	MAPE95	0.2	**PERE70**	0.42
	roof	2 cm timber board + 5 cm rockwool + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.5**	MABA50	0.05	MAILIL	0.05	MAMA67	0.02	**MIBA50**	0.12
m10	gate	**yellow painted iron** / height: 3 m	0.53	MAFE53	0					**SWFE53**	0
55	façade	brick + **green tile cladding**	0.16	MAAZ16	0.01	0100B1	0.15	0100B1	0.15	**TJAZ16**	0.31
	roof	concrete + 6 cm insulation + **terracota tiles** (assuming α = 0100R2 of System DB)	**0.19**	MAFCFC	0	MAIPIP	0.06	MABE19	0.2	**BIFCFC**	0.26

Appendix C: Field Survey – Soil-Cover Types – Soil Profiles and Simple Plants correspondence

Field Survey			Soil Profile (Appendix J)	Simple Plant
plan-referenced ID (Appendix A)	description	Albedo - α	Database-ID	Database-ID
A1	**natural soil** irrigated grass (assuming α = 0100SL of System DB)	**0.2**	**PVTEIR**	**0100XX**
A2	**natural soil** irrigated vegetable garden (assuming α = 0100SL of System DB)	**0.2**	**PVTEIR**	**0100SO**
B0	**natural soil** bare (assuming α = 0100SL of System DB)	**0.2**	**0100SL**	
B1	**natural soil** grass (assuming α = 0100SL of System DB)	**0.2**	**0100SL**	**0100XX**
C	11 cm **granite cobblestone**	0.08	**PVCU11**	
D	**concrete** (averaged α value between two samples, a newer and an older: 0,09 e 0,29)	0.19	**PVBE01**	
E	**tarmac**	0.14	**PVASAS**	

Appendix D: Field Survey + Proposed – 3D Plants – Database-ID correspondence

Field Survey				ENVI-met				further metrics			
		canopy		root							
plan-referenced ID (Appendix A)	notes / botanical species	width (m)	height (m)	width (m)	depth (m)	LAD (m_2/m_3)	Database-ID	tree canopy plan area (m^2)	total leaf gridcell volume (m^3)	total leaf area (m^2)	LAI (m^2/m^2)
a01	*Camellia japonica*	7	8	7	5	1.10	**DI0708**	38.47	94	103.4	2.69
a02		3	5	3	4	1.10	**DI0305**	7.065	26	28.6	4.05
a03	*Camellia japonica*	1	2	1	1	1.10	**DI0102**	0.785	2	2.2	2.80
Proposed trees											
Prunus cerasifera J. F. Ehrch. cv. ***"Pissardii"***		5	6	5	4	0.27	**CB0506**	19.6	56	15.12	0.77
Fagus sylvatica L. cv. ***"Dawyck Purple"***		5	20	5	15	0.38	**CB0520**	19.6	294	111.7	5.70

Appendix E: Wall/Roof Materials – database-ID listing with differing parameters

database-ID	(Appendix F) description Wall/Roof Materials	Default thickness (m)	Absorption	Transmission	Reflection (≈Albedo)
0100B1	*"Brick: aerated" from System Database*	*0.3*	*0.6*	*0*	*0.4*
0100O2	*"Air" from System Database*	*0.01*	*0*	*1*	*0*
MAAC80	Steel	0.003	0.2	0	0.8
MAAC95	Steel	0.003	0.05	0	0.95
MAACRA	Steel Wire	0.004	0.001	0.994	0.005
MAAL50	Aluminium	0.1	0.5	0	0.5
MAAZ15	Ceramic Tile	0.006	0.85	0	0.15
MAAZ16	Ceramic Tile	0.006	0.84	0	0.16
MAAZ19	Ceramic Tile	0.006	0.81	0	0.19
MAAZ23	Ceramic Tile	0.006	0.77	0	0.23
MAAZ44	Ceramic Tile	0.006	0.56	0	0.44
MAAZ49	Ceramic Tile	0.006	0.51	0	0.49
MAAZ50	Ceramic Tile	0.006	0.5	0	0.5
MAAZ52	Ceramic Tile	0.006	0.48	0	0.52
MAAZ58	Ceramic Tile	0.006	0.42	0	0.58
MABA50	Terracota Tile	0.05	0.5	0	0.5
MABB54	Concrete Blocks	0.2	0.46	0	0.54
MABE19	Concrete	0.3	0.81	0	0.19
MABE95	Concrete	0.3	0.05	0	0.95
MAFCFC	Fibre Cement	0.003	0.81	0	0.19
MAFE14	Iron	0.003	0.86	0	0.14
MAFE53	Iron	0.003	0.47	0	0.53
MAILIL	Insulation - Rockwool	0.05	0.5	0	0.5
MAIPIP	Insulation - Polystyrene	0.06	0.5	0	0.5
MAMA67	Timber - Pine	0.03	0.33	0	0.67
MAPE11	Stone - Granite	0.3	0.89	0	0.11
MAPE19	Stone - Granite	0.3	0.81	0	0.19
MAPE29	Stone - Granite	0.3	0.71	0	0.29

MAPE47	Stone - Granite	0.3	0.53	0	0.47
MAPE49	Stone - Granite	0.3	0.51	0	0.49
MAPE53	Stone - Granite	0.3	0.47	0	0.53
MAPE59	Stone - Granite	0.3	0.41	0	0.59
MAPE95	Stone - Granite	0.3	0.05	0	0.95
MARE20	Cement Render	0.02	0.8	0	0.2
MARE29	Cement Render	0.02	0.71	0	0.29
MARE32	Cement Render	0.02	0.68	0	0.32
MARE37	Cement Render	0.02	0.63	0	0.37
MARE48	Cement Render	0.02	0.52	0	0.48
MARE49	Cement Render	0.02	0.51	0	0.49
MARE53	Cement Render	0.02	0.47	0	0.53
MARE56	Cement Render	0.02	0.44	0	0.56
MARE58	Cement Render	0.02	0.42	0	0.58
MARE64	Cement Render	0.02	0.36	0	0.64
MARE65	Cement Render	0.02	0.35	0	0.65
MARE67	Cement Render	0.02	0.33	0	0.67
MARE70	Cement Render	0.02	0.3	0	0.7
MARE72	Cement Render	0.02	0.28	0	0.72
MARE80	Cement Render	0.02	0.2	0	0.8
MARE81	Cement Render	0.02	0.19	0	0.81
MARE83	Cement Render	0.02	0.17	0	0.83
MARE85	Cement Render	0.02	0.15	0	0.85
MARE86	Cement Render	0.02	0.14	0	0.86
MARE87	Cement Render	0.02	0.13	0	0.87
MARE90	Cement Render	0.02	0.1	0	0.9
MARE91	Cement Render	0.02	0.09	0	0.91
MARE92	Cement Render	0.02	0.08	0	0.92
MARE93	Cement Render	0.02	0.07	0	0.93
MARE94	Cement Render	0.02	0.06	0	0.94
MARE95	Cement Render	0.02	0.05	0	0.95
MATA10	Asphaltic Membrane	0.003	0.9	0	0.1

Appendix F: Wall/Roof Materials – remaining-parameter assumptions

(Appendix E) **Description**	**Emissivity** – *ε* (-)	**Specific heat** – *c* (J/[kg*K])	**Thermal Conductivity** – *k* (W/[m*K])	**Density** (kg/m^3)
Aluminium	0.18	880	203	2700[1]
Asphaltic Membrane	0.93[2]	920[3]	1.26[4]	1020[5]
Cement Render	0.54[6]	920[7]	1.1[8]	1506[9]
Ceramic Tile	0.97[10]	1085[11]	0.84[12]	2158[13]
Concrete	0.85[14]	880[15]	1.4[16]	2300[17]
Concrete Block	0.63[18]	880[19]	0.55[20]	900[21]
Fibre Cement	0.96[22]	816[23]	0.13[24]	1600[25]
Insulation - polystyrene	0.9[26]	1400[27]	0.035[28]	31.5[29]
Insulation - Rockwool	0.9[30]	1030	0.039	160[31]
Iron	0.25	530	72	7900[32]
Steel	0.1	420	45	8000[33]
Steel Wire[34]	0.96	1003	0.295	49.197
Stone - Granite	0.96[35]	790[36]	4.61[37]	2691[38]
Terracota Tile	0.9	840	0.81	1700[39]
Timber - Pine	0.89[40]	1500[41]	0.15[42]	424.5[43]

[1] Transposed from the values of 0100AL from System Database

[2] Assumed the value for "*Asphalt*" in (ToolBox 2022a)

[3] Assumed the value for "*Asphalt concrete (with aggregate)*" in (ToolBox 2022b)

[4] Assumed the value for "*Asphalt*" in (Carvill 1993)

[5] Assumed the value for "*Built-up Roofing Asphalt, Type III*" in (AVCALC 2022)

[6] Assumed the value for "*Cement*" in (ToolBox 2022a)

[7] Transposed from the values of 0100C2 from System Database

[8] Assumed the value for "*Cement*" in (Carvill 1993)

[9] Assumed the value for "*Cement, Portland*" in (AVCALC 2022)

[10] Assumed the value for "*Tile*" in (ToolBox 2022a)

[11] Assumed the value for "*Porcelain*" in (ToolBox 2022b)

[12] Assumed the value for "*Porcelain*" in (Carvill 1993);

[13] Assumed the value for "*porcelanato vidrado - Nova Arquitectura*" by Cinca, extrapolating its announced technical properties in (Cinca 2017)

[14] Assumed the value for "*Concrete*" in (ToolBox 2022a)

[15] Assumed the value for “*Concrete*” in (ToolBox 2022a)

[16] Assumed the average value for “*Concrete: dense*” in (Carvill 1993)

[17] Assumed the value for “*Concrete, Portland*” in (AVCALC 2022)

[18] Assumed the value for “*Concrete tiles*” in (ToolBox 2022a)

[19] Assumed the value for “*Concrete*” in (ToolBox 2022a)

[20] Assumed the average value for “*Concrete: medium*” in (Carvill 1993)

[21] Assumed an extrapolation from the weight of a 50 x 20 x 20 cm concrete block in (PAVICER 2014)

[22] Assumed the value for “*Asbestos board*” in (ToolBox 2022a)

[23] Assumed the value for “*Asbestos*” in (ToolBox 2022b)

[24] Assumed the value for “*Asbestos cloth*” in (Carvill 1993)

[25] Assumed the value for “*Asbestos, rock*” in (AVCALC 2022)

[26] Transposed from the values of 0100IN from System Database

[27] Assumed the value for “*Polystyrene*” in (ToolBox 2022b)

[28] Assumed the average value indicated for “*expanded polystyrene*” in (Carvill 1993)

[29] Assumed the average value for “*Polystyrene Expanded*” & “*Polystyrene Extruded*” in (AVCALC 2022)

[30] Transposed from the values of 0100IN from System Database

[31] Assumed the values indicated in (Baubook)

[32] Transposed from the values of 0100IR from System Database

[33] Transposed from the values of 0100ST from System Database

[34] Assuming 4 mm thick steel wires – assuming values of 0100ST from System Database – separated by air – assuming values of 0100O2 from System Database –, we have established two wires in one direction (x) and one wire in perpendicular to those (y). This corresponds to a 0.006 fraction for the values for steel and 0.994 for the values for air.

[35] Assumed the value for “*Granite, natural surface*” in (ToolBox 2022a)

[36] Assumed the value for “*Granite*” in (ToolBox 2022b)

[37] Transposed from the value of *“heat Conductivity”* in 0000GR from System Database

[38] Assumed the value for “*Granite, solid*” in (AVCALC 2022)

[39] Transposed from the values of 0100R2 from System Database

[40] Assumed the value for “*Oak, planed*” in (ToolBox 2022a)

[41] Assumed the value for “*Timber, white pine*” in (ToolBox 2022b)

[42] Assumed the average value for “*Wood*” in (Carvill 1993)

[43] Assumed the average value for “*Pine, white*” in ("Wood Density Chart")

Appendix G: Soil/Ground Materials

description	database-ID	typ of material	water content at saturation	water content at field capacity	water content at wilting point	Matrix potential	Hydraulic conductivity	volumetric heat capacity	Clapp & Hornberger constant b	heat conductivity	composing fractions: Sand	Loam	Sandy Clay Loam	Smashed brick	Cement Concrete	Asphalt (with Gravel	Granite
11 cm granite cobblestone	CUBO11	NS	0.1193	0.0724	0.0497	-0.0849	1.7892	2.0127	2.0221	3.3008	0	0	0.284	0	0	0	0.716
gravel-soil transition (2-8)	TRAG28	NS	0.427	0.183	0.0926	-0.1986	62.48	1.456	4.73	0	0	0.8	0	0.2	0	0	0
gravel-soil transition (3-7)	TRAG37	NS	0.423	0.177	0.0818	-0.1889	76.67	1.524	4.645	0	0	0.7	0	0.3	0	0	0
gravel-soil transition (5-5)	TRAG55	NS	0.415	0.165	0.0604	-0.1695	105.05	1.66	4.475	0	0	0.5	0	0.5	0	0	0
gravel-soil transition (7-3)	TRAG73	NS	0.407	0.153	0.0390	-0.1501	133.43	1.796	4.305	0	0	0.3	0	0.7	0	0	0
concrete-gravel transition (2-8)	TRBE28	NS	0.316	0.108	0.0054	-0.0968	140.8	2.0166	3.24	0.326	0	0	0	0.8	0.2	0	0
concrete-gravel transition (5-5)	TRBE55	NS	0.1975	0.0675	0.0034	-0.0605	88	2.0415	2.025	0.815	0	0	0	0.5	0.5	0	0
concrete-gravel transition (7-3)	TRBE73	NS	0.1185	0.0405	0.0020	-0.0363	52.8	2.0581	1.215	1.141	0	0	0	0.3	0.7	0	0
cobblestone-sand-gravel transition	TRCUBO	NS	0.3674	0.1287	0.0111	-0.1174	158.5789	1.7865	3.8472	0.3301	0.4	0	0.0284	0.5	0	0	0.0716
Sand	0000SD	NS	0.395	0.135	0.0068	-0.121	176	1.463	4.05	0	1						
Sandy Loam	0000SL	NS	0.435	0.195	0.114	-0.218	34.1	1.32	4.9	0		1					
Sandy Clay Loam	0000TS	NS	0.42	0.255	0.175	-0.299	6.3	1.175	7.12	0			1				
Smashed brick	0000BS	NS	0.395	0.135	0.0068	-0.121	176	2	4.05	0				1			
Cement Concrete	0000ZB	AM	0	0	0	0	0	2.083	0	1.63					1		
Asphalt (with Basalt	0000AB	AM	0	0	0	0	0	2.251	0	0.9						1	
Granite	0000GR	AM	0	0	0	0	0	2.345	0	4.61							1

Appendix H: Wall/Roof Constructions

database-ID	description Wall/Roof Constructions	thickness (m)	Composition (Appendices E and F)					
			outside		middle		inside	
			database-ID	thickness (m)	database-ID	thickness (m)	database-ID	thickness (m)
ACAC80	single steel sheet	0.003	MAAC80	0.001	MAAC80	0.001	MAAC80	0.001
ACACRA	steel wire trellis (for pergola)	0.004	MAACRA	0.001	MAACRA	0.002	MAACRA	0.001
AIAL50	insulated aluminium sandwich panelling	0.066	MAAL50	0.003	MAIPIP	0.06	MAAL50	0.003
ARARAR	air (for pergola)	0.3	0100O2	0.1	0100O2	0.1	0100O2	0.1
BEAZ19	tiles on concrete substrate	0.206	MAAZ19	0.006	MABE95	0.1	MABE95	0.1
BEBE19	exposed concrete substrate	0.21	MABE95	0.07	MABE95	0.07	MABE19	0.07
BETA10	asphaltic membrane on concrete substrate	0.23	MATA10	0.03	MABE95	0.1	MABE95	0.1
BIAZ15	tiles on insulated concrete substrate	0.266	MAAZ15	0.006	MAIPIP	0.06	MABE95	0.2
BIBA50	terracota tiles on insulated concrete substrate	0.31	MABA50	0.05	MAIPIP	0.06	MABE95	0.2
BIFCFC	fibre cement on insulated concrete substrate	0.263	MAFCFC	0.003	MAIPIP	0.06	MABE95	0.2
BIPE19	stone on insulated concrete substrate	0.28	MAPE19	0.02	MAIPIP	0.06	MABE95	0.2
BIPE47	stone on insulated concrete substrate	0.56	MAPE47	0.3	MAIPIP	0.06	MABE95	0.2
MIBA50	terracota tiles on insulated timber board substrate	0.12	MABA50	0.05	MAILIL	0.05	MAMA67	0.02
MIFCFC	fibre cement on insulated timber board substrate	0.073	MAFCFC	0.003	MAILIL	0.05	MAMA67	0.02
PAAC80	steel on stone substrate with air gap inbetweenin-between	0.423	MAAC80	0.003	0100O2	0.02	MAPE95	0.4
PEAZ23	tiles on stone substrate	0.406	MAAZ23	0.006	MAPE95	0.2	MAPE95	0.2
PEAZ52	tiles on stone substrate	0.406	MAAZ52	0.006	MAPE95	0.2	MAPE95	0.2
PEBA16	terracota tiles on stone substrate	0.406	MABA50	0.006	MAPE95	0.2	MAPE95	0.2
PERE20	rendered stone	0.42	MARE20	0.02	MAPE95	0.2	MAPE95	0.2
PERE29	rendered stone	0.42	MARE29	0.02	MAPE95	0.2	MAPE95	0.2
PERE37	rendered stone	0.42	MARE37	0.02	MAPE95	0.2	MAPE95	0.2
PERE49	rendered stone	0.42	MARE49	0.02	MAPE95	0.2	MAPE95	0.2
PERE53	rendered stone	0.42	MARE53	0.02	MAPE95	0.2	MAPE95	0.2
PERE56	rendered stone	0.42	MARE56	0.02	MAPE95	0.2	MAPE95	0.2
PERE58	rendered stone	0.42	MARE58	0.02	MAPE95	0.2	MAPE95	0.2

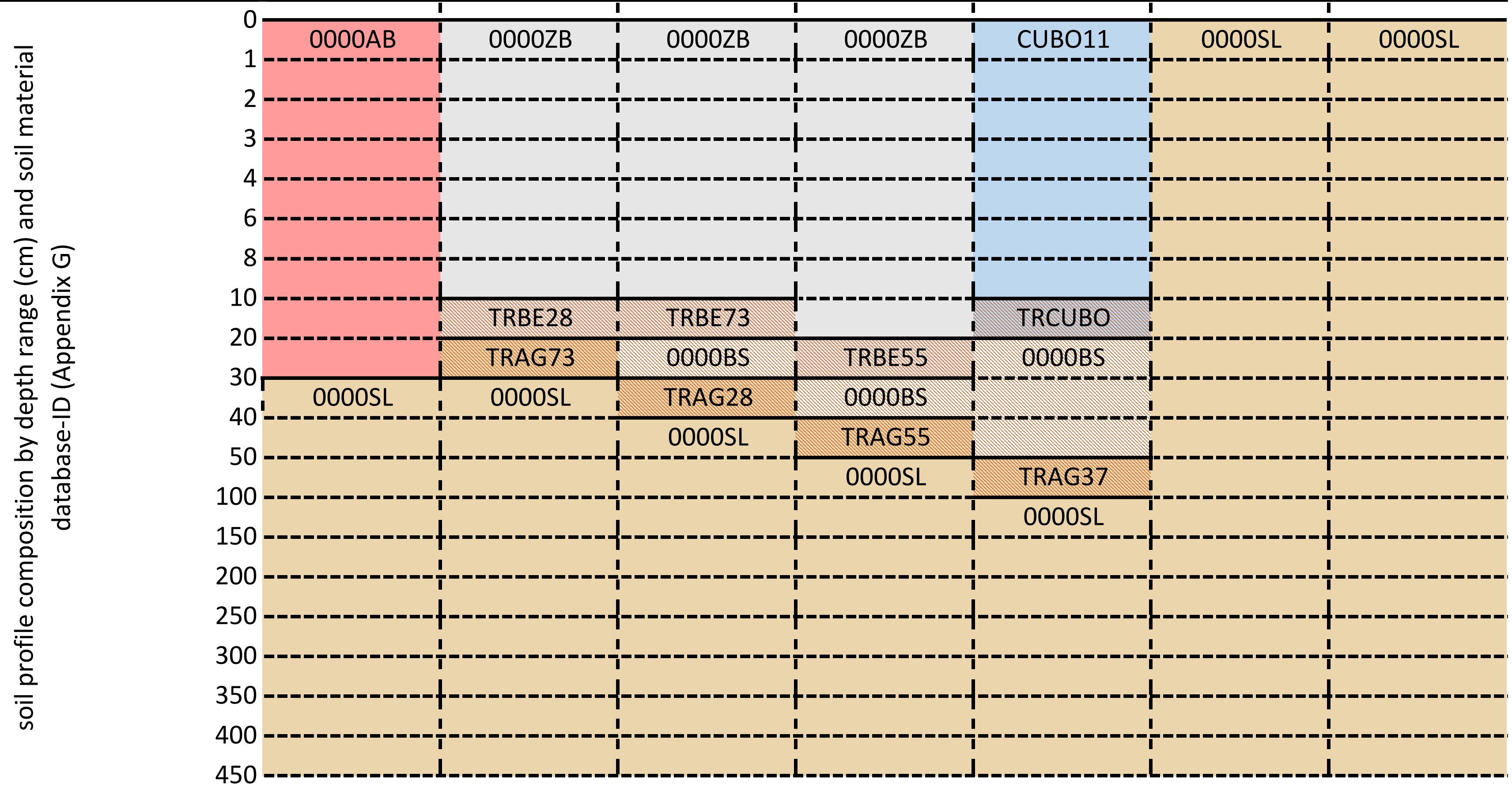
PERE64	rendered stone	0.42	MARE64	0.02	MAPE95	0.2	MAPE95	0.2
PERE65	rendered stone	0.42	MARE65	0.02	MAPE95	0.2	MAPE95	0.2
PERE67	rendered stone	0.42	MARE67	0.02	MAPE95	0.2	MAPE95	0.2
PERE70	rendered stone	0.42	MARE70	0.02	MAPE95	0.2	MAPE95	0.2
PERE80	rendered stone	0.42	MARE80	0.02	MAPE95	0.2	MAPE95	0.2
PERE83	rendered stone	0.42	MARE83	0.02	MAPE95	0.2	MAPE95	0.2
PERE85	rendered stone	0.42	MARE85	0.02	MAPE95	0.2	MAPE95	0.2
PERE90	rendered stone	0.42	MARE90	0.02	MAPE95	0.2	MAPE95	0.2
PERE91	rendered stone	0.42	MARE91	0.02	MAPE95	0.2	MAPE95	0.2
PERE93	rendered stone	0.42	MARE93	0.02	MAPE95	0.2	MAPE95	0.2
PERE95	rendered stone	0.42	MARE95	0.02	MAPE95	0.2	MAPE95	0.2
TAAC95	steel on brick substrate with air gap in-between	0.323	MAAC95	0.003	0100O2	0.02	0100B1	0.3
TIRE48	render on insulated brick substrate	0.38	MARE48	0.02	MAIPIP	0.06	0100B1	0.3
TIRE90	render on insulated brick substrate	0.38	MARE90	0.02	MAIPIP	0.06	0100B1	0.3
TIRE91	render on insulated brick substrate	0.38	MARE91	0.02	MAIPIP	0.06	0100B1	0.3
TIRE92	render on insulated brick substrate	0.38	MARE92	0.02	MAIPIP	0.06	0100B1	0.3
TIRE95	render on insulated brick substrate	0.38	MARE95	0.02	MAIPIP	0.06	0100B1	0.3
TJAZ16	tiles on brick substrate	0.306	MAAZ16	0.006	0100B1	0.15	0100B1	0.15
TJAZ44	tiles on brick substrate	0.306	MAAZ44	0.006	0100B1	0.15	0100B1	0.15
TJAZ49	tiles on brick substrate	0.306	MAAZ49	0.006	0100B1	0.15	0100B1	0.15
TJAZ50	tiles on brick substrate	0.306	MAAZ50	0.006	0100B1	0.15	0100B1	0.15
TJAZ58	tiles on brick substrate	0.306	MAAZ58	0.006	0100B1	0.15	0100B1	0.15
TJRE32	rendered brick	0.32	MARE32	0.02	0100B1	0.15	0100B1	0.15
TJRE70	rendered brick	0.32	MARE70	0.02	0100B1	0.15	0100B1	0.15
TJRE72	rendered brick	0.32	MARE72	0.02	0100B1	0.15	0100B1	0.15
TJRE81	rendered brick	0.32	MARE81	0.02	0100B1	0.15	0100B1	0.15
TJRE86	rendered brick	0.32	MARE86	0.02	0100B1	0.15	0100B1	0.15
TJRE87	rendered brick	0.32	MARE87	0.02	0100B1	0.15	0100B1	0.15
TJRE90	rendered brick	0.32	MARE90	0.02	0100B1	0.15	0100B1	0.15
TJRE94	rendered brick	0.32	MARE94	0.02	0100B1	0.15	0100B1	0.15
TJRE95	rendered brick	0.32	MARE95	0.02	0100B1	0.15	0100B1	0.15

Appendix I: Single Walls

database-ID	description Single Walls	thickness (m)	aerodynamic Roughness Length (m)	Material (Appendices E and F)
				database-ID
SWBB54	rendered concrete block	0.2	0.02	MABB54
SWFE14	iron	0.003	0.02	MAFE14
SWFE53	iron	0.003	0.02	MAFE53
SWMA41	timber	0.03	0.02	MAMA67
SWPE11	stone	0.3	0.02	MAPE11
SWPE29	stone	0.3	0.02	MAPE29
SWPE47	stone	0.3	0.02	MAPE47
SWPE49	stone	0.3	0.02	MAPE49
SWPE53	stone	0.3	0.02	MAPE53
SWPE59	stone	0.3	0.02	MAPE59

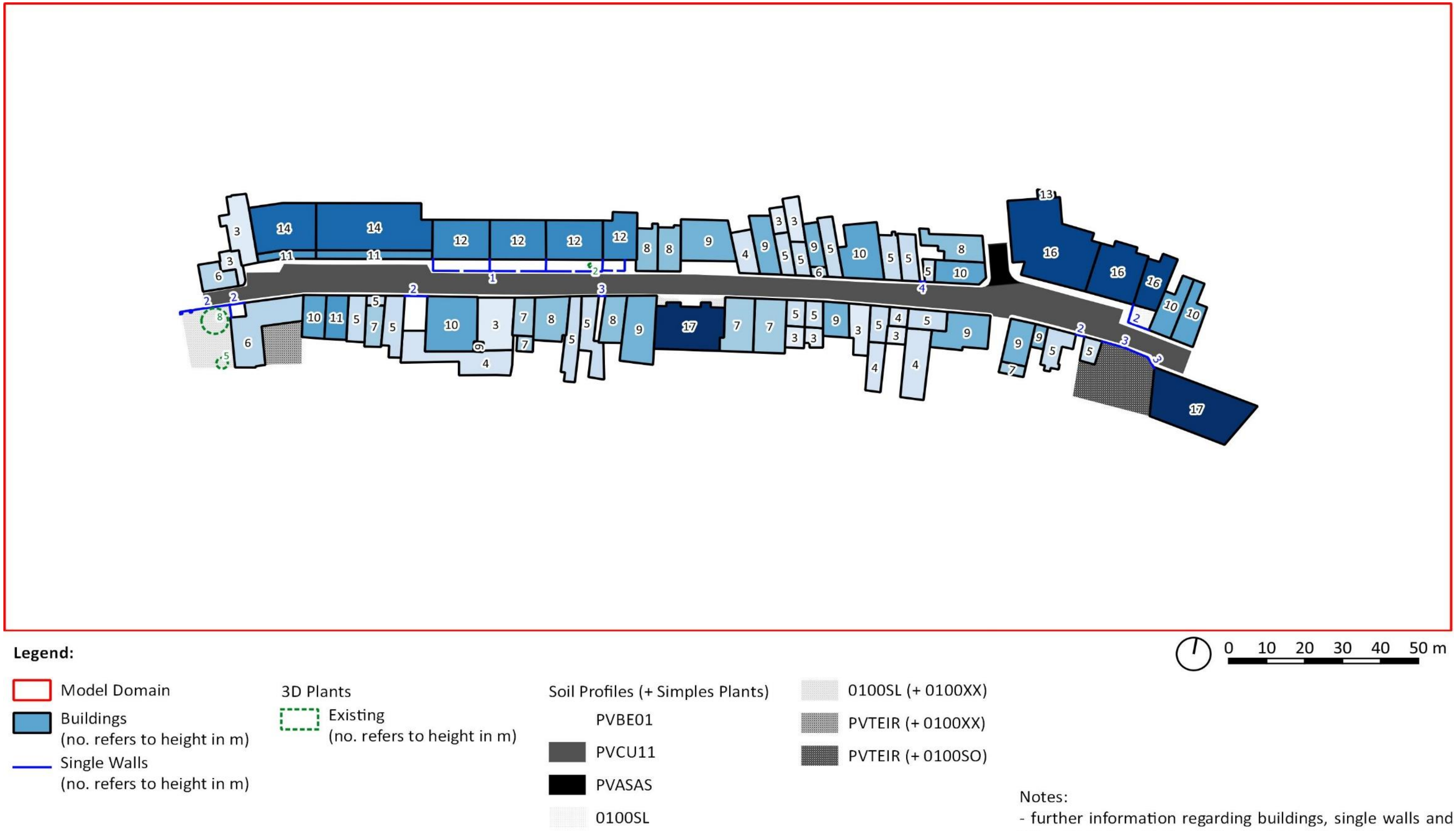
Appendix J: Soil Profiles

Soil Profiles	**tarmac**	**concrete - pedestrian use**	**concrete - mix use**	**concrete - vehicular use**	**11cm granite cobblestone**	**irrigated soil**	**default unsealed soil (sandy loam)**
Database-ID	**PVASAS**	**PVBE01**	**PVBE02**	**PVBE03**	**PVCU11**	**PVTEIR**	**0100SL**
Albedo - α	0.14	0.19	0.19	0.19	0.08	0.2	0.2
ε / Emissivity	0.93	0.85	0.85	0.85	0.96	0.98	0.98
Surface is irrigated	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE



Appendix K: Existing Plan

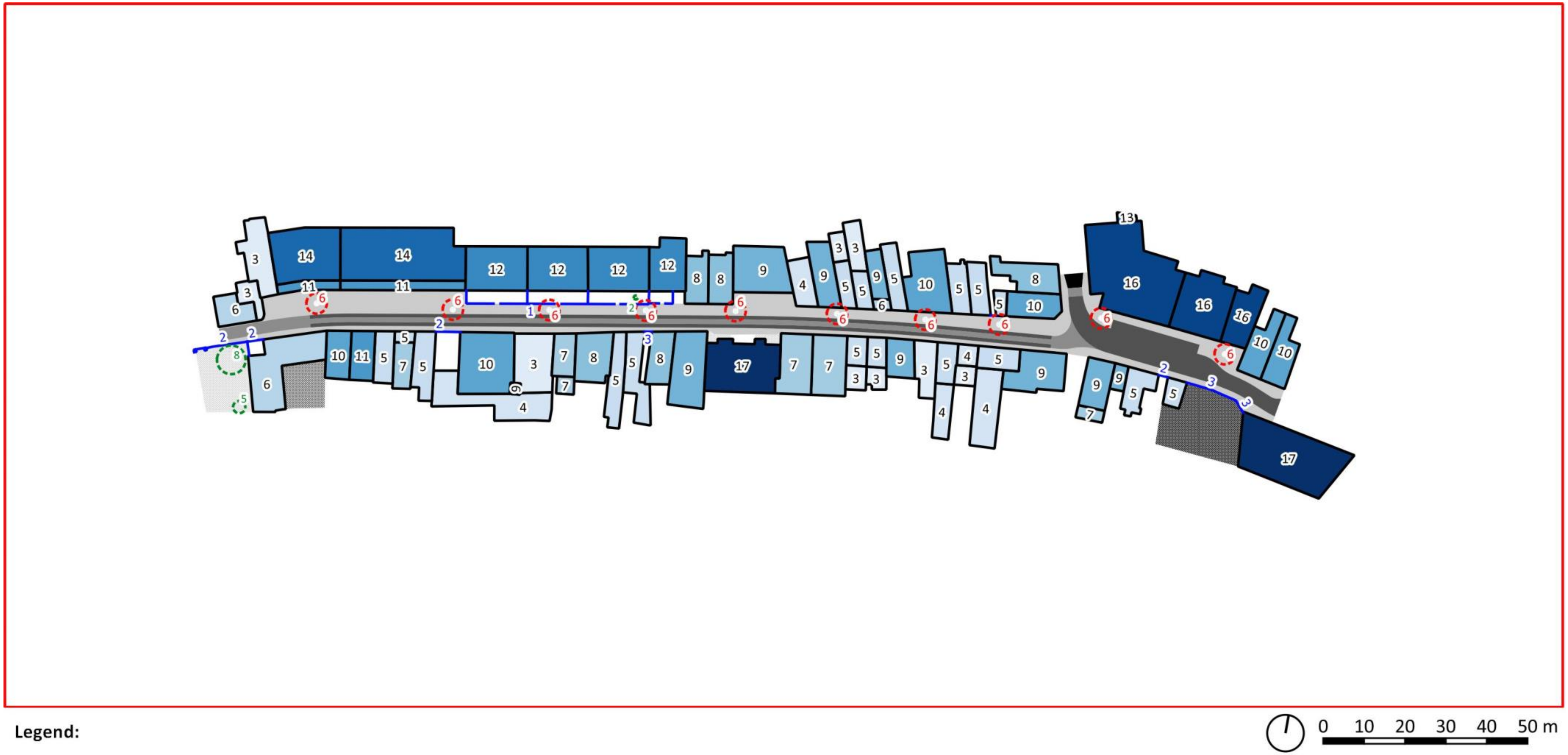
Source: adapted from Porto City Council



Notes:
- further information regarding buildings, single walls and 3D plants' database-ID, refer to field survey documentation;

Appendix L: Scenario-1 Plan

Source: adapted from Porto City Council



Legend:

Model Domain

Buildings
(no. refers to height in m)

Single Walls
(no. refers to height in m)

3D Plants

Existing
(no. refers to height in m)

CB0506
(no. refers to height in m)

Soil Profiles (+ Simples Plants)

PVBE01

PVBE02

PVBE03

PVCU11

PVASAS

0100SL

0100SL (+ 0100XX)

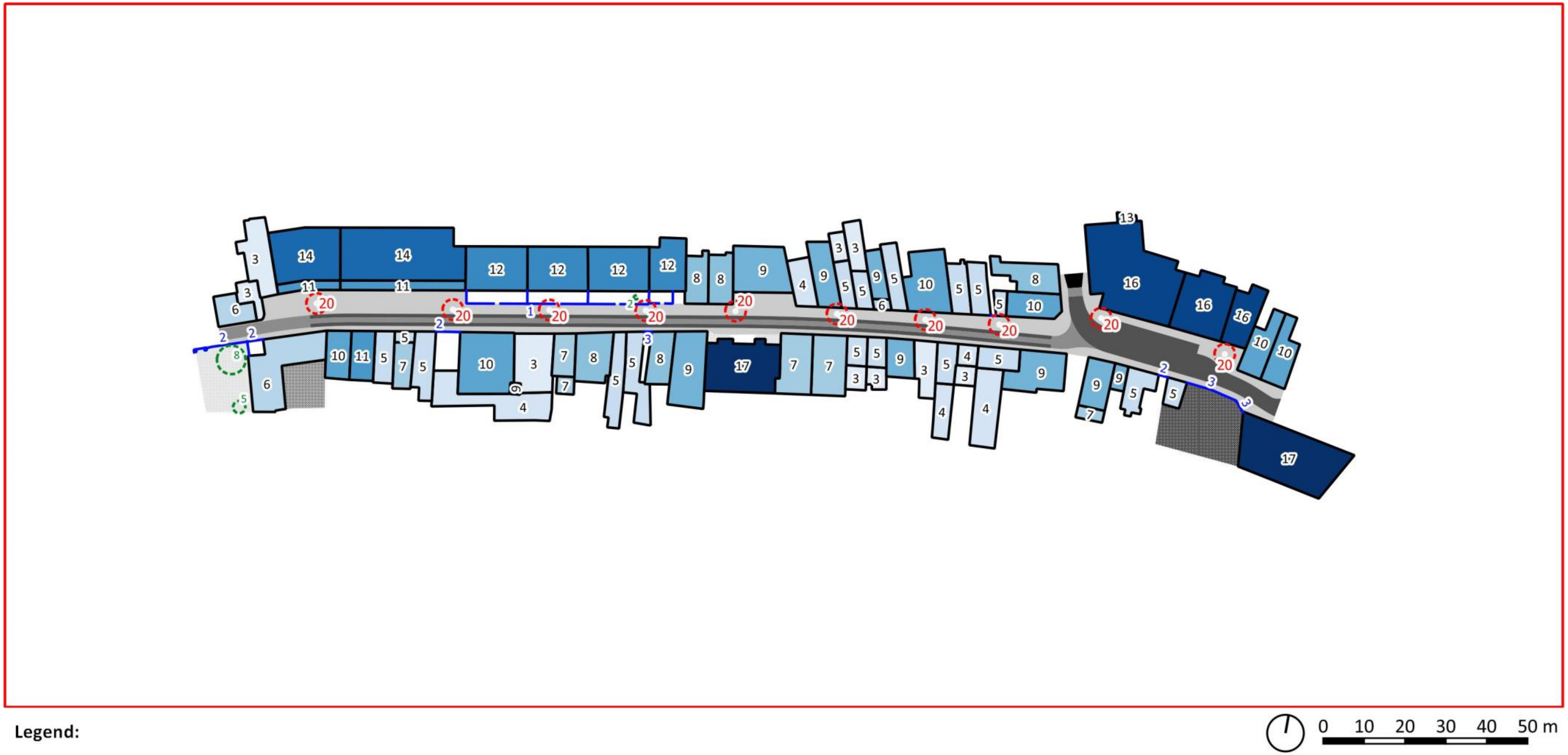
PVTEIR (+ 0100XX)

PVTEIR (+ 0100SO)

Notes:
- further information regarding buildings, single walls and 3D plants' database-ID, refer to field survey documentation;

Appendix M: Scenario-2 Plan

Source: adapted from Porto City Council



Legend:

Model Domain

Buildings
(no. refers to height in m)

Single Walls
(no. refers to height in m)

3D Plants

Existing
(no. refers to height in m)

CB0520
(no. refers to height in m)

Soil Profiles (+ Simples Plants)

PVBE01

PVBE02

PVBE03

PVCU11

PVASAS

0100SL

0100SL (+ 0100XX)

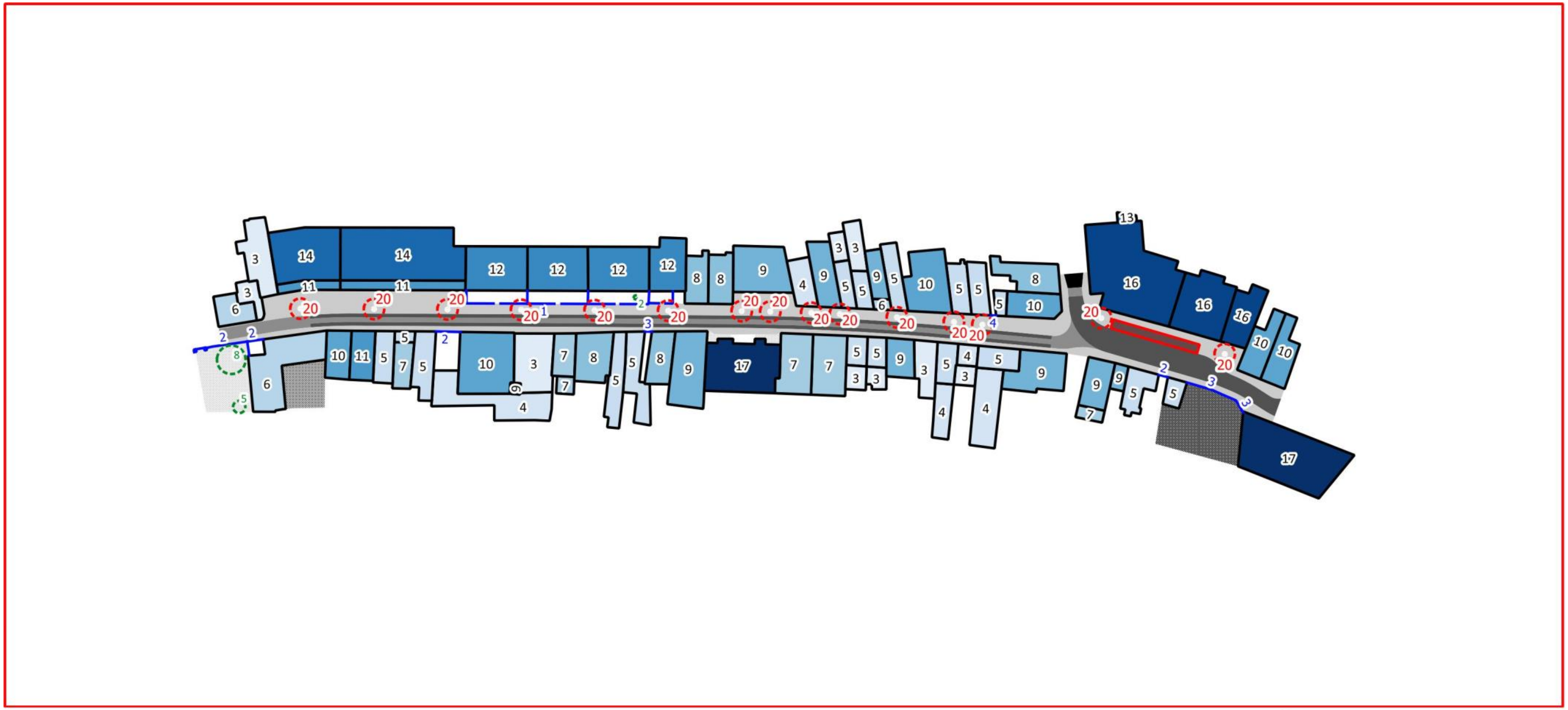
PVTEIR (+ 0100XX)

PVTEIR (+ 0100SO)

Notes:
- further information regarding buildings, single walls and 3D plants' database-ID, refer to field survey documentation;

Appendix N: Scenario-3 Plan

Source: adapted from Porto City Council



0 10 20 30 40 50 m

Legend:

Model Domain

Buildings (no. refers to height in m)

Single Walls (no. refers to height in m)

Green Pergola (refer to notes)

3D Plants

Existing (no. refers to height in m)

CB0520 (no. refers to height in m)

Soil Profiles (+ Simples Plants)

PVBE01

PVBE02

PVBE03

PVCU11

PVASAS

0100SL

0100SL (+ 0100XX)

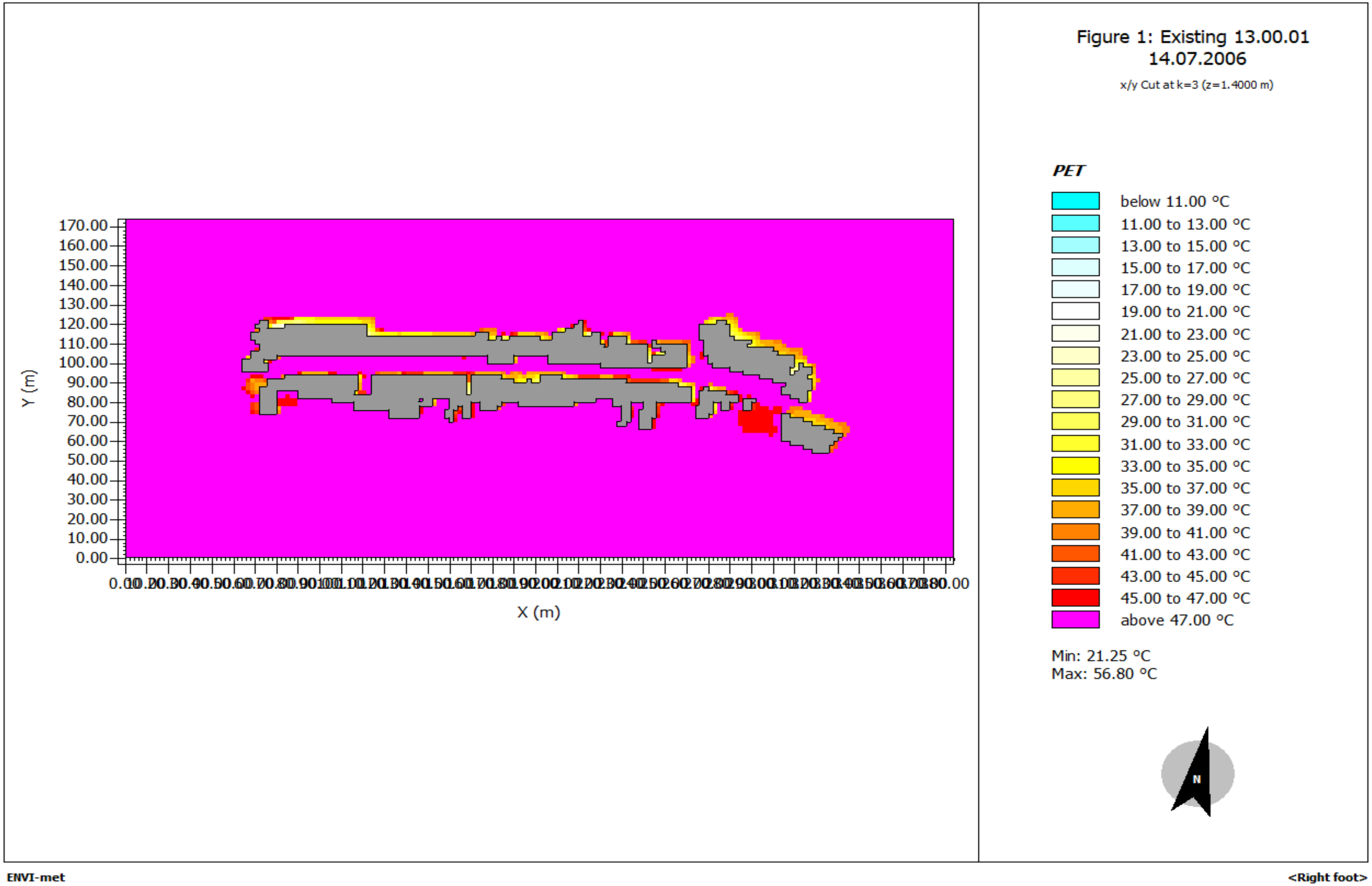
PVTEIR (+ 0100XX)

PVTEIR (+ 0100SO)

Notes:

- further information regarding buildings, single walls and 3D plants' database-ID, refer to field survey documentation;
- Green Pergola modelled as a 3 m high building with greening on its roof. Respective database-ID - Walls: ARARAR / Roof: ACACRA / Roof Greening: RAMADA

Appendix O: Resulting PET



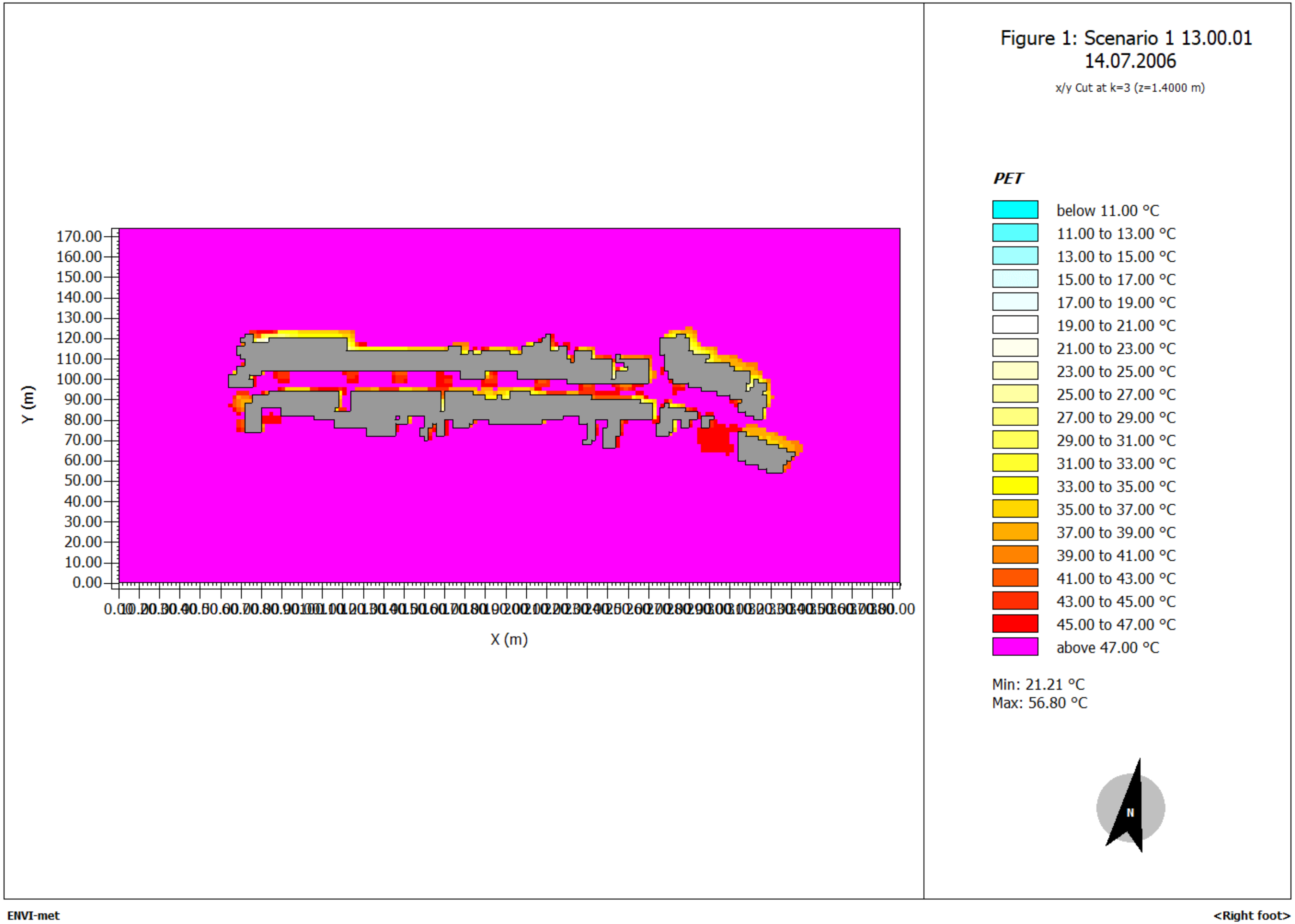


Figure 1: Scenario 1 13.00.01
14.07.2006
x/y Cut at k=3 (z=1.4000 m)
PET
below 11.00 °C
11.00 to 13.00 °C
13.00 to 15.00 °C
15.00 to 17.00 °C
17.00 to 19.00 °C
19.00 to 21.00 °C
21.00 to 23.00 °C
23.00 to 25.00 °C
25.00 to 27.00 °C
27.00 to 29.00 °C
29.00 to 31.00 °C
31.00 to 33.00 °C
33.00 to 35.00 °C
35.00 to 37.00 °C
37.00 to 39.00 °C
39.00 to 41.00 °C
41.00 to 43.00 °C
43.00 to 45.00 °C
45.00 to 47.00 °C
above 47.00 °C
Min: 21.21 °C
Max: 56.80 °C
Y (m)
X (m)
N
ENVI-met
<Right foot>

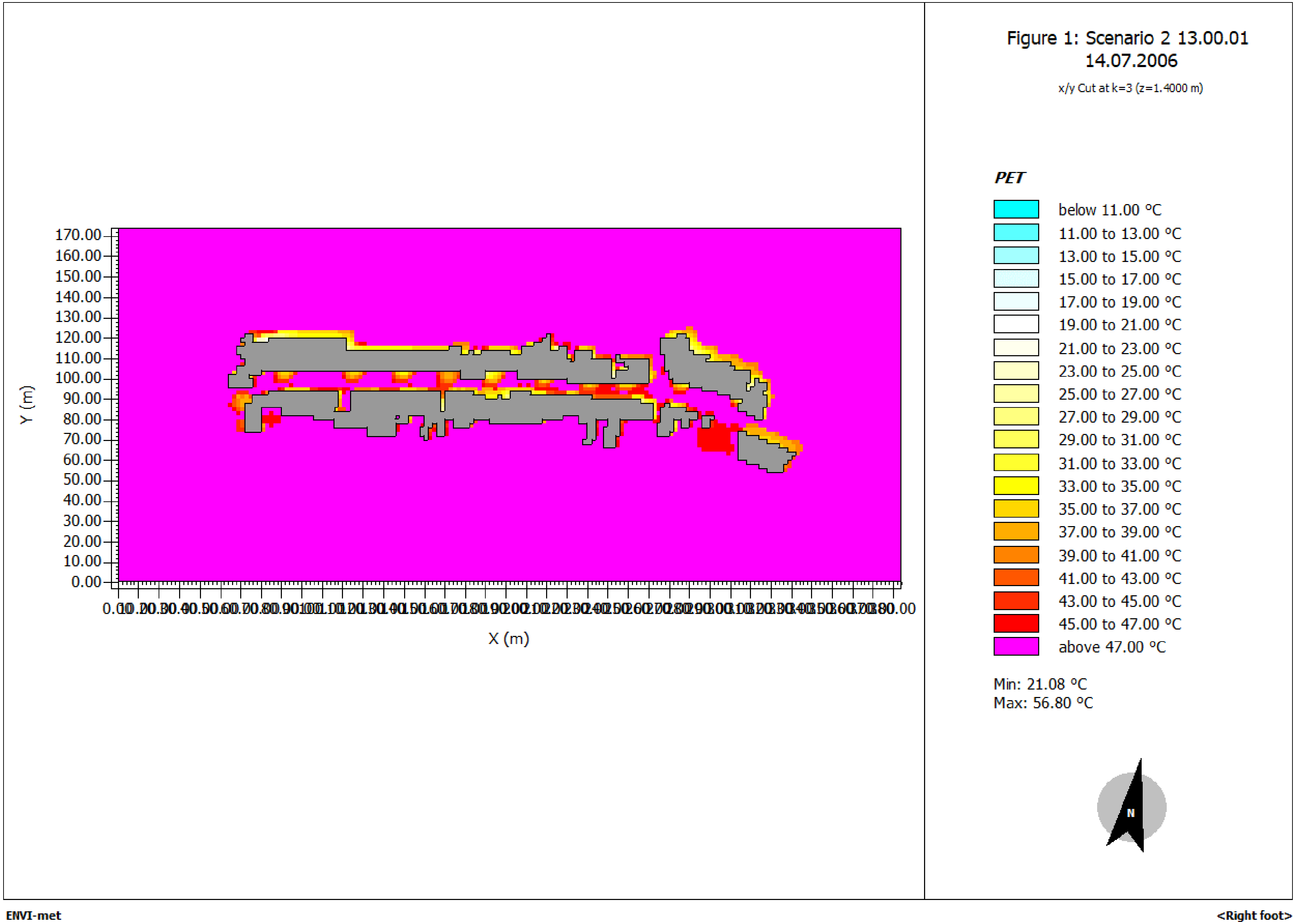


Figure 1: Scenario 2 13.00.01
14.07.2006
x/y Cut at k=3 (z=1.4000 m)
PET
below 11.00 °C
11.00 to 13.00 °C
13.00 to 15.00 °C
15.00 to 17.00 °C
17.00 to 19.00 °C
19.00 to 21.00 °C
21.00 to 23.00 °C
23.00 to 25.00 °C
25.00 to 27.00 °C
27.00 to 29.00 °C
29.00 to 31.00 °C
31.00 to 33.00 °C
33.00 to 35.00 °C
35.00 to 37.00 °C
37.00 to 39.00 °C
39.00 to 41.00 °C
41.00 to 43.00 °C
43.00 to 45.00 °C
45.00 to 47.00 °C
above 47.00 °C
Min: 21.08 °C
Max: 56.80 °C
Y (m)
X (m)
N
ENVI-met
<Right foot>

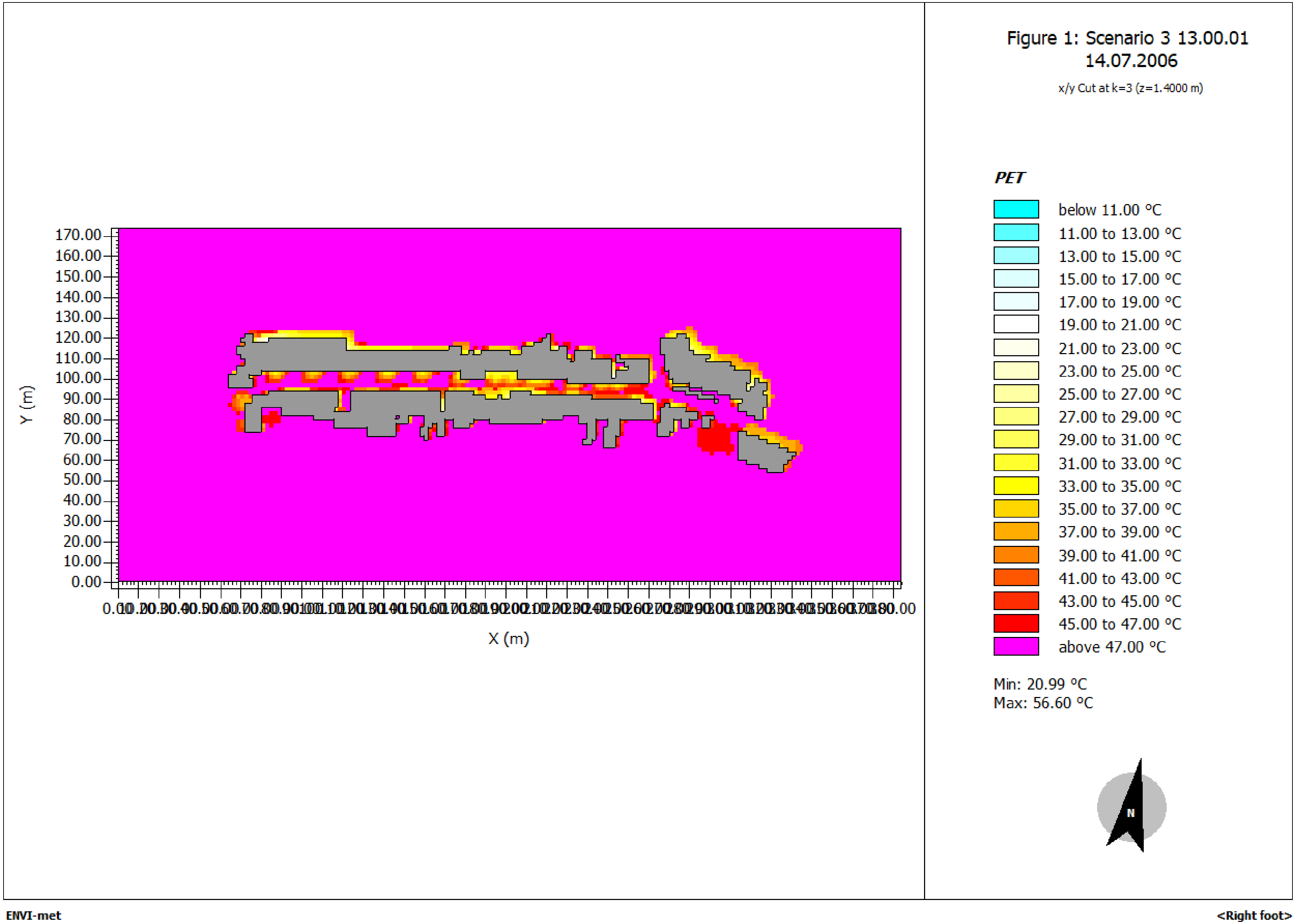


Figure 1: Scenario 3 13.00.01
14.07.2006
x/y Cut at k=3 (z=1.4000 m)
PET
below 11.00 °C
11.00 to 13.00 °C
13.00 to 15.00 °C
15.00 to 17.00 °C
17.00 to 19.00 °C
19.00 to 21.00 °C
21.00 to 23.00 °C
23.00 to 25.00 °C
25.00 to 27.00 °C
27.00 to 29.00 °C
29.00 to 31.00 °C
31.00 to 33.00 °C
33.00 to 35.00 °C
35.00 to 37.00 °C
37.00 to 39.00 °C
39.00 to 41.00 °C
41.00 to 43.00 °C
43.00 to 45.00 °C
45.00 to 47.00 °C
above 47.00 °C
Min: 20.99 °C
Max: 56.60 °C
Y (m)
X (m)
N
ENVI-met
<Right foot>

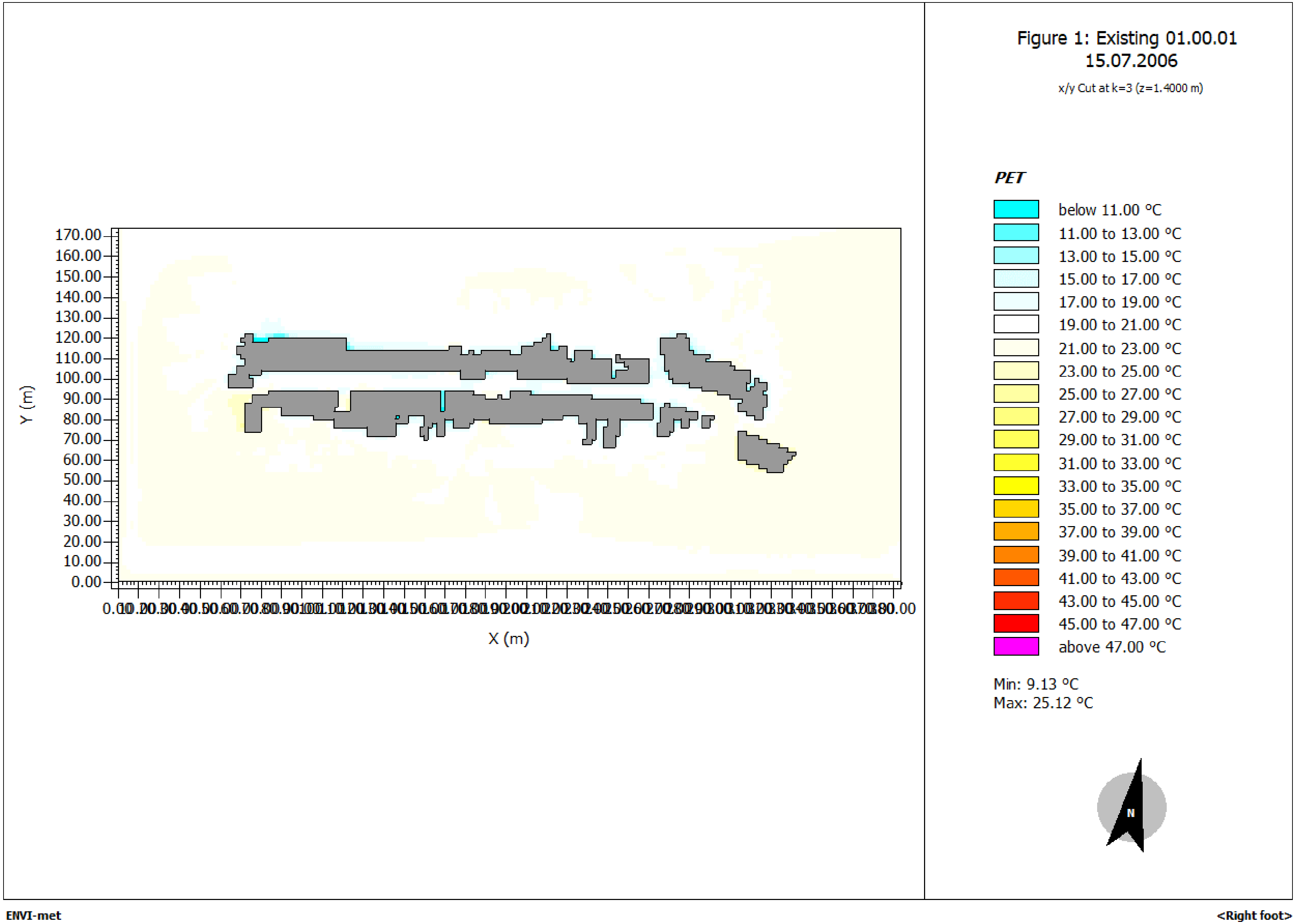
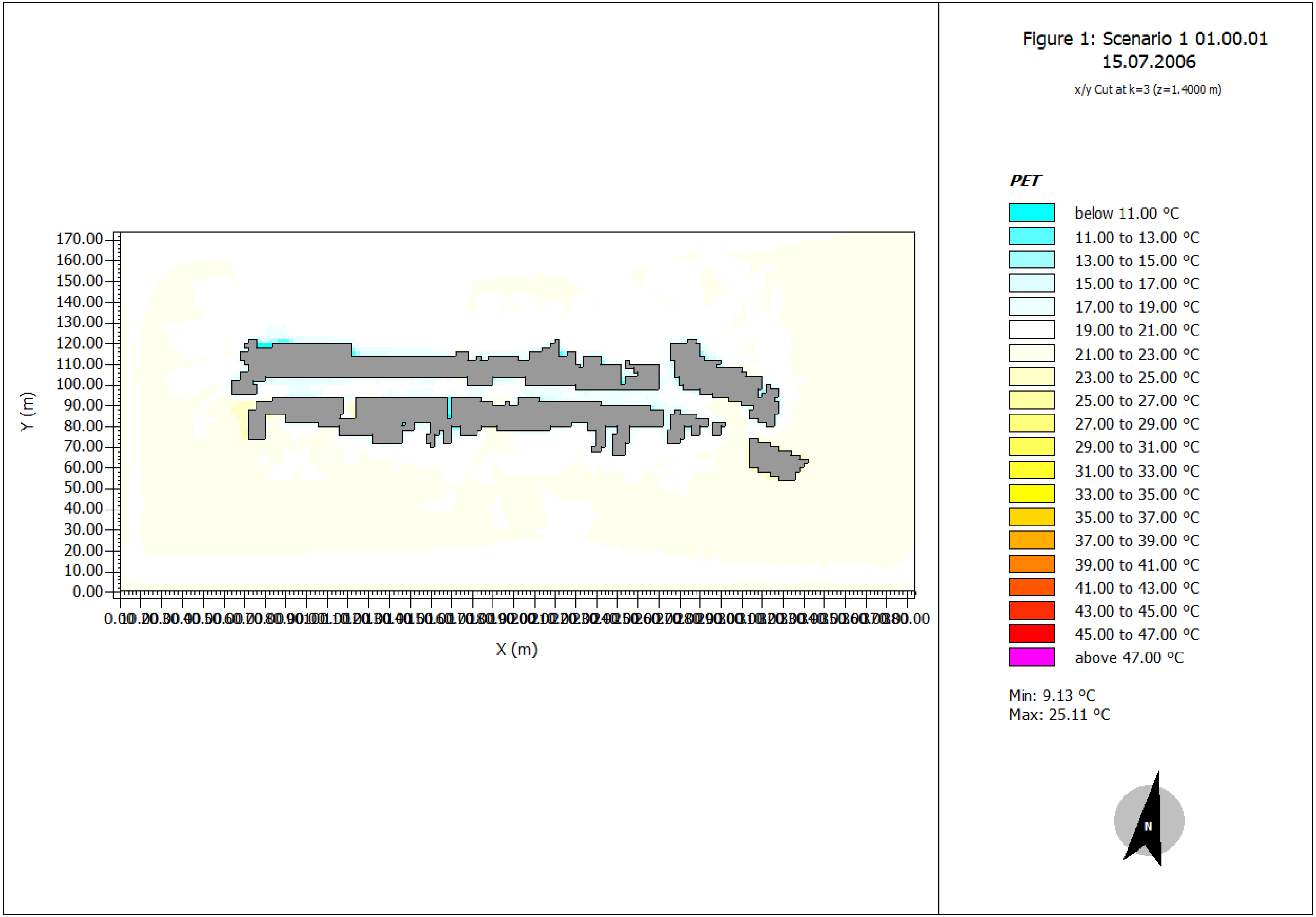


Figure 1: Existing 01.00.01
15.07.2006
x/y Cut at k=3 (z=1.4000 m)
PET
below 11.00 °C
11.00 to 13.00 °C
13.00 to 15.00 °C
15.00 to 17.00 °C
17.00 to 19.00 °C
19.00 to 21.00 °C
21.00 to 23.00 °C
23.00 to 25.00 °C
25.00 to 27.00 °C
27.00 to 29.00 °C
29.00 to 31.00 °C
31.00 to 33.00 °C
33.00 to 35.00 °C
35.00 to 37.00 °C
37.00 to 39.00 °C
39.00 to 41.00 °C
41.00 to 43.00 °C
43.00 to 45.00 °C
45.00 to 47.00 °C
above 47.00 °C
Min: 9.13 °C
Max: 25.12 °C
Y (m)
X (m)
N
ENVI-met
<Right foot>



ENVI-met **<Right foot>**

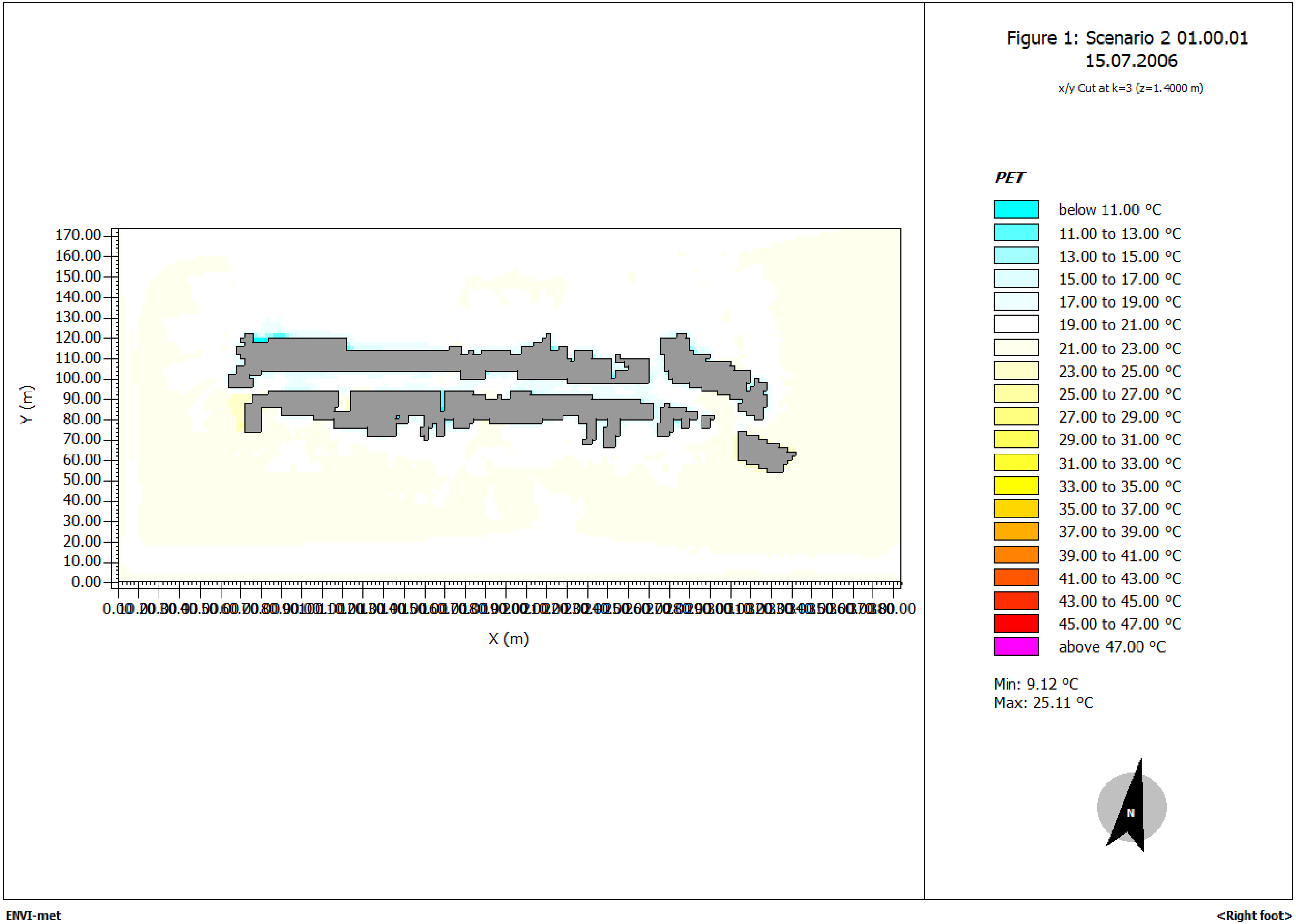


Figure 1: Scenario 2 01.00.01
15.07.2006
x/y Cut at k=3 (z=1.4000 m)
PET
below 11.00 °C
11.00 to 13.00 °C
13.00 to 15.00 °C
15.00 to 17.00 °C
17.00 to 19.00 °C
19.00 to 21.00 °C
21.00 to 23.00 °C
23.00 to 25.00 °C
25.00 to 27.00 °C
27.00 to 29.00 °C
29.00 to 31.00 °C
31.00 to 33.00 °C
33.00 to 35.00 °C
35.00 to 37.00 °C
37.00 to 39.00 °C
39.00 to 41.00 °C
41.00 to 43.00 °C
43.00 to 45.00 °C
45.00 to 47.00 °C
above 47.00 °C
Min: 9.12 °C
Max: 25.11 °C
Y (m)
X (m)
N
ENVI-met
<Right foot>

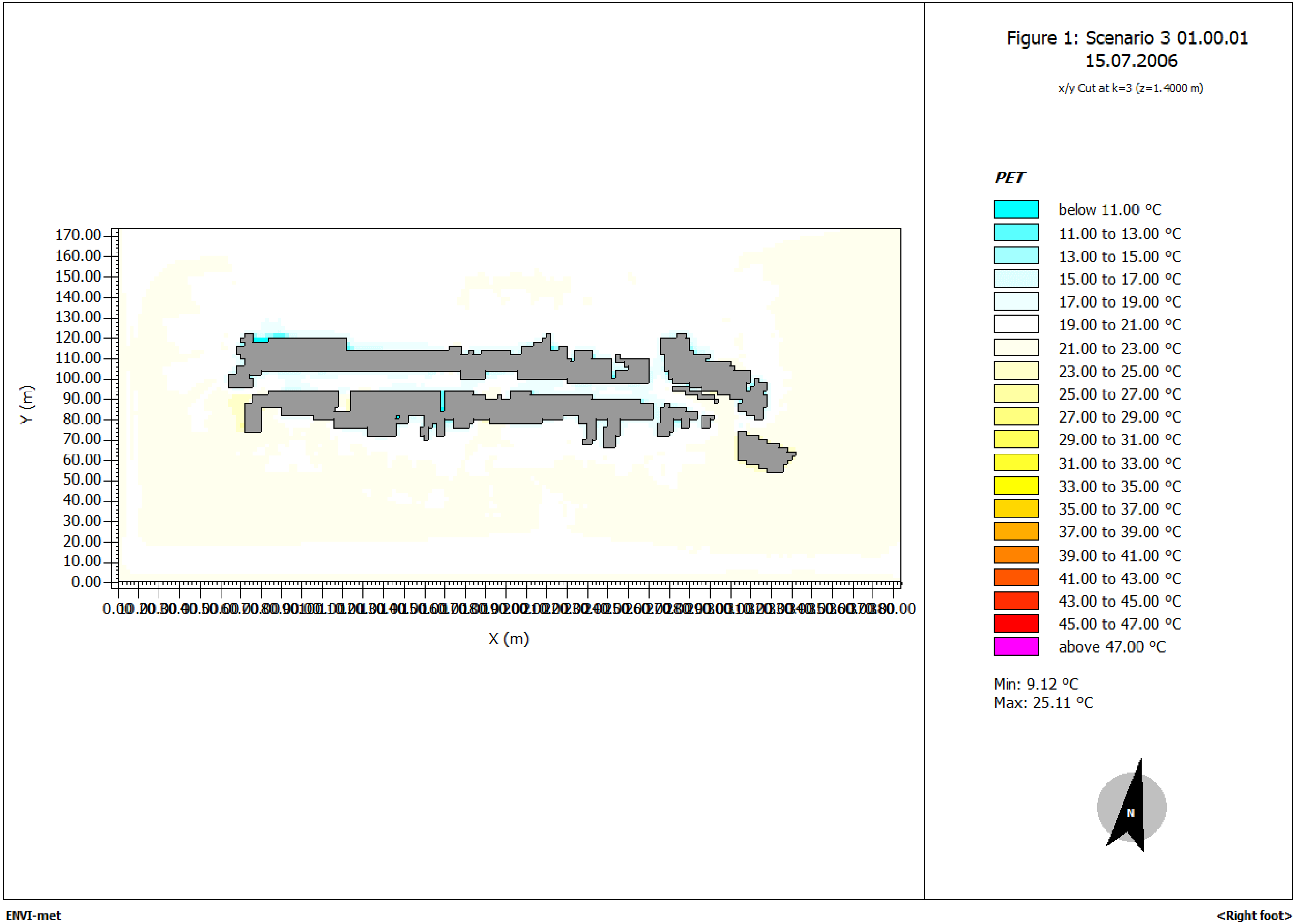


Figure 1: Scenario 3 01.00.01
15.07.2006
x/y Cut at k=3 (z=1.4000 m)
Y (m)
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
X (m)
PET
below 11.00 °C
11.00 to 13.00 °C
13.00 to 15.00 °C
15.00 to 17.00 °C
17.00 to 19.00 °C
19.00 to 21.00 °C
21.00 to 23.00 °C
23.00 to 25.00 °C
25.00 to 27.00 °C
27.00 to 29.00 °C
29.00 to 31.00 °C
31.00 to 33.00 °C
33.00 to 35.00 °C
35.00 to 37.00 °C
37.00 to 39.00 °C
39.00 to 41.00 °C
41.00 to 43.00 °C
43.00 to 45.00 °C
45.00 to 47.00 °C
above 47.00 °C
Min: 9.12 °C
Max: 25.11 °C
N
ENVI-met
<Right foot>

Appendix P: Scenarios-vs-Existing Comparisons

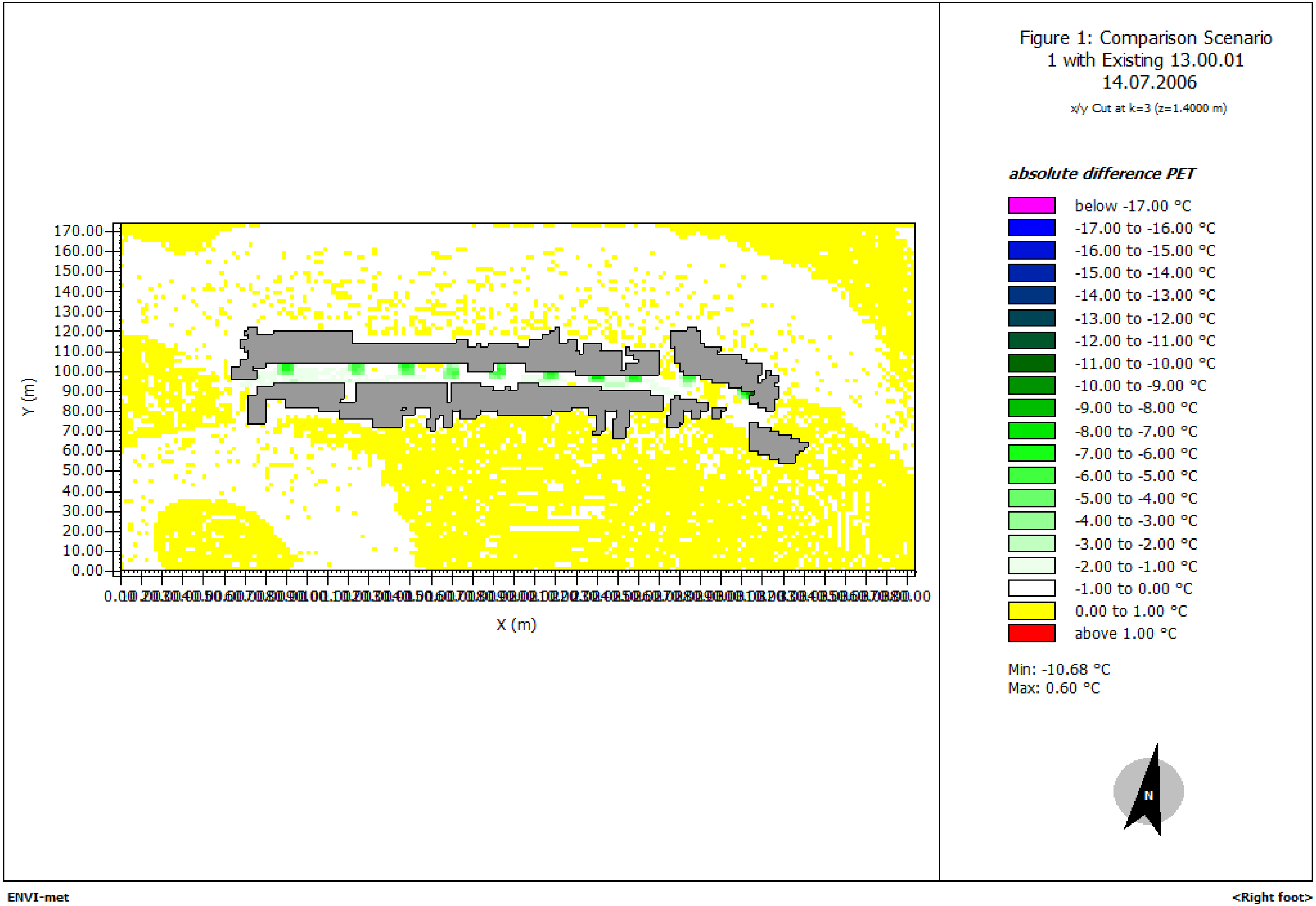


Figure 1: Comparison Scenario 1 with Existing 13.00.01 14.07.2006

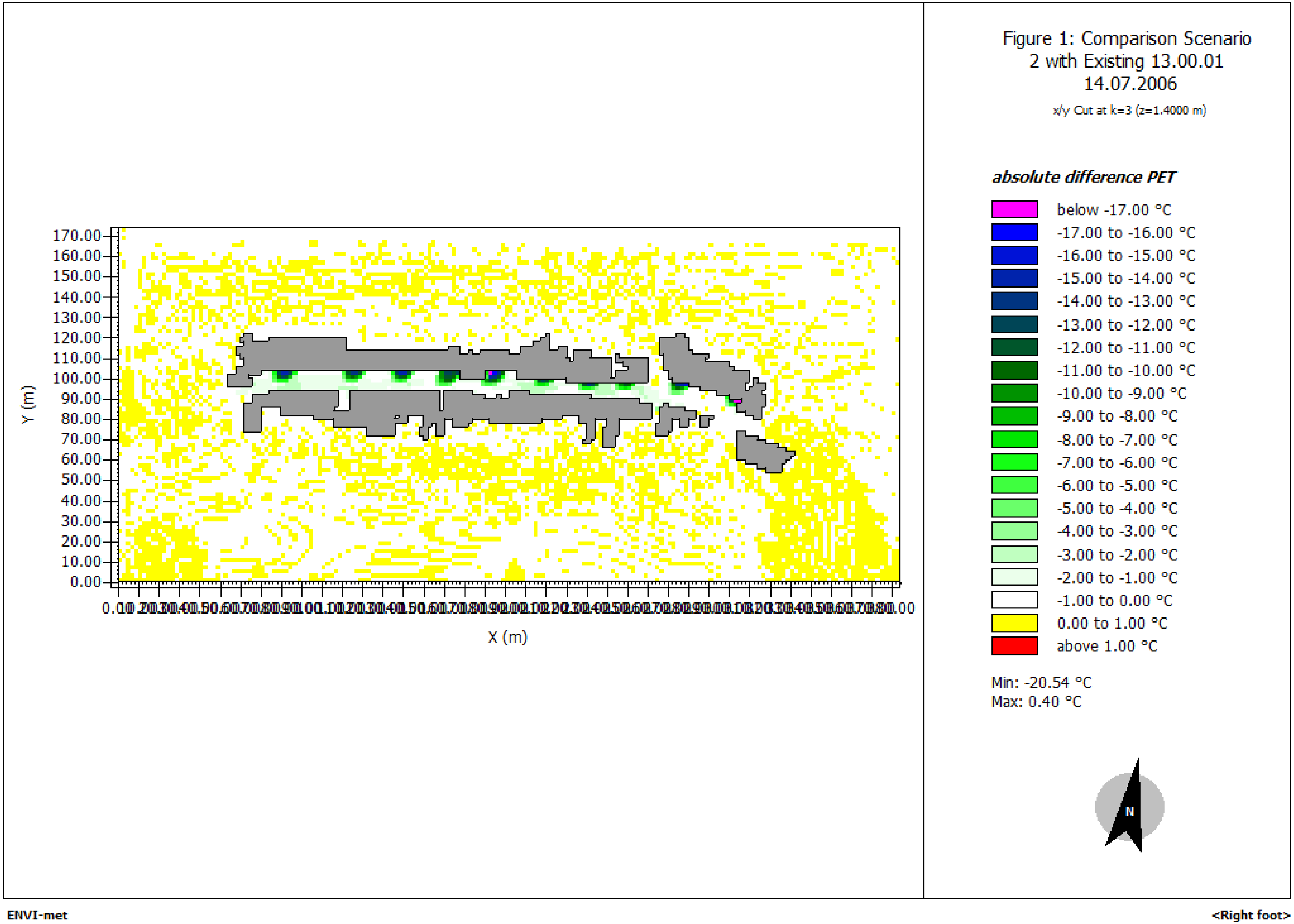
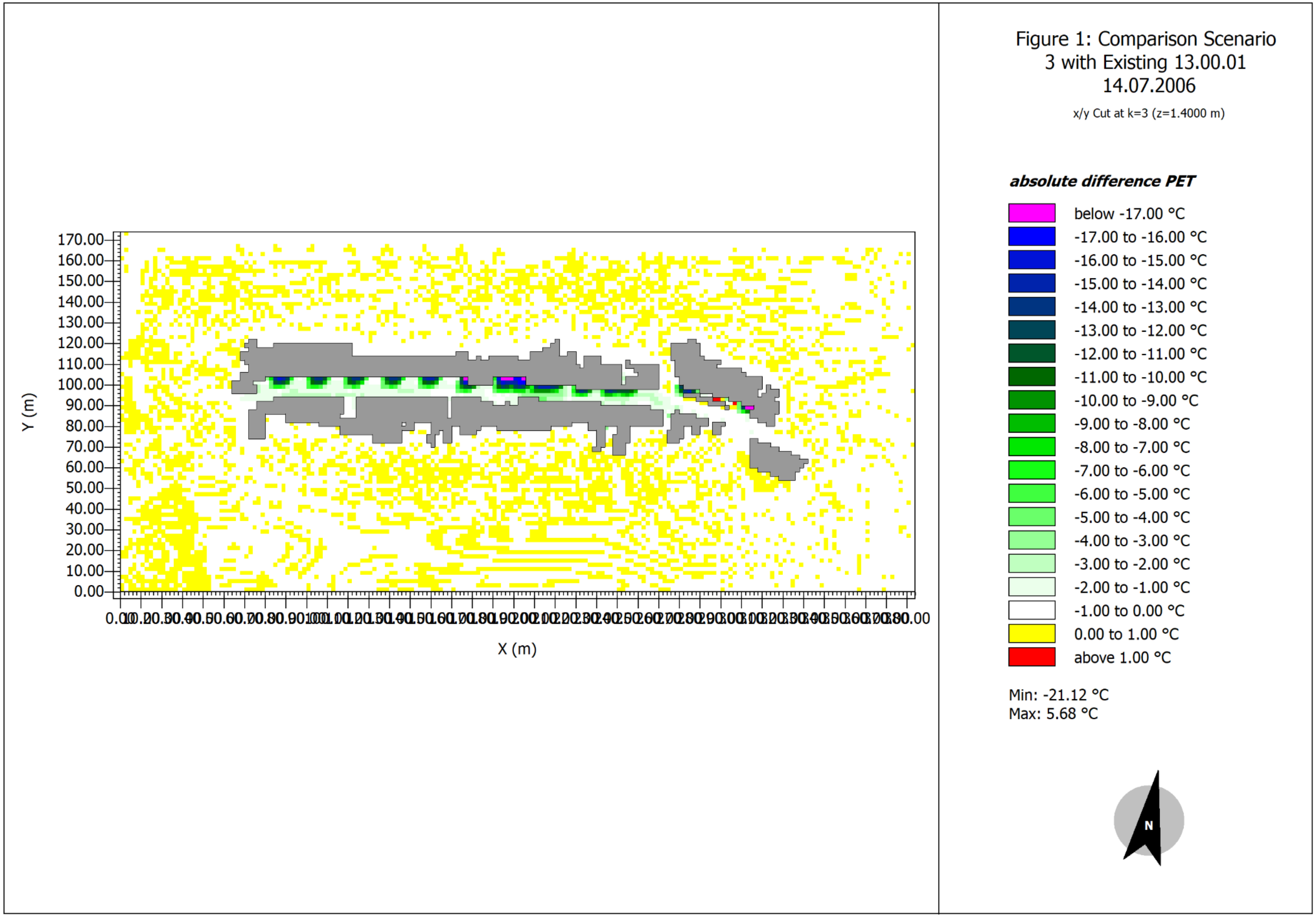
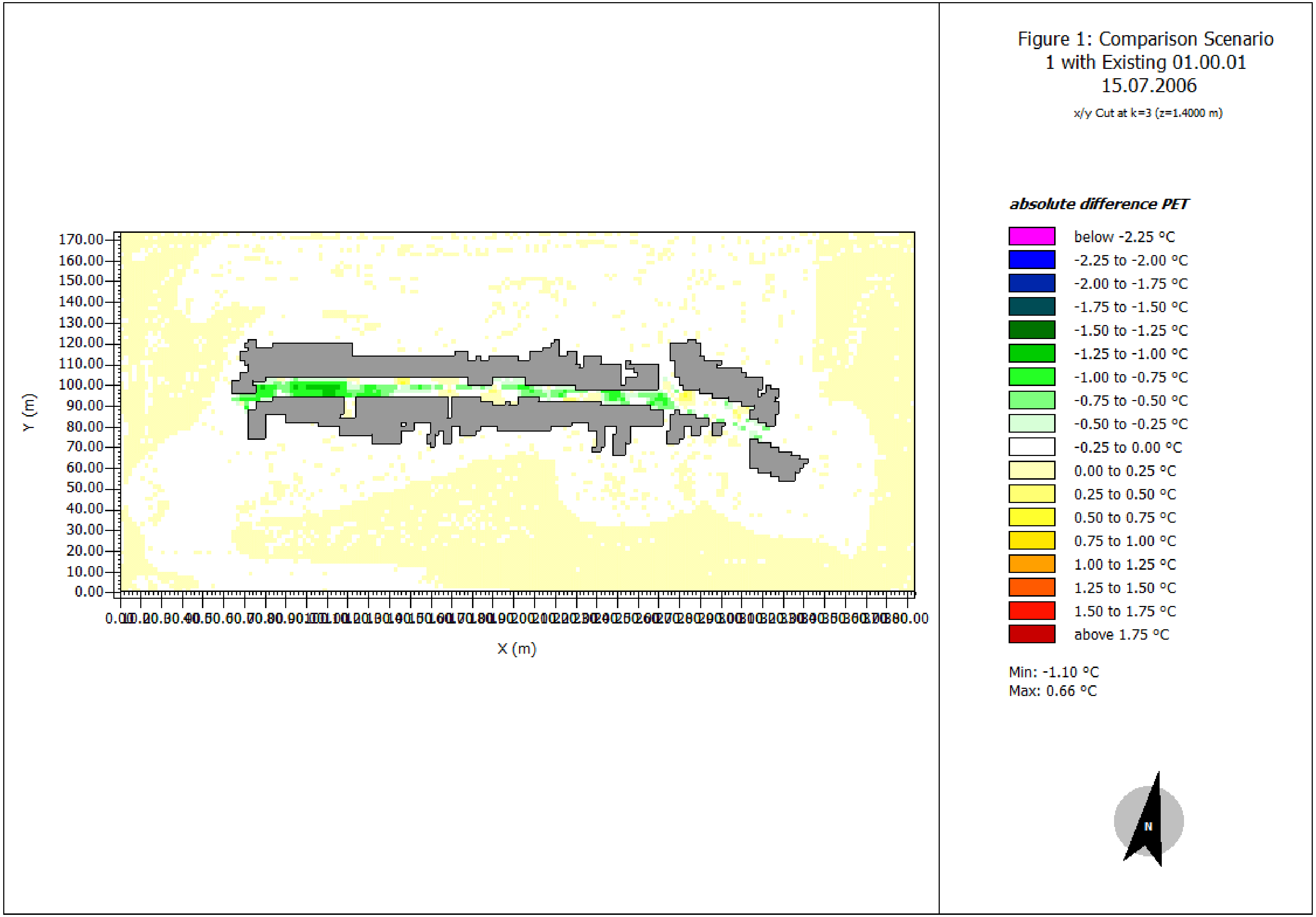


Figure 1: Comparison Scenario 2 with Existing 13.00.01 14.07.2006
x/y Cut at k=3 (z=1.4000 m)
absolute difference PET
below -17.00 °C
-17.00 to -16.00 °C
-16.00 to -15.00 °C
-15.00 to -14.00 °C
-14.00 to -13.00 °C
-13.00 to -12.00 °C
-12.00 to -11.00 °C
-11.00 to -10.00 °C
-10.00 to -9.00 °C
-9.00 to -8.00 °C
-8.00 to -7.00 °C
-7.00 to -6.00 °C
-6.00 to -5.00 °C
-5.00 to -4.00 °C
-4.00 to -3.00 °C
-3.00 to -2.00 °C
-2.00 to -1.00 °C
-1.00 to 0.00 °C
0.00 to 1.00 °C
above 1.00 °C
Min: -20.54 °C
Max: 0.40 °C
Y (m)
X (m)
N
ENVI-met
<Right foot>



ENVI-met **<Right foot>**



ENVI-met

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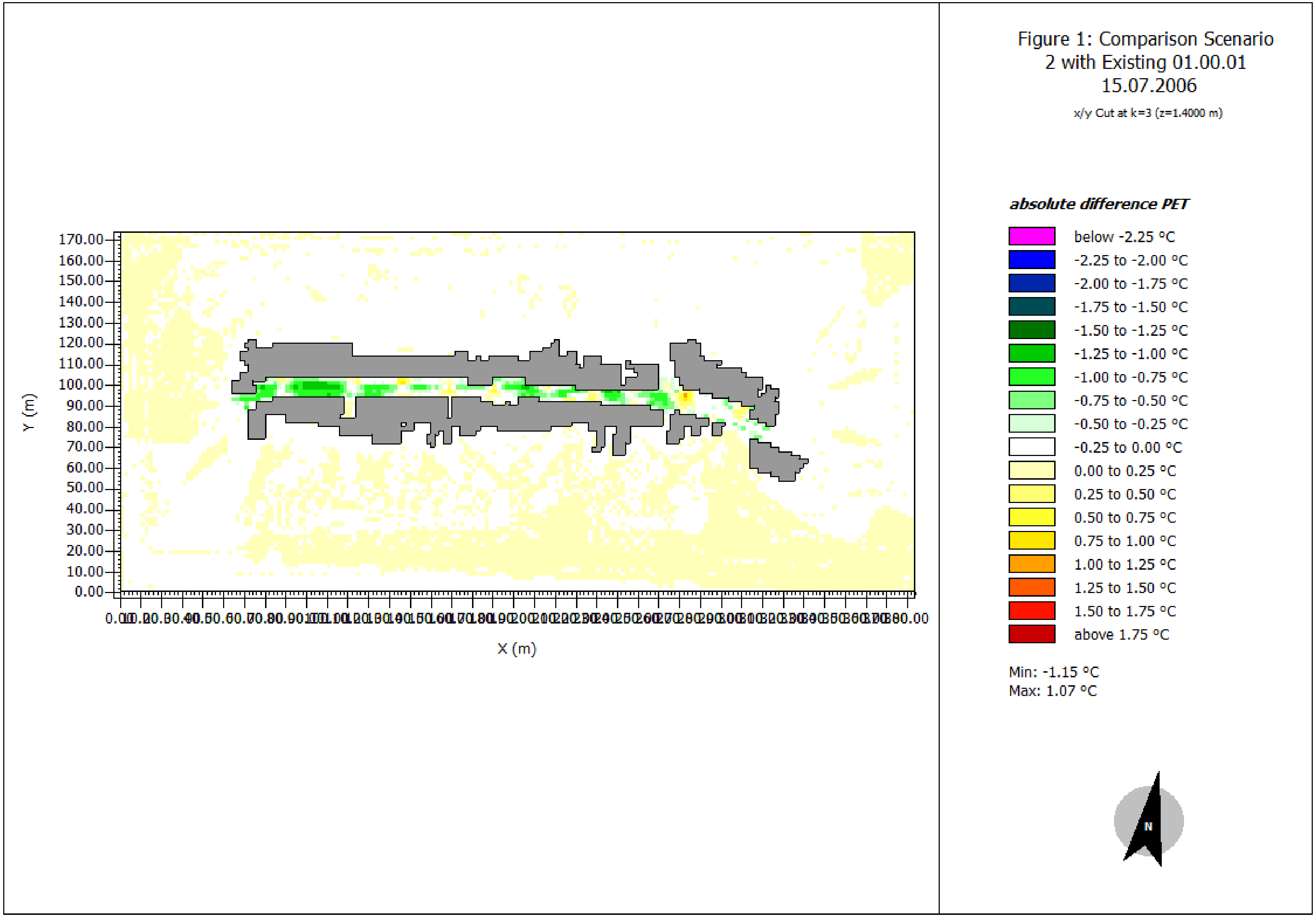

ENVI-met

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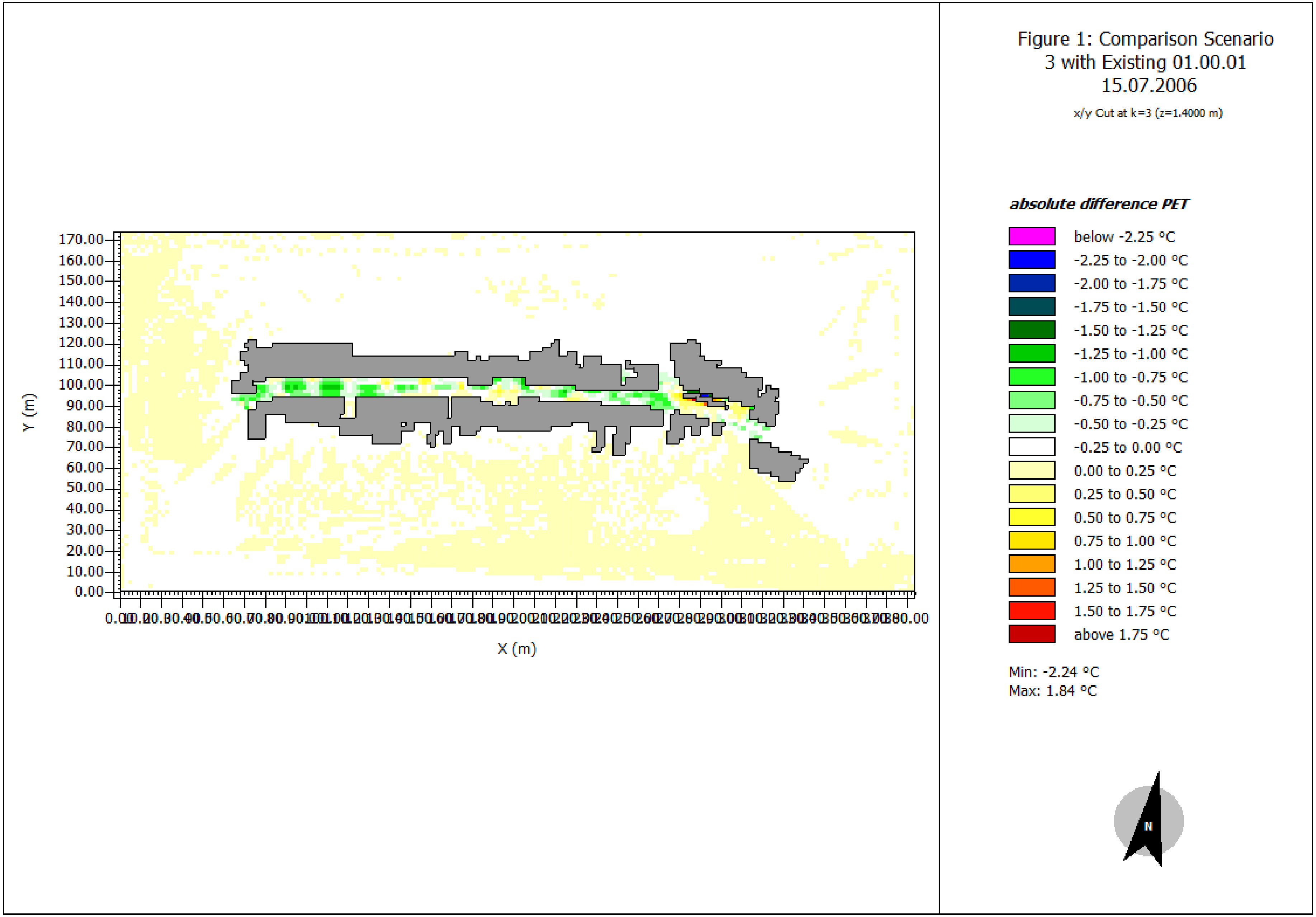
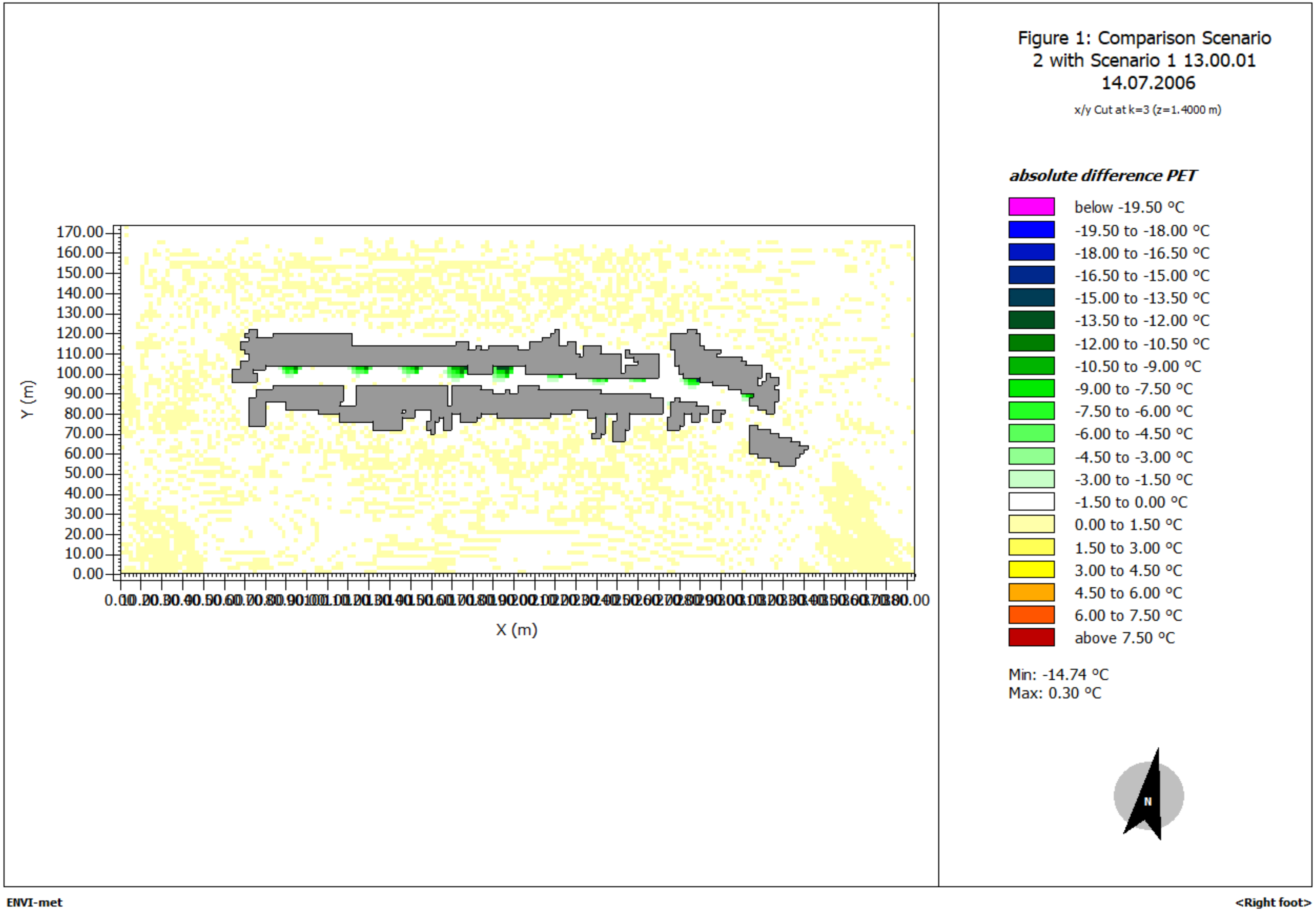


ENVI-met <Right foot>

Appendix Q: Scenario-vs-Scenario Comparisons



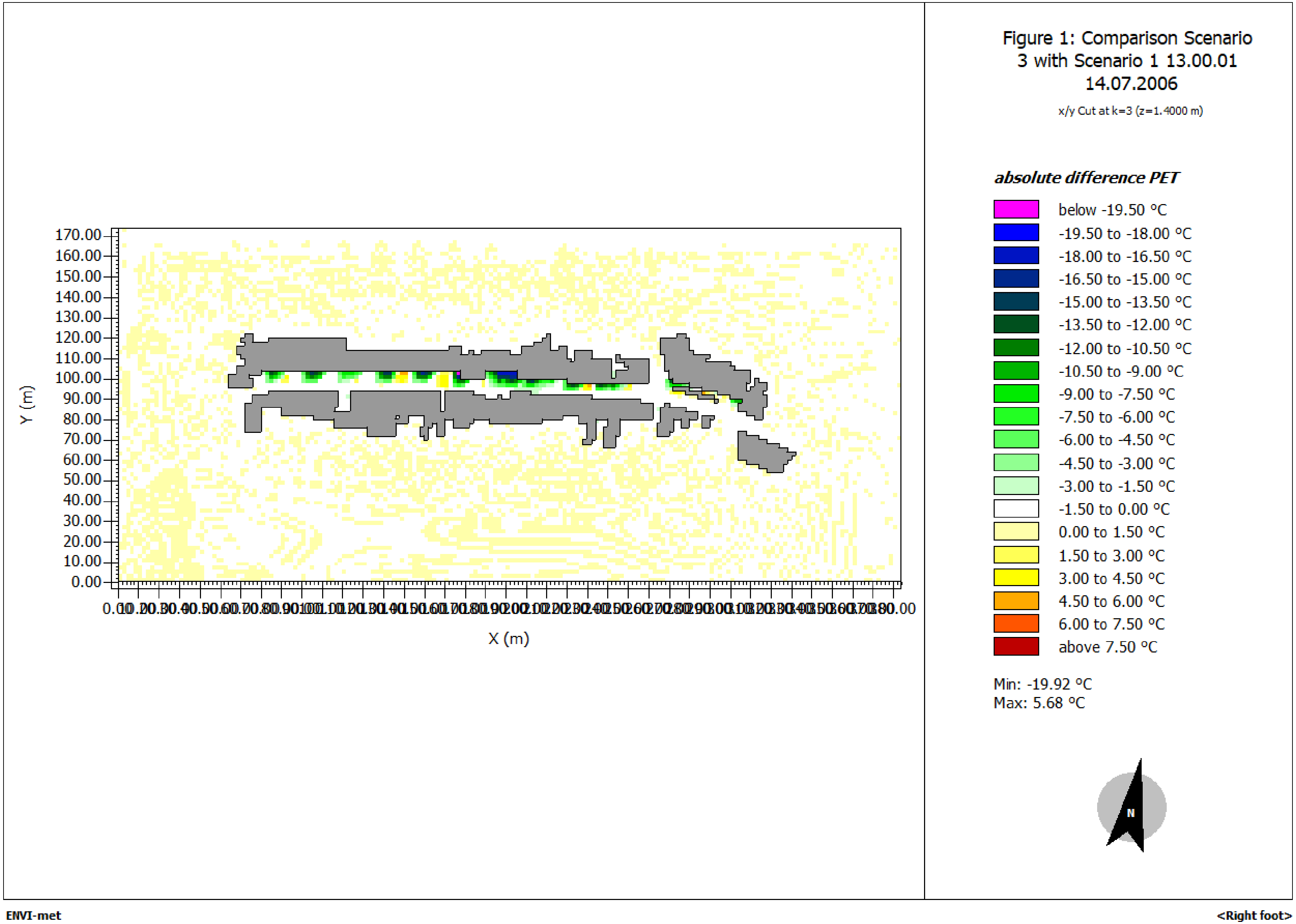


Figure 1: Comparison Scenario 3 with Scenario 1 13.00.01 14.07.2006
x/y Cut at k=3 (z=1.4000 m)
absolute difference PET
below -19.50 °C
-19.50 to -18.00 °C
-18.00 to -16.50 °C
-16.50 to -15.00 °C
-15.00 to -13.50 °C
-13.50 to -12.00 °C
-12.00 to -10.50 °C
-10.50 to -9.00 °C
-9.00 to -7.50 °C
-7.50 to -6.00 °C
-6.00 to -4.50 °C
-4.50 to -3.00 °C
-3.00 to -1.50 °C
-1.50 to 0.00 °C
0.00 to 1.50 °C
1.50 to 3.00 °C
3.00 to 4.50 °C
4.50 to 6.00 °C
6.00 to 7.50 °C
above 7.50 °C
Min: -19.92 °C
Max: 5.68 °C
Y (m)
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
X (m)
N
ENVI-met
<Right foot>

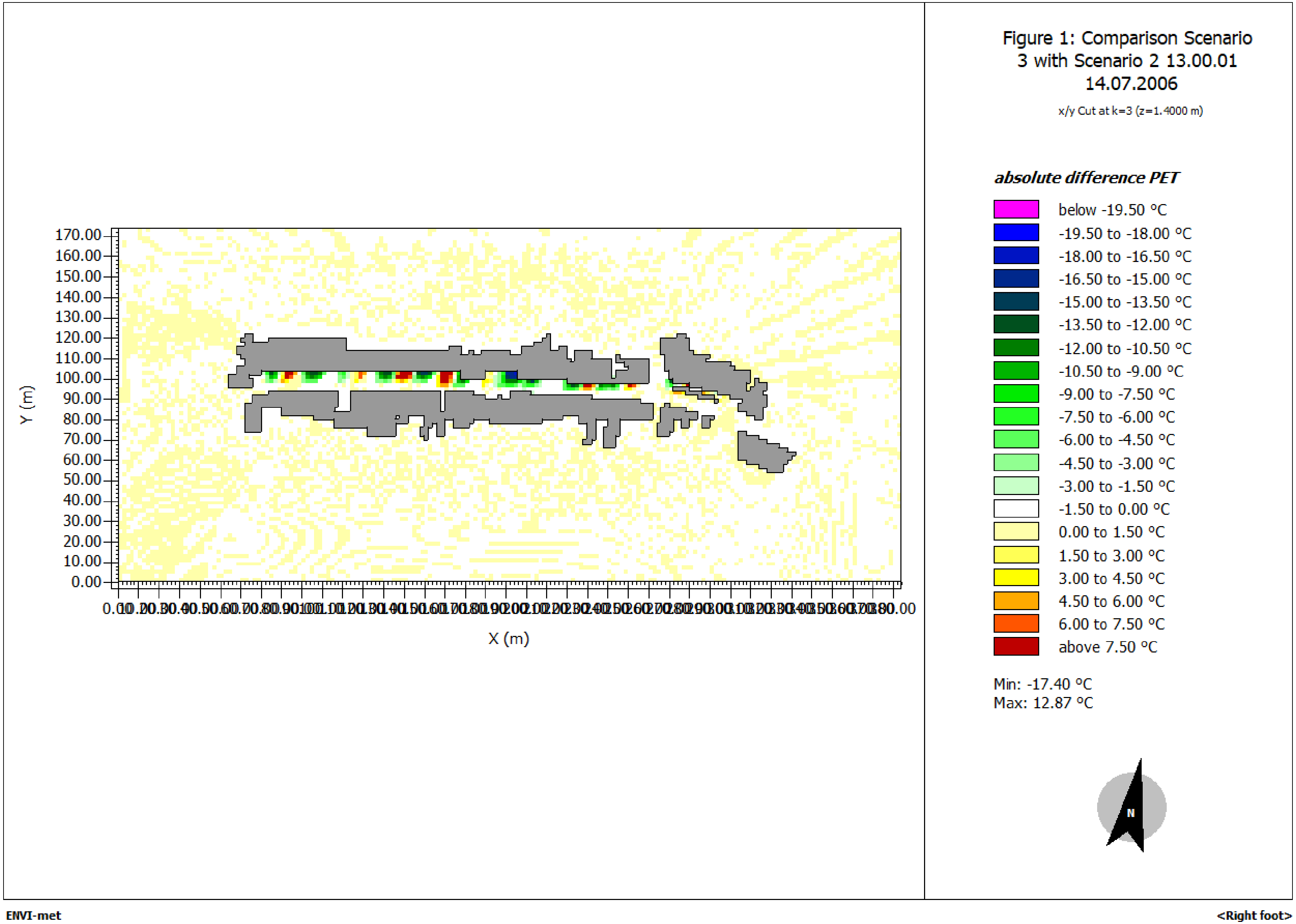


Figure 1: Comparison Scenario 3 with Scenario 2 13.00.01 14.07.2006
x/y Cut at k=3 (z=1.4000 m)
absolute difference PET
below -19.50 °C
-19.50 to -18.00 °C
-18.00 to -16.50 °C
-16.50 to -15.00 °C
-15.00 to -13.50 °C
-13.50 to -12.00 °C
-12.00 to -10.50 °C
-10.50 to -9.00 °C
-9.00 to -7.50 °C
-7.50 to -6.00 °C
-6.00 to -4.50 °C
-4.50 to -3.00 °C
-3.00 to -1.50 °C
-1.50 to 0.00 °C
0.00 to 1.50 °C
1.50 to 3.00 °C
3.00 to 4.50 °C
4.50 to 6.00 °C
6.00 to 7.50 °C
above 7.50 °C
Min: -17.40 °C
Max: 12.87 °C
Y (m)
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
X (m)
N
ENVI-met
<Right foot>

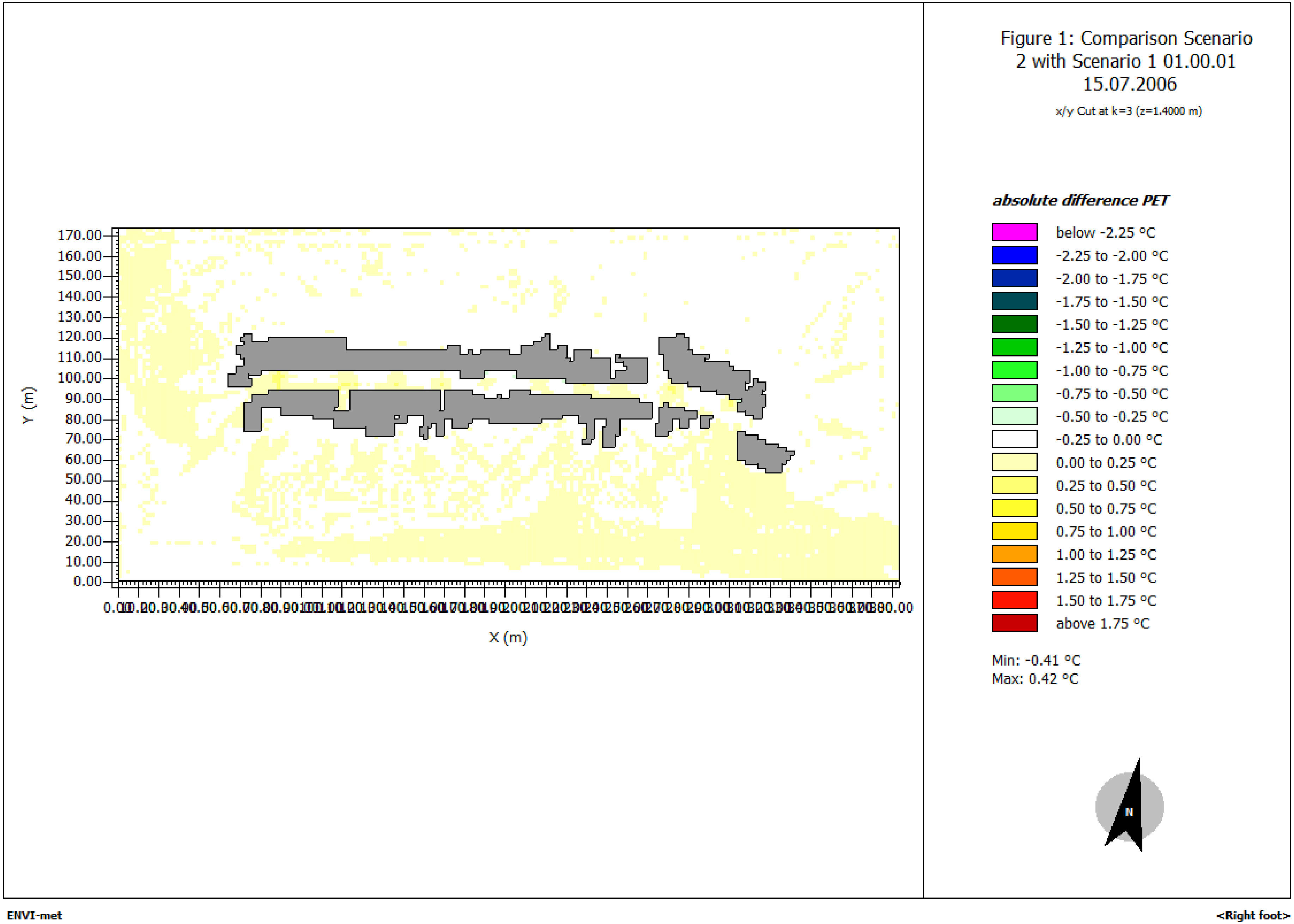


Figure 1: Comparison Scenario 2 with Scenario 1 01.00.01 15.07.2006
x/y Cut at k=3 (z=1.4000 m)
absolute difference PET
below -2.25 °C
-2.25 to -2.00 °C
-2.00 to -1.75 °C
-1.75 to -1.50 °C
-1.50 to -1.25 °C
-1.25 to -1.00 °C
-1.00 to -0.75 °C
-0.75 to -0.50 °C
-0.50 to -0.25 °C
-0.25 to 0.00 °C
0.00 to 0.25 °C
0.25 to 0.50 °C
0.50 to 0.75 °C
0.75 to 1.00 °C
1.00 to 1.25 °C
1.25 to 1.50 °C
1.50 to 1.75 °C
above 1.75 °C
Min: -0.41 °C
Max: 0.42 °C
Y (m)
X (m)
N
ENVI-met
<Right foot>

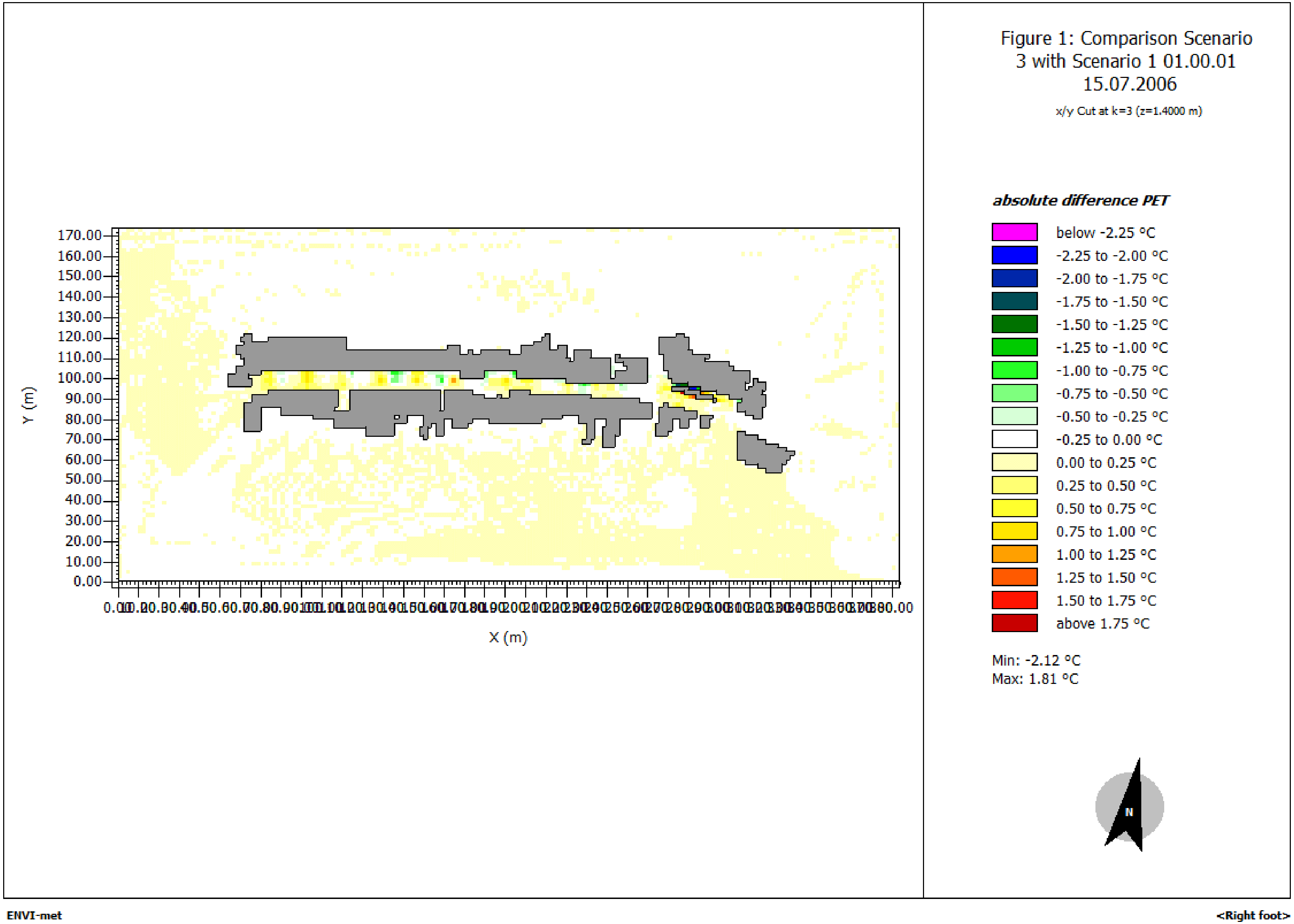
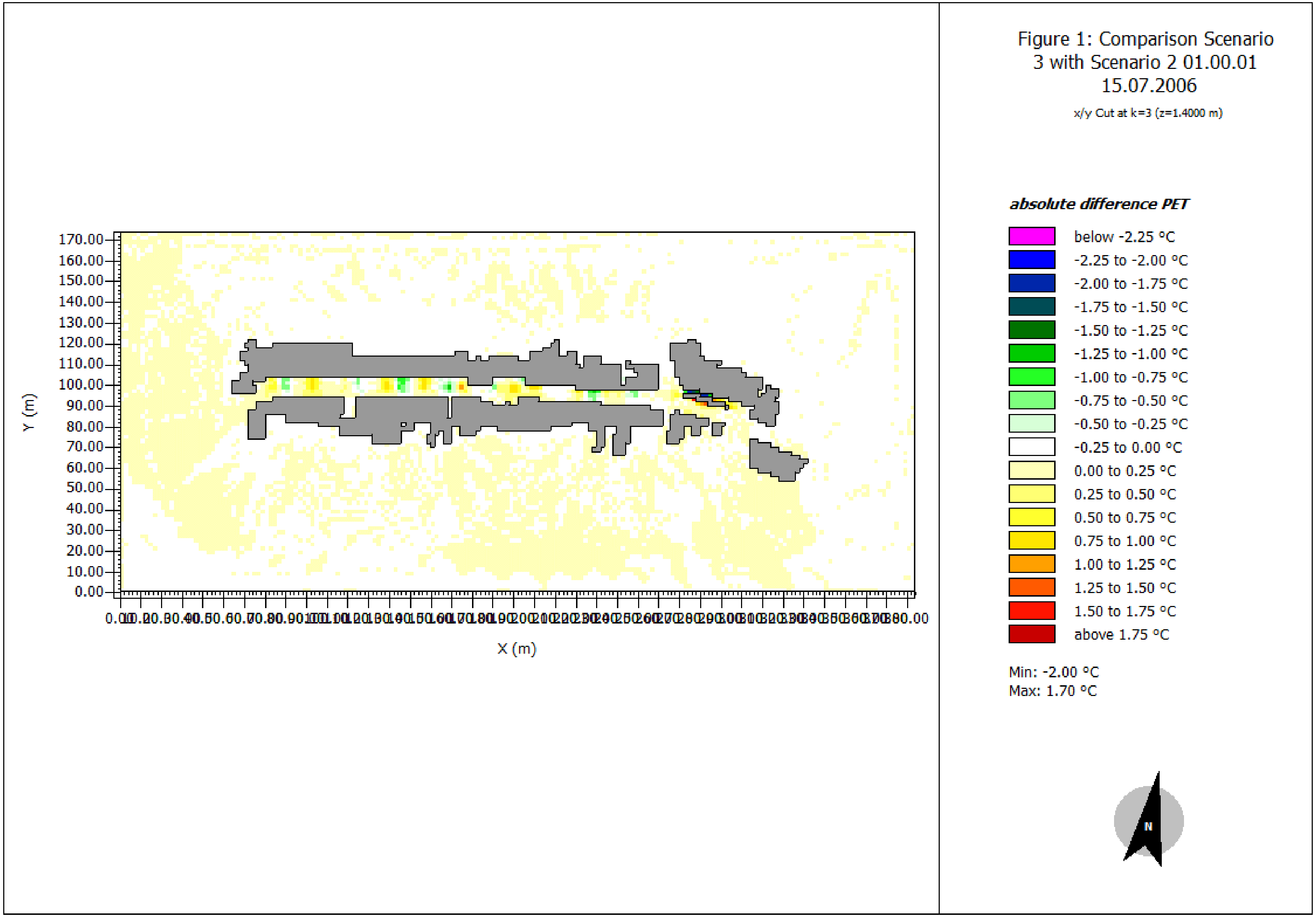


Figure 1: Comparison Scenario 3 with Scenario 1 01.00.01 15.07.2006
x/y Cut at k=3 (z=1.4000 m)
absolute difference PET
below -2.25 °C
-2.25 to -2.00 °C
-2.00 to -1.75 °C
-1.75 to -1.50 °C
-1.50 to -1.25 °C
-1.25 to -1.00 °C
-1.00 to -0.75 °C
-0.75 to -0.50 °C
-0.50 to -0.25 °C
-0.25 to 0.00 °C
0.00 to 0.25 °C
0.25 to 0.50 °C
0.50 to 0.75 °C
0.75 to 1.00 °C
1.00 to 1.25 °C
1.25 to 1.50 °C
1.50 to 1.75 °C
above 1.75 °C
Min: -2.12 °C
Max: 1.81 °C
Y (m)
X (m)
N
ENVI-met
<Right foot>



ENVI-met

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Appendix R: Understanding ENVI-met v5.0.2 – a designer's perspective

ENVI-met is a suite of software packages aimed at configuring, running and analysing microclimatic simulations. 'ENVI-core' (12) is where the simulation is run. To inform the simulator on settings, such as the duration and many other computational options, it requires a *SIMX*-format 'Simulation File' which is produced in 'ENVI-guide' (11). The 'Simulation File' requires an *INX*-format 'Model Area File', which we will focus further down, and, when opting to provide more accurate meteorological input, a *FOX*-format 'Forcing File' created from a *CSV* or *EPW/TRY*-format file in 'Forcing Manager' (10). The *INX*-format 'Model Area File' is created in 'Spaces' (1) which is a 3D representation of the environment one wants to study. The properties of the elements included in this 'Model Area File' are defined in 'DB Manager' (2, 3, 4, 5, 6, 8 and 9), except for trees which require a specific software, the 'Albero' (7).

All elements' configuration settings are stored under a six-alphanumeric-digit database-ID into one of three categories of databases. 'System Database' comes as default with the software and is not editable. 'User' and 'Project Database' are editable but, while 'User' is exclusive to the computer where the software is running, 'Project' is exclusive of a single project. For instances, one computer can have many 'Project Databases' but, can only have one 'User Database'. If database-ID are conflicting between databases, the project's 'Project Database' takes precedent followed by 'User' and only then by 'System'.

The simulation-resulting data can then be read, compared, analysed and displayed in 'Leonardo'. Indexes, such as PET, can be calculated in 'BIO-met' and included in 'Leonardo'.

Further detail in ENVI-met's logic begins with the software that, perhaps from a designer's perspective, is easiest to grasp.

1. 'Spaces'

As designer, the first impression one gets from ENVI-met's 'Spaces' is its strictly orthogonal 3D modulation with its low maximum resolution of 0.5 x 0.5 x 0.5 m parallelepipeds (**Figure 21**). It translates space in a quite pixelated manner.

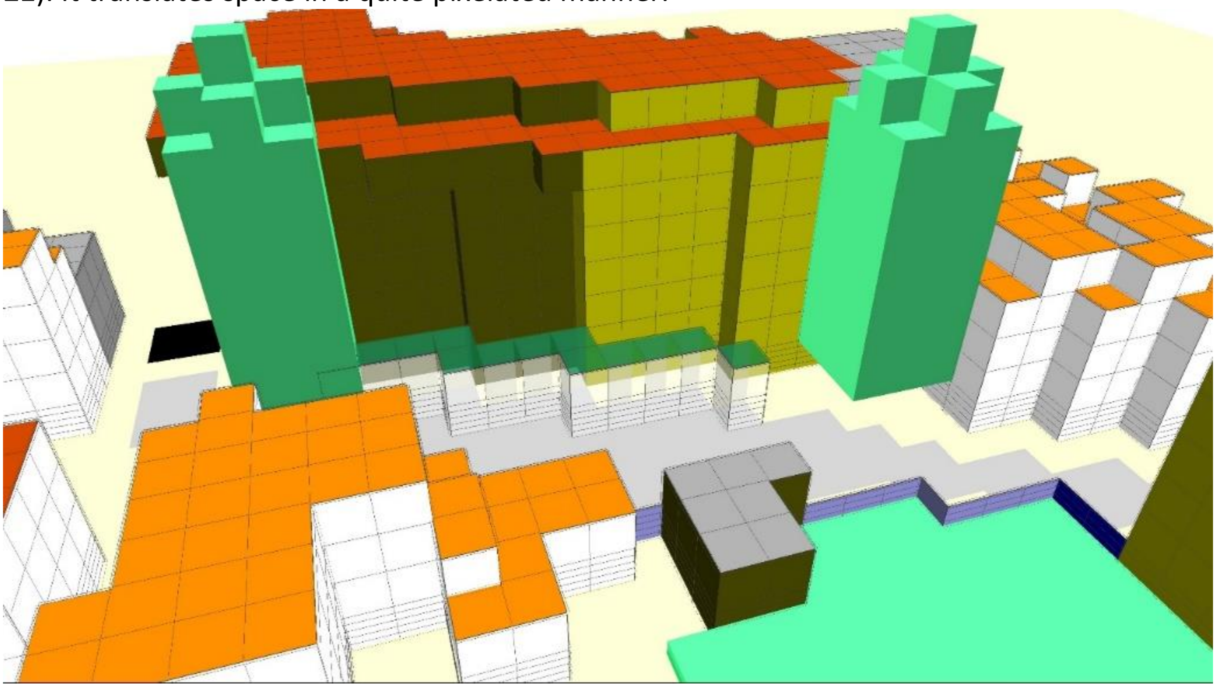

Figure 21: 'Scenario-3' 3D visualisation in 'Albero'
2 x 2 x 2 m grid cell size

Still, in order to keep the processing time of simulations within a reasonable time, it is common to use lower resolutions such as 2 x 2 x 2 m and, for the moment, ENVI-met's technical support recommends not to consider any topographical features in order to simplify the calculation and analysis (ENVI-met 2022). Hence, one should preferably consider sites where geographic features are not so significant and keep in mind that some finer details will not be possible to be included. The 'Spaces' model elements, although framed in these parallelepipedal grid cells, are organized as shown in **Table 15**.

'Spaces' elements	Description
'Buildings'	'Buildings', as its name suggests, are the elements that stand to represent buildings. These are always defined in all three dimensions and must specify a wall and a roof material – 'Wall/Roof Constructions' (2). It allows the presence and specification of vegetation on its walls and/or roof – 'Greenings' (4). Once 'Detailed Design' mode is set, one can fiddle with each individual parallelepiped face's material and whether it has and, if so, which vegetation on. Both 'Wall/Roof Constructions' and 'Greenings' settings are edited in 'DB Manager'.
'Vegetation'	'Vegetation' is sub-divided into 'Simple Plants' (5) and '3D Plants' (7). 'Simple Plants' aim to represent general ground cover – from grass to thicket of shrubs or even bushland. It is only defined in plan – two-dimensional – but its height and other properties are customizable when configuring the 'Simple Plants' in 'DB Manager'. '3D Plants' is a more elaborate composition that aims to represent individual trees. These are only located in Spaces but can be three-dimensionally modelled in 'Albero'.
'DEM'	'DEM' is used to model topographical features. However, as it is still recommended not to use them (ENVI-met 2022), these are not considered here.
'Soil and Surface'	'Soil and Surface' define the composition of the sub-soil down to 4.5 m deep and its surface properties through the attribution of 'Soil Profiles' (8) on plan – two-dimensionally (2D). 'Soil Profiles' are edited in 'DB Manager'.
'Sources'	Attempts to represent anthropogenic inputs – such as the emission of traffic pollution – but can also be used to translate a water fountain. These can only be defined on plan as a point, line or area. Its height and other properties can be edited in 'DB Manager'. These elements are not considered here.
'Single Walls'	'Single Walls' (9) are used to translate finer details that 'Buildings' cannot – such as garden fences and awnings. It can only be introduced in the model once 'Detailed Design' mode is set. These are three-dimensionally located but they are restricted to one face. Although the base of its localization is the ground plan, x-y, one can choose on which axel to locate it. Either vertically – x or y – or horizontally – z. One can define its total height, distance off the ground and material settings and, similarly to buildings, fiddle with every single surface's attribute or even delete them. 'Single Walls' properties are edited in 'DB Manager'

Table 15: Overview of 'Spaces' elements

The model space, or 'Model Domain', must be rectangular and properly geolocated, for the purpose to better reproduce the sun's path in the sky. As a rule of thumb, it is recommended to allow a distance between the 'Buildings' and the edge of the 'Model Domain' of at least the same as the height of the closest 'Buildings'. However, it is also possible to rotate it out of grid north and ensure a more effective size and grid direction 'Model Domain' without sacrificing the accuracy of its solar orientation (ENVI-met 2019).

'Spaces' presents two modes of edition. 'Concept Design' mode is the first stage where the model is translated in 2.5D. One cannot introduce 'Single Walls' or individually edit each cell face of a 'Building', for that, one must be in the second mode, 'Detailed Design', which is fully 3D. It is possible to build the whole 3D model in 'Spaces' however, when dealing with irregular shapes from reality and requiring an accurate transposition of *CAD* technical drawings into it, it might be challenging.

In that case, one can resort to 'SketchUp Pro' to import, for instances, the relevant *DWG*-format *CAD* drawing upon which one can model the volumes and then, through a plugin in 'SketchUp Pro' – 'Envimet-inx v2.0.1' (GitHub 2022) –, convert it into 2.5D *INX* format. This plugin allows one to, within 'SketchUp Pro', define the 'Model Domain' size, rotation and geolocation, within which it can be added and configured 'Buildings', with or without 'Greenings', 'Vegetation', 'DEM', 'Soil and Surface' and 'Sources' (ENVI-met 2020).

As one configures each element, one must already insert the intended database-ID codes. For instances, when configuring a 'Building', one must select the 'Wall/Roof Constructions' (2) for its wall and roof, and, if applicable, its 'Greenings' (4) by the corresponding database-ID. After all elements are configured within the also defined 'Model Domain', one must select all of them and, through the plugin, save as an *INX*-format file. One can then open it in 'Spaces' on 'Concept Design' mode. Any 'Single Walls' (9) or individual cell face edition of a 'Building' must be done in 'Spaces' once set to 'Detailed Design' mode (ENVI-met 2019). **Table 16** provides further information on the plugin's requirements regarding the to-be-converted SketchUp-entities in relation to the intended ENVI-met-entity type.

ENVI-met entity	SketchUp entity requirements
'Wall/Roof Construction' + 'Greening'	3D closed volume
'Soil Profile'	Surface
'Simple Plant'	Surface
'3D Plant'	Must be a component

Table 16: 'SketchUp' entity requirements in relation to ENVI-met entity (GitHub 2022)

At last, given the need to keep the number of parallelepipedal cells as low as possible, in order to save in processing times, the height of grid cells – z axel – can be varied using two features. 'Telescoping' the higher up grid cells – the grid cells' heights will increasingly grow at an editable rate from a definable height off the ground up – and/or splitting the lowest grid cell's height in 5 sub cells. This last feature can allow a finer data-processing at the volume of air closest to the ground. This is particularly important in regards to the height-dependent variation of impacts of longwave and diffused shortwave radiation emitted from the ground.

Following **Table 15**'s appearance order, each ENVI-met entity and associated software within the ENVI-met system is now further described. In the case of entities that are a make-up of a number of other 'composing entities' that may have not been previously described, those 'composing entities' are described in the next thereafter part.

2. 'Wall/Roof Constructions' – 'DB Manager'

'Wall/Roof Constructions' are a make-up of three layers of individual 'Wall/Roof Materials' (3) which can have different thicknesses. The three-layered combination allows better representation of the often-complex construction details of external walls and roofs. For instances, this allows the climatic differentiation between two façades which, despite both being rendered and painted with the same colour, only one has applied an External Thermal Insulation Composite System (ETICS). It is obvious that the presence of, say, 6 cm of insulation under the rendering layer instead of being in direct contact with the brick or stone substrate will result in reduced heat accumulation in the wall's inner substrate and increased heat in the wall's outer rendering layer. Apart from the definition of each layer 'Wall/Roof Materials' and thickness, one can define whether the construction can support 'Greening' (4), be only used as wall, roof or both and its aerodynamic roughness length of its outer layer. Oke et al. (2017, 479) define 'aerodynamic roughness length' as: *"Roughness length (z_0)- (also aerodynamic roughness length) a measure of the roughness of a surface to airflow. The theoretical height above zero-plane displacement at which the mean wind speed becomes zero when the logarithmic wind profile is extrapolated downward towards the surface. It can be approximated from the arrangement, spacing and height of the urban elements. (…)"*

3. 'Wall/Roof Materials' – 'DB Manager'

'Wall/Roof Materials' make up 'Wall/Roof Constructions' (2) and 'Single Walls' (9). **Table 17** shows the input settings that can be specified.

'Parameter'	Units	Definitions / Observations
'Absorption'	-	"Absorptivity (ϕλ) – the relative fraction of irradiance of a particular wavelength reaching a surface that undergoes absorption. Values of absorptivity range between 0 (no absorption) to 1 (blackbody)." (Oke et al. 2017, 469)
'Transmission'	-	"Transmissivity (ψλ) – the relative fraction of the irradiance of a particular wavelength reaching a layer of air that passes through without absorption or reflection." (Oke et al. 2017, 482)
'Reflection'	-	"Reflectivity (ωλ) – the relative fraction of the irradiance of a particular wavelength reaching a surface that is reflected." (Oke et al. 2017, 478) "Albedo (α) – the ratio of the shortwave radiation reflected by a surface (reflectance) to the shortwave radiation reaching that surface (irradiance)." (Oke et al. 2017, 469)
'Emissivity'	-	"Emissivity (ε) – ratio of total radiant energy emitted per unit of time per unit of area of a surface at a specified wavelength and temperature to that of a blackbody under the same conditions." (Oke et al. 2017, 472)
'Specific heat'	J/(kg*K)	"Specific heat (c) – amount of heat absorbed (or released) by unit mass of a system for a corresponding temperature rise (or fall) of one degree." (Oke et al. 2017, 480)
'Thermal conductivity'	W/(m*K)	"Thermal conductivity (k) – physical property of a substance describing its ability to conduct heat by molecular motion." (Oke et al. 2017, 482)
'Density'	kg/m3	–

Table 17: Input settings to be defined in 'Wall/Roof Materials'

4. 'Greenings' – 'DB Manager'

Similar to 'Wall/Roof Constructions' (2), 'Greenings' are a make-up of layers with customizable thicknesses of other database's elements. In this case, it must contain a layer of a 'Simple

Plant’ (5) and has the option to include three layers of ‘Soil/Ground Materials’ (6) as substrate. This substrate has further properties settings such as its emissivity, albedo, water coefficient and dimension of air gap, if any, between substrate and ‘Wall/Roof Construction’. Furthermore, LAI can be defined and also the ‘Leaf Angle Distribution’ – a range between the leaves’ surfaces being perpendicular and parallel to the substrate surface.

5. ‘Simple Plants’ – ‘DB Manager’

‘Simple Plants’ are used to make up ‘Greenings’ (4) or as independent entities over ‘Soil Profiles’ (8). **Table 18** shows the input settings that can be specified .

‘Parameter’	Units	Definitions / Observations
‘CO2 fixation type’	-	Either ‘C3’ or ‘C4’
‘Leaf Type’	-	Either ‘Gras’, ‘Deciduous’ or ‘Conifer’
‘Albedo’	-	Definition of Albedo in Table 17.
‘Transmittance’	-	Definition of Transmissivity in Table 17.
‘Plant height’	m	-
‘Root zone depth’	m	-
‘Leaf area LAD profile’	m^2/m^3	LAD value at each tenth of the plant’s height
‘Root area RAD profile’	m^2/m^3	Root Area Density (RAD) value at each tenth of total-root-zone depth
‘Season profile’	-	Monthly total leaf coverage rate

Table 18: Input settings to be defined in ‘Simple Plants’

6. ‘Soil/Ground Materials’ – ‘DB Manager’

‘Soil/Ground Materials’ are used to make up ‘Soil Profiles’ (8) and ‘Greenings’ (4). **Table 19** shows the input settings that can be specified.

‘Parameter’	Units	Definitions / Observations
‘Type of material’	-	Either ‘Natural soil’ (NS), ‘Artificial material’ (AM) or ‘Water body (deep)’ (WB)
‘Water content at saturation’	m^3/m^3	Water / soil
‘Water content at field capacity’	m^3/m^3	Water / soil
‘Water content at wilting point’	m^3/m^3	Water / soil
‘Matrix potential’	-	At water saturation
‘Hydraulic conductivity’	m/s* 10**-6	Ease of fluids to flow through material
‘Volumetric heat capacity’	J/(m3k) * 10**6	Of dry soil
‘Clapp & Hornberger constant b’	-	-
‘Heat conductivity’	W/(m*K)	Definition of Thermal conductivity in Table 17.

Table 19: Input settings to be defined in ‘Soil/Ground Materials’

7. ‘3D Plants’ – ‘Albero’

Being a 3D element, ‘3D Plants’ are configured in a specific software, ‘Albero’. Trees are translated in ENVI-met as a 3D agglomerate of parallelepipeds in space. Each parallelepiped, a grid cell, is set to have an amount of leaf area per volumetric unit of air, LAD. The same logic applies to the tree’s roots but as RAD. Originally, these tree models – ‘Grid Based Model’ –

were generated with a tool – 'Add rotation plant…' – that works as a lathe and is still limited to ENVI-met's resolution (**Figure 22**).

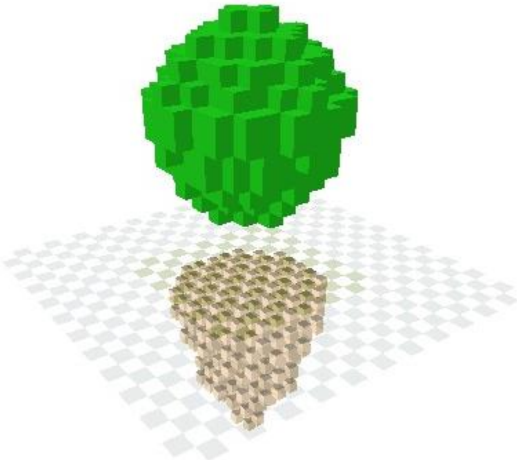

Figure 22: 'Grid Based Model' tree – 'Spherical, medium trunk, dense, medium (15m)*' – 01SMDM*
Source: 'Albero' 5

Recently, a new model – Quantified Structural Model – has been added, which shapes the tree in two steps (Bruse 2021). First, a finer 3D model of the tree, including its individual leaves, trunks and twigs, is created through Lindenmayer Algorithmic System – 'L-System' (**Figure 23**). Then, this finer model is translated into the grid-based model including its LAD values (**Figure 24**).

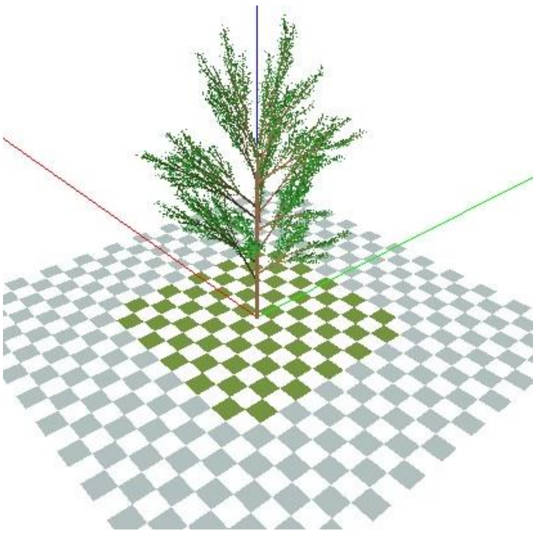

Figure 23: 'L-System'tree – 'Sweet Chestnut/Maron (middle)*' – 020032*
Source: 'Albero 5'

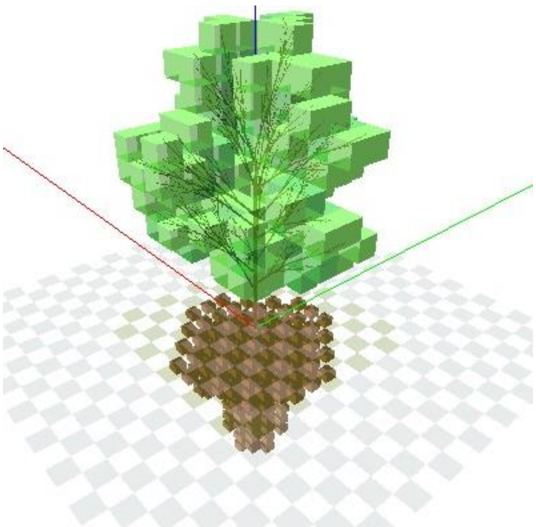

Figure 24: 'Quantified Structural Model' tree – *'Sweet Chestnut/Maron (middle)' – 020032*

Source: 'Albero 5'

The resulting model's shape and LAD-value variation is closer to that of a real tree. Nevertheless, both models result in the spatial distribution and the respective LAD or RAD values attributes of each grid cell. Beyond this 3D shaping and grid cell value attribution, one can specify the input settings shown in **Table 20**.

‘Parameter’	Units	Definitions / Observations
‘Basic plant physiology’		
‘CO2 fixation type	-	Either ‘C3-Plant’ or ‘C4-Plant’
‘Leaf Type’	-	Either ‘Grass-like Leafs’, ‘Decidous Leafs’ or ‘Conifer Leafs’
‘Foliage shortwave albedo’	-	Definition of Albedo in Table 17.
‘Foliage shortwave transmittance’	-	Definition of Transmissivity in Table 17.
‘Isoprene capacity’	-	-
‘Leaf weight’	g/m^2	-
‘Tree calendar settings’	-	Monthly total-leaf-coverage rate
‘Root zone’		
‘Root depth’	m	-
‘Root diameter’	m	-
‘RAD depth profile’	m^2/m^3	RAD value at each tenth of total-root-zone depth
‘Horizontal extent profile’	-	Fraction of total-root diameter at each tenth of total-root-zone depth
‘Plant biomechanics’		
‘Density of wood’	kg/m^3	-
‘Youngs modulus E’	GPa	-
‘Fraction young E to shear G’	GPa	-
‘Modulus of rupture – straight segment’	MPa	-
‘Modulus of rupture – branch connection’	MPa	-

Table 20: Input settings to be defined in ‘3D Plants’

8. ‘Soil Profiles’ – ‘DB Manager’

Similar to ‘Wall/Roof Constructions’ (2) and ‘Greenings’ (4), ‘Soil Profiles’ are a make-up composed of layers of other elements but, its layers’ thicknesses are not customizable. In this case, it is made up of ‘Soil/Ground Materials’ attributed to progressively thicker soil layers down to a 4.5 m depth and a total 19 layers (**Figure 25**). Beyond the vertical arrangement of materials, one can define the surface’s albedo (**Table 17**), emissivity (**Table 17**) and aerodynamic roughness length (2), as well as whether it is irrigated. Specific to water bodies, one can define its turbidity/extinction and mixing coefficient.

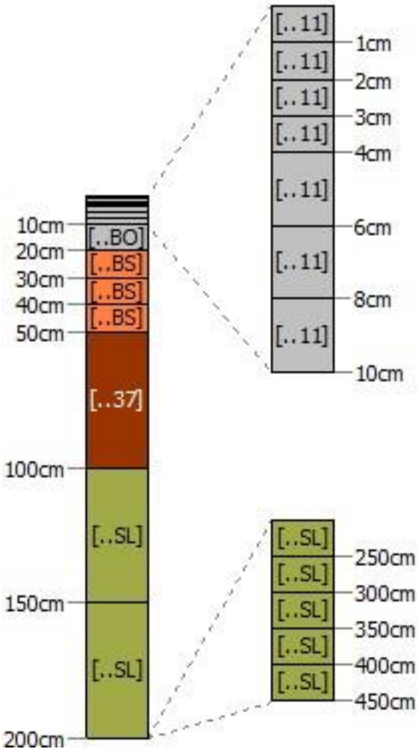

Figure 25: ENVI-met's 'Soil Profiles' layering framework
Source: 'DB Manager'

9. 'Single Walls' – 'DB Manager'

In contrast to 'Wall/Roof Constructions' (2), 'Single Walls' are only made up of a single layer of 'Wall/Roof Materials' (3) which thickness can equally be defined together with the material's aerodynamic roughness length (2).

The following parts move away from the 'Model Area File' and describe the software packages that configure the meteorological and simulation settings. Starting now with the meteorological settings.

10. 'Forcing Manager'

One can import *EPW/TRY*- or *CSV*-format data from weather stations into ENVI-met system through 'Forcing Manager' software. As for the *CSV* files, data must follow the same order, units and format as required by the system (**Table 21**) as well as information regarding the height at which the measurements were taken, the aerodynamic roughness length (2) and whether the radiation was measured on a horizontal surface. The imported data is then saved in *FOX* format which may be used to configure a simulation in 'ENVI-guide'.

Parameter	Format/Units
'Date'	DD.MM.YYYY
'Time'	HH:MM:SS
'Direct shortwave radiation'	W/m^2
'Low altitude clouds cover'	0-8
'Diffused shortwave radiation'	W/m^2
'Medium altitude clouds cover'	0-8
'Longwave radiation'	W/m^2
'High altitude clouds cover'	0-8
'Absolute air temperature'	K
'Relative Humidity'	%

Parameter	Format/Units
'Windspeed'	m/s
'Wind direction'	°
'Precipitation '	mm

Table 21: Formats or units to be used for importing weather data from a *CSV*-format file into 'Forcing Manager'

11. 'ENVI-guide'

'ENVI-guide' software is where the simulation is configured. One defines which 3D model – *INX*-format 'Model Area File' (1) – is to be tested under which meteorological conditions – this is where the *FOX*-format file from 'Forcing Manager' (10) can be used –, the time period to be simulated and whether the computer is only allowed to use a multi-core *CPU* for parallel processing. Beyond these, several other settings can be added as 'Optional Sections' that focus on 'Soil', 'Radiation', 'Building', 'Pollutant', 'Plant', 'Timing', 'Output' and 'Expert'. This simulation settings are then stored in a *SIMX*-format 'Simulation File'.

Here, only the 'Radiation Section' is analysed and which is divided into three aspects:

- 'Ray Tracing and IVS Height Cap' – how each grid cell calculates its incoming secondary radiation – long- shortwave radiation emitted and/or reflected from objects.
- 'Mean Radiant Temperature Calculation Method and Minimum Longwave Radiation Cap' – which method and model is used to calculate the mean radiant temperature;
- 'Advanced Canopy Radiation Module and Solar Adjustment Factor' – whether to use the advanced canopy radiation transfer module, which attempts to better simulate the scattering and attenuating effect within plants on direct shortwave radiation.

As for 'Ray Tracing', there is a recent development (Simon 2021). Up until version 5, ENVI-met would calculate each cell's incoming secondary radiation as follows:

$$Q_{total} = Q_{sky} * VF_{sky} + Q_{build,avg} * VF_{build,avg} + Q_{veg,avg} * VF_{veg,avg} + Q_{soil,avg} * VF_{soil,avg} \quad \textbf{(1)}$$

In **Equation 1**, Q_{sky} stands for radiation from sky and VF_{sky} for sky view factor. $Q_{build,avg}$ stands for average secondary radiation emitted/reflected from all-model's buildings and VF_{build} for building view factor. $Q_{veg,avg}$ stands for average secondary radiation emitted/reflected from all model's vegetation and VF_{veg} for vegetation view factor. At last, $Q_{soil,avg}$ stands for average secondary radiation emitted/reflected from all model's soils and VF_{soil} for soil view factor. The view factor is not only calculated from the upper hemisphere but also from the lower. The whole sphere view is considered. This method is called 'Average View Factor' (AVF) as it only considers the average value of radiation of each type of object in the whole model. If the, say, building that the grid cell's sphere sees is hotter than most, the radiation value for that fraction of building view is exactly the same as for all the other building views in the model (Simon 2021).

To allow a more accurate consideration of the obvious diversity of incoming-radiation values from objects, the 'Indexed View Sphere' (IVS) method allows each grid cell to store which and how much of which object is receiving radiation from. To this end, the analysis of the view sphere is subdivided into a number of facets, such as an assembly of several photographs to form a whole picture instead of only a single photograph. Each sphere's facet corresponds to a ray that is shot from the grid cell outwards and, as this hits an object, defines which part of which object is 'seen' in that direction and, hence, be considered. The number of facets can be customized and, obviously, the greater the number of facets, the greater the detail of the diversity of incoming radiation characteristics. Similarly, to the grid cell's height – z axel –

'Telescoping' and/or lower ones' subdivision mentioned in 1, it is possible to define a 'Height Cap' only up to which a higher precision of calculation is to be employed and, just like that, spare processing time.

12. 'ENVI-core'

'ENVI-core' is solely used to run the simulations, having as input the *SIMX*-format 'Simulation File' created in 'ENVI-guide' (11).

Appendix S: Appendices' references

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