INTELLIGENT ROOFTOP GREENHOUSES AND GREEN SKYLINE CITIES

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ABSTRACT

The paper proposes a new concept of green building, able to oppose the global warming, the Intelligent Rooftop Greenhouse iRTG, as a development of the Integrated Rooftop Greenhouse IRTG. Our approach is to replace conventional roofs with IRTGs, which are constructively connected with the interior of the building by flows of energy, gazes (mainly O_2 enriched air from RTG to building and CO_2 enriched air from building to RTG) and water in order to improve the building's metabolism. A tight human plant symbiosis is created such way. iRTGs perfect this architecture by actively controlling the energy, gazes and water flows, by collecting the available renewable energy resources (geothermal, sun, wind) and by adding Internet of Things IOT features to the system, in order to connect it to a surrounding Smart City. This way iRTGs may achieve an efficient integrated management of energy, gases and water, using just existing technologies: heat pumps (water to water for building's basement and air to air for greenhouse), solar panels, IOT equipment, etc., controlled in a smart/intelligent manner. If a Smart City is composed mostly of iRTG buildings it becomes a Smart Green Skyline City, with low carbon footprint and high carbon offset. The paper provides a mathematical iRTG model.

Keywords: Roof top greenhouse, building metabolism, renewable energy, mathematical model, urban sustainability.

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INTRODUCTION

Each oxygen molecule we breathe was produced by photosynthesis. Oxygen is very reactive, without the presence of plants most of oxygen atoms would be fixed into diverse inorganic compounds. Unfortunately, especially starting from the Industrial Revolution around 1760, our civilization intervened into the natural balance of the atmosphere, replacing huge amounts of oxygen with carbon dioxide, as a result of burning fuels and deforestations. CO_2 is causing global warming because of the greenhouse effect. This tendency put in danger our very future and as rational and responsible beings, we must find solutions for a new sustainable technological establishment, before being too late.

The last decade witnessed the beginning of an historical shift towards low foot-printed and high offsetting carbon dioxide technologies. The political will of the majority of the countries to oppose global warming has been officialised by the the 2015 United Nations Framework Convention on Climate Change of Paris [1].

Practical solutions to materialize the 2015 Paris Convention proved to be not easy to find and the shift towards green, recyclable and low energy materials and for the efficient exploitation of the renewable energy is expensive even for rich countries. We still believe in a favourable conjuncture for questing and testing new concepts, in the sense of the Paris Convention's, since the actual building and renewable energy technologies have reached the maturity stage, offering a wide variety of products at settled prices.

What is still missing are the holistic and synergistic visions, able to optimize the current efforts towards carbon fingerprints reduction and offset increasing.

Our approach assumes the following arguments:

- We must rebuild a sustainable balance between humans and plants at planetary scale;
- The only meaningful resource we dispose is represented by our cities;
- Simple and cheap solutions for chronical issues are not to be expected, a multi¬disci-plinary and holistic approach is needed, in the sense of the System Engineering, includ-ing Physics, Civil Engineering, Renewable Energy and Water Management, Human and Plant Physiologies, Architecture and Urbanism, Information Technology, Economy, etc.
- Binding so many elements into a single feasible entity is possible only if we will be able to identify and to grow synergies between them.
- Our strategic objective is to build a new relationship between cities and agriculture.

CITY AND AGRICULTURE

Traditionally, people were living in villages and towns, while agriculture was practiced on the surrounding lands. That is natural, given the big land surfaces asked by tra-ditional outdoor agriculture to feed the population. Agriculture was to be found inside cities only during food crises (consequences of natural or political catastrophes, sieges, etc.) We consider the actual climate changes as a major crisis in development, so we wish to bring again agriculture into our cities. This approach is now of high interest for the scientific research. One can identify two significant approaches:

- *Urban Agriculture* (UA) [2], [3], etc. working on modalities to cultivate plants into cities. At present, UA is a growing trend with a broad variety of typologies, from hightech to traditional, from private terraces to public gardens. UA brings numerous ad-vantages: it promotes sustainable development, food safety and affordability, environmental and food education, local economy, biodiversity and therefore it should be in-cluded in cities urban and management plans.

However, even if one can find small vineyards even in metropolis such as Paris, we consider that UA is not a sustainable solution, because unshackled land surfaces into cities are just exceptions to the rule of increasingly crowded towns.

- *Building-Integrated Agriculture* (BIA) [4], [5], working on modalities to cultivate plants into or onto buildings. Since outdoor urban land surfaces are severely insufficient for agriculture, the only sustainable option remains BIA. Introducing decorative plants into our environment is welcome, it creates a sense of comfort and beauty. However, if we want to achieve a significant carbon offset, plants' density should be much higher than the decorative level, which is hardly acceptable. A thumb rule inferred from references (ref. [6] for instance) shows that the carbon footprint of one person can be neutralized by 222 m2 of hardwood trees, which is roughly equivalent to the same surface of a wellmanaged greenhouse. Obviously, a building's inner space is not appropriate for this task.

BIA onto buildings means to overlap plants habitat upon hu¬mans' habitat. We assume that this is the best solution for our problem. The idea is not new, Rooftop Greenhouses (RTG) are wellknown for decades. Replacing the rather useless traditional roofs with greenhouses exerts some constructive difficulties, offering instead the presence of plants and better insulations for buildings. However, RTGs have failed to overcome the demonstrative stage, due to a weak economic efficiency. Their current applications are so far restricted mostly to industrial parks [7] or office buildings [8].

The newest concept in this sense, the Integrated Rooftop Greenhouse (IRTG), seems to be destined to a better future [9], [10], [11]. Integrating RTGs with buildings means to introduce air, energy and water exchanges between them, creating an indoor humansplants symbiosis, with numerous advantages for both sides, given their complementarity. IRTG present an improved building metabolism and constitutes a platform for integrated energy, water and gases management, including the surrounding renewable energy and water resources [9]. These connections are lacking at conventional RTGs.

A Spanish initiative towards the identification of potential IRTG locations in cities uses special maps realized by airborne sensors, Light Detection and Ranging (LIDAR) and Long Wave Infrared (LWIR) [12].

THE BARCELONA INTEGRATED ROOFTOP GREENHOUSE

The first IRTG prototype is to be found in Barcelona, as a result of the FertileCity Project. The Institut de Ciència i Tecnologia Ambientals (ICTA) IRTG is located in the Autonoma University Campus of Bellaterra, Barcelona, Spain. The building was designed and built in 2014 as a compact, multi-functional volume, with energy efficiency and employing mainly the BIA concepts. The building's area is of 7,200 m2 distributed in 6 plants with offices, lab-

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oratories, common spaces, parking and warehouses [17]. The building has four RTG spaces of around 490 m2 that are inte-grated into the building's roof and make up the ICTA-IRTG (Fig.1), aiming to grow crops by hydroponic technology and also promoting the humans-plants symbiosis. That allows to maintain the ideal condi-tions indicated by FAO for the cultivation of vegetables in Mediterranean areas (14 °C to 26 °C).

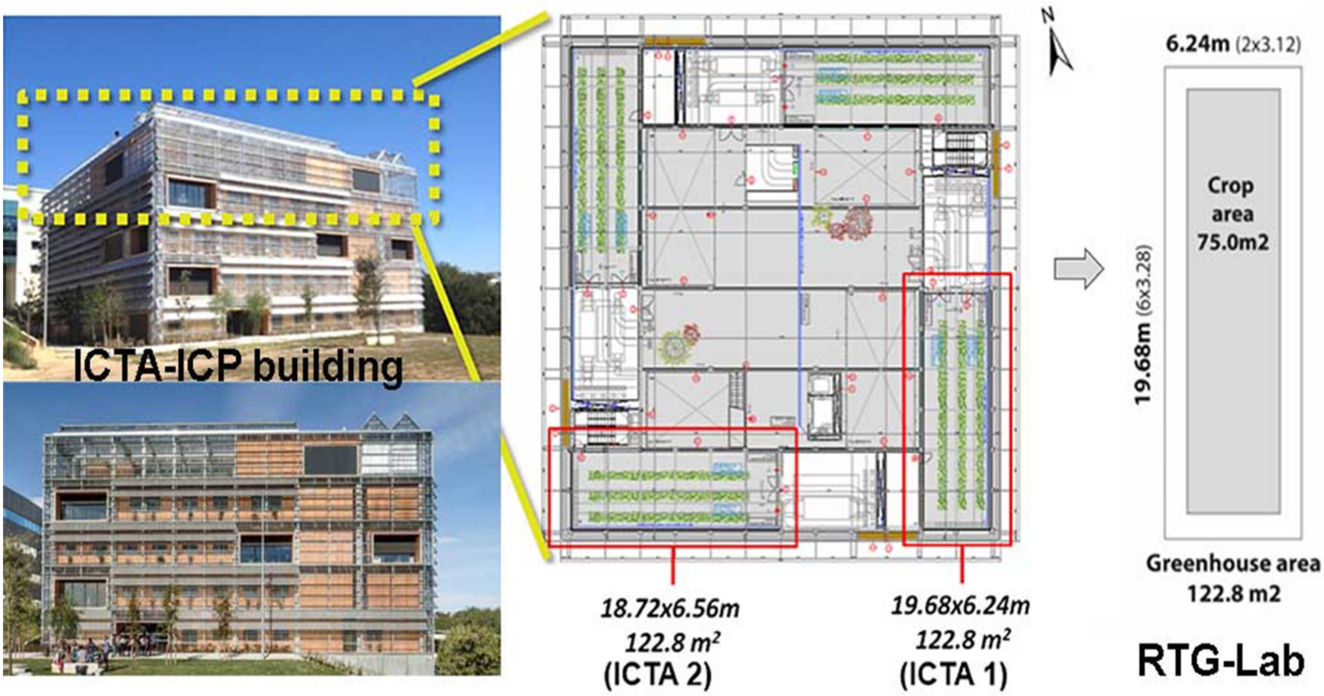

Fig 1. The ICTA building with the Integrated Rooftop Greenhouse [9]

The most favorable seasons for the IC-TA-IRTG crops proved to be autumn, win-ter and spring. Thus, with an average tem-perature of 20.3 °C (maximum of 26.1 °C and minimum of 16.1 °C), which is an ideal range in the Mediterranean area, the au-tumn turned out to be the ideal season for the highest yield of the crop. During win-ter the behavior of the ICTA-IRTG was also satisfactory. Summer, on the other hand, turned out to be the most difficult season for the proper development of the crop, because of the overheating [17].

The ICTA building is structured around a central atrium and has a double skin façade. One takes advantage of the re-sidual heat of the building (e.g., air from the labs), the CO_2 concentration in this residual air (which will be used as natural fertilizer), and the rainwater collected on the rooftop. The ventilated air from the occupied spaces is delivered to IRTG by air handling units (AHUs) and the displace-ment ventilation and air heated by solar radiation is rising through the double skin cavity (see Fig.2)[17].

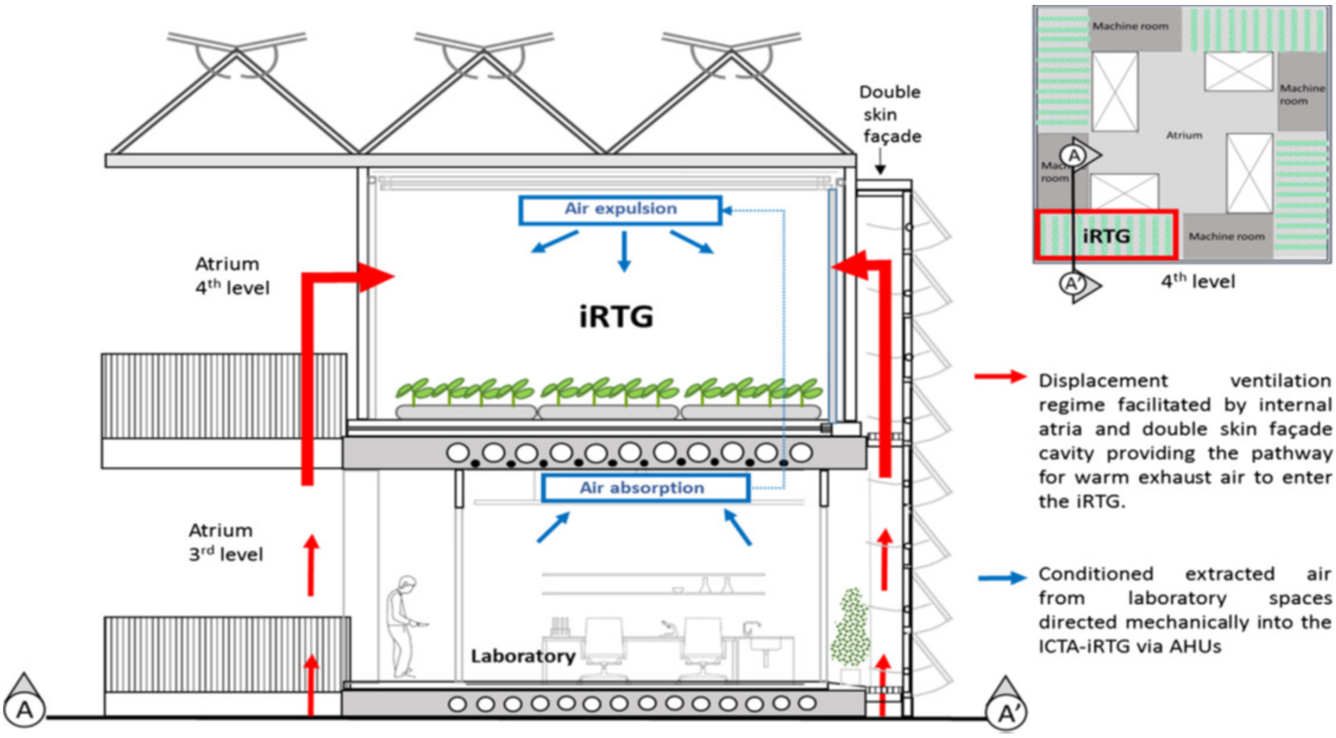

Fig 2. Three main flow paths for heat exchanges between building and IRTG [17]

The building has 5 internal climates adapted to the functions of the spaces [17]:

1) Laboratories, with heating/cooling to achieve a temperature range of 21–25 C°;

2) Workspaces and offices, with heating/cooling and a temperature range of 17–26 C°;

3) Common spaces, unheated/uncooled; the temperature may fluctuate with the season;

4) IRTG, unheated/uncooled, the temperature range varies as a function of the outside conditions and thermal interactions with the underneath building;

5) Parking and underground cellars, in free-float mode, their temperature ranges vary as a function of outside conditions.

A software tool has been developed to control the IRTG-Lab. This tool is flexible to support the management of the temperatures based on the crop's requirements. This management is also compatible with the building usage because the software tool takes into account the building requirements like users' optimum temperature and air quality. For the management tool it is necessary to define multiple control configurations that permit to carry out desired conditions in shared building environment, in order to deter-mine the most efficient and effective IRTG operation. This management system will improve by incorporating an intelligent system, capable to take auto¬matic decisions in order to achieve predefined temperature, hu-

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midity and CO_2 conditions. The temperature and humidity control equipment contain a data logger, 12 temperature probes using ther-mistors and 3 humidity probes. The sensors are uniformly distributed inside RTG and in other spaces of the building's rooftop level. Measurements are taken every 5 seconds and an average is done every 10 minutes. External data is obtained from the meteoro-logical station of Sabadell Agricultural Park. For example, **Fig. 3** shows the recorded temperatures between February 19-23, 2015 [8].

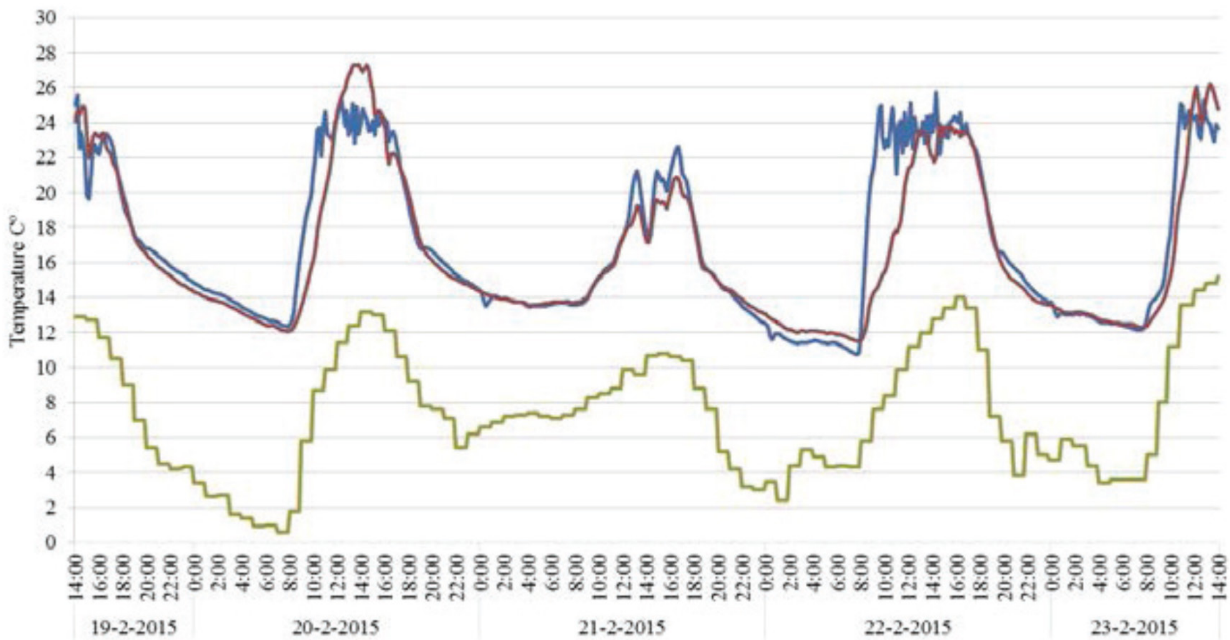

Fig. 3. Temperatures between February 19-23, 2015. The blue curve is IRTG-Lab temperature, the red is RTG temperature and the green is external temperature [8]

SPECIFICATIONS FOR AN INTEGRATED ROOFTOP GREENHOUSE

It is known that interdisciplinary and complementary bodies of knowledge, organized according to the *Systems Engineering* principles, are able to achieve performances beyond the sum of the individual components' performances. Having this in mind, we propose a generic IRTG system, descripted by a set of specific features:

1) The IRTG must take advantage of all the renewable energy and water resources that are available in the urban environment (sun, wind, rain waters, wasted waters, geothermal the most reliable of all, etc.) That is why, among other features, they must be conceived as *Renewable Energy Exploitation Systems* (harvest, storage, local optimal use, etc.). The design should be adapted to the urban environment. Instead of bulky and dangerously spinning wind turbines, air-to-air heat pumps should be used. Photovoltaic panels are not necessary because urban buildings are conveniently provided

with electricity. Instead, they should be replaced by solar thermal systems, able to store the solar energy generated by the greenhouse effect. The main renewable energy device, namely the water-to-water heat pump, should use ground-coupled heat exchangers instead of water wells, because phreatic waters in urban regions are unreliable and insufficient for high buildings' concentration. Such heat exchangers can be integrated into the buildings' foundations.

2) An opportune development of the IRTG concept should begin, as in the case of the industrial buildings, automobiles, trains or air-plains, with a network that is providing connectivity and is integrating sensors, actuators, communication devices and distribut-ed controllers able to take smart decisions. In other words, the IRTGs must be turned into iRTGs, *Intelligent RTGs, an Internet of Things subject*.

3) In sum, the iRTGs must be conceived as *Smart City basic cells*. The IRTG architecture confers an inherent capacity for managing in an integrated and smart way the renewable energy, water and gases resources that are to find in our cities.

4) Due to these features, the iRTG electricity, water and gas consumption should not exceed in any mean an equivalent conventional building consumption. Turning an existing conventional building into an iRTG should not affect the existing infrastructure. Such way, according to the disposable resources, one can gradually transform the nowadays cities into future *Green Skyline Cities*, composed exclusively of iRTGs.

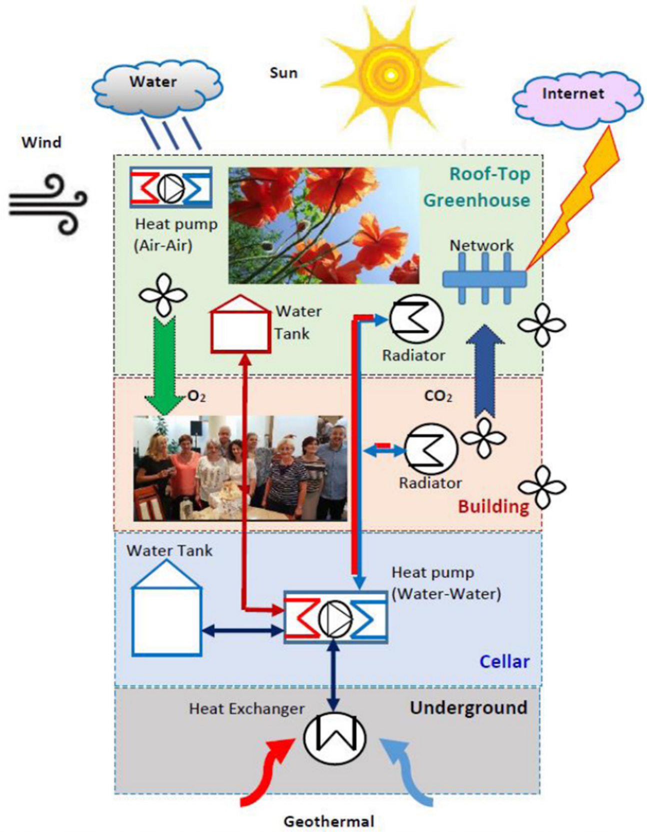

Fig. 4. *A generic Integrated Rooftop Greenhouse system*

AN INTEGRATED ROOFTOP GREENHOUSE MATHEMATICAL MODEL

We introduce a structural reduced order model, composed of six differential equations of first order, which describes the main IRTG physical processes.

The model subsumes the following parameters: V[m^3] volumes, ρ[kg/m^3] air density, ca [J/kg·°K] air specific heat, T[°C] temperatures, D[m^3/s] air flows, a [W/m^2·°K] mean heat transfer coefficients through walls, S[m^2] radiant surfaces, N number of persons, P_O[W] mean power emitted by a person, P_{GE}[W] power of the greenhouse effect, P[W] heat-ing/cooling power, τ[s] time delays, C[kg/m^3] concentrations, Q[kg/m^3·s] gas emission flows (by plants and persons). U is the recirculation factor, thus [1-U(t)] represents the fresh outside air proportion in a ventilated air flow. Index G

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refers the greenhouse, index B the building, index RTG the IRTG ventilation system and index E the environment.

Equation (1) models the evolution of the RTG temperature under the influences of the air exchanges with environment and underneath building, the greenhouse effect, the pre-sence of people and the action of the heating/cooling equipment:

$$V_G \cdot \rho \cdot c_a \cdot \frac{T_G(t)}{dt} = \{[1\text{-}U_G(t)] \cdot D_G(t) \cdot \rho \cdot c_a + \propto_G \cdot S_G\} \cdot [T_E(t)\text{-}\ T_G(t)] + N_G \cdot P_o + P_{GEG} + \\ + P_G(t\text{-}\tau_G) + D_{B\rightarrow G}(t\text{-}\tau_{B\rightarrow G}) \cdot \rho \cdot c_a \cdot [T_B(t)\text{-}T_G(t)] \quad (1)$$

Equations (2) and (3) model the RTG oxygen and carbon dioxide concentrations under the influence of the air exchanges with the environment and the underneath building, and of the presence of people (Q_{O2}, Q_{CO2}) and plants (Q_{O2G}, Q_{CO2G}):

$$V_G \cdot \frac{dC_{O2G}(t)}{dt} = [1\text{-}U_G(t)] \cdot D_G(t) \cdot [C_{O2E}(t)\text{-}\ C_{O2G}(t)] \text{ - } N_G \cdot Q_{O2} + Q_{O2G} + \\ + D_{B\rightarrow G}(t\text{-}\tau_{B\rightarrow G}) \cdot [C_{O2B}(t)\text{-}C_{O2G}(t)] \quad (2)$$

$$V_G \cdot \frac{dC_{CO2G}(t)}{dt} = [1\text{-}U_G(t)] \cdot D_G(t) \cdot [C_{CO2E}(t)\text{-}\ C_{CO2G}(t)] + N_G \cdot Q_{CO2} + Q_{CO2G} + \\ + D_{B\rightarrow G}(t\text{-}\tau_{B\rightarrow G}) \cdot [C_{CO2B}(t)\text{-}C_{CO2G}(t)] \quad (3)$$

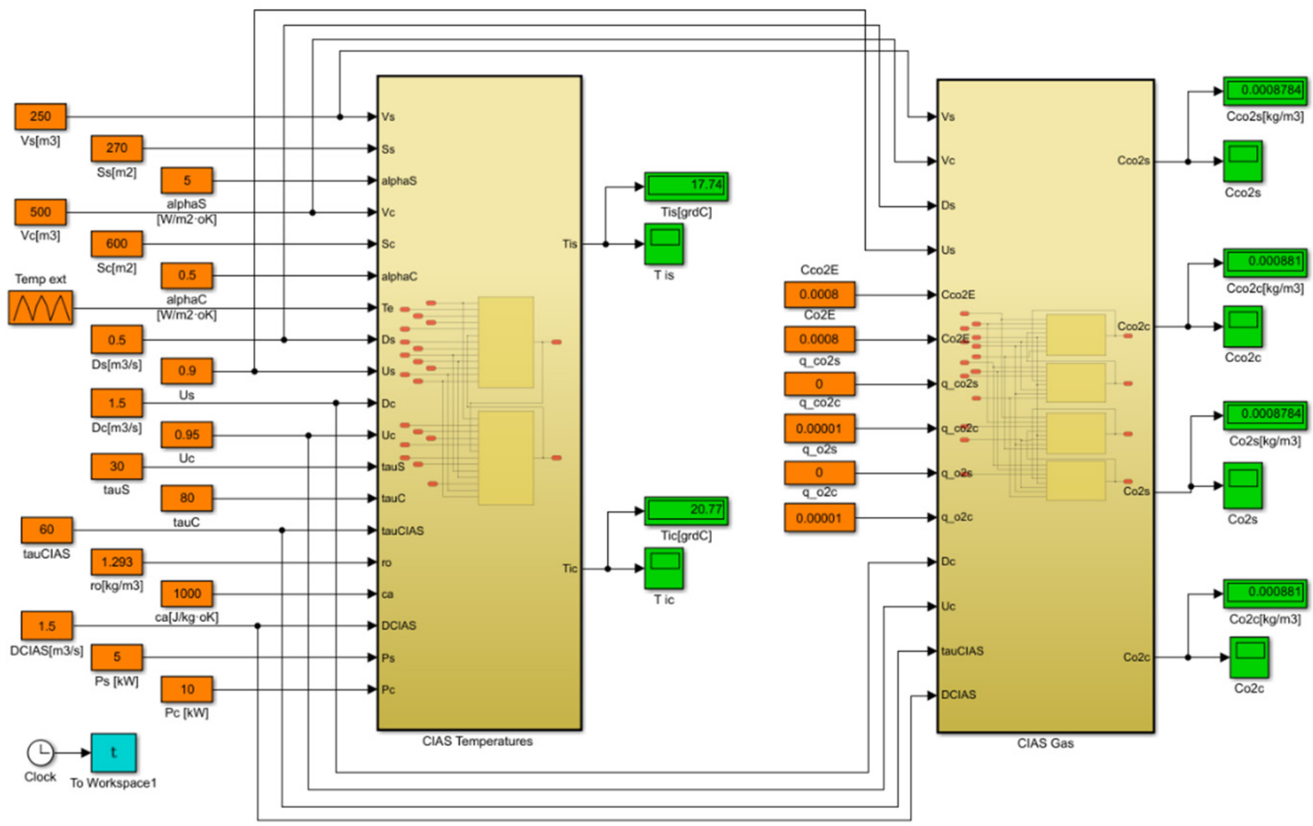

Fig. 5. *A Matlab-Simulink implementation of the IRTG model*

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Equations (4), (5) and (6) model in the same way the building's variables:

$$V_B \cdot \rho \cdot c_a \cdot \frac{T_B(t)}{dt} = \{[1\text{-}U_B(t)] \cdot D_B(t) \cdot \rho \cdot c_a + \propto_B \cdot S_B\} \cdot [T_E(t)\text{-} T_B(t)] + N_B \cdot P_o + P_{GEB} + P_B(t\text{-}\tau_B) + D_{G\to B}(t\text{-}\tau_{G\to B}) \cdot \rho \cdot c_a \cdot [T_G(t)\text{-}T_B(t)] \quad (4)$$

$$V_B \cdot \frac{dC_{O2B}(t)}{dt} = [1\text{-}U_B(t)] \cdot D_B(t) \cdot [C_{O2E}(t)\text{-} C_{O2B}(t)] \text{ - } N_B \cdot Q_{O2} + D_{G\to B}(t\text{-}\tau_{G\to B}) \cdot [C_{O2G}(t)\text{-}C_{O2B}(t)] \quad (5)$$

$$V_B \cdot \frac{dC_{CO2B}(t)}{dt} = [1\text{-}U_B(t)] \cdot D_B(t) \cdot [C_{CO2E}(t)\text{-} C_{CO2B}(t)] + N_B \cdot Q_{CO2} + Q_{CO2B} + D_{G\to B}(t\text{-}\tau_{G\to B}) \cdot [C_{CO2G}(t)\text{-}C_{CO2B}(t)] \quad (6)$$

The future work on this model will be the accurate identification of the ICTA building on behalf of the recorded experimental data and the optimizing of the model with neural net¬works or genetic algo¬rithms, according to a previously used methodology [14].

ON THE INTELLIGENT ROOFTOP GREENHOUSE CONTROL

The IRTG model described by equations (1-6) is corresponding to a MIMO system (Multiple Input Multiple Output) with the following structure:

Inputs: P_G, P_B, $D_{B\to G}$, $D_{G\to B}$, D_B and D_G

Outputs: T_G, T_B, C_{O2G}, C_{O2B}, C_{CO2G} and C_{CO2B}

Simulations following different meaningful scenarios help us to identify the best control method. First, we must choose between *Optimal Control* (OC) and *Soft Computing* (SC).

OC uses numerical algorithms and it can achieve optimal performances in respect of one or several performance indexes: speed, accuracy, costs, etc. OC relies on quantitative analysis and numerical repre¬sentation of knowledge. OC is recommended when one dispose of reliable knowledge about the controlled plant.

SC is complementary, relying on qualitative analysis and symbolic knowledge representation (linguistic, graphical, etc.) The most popular SC technique, the Expert Control (EC), emulates the way decisions are taken by human operators. SC is recommended when our knowledge about the controlled plant is imprecise, uncertain or approximate. For iRTGs which are HVACs (*Heating, Ventilation, Air-Conditioning*), very nonlinear and time varying, the SC (mainly EC such as used in ref. [15]) is considered to be ideal since the early 80s, especially because humans and plants are tolerant to weather parame-ters' variations (temperature, humidity and air composition), so the accuracy and preci-sion that are the attributes of OC are not critical. Instead, features that SC can ensure, such as stability, adaptation, robustness, prediction or automate learning are essential.

Applying iRTGs at large scale entails a large variety of climate parameters, architectural solutions, equipment selections, etc. This is meaning that almost each objective will need its own control solution and tuning. That is clearing leading us towards the SC option.

The *Expert Systems* consist in:

a) Bases of control/decision rules of IF-THEN type, heuristically designed by spe-

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cial¬ists in the application's domain (not necessarily and in computer science); if the rules are of fuzzy type, the system becomes a *Fuzzy Expert System* [16].

b) Inference algorithms, using the rules to synthesize the output control actions.

The following linguistically expressed rules are illustrating this method.

IF T_E is Cold **AND** T_B is Cool **THAN** U_B is 1: the fresh air admission is closed preserving energy into the building; the building is ventilated through RTG

IF T_E is Cold **AND** T_G is Cool, and P_{GE} is low **THAN** U_G is 1: no fresh air into RTG, preserving energy during cold nights

IF T_E is Cold AND T_G is Cool, and PGE is High **THAN** U_G is Min: maximum amount of fresh air, taking advantage of the greenhouse effect, during cold sunny days

IF T_E is Warm **AND** T_B is Cool THAN U_B is Min: warm air from outside

IF C_{O2G} is High **AND** T_G is Not Cool THAN

$D_{G->B}$ is ON: RTG provides O_2 to building

IF C_{O2G} is Low **THAN** $D_{G->B}$ is OFF: when the plants are not producing O_2

IF C_{CO2B} is High **THAN** $D_{B->G}$ is ON: the building provides CO_2 to RTG

The following figures, issued out of preliminary simulations using the computer model, show typical performances for two iRTG temperature controllers: a PID one and a fuzzy-interpolative one – belonging to the SC family. The control action was applied by P_B, consisting in heating the building, aiming to keep T_B around 24 oC.

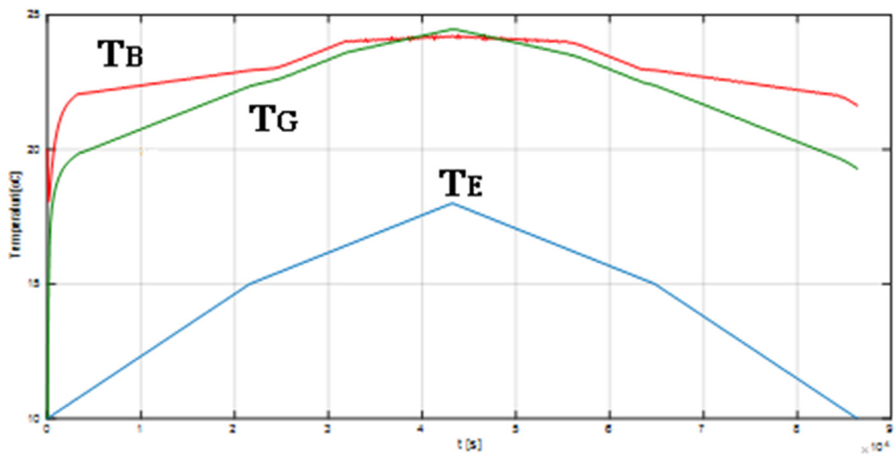

Fig. 6. The performance of a PID controller

Fig. 6 is showing the performance of a PID controller. One can observe a very good accu¬racy of the directly controlled parameter, namely TB. However, this accuracy is associated with an overshot, consequence of the transient regime. Overshooting is undesirable and energy wasting. TG was not directly controlled.

The performance of the expert type fuzzy-interpolative controller from Fig. 7 is less accu¬rate, but more robust, with no overshooting.

These simulations are only demonstrative, the choice and the proper tuning of the iRTG controllers need further more efforts, performed on a validated model.

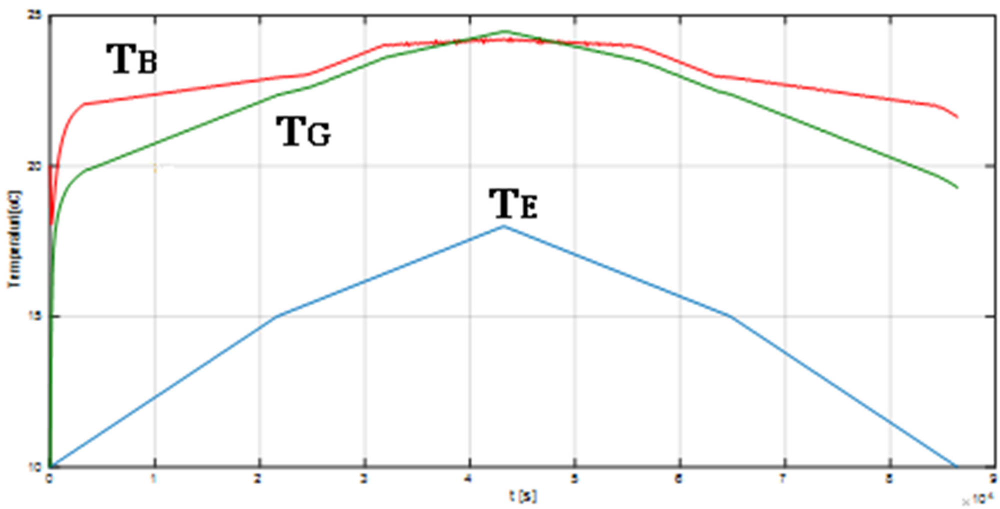

Fig. 7. *The performance of an expert type fuzzy-interpolative controller*

Future works intend to investigate different control configurations, the way in which tem¬perature, humidity and gas composition could be corelated into an integrated optimal way.

Another iRTGs research topic is the IOT upgrading and the Smart City connection.

CONCLUSION

This article is an extended version of the paper entitled *Integrated Rooftop Greenhouses and Green Skyline Cities* by Marius M. Balas, Jelena Nikolic, Ramona Lile, Mihaela Popa and Roxana Beiu, presented at *SGEM Vienna Green International Conference*, Hofburg Congress Center, 3-6 December 2018. Compared to the initial paper, this article is detailing the description of the IRTG prototype and it is providing and discussing simulations results.

Two new green building concepts are discussed: the Integrated Rooftop Greenhouse which results after connecting the rooftop greenhouses with the underneath building by flows of energy, water and gases and the *Intelligent Rooftop Greenhouse* which is controlling in an intelligent way the energy, water and gases exchanges. iRTGs are gathering the disposable renewable energy resources: sun (by thermal panels), wind (by air to air heat pumps), geothermal (by water to water air heat pumps), and water resources (rain water, household grey water, water vapors), storing and delivering them wherever and whenever needed. iRTGa are also connected to the surrounding *Smart City*. A benefic humanplants symbiosis is created by circulating O_2 enriched air from rooftop greenhouse to building and CO_2 enriched air from building to rooftop greenhouse.

The first IRTG prototype, realized by the Spanish program *Fertilecity*, is presented.

A prerequisite for the IRTG to successfully fulfill the desired tasks is to benefit of meaningful knowledge about the physical phenomena that are taking place within it. In this purpose the paper provides a mathematical structural reduced order IRTG model, capable to assist the sizing of the system in most respects: architectural

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solutions, con-struction materials, sizing of the components (renewable energy, water management, ventilation fans), as well as the testing of the control algorithms.

Simulations are illustrating the performances of two temperature control algorithms: a PID and a fuzzy-interpolative one.

In order to meet the emerging Smart Cities specifications, iRTGs must be updated as an *Internet of Things* subject. Due to the smart use of renewable energies, the iRTG energetic footprint is low so existing buildings could be upgraded to iRTGs without perturbing the current urban infrastructure. This is leading us towards the possibility to extend the use of iRTG at the scale of a whole city, *The Green Skyline City*, a structure with increased carbon offset capacity due to the massive presence of plants, able to oppose the global warming.

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