Better-B

Deliverable D3.6

Hygrothermal model of empty hives

Point of Contact	**Ruffio Emmanuel**
Institution	**Co-Actions (COA)**
E-mail	**emmanuel.ruffio@alt-rd.com**
Phone	**+33672628965**

Project Acronym	**Better-B**
Project Title	**Improving Bees' Resilience to Stressors by Restoring Harmony and Balance**
Project No.	**101081444**
Topic	**HORIZON-CL6-2022-BIODIV-02-03-two-stage**
Project start date	**1 June 2023**
Nature	**Other (algorithm)**
Dissemination level	**Public**
Due date	**M24**
Date of delivery	**M24**
Lead partner	**CoActions (COA)**
Contributing partners	**University of Montpellier (UM)**
Author	**Ruffio Emmanuel (COA)**
Reviewers	**Matthew Webster (UU), Dirk de Graaf (UGENT)**

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

This work was supported by the Better-B project, which has received funding from the European Union, the Swiss State Secretariat for Education, Research and Innovation (SERI) and UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (grant number 10068544).

Revision History

Version	Date	Author	Comment
0.1	12.05.2025	Emmanuel Ruffio	First draft
0.2	22.05.2025	Matthew Webster	Review by the WP leader
0.3	23.05.2025	Anna Dupleix	Minor revisions
0.4	26.05.2025	Emmanuel Ruffio	Update of Figure 5
0.9	27.05.2025	Dirk de Graaf	Review by the coordinator
0.95	27.05.2025	Kirsten Leufgen	Version for review and approval by the general assembly
1.0	28.05.2025	Lina De Smet, Kirsten Leufgen	Final version, approved by the general assembly

Contents

Abbreviations, Participant short names

Participant short names

AU	**Aarhus Universitet**
COA	**Co-Actions**
IPB	**Instituto Politécnico de Bragança**
IRIAF	**Instituto Regional de Investigación y Desarrollo Agroalimentario y Forestal de Castilla-La Mancha**
IZSLT	**Istituto Zooprofilattico Sperimentale delle Regioni Lazio e Toscana**
KUL	**Katholieke Universiteit Leuven**
MLU	**Martin-Luther-Universität Halle-Wittenberg**
NB	**Norges Birokterlag Forening [Non-governmental organisation**
SCIPROM	**SCIPROM Sàrl**
TNTU	**The Nottingham Trent University**
UCOI	**Universidade de Coimbra**
UGENT	**Universiteit Gent**
UJAG	**Uniwersytet Jagiellonski**
UM	**Université de Montpellier**
USAMV	**Universitatea de Științe Agricole și Medicină Veterinară Cluj-Napoca**
UU	**Uppsala Universitet**
VDSJ	**Van Der Steen Joseph**
WR	**Stichting Wageningen Research**

List of Figures

Summary

This document provides an overview of the hygro-thermal models implemented in the Better-B work on thermal interactions between empty hives and their environment, which contributes to the project's research on resilience to climate and heat stress. The objectives of these models are to provide tools to analyse and to simulate the hygro-thermal behaviour of empty hives. Moreover, they constitute the basis of all future developments which are planned for the thermal analysis of inhabited hives.

The first section recalls the context of this deliverable, where it comes from and where it goes. The software and the programming language are introduced as well as the reasons behind these choices. The main assumptions used to derive these models are also mentioned. The online GitHub platform is then introduced with the concept of cloud-based repository. This online tool was indeed chosen to ease the further developments of these models and favour their dissemination, especially among researchers.

The second section introduces and describes the current content of the GitHub repository. A brief description of the directories and files is given.

The main results are finally discussed and possible future developments for the next two years are outlined.

1. General description

1.1 Context

This deliverable is part of our study of thermal interactions between an empty hive and its close environment. We chose to work exclusively on empty hives to focus on the thermal effect of materials, coatings, geometry and surrounding environment. Although beekeepers in northern and southern Europe use very different type of hives due to climate constraints, the emphasis was made on the Dadant hive which is common in middle latitude of Europe. Since it is quite similar to the Langstroth hive, conclusions drawn for the Dadant hive may probably hold for this type of hive and for other similar frame-based hives.

As a comparison, two other hives are analysed: log hive and one ecological hive (Figure 1). These hives differ by their objectives and by their thermal characteristics. Dadant hives are commonly used by professional beekeepers since they are convenient for honey production. The log hive was well known in some regions of France but is no longer used by professionals. Its main thermal characteristic lies in the fact it is put on the ground and thus benefits from its large thermal capacity that strongly mitigates temperature variations. The ecological hive considered here was designed to mimic the trunk hive characteristic (thick and insulated walls) but is not put directory on the ground to preserve wood from moisture. Moreover, this hive was designed with the bee colony health in mind and not honey production.

Better-B work on thermal interactions between empty hives and their environment was divided into several independent studies:

1. Analysis of heat and mass transfer between a hive and its environment, development of simplified steady state models and estimation of physical parameters involved using scientific literature or experiments.
2. Development of a hygro-thermal model to simulate the evolution of in-hive temperature and humidity.
3. Development of dedicated sensors and in-field instrumentation of hives to get reliable data to compare hive thermal behaviour and to provide reliable input data for the models.

This deliverable is related to the second point and consists of a set of algorithms developed for these three types of hive. For each hive type, two algorithms have been implemented based on a hygro-thermal model. The first is devoted to the simulation of in-hive temperature and humidity based on weather conditions given the hive parameters (related to the hive geometry, hive environment, hive materials).

The second algorithm is used to perform a parametric study of the hive. More precisely, it consists in computing the so called "sensitivity functions", i.e., the temperature and humidity changes induced by a change of any parameter. It allows identifying the key parameters that have the largest effect on the in-hive climate and which have the greatest impact on the passive thermal robustness of an empty hive. In this

a) Dadant hive

b) Log hive with the stone roof removed

c) Ecological hive with octagonal shape and roof removed

Figure 1. Dadant hive, trunk hive and ecological hive analysed

context, the thermal robustness of a hive is a measure of the in-hive climate stability versus external changes. The parameters can be related to the hive materials, the hive structure (thickness, stacking…) or the hive environment (ground albedo, shading, surrounding objects…).

1.2 Programming language

The hygro-thermal models and the algorithms which derived from them, are implemented in Octave programming language (https://octave.org/). Octave is a software and a language for scientific computing first released in 1994. Octave is free, opensource and is released under the GNU General Public License. It is available on all common platform (Windows, GNU/Linux, macOS, BSD). The core functionalities of Octave are very similar to the widely used, well-known and commercial MatLab software developed by MathWorks company. Although Octave is licenced under GPL, programs developed in this language can be released under any licence.

1.3 Motivations

There are currently numerous softwares available to perform thermal modelling such as the open-source library "TNSolver" for Octave and the Simscape package (especially its thermal library) for Matlab. However, they are too limited to perform beehive simulation since it involves 3D heat conduction in quite complex shapes and these tools are not designed for this. On the other side, commercial softwares (like Comsol, Fluent, Simcenter…) with extended modelling capacity are widely used in the industry and allow complex systems to be modelled using convenient graphical user interface. However, it turns out they might not be appropriate to future needs of the Better-B project and after the Better-B project. Several reasons can be mentioned:

- They are generally expensive which restricts their usage to laboratory or industry.
- In a research context, it is preferable to have complete knowledge and control on the equations involved in the model and on the numerical methods used to solve them.
- For future developments within the Better-B project, especially for the thermal analysis of inhabited hives, it is desirable to have command-line based model instead of a graphical user interface. Indeed, the hygro-thermal models of hive will probably be integrated in an optimization procedure to estimate the energy produced by the colony.
- Concerning future development: due to the extensive modelling possibilities, commercial softwares involves generally more computationally intensive algorithms than dedicated and specialized software. Although, computation time is currently not so relevant, it may become a key element in future development with embedded devices.

1.4 Assumptions

The hygro-thermal models are developed based on standard physical equations related to heat and mass transfers. Among the numerous underlying assumptions of such models, it is worth mentioning several key assumptions that were done for their development:

- No fluid dynamic modelling: the air inside the hives is assumed static.
- The heat transfer model and the water transfer model are weakly coupled. It means the water transfer does not change significantly the temperature profiles in the hive. In practice, the heat transfer equations are first solved to compute the temperature profiles in the hive. These profiles are then introduced into water transfer equations to compute the vapour flow through the parts of the hive.
- The water transfer equation is mono-dimensional and the moisture content of the wood is assumed to be lower than the fibre concentration point.

These models are implemented assuming a specific hive geometry. If the geometry is changed, for example by adding a super, an insulation material, by closing the floor, the hygro-thermal model has to be changed accordingly.

Some of the assumptions mentioned above may be relaxed later if the future developments for the thermal analysis of inhabited hives show the need to do so. For example, the fluid dynamic inside the hive is currently taken into account by using convection coefficient, but simplified Navier-Stokes equations could be solved to handle more complex air dynamic, especially around the frames.

1.5 Library dependency

The hygro-thermal models are implemented using a library called “HiveTemp” developed by COA since 2021. This library was then further developed for the University of Montpellier (UM) in a French national funded project [3] between 2022 and 2023. This library is in constant evolution and in the context of the present study, among numerous minor improvements and bug fixes, new functions were added to this library:

Functions to solve the unsteady one-dimensional water transfer equation in wood.

A function was implemented to solve the 3D heat transfer equation inside a hollow cylinder.

A function was added to compute the self-shadowing effect of trunk hive roof.

The models released in this deliverable are the basis for the thermal analysis of inhabited hives by developing a hygro-thermal model of the bee colony. This model will be integrated inside the empty hive model. As a result, the algorithms and the corresponding source files released in the present work will be continuously improved and updated in the coming two years, for thermal analysis of inhabited hives.

1.6 Dissemination

To ease the dissemination of this deliverable and to keep track of all future updates, it was chosen to release the source code of the models and of the HiveTemp library on internet using a public GitHub repository. GitHub (https://github.com/home) is a well-known cloud-based platform that provide online services for storing and managing project files. It provides tools for collaborative work, and an online version control for tracking all changes done to the project. A repository is the name given to a cloud storage used to host the project files. It can be private or public. If public, all files are freely accessible over the internet. However, to allow anyone to use, change or distribute the project, a licence must be specified. Since HiveTemp is distributed under the GPLv3 licence [1] which is a copyleft licence, this deliverable must use the same licence since it reuses part of HiveTemp library source files. The GitHub repository can be accessed at the following address: https://github.com/Alt-RD/Better-B.

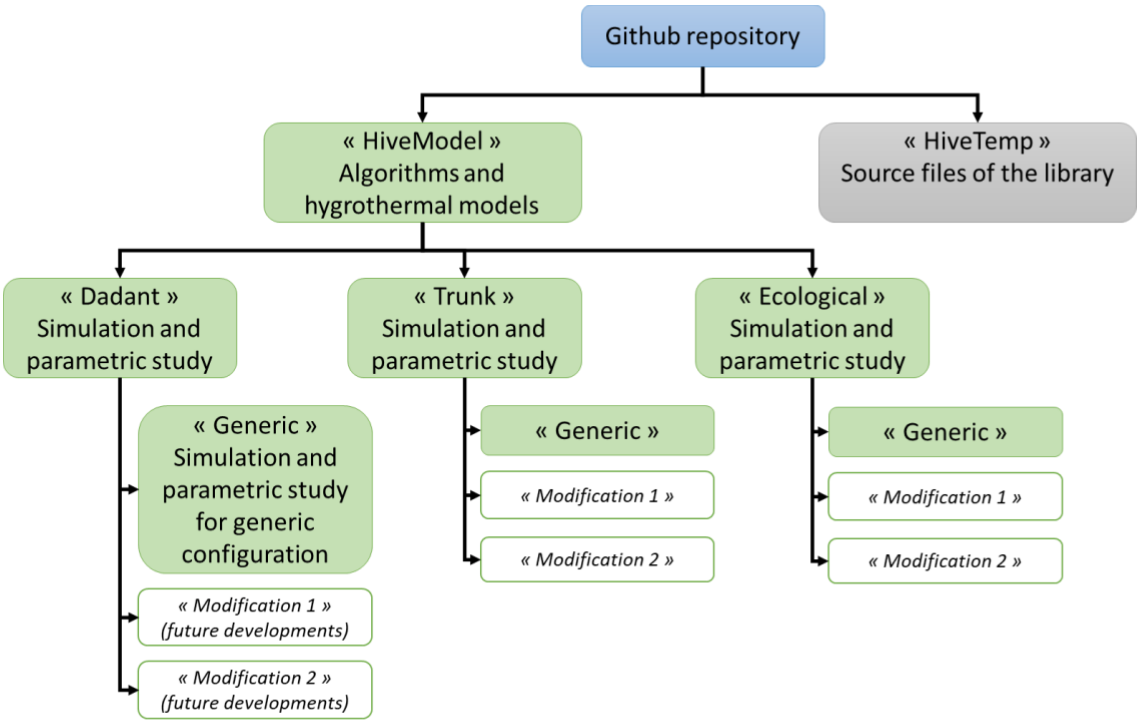

Figure 2. Structure of the GitHub repository with the main directories

2. Description of the GitHub repository

2.1 Content

The GitHub repository currently contains about 90 source files written in Octave programming language. These files are named and grouped into directories based on the operations they perform. There are two main directories at the root of the repository (Figure 2):

The "HiveModel" directory contains the files related to the hive hygro-thermal models (about 20 files) implemented based on the HiveTemp library.

The "HiveTemp" directory contains all files related to the HiveTemp library (about 70 files).

The HiveTemp library is a set of functions which perform basic operations. They must be combined to define the geometric shape of the hive and to solve the heat and mass transfer equations. To keep the HiveTemp library general and independent of any specific application, it was chosen to separate the hive hygro-thermal models from of the HiveTemp library.

Each source file of the repository contains the standard header of the GPLv3 licence Figure 3. Few lines are added to mention the Better-B project. Concerning the source files of the HiveTemp library, the header was changed similarly only for the files that were significantly changed for the present thermal analysis of empty hives.

Since both the hive models and the HiveTemp library are in full development, no comprehensive documentation has been written yet. Instead, it was preferred to add a brief documentation inside the source files, below the licence header. This approach allows easy update of the documentation and prevent mismatches with the current source code version that would be misleading for the user.

```
%  This file is part of project HiveModels.
%  This work was supported by the Better-B project, which has received
%  funding from the European Union, the Swiss State Secretariat for
%  Education, Research and Innovation (SERI) and UK Research and
%  Innovation (UKRI) under the UK government's Horizon Europe funding
%  guarantee (grant number 10068544).'
%  https://www.better-b.eu/
%
%  Copyright (c) 2023-2025: CoActions-AltRD-Emmanuel Ruffio
%  Author: emmanuel.ruffio@alt-rd.com
%
%  HiveModels is free software: you can redistribute it and/or modify
%  it under the terms of the GNU General Public License as published by
%  the Free Software Foundation, either version 3 of the License, or
%  any later version.
%
%  HiveModels is distributed in the hope that it will be useful,
%  but WITHOUT ANY WARRANTY; without even the implied warranty of
%  MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
%  GNU General Public License for more details.
%
%  You should have received a copy of the GNU General Public License
%  along with HiveModels.  If not, see https://www.gnu.org/licenses/
```

Figure 3. Licence header inserted at the top of every source file

2.2 Hive models

The directory “HiveModel” contains the source files of hygro-thermal models. It is split again into three subdirectories, one for each hive type: Dadant, Trunk, Ecological (Figure 2). To anticipate future developments related to hive modifications, a directory called “generic” contains the hygro-thermal model of the hive using its standard configuration, i.e., with no significant or specific change. The same approach is used for the two other hive types.

For each hive configuration, the corresponding directory contains a set of about 10 files (Figure 4) that correspond to the two algorithms: simulation and sensitivity analysis (parametric study). The set of files is generally the same for all hives and configurations, but this rule is not strict. More files may exist if it is considered convenient. The source files are split in two types: scripts (with prefix “s”) and functions (without prefix). Scripts can be executed directly in Octave software whereas functions require input arguments to be specified. Defining functions is not mandatory but it allows splitting the main algorithms into several independent sections to avoid excessively large source files, prevent code duplication, improve readability and ease comprehension.

Concerning the directory called “input”, it contains data files related to local weather conditions that can be selected as input data to run the simulation or the sensitivity analysis. External weather conditions can be provided by several different sources: database [4], models, or in field measurements. For this deliverable, this directory contains the data provided by the experimental apiary where the hives are installed.

« Dadant » Simulation and parametric study

« Generic »: Simulation and parametric study

« Input »: Data files specifying external weather conditions that can be used as input data for simulations or parametric studies.

sSimulation.m	Script file: main source file to start a simulation
sSimulationPlot.m	Script file: plot the result of a simulation
sSensitivity.m	Script file: main source file to perform parametric study
sSensitivityPlot.m	Script file: plot the result of the parametric study
SetupParams.m	Function: set up all parameters of the hive defined by the user
SetupThermalModel.m	Function: build the thermal hive model based on hive parameters
SetupHygroModel.m	Function: build the hygro -thermal hive model based on hive parameters
SimulationSetupCommands.m	Function: set up the commands (ex: weather conditions) that will drive the simulation
SensitivitySetupCommands.m	Function: set up the commands that will drive the parametric study

Figure 4. Standard source files for each hive type and for each configuration

2.3 HiveTemp library

The directory "HiveTemp" contains the source files of the HiveTemp library. Although this library has been developed by COA for thermal modelling of hives, it is not restricted to this field.

The general principle of this library is to define complex shapes (like beehives) by defining and connecting elementary shapes like rectangular cuboids (Figure 5). A space discretization using the Finite Volume Method (FVM) [2] is then applied to each elementary volume to get a matrix formulation of the heat and mass transfer equations. The matrices of all elementary volumes are finally merged into larger matrices to get one single matrix equation which is solved numerically by applying a time discretization.

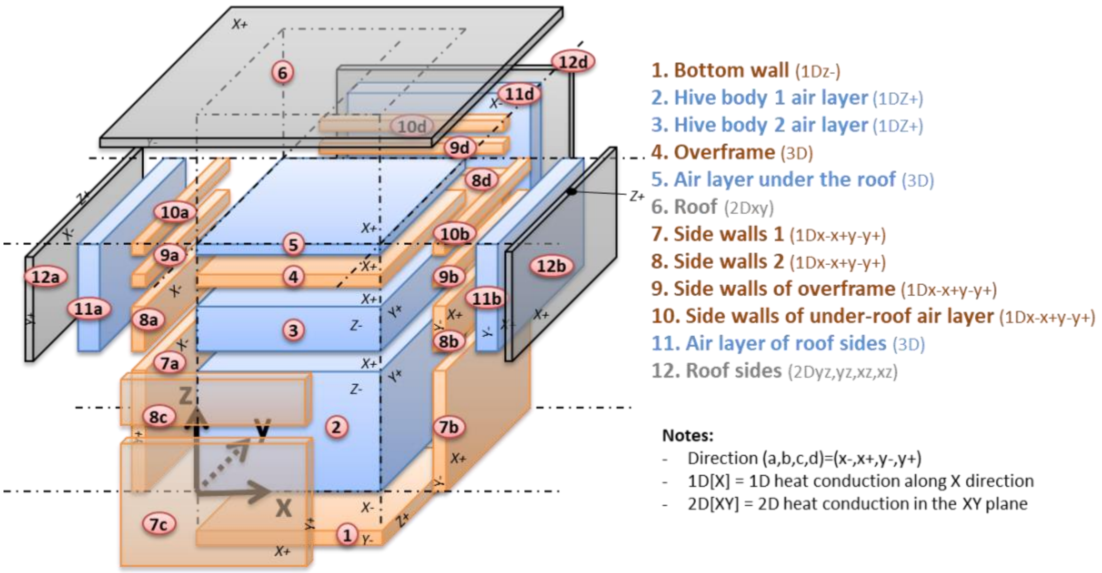

Figure 5. A Dadant hive geometry defined by a composition of rectangular cuboids using the HiveTemp library

A brief description of each directory and file is given in Figure 6.

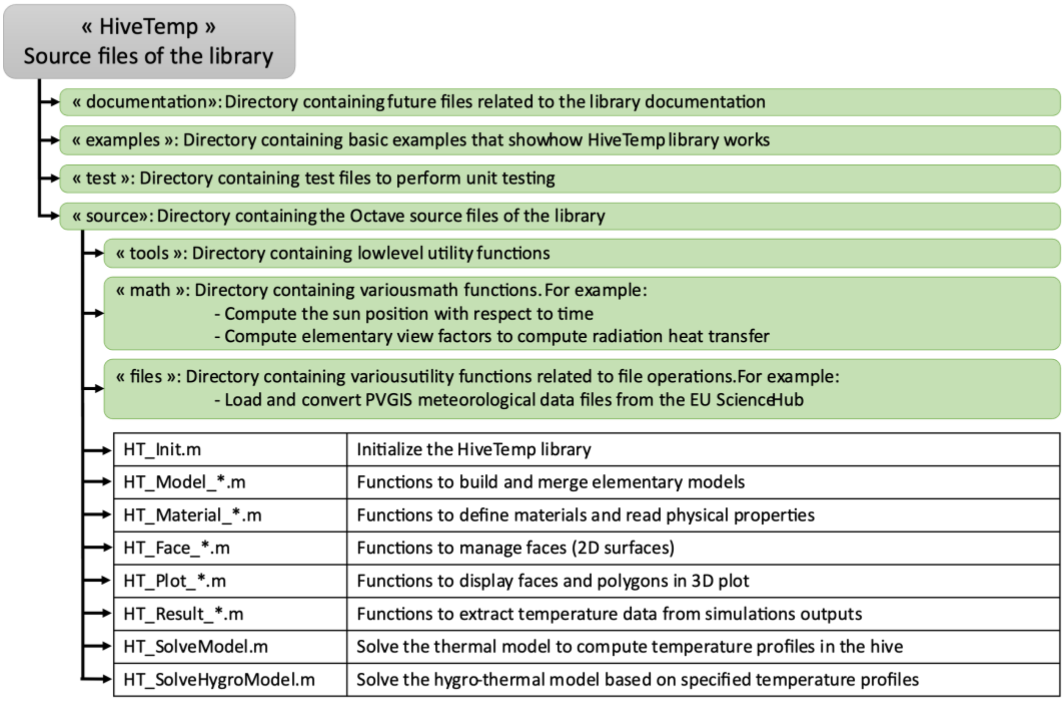

Figure 6. Description of directories and files in the HiveTemp library

3. Conclusion

The main objective of our study of the thermal interactions between empty hives and their environment was to set up several tools for experimental, theoretical and numerical analysis of beehive thermal behaviour, especially the thermal interaction between the hive and its environment. Specific sensors and methods were developed and are now fully operational so that experiments are continuously running.

Despite its apparent simplicity, the heat and mass transfers inside an empty hive involves many physical processes. Until now, most analysis were driven by experimental results. A theoretical analysis of heat transfer was generally done after in-field experiments revealed interesting or surprising results. For example, once it was clear that a black roof was similar to a steel roof in term of temperature, a simplified steady state thermal model was setup and experiments in laboratory were carried out to understand the interaction between the sun radiation and the external faces of the hive, especially the roof. As the roof turns out to be significant for the in-hive temperature and the centre of attention of many beekeepers, an additional model was developed and an algorithm was implemented to compute the steady-state heat transfer through the hive roof depending on materials properties and how materials are stacked up. It allowed the thermal conductance of many different roofs to be estimated and compared. It is not surprising that beekeepers have shown interest in this kind of results since they are quite straightforward to understand and closer to their practical questions.

Concerning the present deliverable, it is all about the numerical aspect of thermal interactions between empty hives and their environment. A hygro-thermal model was developed based on a theoretical analysis of heat and mass transfers for three different hive types: Dadant hive, log hive and one ecological hive. These models were then implemented using the Octave programming language and the HiveTemp library. Some additional functions have to be developed for this library to deal specifically with mass (water) transfer within wood. To simplify calculations, several key assumptions were made, related to the fluid dynamic, the coupling between heat and mass transfer, etc.

The simplified models described above are local and assume all physical quantities are independent of time. On the contrary, the hygro-thermal models are now based on the unsteady heat and mass transfer equations which means the models are able to simulate the time evolution of the temperature and humidity anywhere inside the hive. However, this obviously requires making lots of assumptions and many parameters have to be specified by the user, related to the geometry, the materials, the coatings or the environment.

A public GitHub repository was set up to store all source files related to the models and the library. An overview of the main directories and main files were given. The GPLv3 licence was chosen to protect the project files and to ease the dissemination of these tools.

4. Outlook

The hygro-thermal models of this deliverable are the basis of the future work in Better-B project. For the thermal analysis of inhabited hives, these models will be extended by developing an hygro-thermal model of the bee colony. In this next task, two algorithms will be developed as well: (1) to estimate the energy produced by the colony and (2) to predict critical hive temperatures several hours or few days before. Although it is not clear yet if this modelling approach is the most convenient and will be appropriate for such algorithms, the knowledge acquired from this work give valuable insights for their development. Not only is the prediction precision uncertain, the main drawback of such direct modelling approach is indeed the large number of input parameters and boundary conditions that must be provided by the user. It is obviously out of question to ask the user, especially the beekeeper, to specify such technical data. Moreover, hygro-thermal models remain quite technical and involve numerous simplifications and assumptions, as well as specific mathematical and numerical tools. As a result, numerical simulations are a useful tool for researchers to understand the heat and mass transfer dynamics but they are unfortunately of little use to the beekeeper.

However, the sensitivity analysis that can be carried out by these models give much more valuable information for the beekeepers and is at the core of ongoing works in task 6.1 which consists in producing an illustrated booklet to give guidance in hive construction under climate change pressures. By using a sensitivity analysis, it will be indeed possible to have a good insight to the answer of the question “what happens if I change this”. For example, what happens if the thickness of hive walls is reduced? What happens if the hive is rotated? What happens if the insulating material is inserted? What happens if an aluminium sheet is installed there? What happens if the roof is painted? The hygro-thermal models will thus be used to perform comprehensive numerical sensitivity analysis that will complement and validate some of the sensitivity analysis that are carried out experimentally using instrumented hives.

The GitHub repository that was set up is a convenient tool to store, track and manage any modifications done to the project by either the authors or by anyone who want to contribute to and distribute this research. As it stands now, it is primarily aimed at researchers in thermal sciences. Some parts could become accessible to beekeepers with engineering background through relatively few additional developments, such as a more extensive documentation or the implementation of a graphical user interface which is possible in Octave software. Although it is not planned in Better-B project, it may be developed in the future. It is indeed believed this GitHub repository is a long-term project and will remain active after the end of the Better-B project.

References

[1] GNU General Public Licence, Version 3, 29 June 2007, https://www.gnu.org/licenses/gpl-3.0.en.html

[2] Eymard R., Gallouet T., Herbin R., The Finite Volume Method, Handbook of Numerical Analysis, North Holland, 2000, P. Ciarlet et J.L. Lions, 713-1020

[3] Project « Outil numérique d’aide à la décision pour limiter l’impact du réchauffement climatique sur les colonies d’abeilles domestiques », LMGC, Laboratory of Mechanics and Civil Engineering, Funded by France-Relance-ITN6, Sep. 2021

[4] Photovoltaic Geographical Information System (PVGIS), The Joint Research Centre: EU Science Hub, 05/2025, https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en