GA-optimisation of a curtain wall façade for different orientations and climates

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Abstract

The importance of considering the environmental performance of buildings since the conceptual stages of the design process is growing as a consequence of the restrictive requirements of building regulations and energy certification. The building envelope plays a central role in controlling the thermal, the acoustic and the light flows exchanged between the indoor and the external environment. Therefore designing a good façade system and installing it properly is fundamental to increase the overall performance of the building.

This study focused on a modular curtain wall façade that can integrate photovoltaic panels on its opaque areas. The aim was to identify the layouts that minimise total cost, calculated as the sum of investment and operation costs, and at the same time maximise daylighting in the rooms. The methodology consisted in a simulation based multi-objective optimisation solved by means of Genetic Algorithms, whose behaviour is inspired by Darwin's Theory of Evolution.

An office room was modelled and its façade divided into twelve modules of equal size, two of which were fixed glazed elements and the remaining ten having three possible construction types: glazing, spandrel or photovoltaic elements. The optimisation process assigned a specific construction to each of the ten modules in order to obtain a set of façade layouts that fulfill both objective functions. Different climatic scenarios and orientations were considered.

The dynamic thermal simulations were carried out with *EnergyPlus* while the optimisation employed a modified version of the widely used NSGA-II Genetic Algorithm. A custom-made software was written in *Matlab* in order to interface the simulation and optimisation processes, to automate their interaction and to make the input of the problem's parameters easier through a graphical user interface.

1. Introduction

The façade plays a key role in the design of buildings that need to meet strict requirements of energy efficiency and provide internal comfort conditions at the same time. In air-conditioned buildings, and especially in office buildings that have highly glazed curtain wall façades, the energy consumption levels for heating, cooling and artificial lighting strongly depend on solar exposure and on the performance of the building envelope. The latter is responsible for heat losses, solar heat gains and it allows for daylighting. The design of a good façade is a very challenging task because of the complicated interactions between the various parameters involved.

Traditionally different variable assignments on building operation were compared by parametric studies, often employing dynamic energy simulation programs. In this study an automated search for one or more optimal solutions is performed through a procedure that couples an optimisation program to a simulation program. This solving method is known as simulation based optimisation.

In the field of building design, the simulation can be carried out by any program that can evaluate a model of the object under study, such as available dynamic energy simulation programs (*EnergyPlus*, *TRNSYS*, etc.). The optimisation is usually based on evolutionary algorithms, a family of population based probabilistic algorithms that proved to be suitable in solving problems where the objective function is calculated by external simulation programs.

A Genetic Algorithm (GA) and an artificial neural network were used in a multi-objective optimisation in order to find envelope and HVAC parameters that minimise energy consumption and guarantee the internal comfort at the same time (Magnier et al., 2010). Particle swarm (PSO) algorithms were applied to optimise life-cycle cost of a single detached house in Finland (Hasan et al., 2008).

Narrowing down to envelopes, some authors focused on residential buildings optimising the size of windows (Caldas et al., 2002), some considered the characteristics of the envelope (Znouda E. et al., 2007) and others took into account also the shape of the building (Tuhus-Dubrow D. et al., 2010).

In the present work the layouts of a curtain wall façade of an office building that optimise cost and at the same time guarantee good daylight provision are researched. This is accomplished by coupling an open source dynamic energy simulation program, *EnergyPlus*, to a NSGA-II Genetic Algorithms implemented in *Matlab*. A specific program, ePlusOpt, was written to couple *EnergyPlus* and *Matlab* and a graphical user interface was created to simplify its use.

2. Optimisation

2.1 Mathematical background

Optimisation is a process aimed at finding the best solutions of a problem by means of minimising (or maximising) one or more objective functions that describe the problem itself. The procedure comprises a model of the problem and an optimisation algorithm that minimises the objective function. The optimisation model comprehends variables, constraints and the aforementioned objective function.

When conflicting aims need to be satisfied at the same time, a single objective function is not enough to describe the problem. In this case, a multi-objective optimisation made up by two or more objective functions must be set up.

In mathematical terms, a multi-objective problem can be written as:

$\Omega \subset \mathbb{R}^n X \subset \mathbb{R}^n$ parameter space

$Z \subset \mathbb{R}^k \Lambda \subset \mathbb{R}^k X \subset \mathbb{R}^n$ image of X

$\mathbf{x} \in \Omega$ vector of decision variables

$\mathbf{z} = F(\mathbf{x})$ performance vector

The problem has no unique solution and the concept of non-inferiority (Zadeh, 1963), also known as Pareto optimality (Censor, 1977), must be introduced to characterize the objectives. A non-inferior solution is one in which an improvement in one objective requires a degradation of another.

A point $z^* \in \Omega$ is defined as a non-inferior solution if for some neighbourhood of x^* there does not exist a Δx such that:

$(x^*+\Delta x) \in \Omega$

$F_i(x^*+\Delta x) \leq F_i(x^*)$, i=1,..., m

$F_j(x^*+\Delta x) < F_j(x^*)$, for at least one j.

Multi-objective optimisation is concerned with the generation and selection of non-inferior solution points, also called Pareto optima.

2.2 Genetic Algorithms

In simulation based optimisation, where external dynamic simulations are employed to compute the value of the objective function, the latter is highly discontinuous and non-differentiable. Evolutionary algorithms have proved to be particularly suitable in this field and they offer the additional advantage of their capability in handling huge amounts of variables and potential solutions (Wetter & Wright, 2004). Genetic algorithms are part of this family of population-based probabilistic methods. Their behaviour is inspired by the biological evolution, based on natural selection and genetic recombination. A population of individuals, possible solutions, is first randomly generated and then repeatedly modified through genetic operators (selection, crossover and mutation). At each step, the GA selects individuals with the best fitness function value from the current population to be parents of the children for the next generation. Over successive generations, the population evolves toward an optimal solution.

2.3 ePlusOpt

In optimisation problems where the value of the objective function depends on the results obtained by an external simulation program, there is the need to configure the correct communication between the latter and the optimisation solver. To simplify and to automate this operation a specific program, named *ePlusOpt*, that couples *EnergyPlus* and *Matlab* was developed.

Given that the user has already prepared the energy simulation model to be employed for the dynamic thermal simulations, *ePlusOpt* guarantees the communication between the GA in *Matlab* and the *EnergyPlus* software through a series of functions and scripts. The core of this interaction happens inside the fitness function, which is called by the GA to compute the objectives of the optimisation.

The combination of the variables encoded in the chromosome of each individual is passed to a function that writes them inside a data set that is part of the energy model used for the simulations. Subsequently another function starts the simulation of the updated input file by calling the *EnergyPlus* executable file. When the simulation ends and the output files are produced, a third function retrieves from them the values of the output variables that were requested by the user. The fitness function finally uses these values to compute the objective(s). Figure 1 shows how these interactions work.

A graphical user interface was programmed to make the definition of an optimisation process and the management of the data easier and faster.

A standard version of the NSGA-II was modified by supplying some bespoke functions in order to make it work with a custom-built data type.

For more details about the routines and the interaction between the two programs, see Rapone, 2011.

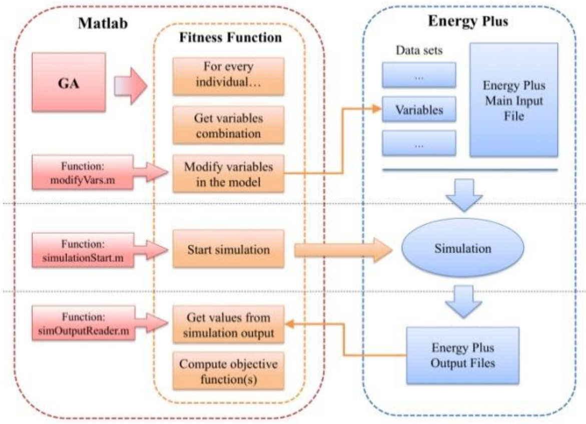

Fig. 1 – Coupling of the GA and EnergyPlus

3. Case study

To prove the effectiveness of ePlusOpt, a curtain wall façade of an office room was optimised in order to find the layouts that guarantee minimum total cost and maximum daylighting at the same time.

To see how climate and tariffs affect the results, additional optimisations were carried out for different European countries.

3.1 Thermal model

An *EnergyPlus* thermal model of an office room was built and used for the simulation based optimisation.

The room has a floor area of 50 m^2 and an overall height of 4.1 m. It is placed in the corner of an intermediate floor, so it has two sides facing outside. Both the internal partitions in plasterboard and the floors in reinforced concrete are modelled as adiabatic (Table 1); the smaller façade facing outdoors is completely opaque with a thermal transmittance of 0.25 W/m^{2}K. The main façade is a curtain wall façade modelled with a backing surface that embodies the behaviour of the aluminium frames of the curtain wall units. The thermal transmittance of this part is a mean value of the real transmittance of the frames, calculated as 4.2 W/m^{2}K. All modules are sub-surfaces cut-out in this backing surface, with characteristics described in the following paragraph.

Two reference points positioned at desk level inside the room, as pictured in Figure 2, are used to control the daylighting in the zone. Based on the levels of daylight coming in from the windows, they trigger the use of artificial lights in the room. When the glare index is greater than 22 the venetian blinds are closed automatically.

The plant system is considered to have unlimited capacity and can thus always maintain the required setpoint temperatures during the periods of peak heating and cooling loads.

The overall annual efficiency of the heating system is assumed to be 0.8, while for the coefficient of performance of the cooling system a value of 2.5 is taken. Other properties of HVAC system are shown in Table 2 together with the internal gains.

The simulations were carried out for a year time period using the weather files downloadable from the U.S. Energy Department's website.

Floors				
Layer	c_v [J/kg K]	ϱ [kg/m³]	λ [W/mK]	s [m]
Concrete slab	1000	2000	1.13	0.25
Double ceiling (plasterboard)	840	950	0.16	0.025
Double floor (tile)	800	1900	0.84	0.025
Internal Partitions				
Layer	c_v [J/kg K]	ϱ [kg/m³]	λ [W/mK]	s [m]
Plasterboard	840	950	0.16	0.025

Table 1 – Properties of adiabatic walls and floors

INTERNAL GAINS	VALUE
People (max 6 people)	126 W/person
Electric equipment	15W/m²
Lights	8 W/m²
HVAC SYSTEM	VALUE
Infiltration	0.15 ach
Mechanical ventilation	max 1 ach
Heating setpoint / setback	20°C / 12°C
Cooling setpoint / setback	25°C / 32°C

Table 2 – Model assumption: internal gains and HVAC system

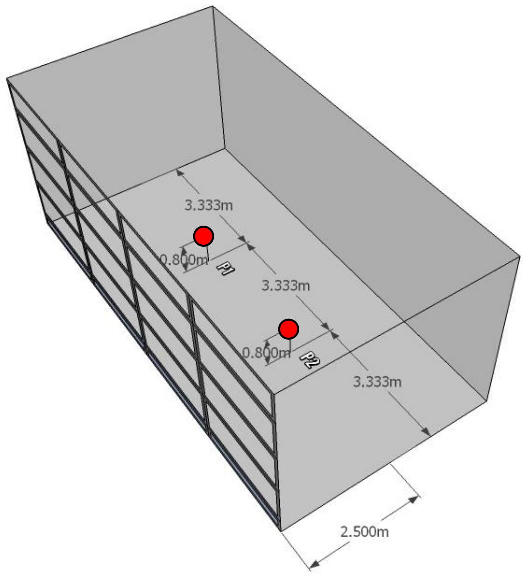

Fig. 2 – Disposition of daylighting reference points in the model

3.2 Façade description and variables

The assembly of the main façade, sketched out in Figure 3, consists in a central area made up of variable panels and in two strips of spandrel panels covering the service spaces above and below.

The central area is subdivided in three rows and four columns, thus generating a grid of twelve equal modules with an area of 2.5 m² each. The two central ones were assumed to be fixed and glazed in order to provide a minimum window area that corresponds to 10% of the floor area, while the other ten modules were allowed to vary and consist in any of the three following construction types:

- Spandrel panel

  The construction is that of a simple opaque panel consisting in an outer cladding layer, an insulation layer and a vapour barrier followed by an internal gypsum board (see Table 4). Since the climate changes for every city, the thickness of the insulation is calculated according to the limit of U-value imposed by national energy building codes. The thickness values adopted are shown in Table 3.

- Glazed panel

  It is constituted by a double glazed unit with a clear internal glass pane and an external pane with a solar control coating. The thermal, solar and visual characteristics are reported in Table 5.

- Photovoltaic Panel

  The BiPV panels construction is the same as the spandrel panel with the addition of the layer containing polycrystalline silicon photovoltaic cells on the external surface (see Table 4). The efficiency of the cells is assumed to be 14%.

  The PV panels are modelled in *EnergyPlus* with objects that simply apply their overall energy conversion efficiency to the incident solar radiation. They are then connected to an *inverter* object with an efficiency of 0.9.

COUNTRY	**Insulation thickness [m]**	**LAW**
Austria	0.15	OIB RICHTLINIE 2008
Germany	0.18	EnEV 2009
Greece	0.08	B 407/2010
Italy	0.13	DM 26/01/2010
Spain	0.06	Ahorro de Energia
UK	0.15	Building Regulations 2010

Table 3 – Insulation thickness

SPANDREL PANEL				
Layer	c_v [J/kg K]	ρ [kg/m³]	λ [W/mK]	S [m]
Cladding	840	2500	0.7	0.015
Insulation	840	80	0.04	0.15
Gypsum board	830	785	0.16	0.015
PV PANEL				
Layer	c_v [J/kg K]	ρ [kg/m³]	λ [W/mK]	S [m]
PV cells	840	2700	0.78	0.010
Insulation	840	80	0.04	0.15
Gypsum board	830	785	0.16	0.015

Table 4 – Panels properties

U-VALUE	g-VALUE	LT
1.14 W/m²K	0.58	75%

Table 5 - Characteristics of the glazing modelled

Ten variable modules that can assume three different values means that the possible combinations are 3^{10} = 59049. To increase the daylighting a rule was implemented in the algorithm so that when glazed panels are present, they are first positioned in the two upper rows and only subsequently in the lower one.

A base configuration where all the variable modules were chosen to be simple spandrel panels was taken as reference case. The energy consumption levels for space heating, cooling and artificial lights stemming from the energy simulation of this case were recorded to be later compared with the ones arising from all other possible compositions generated during the optimisation process.

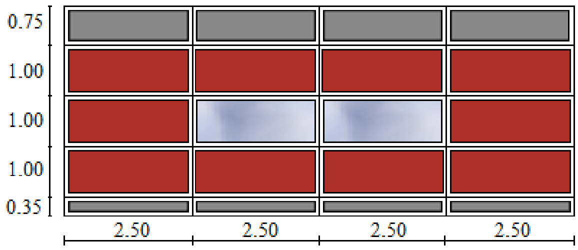

Fig. 3 – Layout of the curtain wall façade

3.3 Algorithm properties

As a result of a sensitivity analysis done by applying different algorithm properties to the same case study, the optimisations are performed with a population of 30 individuals and each process is repeated for 20 generations. The elite children are two and the cross-over fraction is 0.8.

3.4 Objective functions

The double-objective optimisation aim is to investigate the trade-off between the costs related to the improvement of the façade and the daylighting performance.

The first objective function is defined by the sum of investment and operation costs to be faced when upgrading the reference façade with more glazed panels or with building integrated photovoltaics:

$$F_1 = c_{tot} = c_{inv} + c_{op} \quad (1)$$

The investment costs are estimated as:

$$c_{inv} = n_G \cdot p_G + n_{PV} \cdot p_{PV} \quad (2)$$

The differential costs between spandrel modules and the other panels taken in account are estimated by averaging product prices in European countries. The assumptions made are shown in Table 6.

Replacement of a spandrel panel	price
With a glazed panel	+200€
With a PV panel	+600€

Table 6 – Prices assumptions

The operation costs are evaluated in 20 years as:

$$c_{op} = UPV^* \cdot [dE_{heat} \cdot t_{gas} + (dE_{cool} + dE_{lights}) \cdot t_{el}] - 20 \cdot E_{PV} \cdot t_{feed} \quad (3)$$

The electricity produced by PV panels as well as the energy consumption are retrieved from *EnergyPlus* output files. Then the differential energy demands between the reference case and the other possible façade layouts are calculated in *Matlab*. The values obtained are multiplied for the energy tariffs: natural gas (used for space heating) and electricity (used for space cooling and artificial lighting) prices are taken from Eurostat 2012 (except gas rates for Athens, taken from www.aerioattikis.gr). The energy rates are reported in Table 7.

The feed-in tariffs are taken from current national standards; the values are shown in Table 8.

The operating costs are considered for a period of twenty years in order to correspond to the average duration of the feed-in contracts for PV production prefigured by national laws. Since the feed-in tariff value is guaranteed during this period, the yearly savings arising from PV energy production are just multiplied by twenty. On the other hand, the yearly operation costs cannot be considered constant over the years because the energy prices are likely to rise during a twenty year period. Besides, since the evaluation of the costs is done at the present time, there is the need to calculate the present value of these non-uniform amounts recurring over the period considered. Hence, using life-cycle cost analysis concepts, the modified uniform present value factor is calculated with the following formula:

$$UPV^* = \frac{1+e}{d-e} \cdot \left[1 - \left(\frac{1+e}{1+d}\right)^y\right] = 18.08 \quad 4)$$

where the assumed real interest rate d is 3% and the escalation in energy price is 2%.

COUNTRY	**Gas tariff [€/kWh]**	**Electricity tariff [€/kWh]**
Austria	0.072	0.197
Germany	0.064	0.253
Greece	0.078	0.124
Italy	0.088	0.208
Spain	0.054	0.209
UK	0.052	0.158

Table 7 – Natural gas and electricity tariffs (including taxes)

COUNTRY	**tariff [€/kWh]**	**Years**	**LAW**
Austria	0.276	13	ÖSET-VO 2012
Germany	0.243	20	EEG 2012
Greece	0.305	20	3468/2006 and adjournments
Italy	0.282	20	V Conto Energia
Spain	0.3357	25	BOE num.315, p.146709
UK	0.22	20	Energy Act

Table 8 – Feed-in tariffs

The second objective function is an indicator of daylighting performance: the number of hours during a whole year in which the illuminance in both reference points is higher than the target value of 500 lux. This is a straightforward approach to evaluate the quantity of daylight entering the room, as it is directly related to the number and position of glazing panels on the façade. The minus sign is used because the aim is to maximise this amount of hours.

$$F_2 = -h_{ill>500} \quad (5)$$

4. Results

Optimisations were run for every city and every orientation in order to explore how climate and tariffs affect the results. At the end of each process a set of twelve solutions is found (in some cases two or more solutions are coincident). The results obtained for every city together with the Pareto front, represented as a polynomial trend line, are shown in Figures 4-9. In all countries, despite the differences in climate and feed-in tariffs, the best benefits are achieved for the southern orientation: most of the results suggest the use photovoltaic panels and this is why the Pareto front reaches towards higher gains. Furthermore, southern exposures, likewise western ones, guarantee a high number of hours when daylight exceeds the target value of 500lux. On the contrary, the Pareto front resulting for the northern orientation is narrow. This means that the layouts of each set of solutions vary more in terms of daylight than in terms of costs.

The total 288 possible layouts found are not reported in detail but the properties of an "average solution" of each case study are shown in Figures 10-12.

These solutions were worked out by averaging the characteristics (panel typology, energy demands and costs) of the twelve solutions obtained for each orientation in each city.

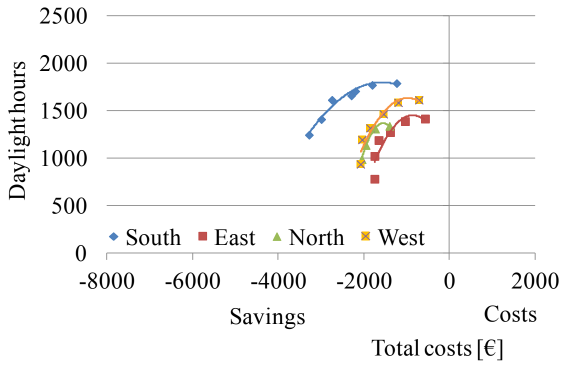

Fig. 4 – Results obtained for Berlin

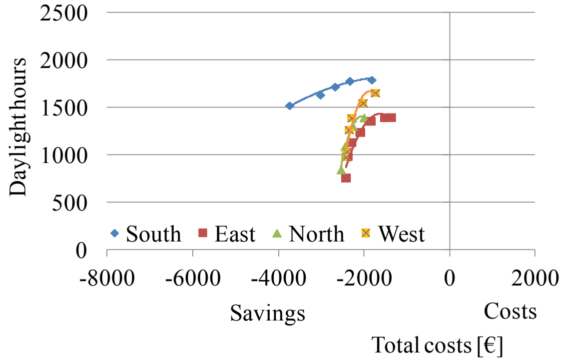

Fig. 5 – Results obtained for London

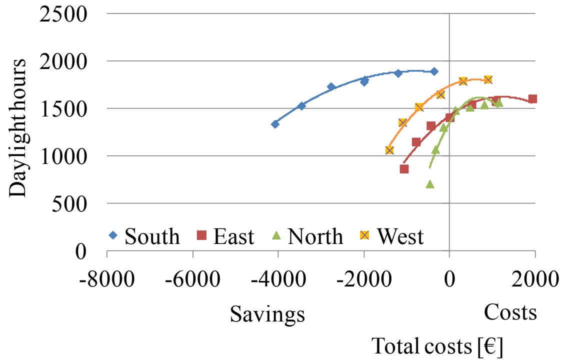

Fig. 6 – Results obtained for Vienna

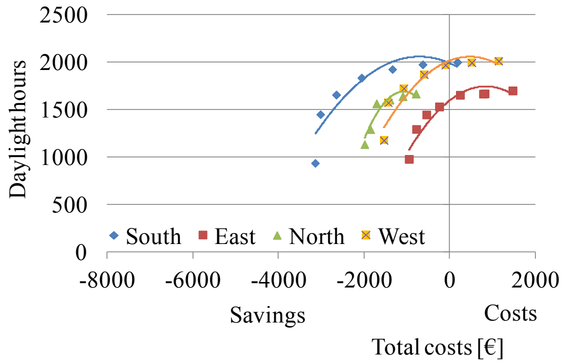

Fig. 7 – Results obtained for Rome

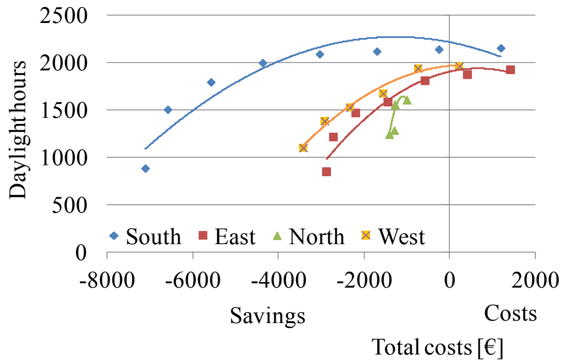

Fig. 8 – Results obtained for Madrid

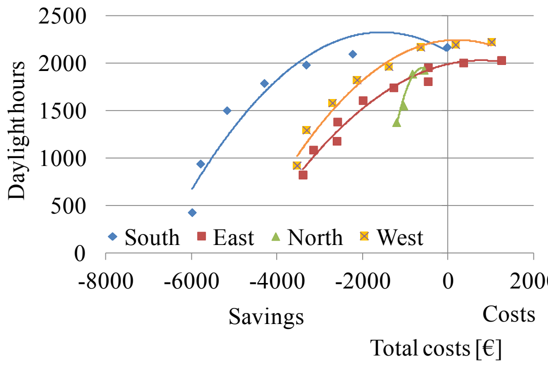

Fig. 9 – Results obtained for Athens

The average number of each kind of module assigned by every optimisation is shown in Figure 10. As expected, the number of photovoltaic panels strongly depends on climate, exposure and tariffs. It is remarkable that the results of all optimisation processes suggest the installation of additional glazed panels compared to the reference case.

The number of spandrels modules that should be replaced by glazed ones varies, on average, from 3 (Athens, southern exposure) to 6 (Rome, northern exposure).

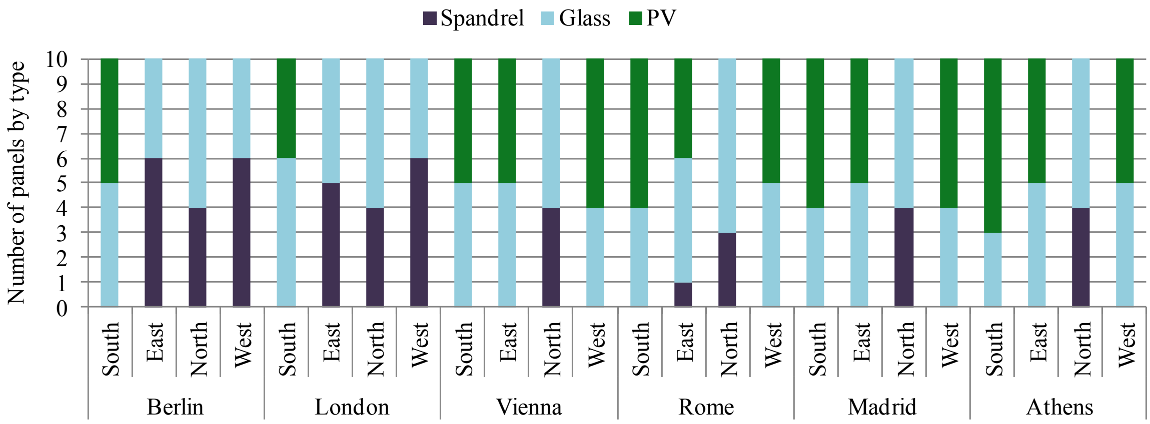

Fig. 10 – Average number of each kind of module assigned in the set of twelve solutions

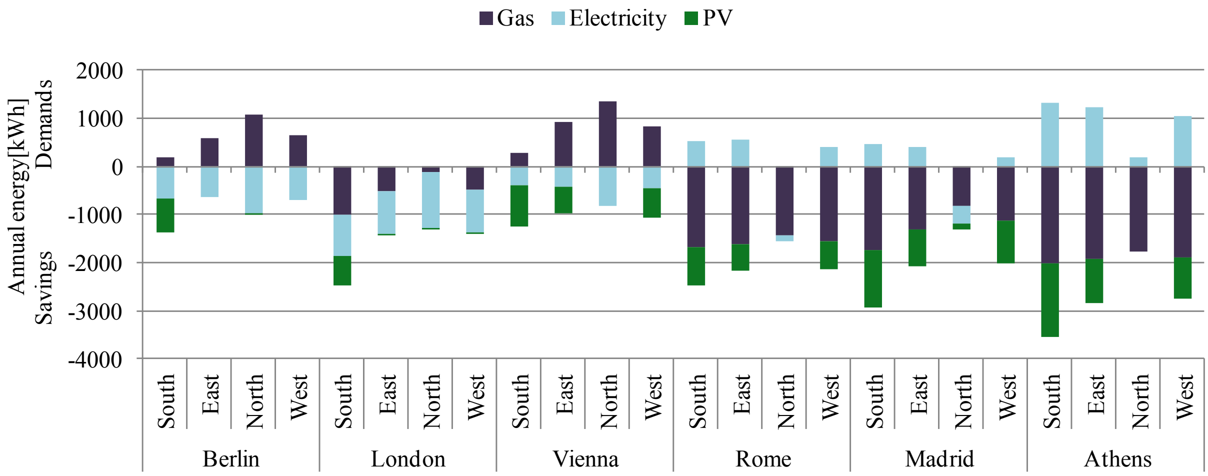

Fig. 11 – Average annual energy demands and savings (compared to reference case)

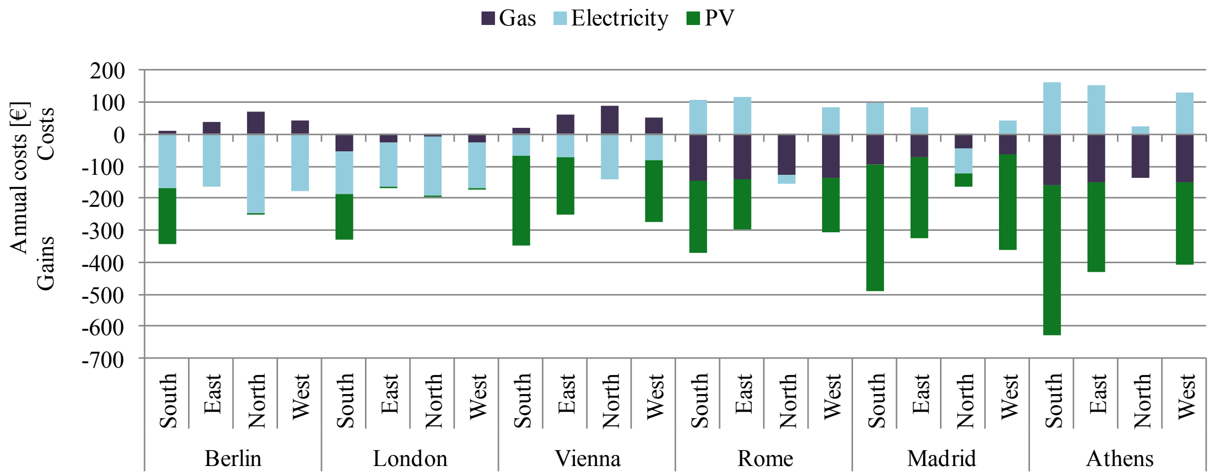

Fig. 12 – Average annual costs (compared to reference case)

Energy consumption and the related costs are displayed in figures 11 and 12. The comparison of the results underlines that choosing one of the optimal solutions in hot climates allows achieving more savings for heating, which means lower yearly natural gas costs. On the other hand, the layouts suggested for cold climates guarantee lower consumptions for cooling, then less electricity costs.

All solutions with improved daylight, besides the advantages they bring in terms of visual comfort, also help cutting the energy consumption related to artificial lights, which has a positive impact on electricity costs.

5. Conclusions

In this paper an optimisation-simulation tool developed in *Matlab*, *ePlusOpt*, is presented. Its main feature is the automatic integration within the optimisation process of energy simulations to be performed with *EnergyPlus.*

The program was employed to carry out optimisations of a curtain wall façade of an office room placed in different climates. The aim of the study was to find the façade layouts that minimise costs and maximise daylight by varying the type of panels installed. The optimised solutions found provide diverse design alternatives, as they represent different trade-offs between the two objectives.

The encouraging results found for the case studies confirm that simulation based optimisation can be a valuable instrument in the early design stages of energy efficient façades because it can provide a number of optimised solutions to be presented to the decision makers for the ultimate choice. Moreover, the developed program *ePlusOpt*, thanks to its graphical user interface and the automatic coupling of the programs, has proven to be a good tool to set up and carry out simulation based optimisation processes.

6. Nomenclature

Symbols

c_v	specific heat capacity (J/kg K)
ϱ	density (kg/m^3)
λ	conductivity (W/mK)
s	thickness (m)
F	objective function
c	cost (€)
n	number (-)
p	price of replacement (€)
a	side length (m)
dE	differential energy consumptions
E	energy produced
t	Tariff
UPV*	modified uniform present value factor
e	escalation in energy price
d	real interest rate
y	number of years
h	Hours

Subscripts/Superscripts

1	first objective function (€)
2	second objective function (hr)
in	Investment
tot	Total
op	Operation
G	Glazed
PV	Photovoltaic
heat	Heating
cool	Cooling
lights	artificial lights
gas	natural gas
el	Electricity
feed	feed-in
ill>500	illuminance greater than 500 lux

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