# Simplified model for studying facade materiality impact on urban canyon energy balance

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**Zusammenfassung Résumé Abstract**

Avec l'augmentation de la population urbaine et les changements climatiques actuels, la lutte contre l'effet d'ilot de chaleur urbain est une préoccupation publique grandissante. Des études de plus en plus nombreuses portant sur le sujet sortent chaque année mais, alors que les connaissances sur ce phénomène et sa compréhension générale s'améliorent, le fossé séparant les scientifiques et les planificateurs urbains se creuse. La présente étude, tout en ayant pour but de répondre à la question de l'impact des matérialités de façades via leur albédo, leur masse thermique et leur fraction vitrée, poursuit également le but de rendre plus accessible la compréhension des phénomènes en jeu et des résultats pour les architectes, les urbanistes et les pouvoirs publics. Les résultats ont démontré l'efficacité que pourrait engendrer la modification de ces caractéristiques des matériaux sur le bilan énergétique du canyon urbain, résultats applicables tant pour de nouvelles constructions que dans le cadre de rénovation de bâtiments. Le développement d'un modèle de simulation simplifié dédié aux paramètres seuls de l'étude a également rempli l'objectif de rendre plus accessible l'impact de chaque changement de caractéristique des matériaux sur les divers modes d'échange thermique au sein du canyon.

With the increase of population living in cities and with the climate change, Urban Heat Island effect mitigation is more than ever a society preoccupation. Study number about the topic increases exponentially and while more knowledge on the phenomenon is acquired, the comprehensiveness gap rises between scientists and actors of city planning. This present study, while aiming to evaluate the impact of facades materiality on energy balance also follows the objective of making the results more accessible for a better appropriation by public policymakers, urban planners and architects. The study underlines the impact of albedo, thermal mass and window fraction on energy balance and shows easily implementable results both for new constructions and refurbishment. The development of a simplified calculation model has also shown its value to make the process involved in energy exchange and the results more understandable.

## 1. Scope

With already more than half of the worldwide population living in cities, and even more than 75% for West-European countries, and with the global warming increasing, the quality of life in cities and their energy consumption tend to take an increasing place in our society preoccupation.

Due to the need for climatic adaptation of our cities in order to mitigate Urban Heat Island (UHI) effect and to limit the impact of heat-waves on people discomfort and on vegetation, several studies have been conducted during the past decades to better understand the energy balance of urban canyon and cities and the causes of UHI effect. At the beginning mostly based on computer models and for theoretically infinite canyon, those models tend now to be replaced by 3D models of calculation by finite elements, more likely to represent a real city configuration.

Although this allows to use the model in near to real conditions, it also makes them much more complex to understand and use properly, mostly due to the complexity of describing the real city and to the number of hypotheses required to execute those model in accordance with the time at disposal and computer power available today.

While lots of study nowadays aim to underline the efficiency of vegetation to mitigate the UHI effect, it seems to exist only few study focusing on how the vegetation is itself impacted by its environment. Assuming that a vegetation in good condition would be more efficient, and that vegetation might therefore come as an improvement of city climate and not as the only solution, the present study aims to do a step backward and to look at the possibility of action existing at the urban envelope scale.

Indeed, while several obstacles might come when considering the implementation of vegetation such as for example road template size for trees, buildings skin which represent an import part of cities envelope are generally quite accessible, either for new buildings for which every possibility can be explored, but also for refurbishment for which it is mainly a matter of public policy choices.

Another important goal for the study was to look at the capacity of “old fashion” model to still give proper results in comparison to newer much more complex model, and to observe in which way it would allow to assess the problematic in a simpler way, parameter by parameter, to be able to have rules easy to understand and implement, which would be more suitable for public policy choices and implementation.

Actually, while the general scientific knowledge about city energy balance increases, it seems to appear more and more complex to extract from the results simple rules that could be implemented at an upper scale in order to drive our cities transformations.

For those reasons, this study focuses on two main parameters of facades that play an important role on energy balance, the albedo and the available thermal mass. Both being easily modifiable for existing building.

The study also focuses on a third facade parameter which is the window fraction. While not being easily modifiable in the case of refurbishment, it seemed important for the author to allow architects and other actors of the field of construction to understand the impact of window fraction not only from the point of view of within the building, subject more and more well known, but also from the point of view of the near building environment and micro-climate.

To assess the problematic of the study, it has been chosen to limit the number of scenario to allow an easier analysis of the big tendencies when coming to the extreme value the parameters can take (e.g.: albedo of 0 or 1). While being purely theoretical values most likely not to be found in real common construction materials, it allow to underling the margin within which it is achievable to work in when considering solutions for UHI mitigation.

The field of study presented here, both for in-situ measurement used to validate and calibrate the model and for the model execution itself is Geneva at the summer solstice. This allows the results to be validated for most western European cities with similar climate and solar geometry.

## 2. Methods

To answer the research questions, a calculation model has been developed to fully access which thermal exchange mechanisms are taken into consideration and how. The model, developed in Python, allow the modification of the main canyon characteristics - described below - and of the climatic data used to force the model. Thus, it can be used for any canyon geometry, orientation, location and climatic condition. While the basic step of computation for the model is down to a second, results are given hourly and daily in order to facilitate the analysis.

### 2.1 Model required inputs

The model requires climatic data to solve shortwave and longwave radiation balance and convective exchanges between surfaces and canyon air mass. The input data required, on an hourly basis, are the beam horizontal radiation, the solar diffuse horizontal radiation, the longwave downward radiation from atmosphere and the city air temperature. For this study, the data were taken from meteorological database and adapted to represent a hot reference period in Geneva.

### 2.2 Model and study hypotheses

#### Canyon general geometry

The canyon is considered as symmetrical and infinite. This allows to focus on the calculation of a reduced cross section, to consider no side border effects and to simplify every calculation for reflections and radiative exchanges. Building's roofs are supposed to be horizontal allowing to put the upper limit for reflections and radiative exchanges at the top of the facade. Thus, facades and ground have a view factor of 0 with roofs, and vice-versa.

#### Model thermal exchange adiabatic limits

Walls are considered as insulated. Either with external insulation and a finishing layer or with internal insulation and a massive, structural layer in contact with the canyon. In both case and for simplification reason only the external layer of walls exchange with the canyon and insulation is considered as efficient enough on a daily thermal circle basis to avoid exchange between external layer and the building. For the same reason of simplification, the lower limit of the ground layer is also considered as adiabatic and thus the ground layer does not exchange with deeper soil. Concerning transparent surfaces, the thermal exchange limit is the inner side of the surface which does not exchange energy with the building internal surfaces or air.

#### Model thermal exchange simplification

The model takes into account one level of reflections for shortwave radiations, as it is at least required to have correct results according to (Harman, Best, and Belcher 2004)[1]. Shortwave radiations are considered as having a fully diffusive reflection when hitting opaque materials, which are ground and walls surfaces, and to have a fully specular reflection when hitting glazing (Lienhard and Lienhard 2008)[2]. This also means that, while the direct and diffuse radiations reflected by opaque surfaces are both reflected on other canyon surfaces and to the sky, they are always fully reflected to opposite facade or ground by glazed surfaces. The albedo is considered as constant for every incidence angle.

Concerning longwave radiations, the model considers no reflections as the materials used for the study are considered as all having a relatively high emissivity - above 0.8 - which is the acceptable limit of this hypothesis as discussed in (Harman, Best, and Belcher 2004)[1]. The emissivity is considered as identical in every direction.

The energy transmitted to buildings inner environment through glazed surfaces is considered as given back to the canyon air through ventilation, without the use of heat pump. This has been made in order to conserve the energy balance and to avoid a "loss of energy" which would have created an artificial energy sink in the model, preventing to correctly compare opaque walls with transparent ones by lowering the energy conservation in the model limit.

### Transparent surfaces simplification

As windows characteristics may vary a lot according to their model, windows have been simplified and resumed as a one layer material defined by its thickness, volumetric mass density, albedo, emissivity, heat capacity and “shortwave transparency”. This allow to keep the model simple and to focus on the parameter of the study (albedo value and mode, energy repartition within the canyon).

### Thermal inertia sub-model

For layers with high thermal storage capacity - walls with inner insulation and ground - a sub model divide the layer into sub-layers in order to compute thermal storage repartition within the materials and to retrieve a correct surface temperature. The simple inertia model has been developed based on laboratory measurement.

### Fixed characteristics

The street covering, although being modifiable, has been fixed for the study as the aim was to focus on facade materiality. It represent a mixed of asphalt and concrete street which is one of the most common type for streets open to motor traffic.

Emissivity of all materials has been fixed to 0.95 which is close to the reality of most common construction materials and as it is considered as harder to modify as it is an inherent material characteristic, in opposition for example of albedo or thermal mass which can be easily modifiable in refurbishment and which are free of choice in new construction.

To keep the model simple and manageable and as it is in accordance with a “worst case scenario”, no wind is taken into consideration in the study.

## 2.3 Model validation

The model has been validated both by “pushing it to its limit” to confirm the trend of the results in various extreme condition of canyon geometry and climatic condition, and then by comparison with laboratory and in-situ measurement. Both validation method confirmed the correct comportment of the model and the correct trend of the results in term of surfaces temperature.

## 2.4 Study cases

The study has focused on three main parameters modifications, each treated separately. The first series of scenario were made to focus on the impact of albedo value and mode - diffuse or specular – on solar incoming energy repartition. The second and the third series of scenario focus respectively on walls thermal mass capacity and on facade window fraction impacts on hourly energy balance. A summary of facade characteristics for each series of scenario is available bellow.

| Reference n° | Window fraction | Albedo | Reflection mode |
|---|---|---|---|
| A1-0 | 0 | 0 | Diffuse |
| A1-1 | 0 | 1 | Diffuse |
| A2 | 1 | 1 | Specular |

*Table 1 Window fraction, albedo and reflection mode for the first series of scenario.*

| Reference n° | Layer thickness | Volumetric mass | Heat capacity |
|---|---|---|---|
| B1 | 20 cm | 2400 | 900 |
| B2 | 1.5 cm | 2400 | 900 |
| B3 | 1.5 cm | 800 | 450 |

*Table 2 Layer thickness, volumetric mass and heat capacity for the second series of scenario. Albedo is fixed at 0.4, window fraction to 0 and the reflection mode as diffuse.*

The third series of scenario is based on the scenario B2 with respectively 0, 0.45 and 0.9 for window fraction. Scenario are named respectively to the window fraction as B2, B2-45 and B2-90.

## 3. Results

### 3.1 Albedo value and reflective mode impact on canyon energy balance

The first series of results focuses on facade albedo value and mode on the instant and daily energy balance in the canyon. For this study case, the model has been executed for three canyon aspect ratio: 0.5 (facade height = ½ street width), 1 (facade height = street width) and 2 (facade height = 2 street width), and for four canyon orientations: North-South, East-West, NE-SW and NW-SE.

#### Fraction of solar incoming energy directly reflected to the sky

The comparison between the 3 façade scenario A1-0, A1-1 and A2 first shows that a canyon with facades with a high diffusive albedo (A1-1) has the highest ability to reflect incoming energy directly to the sky. For all canyon aspect ratio and orientation, the scenario A1-1 shows a percentage of incoming solar radiation reflected to the sky going from 13% to 20% while the scenario A1-0 and A2 show results between 7% for the best case to 1% for the worst.

#### Fraction of solar incoming energy received by ground surface

On the same basis as the previous scenario, the second analysis focused on the part or solar energy incoming on the ground level. Results are summarised in table 3 below.

| | A1-0 | A1-1 | A2 |
|---|---|---|---|
| AR 2 | 20 to 30% | 40 to 50% | 50 to 85% |
| AR 1 | 35 to 55% | 65 to 75% | 75 to 90% |
| AR 0.5 | 55 to 75% | 85 to 90% | 90 to 95% |

*Table 3 Part of incoming solar energy received by ground for the three scenario A1-0, A1-1 and A2, for the three aspect ratio of 0.5, 1 and 2 and for the four orientation N-S, E-W, NE-SW and NW-SE, rounded at 5% precision.*

*Note from author: sum of energy reflected to sky and energy received by ground not equal to 100% even when facades albedo equal to 1 due to the number of reflection -1- taken into consideration. The difference calculated is of an order of 3%, giving the margin of error of the hypothesis.*

#### Daily total incoming energy on ground

Figure 1 shows the ground daily incoming solar energy. The biggest difference being noticed for narrow canyon for which the incoming energy is higher of 6% for scenario with high diffuse albedo compared to scenario with low albedo, and even of 16% for the scenario A2 compared to A1-0.

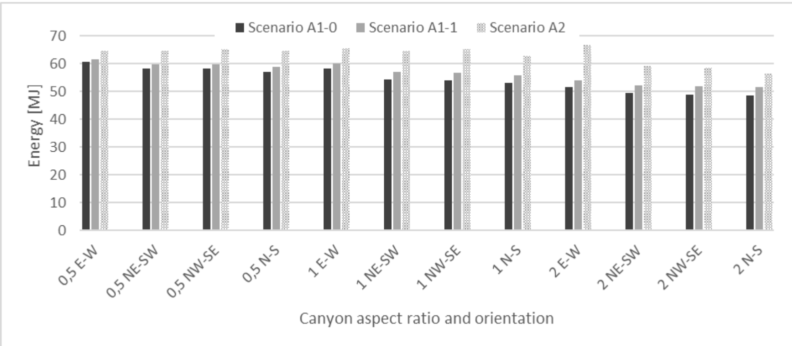


*Figure 1 Total shortwave energy received by ground surface for a 24h period, harmonized for the three canyon aspect ratio to compare the 3 scenario with the same solar incoming energy in the canyon.*

### 3.2 Façade walls heat storage capacity impact on canyon energy balance

The second series of scenario aimed to evaluate the impact of facades heat storage capacity on energy balance within the canyon. For this study case, a North-South canyon with an aspect ratio of 1 has been used (facades height equal to street width). The orientation has been chosen to maximise the part of solar energy received by facades. The three facades scenario B1, B2 and B3 respectively represent heavy walls with high thermal mass materials, thin walls with high thermal mass materials and thin walls with low thermal mass materials. Window fraction is equal to zero.

For this study case and the following ones, the canyon air temperature is corrected according to canyon surfaces mean temperature following (Panao, Gonçalves and Ferrao, 2006)[3].

Following figures 2, 3 and 4 show ground temperature and facades temperatures (Fi East oriented facade, Fj West oriented facade) for the three facade scenarios.

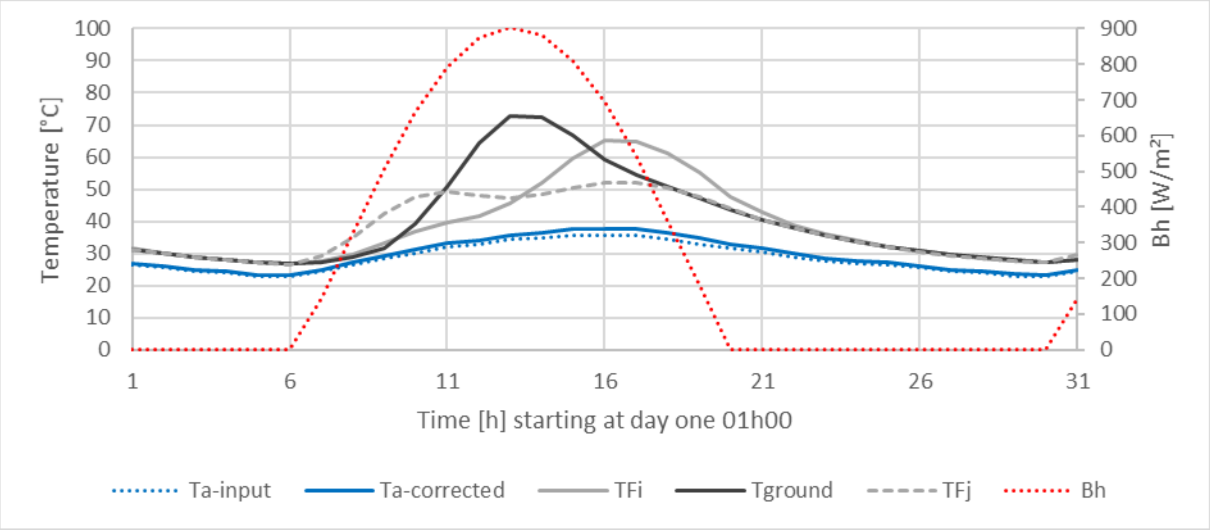


*Figure 2 Canyon surfaces temperature for scenario B1 (heavy walls – high thermal inertia)*

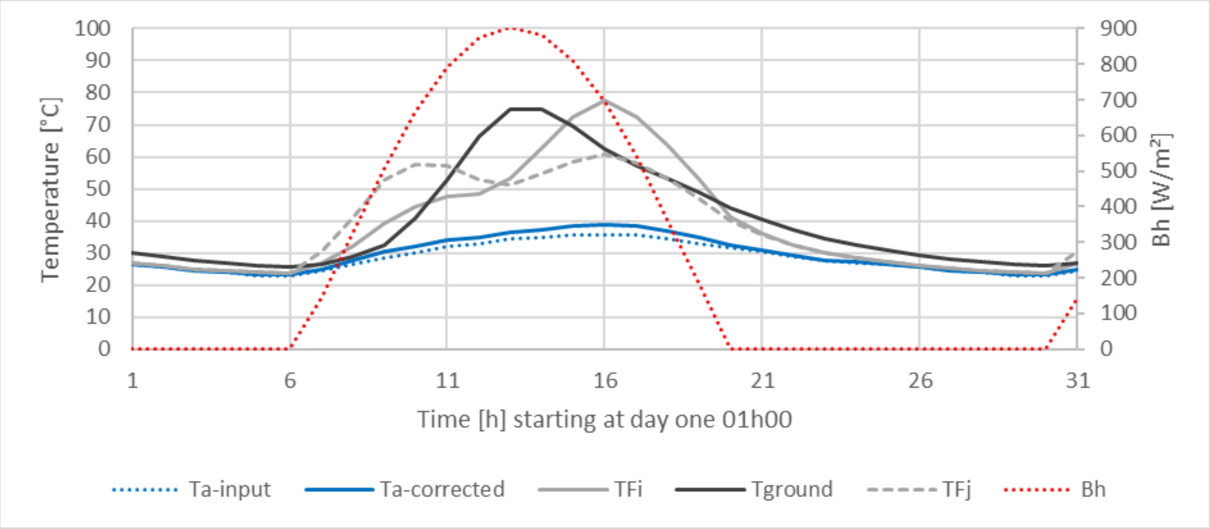


*Figure 3 Canyon surfaces temperature for scenario B2 (light walls – high thermal inertia)*

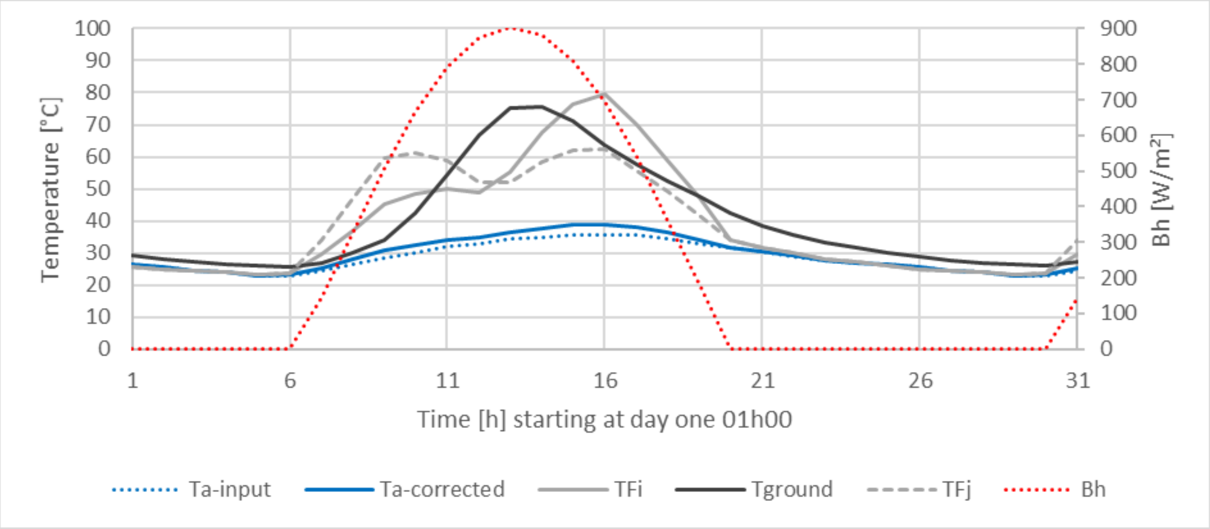


*Figure 4 Canyon surfaces temperature for scenario B3 (light walls – low thermal inertia)*

The first noticeable result is the difference of temperature elevation for scenario B1, B2 and B3. As expected, heavy walls with high thermal inertia -B1- are significantly cooler than thin walls either with high or low thermal inertia (of an order of 15 to 20°C).

Those results also show that, for the ground materiality chosen for the study, facade materiality only has a small impact on ground temperature on a one day period. The scenario B1, with thick walls with high thermal mass facades result in having the ground temperature lowered from about 2°C during the day and increased of about the same order at night.

While every surfaces started at the same temperature at day zero 00h00, we can notice that at start and end of day one ground temperature never reach air temperature at night. This is also noticeable for thick walls – high thermal inertia (scenario B1) while thin facades (scenarios B2 and B3) both cool enough to reach canyon air temperature at night. While it takes around of 5 hours for thin walls with high thermal inertia -B2-, it is achieved in almost half of this time for thin walls with low thermal mass -B3-.

Figures 2, 3 and 4 also show a major difference in the facades temperature profile due to longwave exchanges. This can be observed through the elevation of temperature of facades when not exposed to direct sun (Fj on the morning and Fi on the afternoon). While facades temperature are lower in case B1 and then exchange less energy by radiation with other canyon surfaces and then result in a small temperature elevation for facades not exposed, in case B2 and B3 shaded facades received more energy from exposed one that have a higher temperature due to the small thermal inertia capacity. This is strongly noticeable at hour 11 where shaded façade Fj reaches about 40°C for case B1 when it reaches around 50°C for case B2 and B3.

When looking at the ground temperature evolution before sunrise for several days, as shown in figure 5, it is also noticeable that a canyon with a higher thermal mass available for facades lower the ability of the ground to cool at night due to longwave radiation exchanges, resulting in an elevation of its temperature before sunrise. Day zero is not shown as it correspond to the model calibration (all surfaces temperature equal air temperature at start).

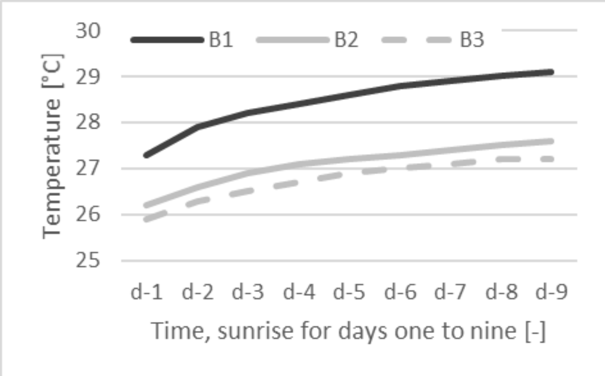


*Figure 5* *Ground temperature before sunrise for scenario B1, B2 and B3, starting at day one (second day of the model).*

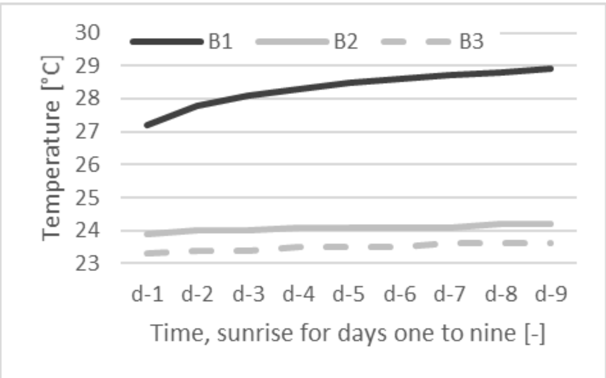


*Figure 6* *Facade Fj temperature before sunrise for scenario B1, B2 and B3, starting at day one (second day of the model).*

The same observation can be made on facades temperatures (see figure 6) for which starting temperature before sunrise is hardly unchanged in scenario B2 and B3, while on a several day period the starting temperature of facades increase for scenario B1 due to both the ability of facades to store energy and to the elevation of ground temperature which exchange more energy with facades during the night, preventing them to cool (reciprocity with previous statement for ground temperature).

Results also show that heavy walls with high thermal inertia (scenario B1) tend to limit the instant energy exchange during the day, being the resultant of lower surfaces temperature, and to increase them at night as surfaces takes longer time to cool as more energy was stored within the materials and as surfaces radiate less.

### 3.3 Façade window fraction impact on canyon energy balance

The last series of scenario tested for the study focused on the impact of facades window fraction on the canyon energy budget. Facades with higher window fraction change the canyon energy balance by two ways. It first changes the reflection mode for incoming solar energy, by having a specular comportment for reflection. It also changes the canyon energy budget by allowing energy to “exit” the canyon by entering inside buildings. To be reminded, it is considered that the energy transmitted to building through glazed surfaces is given back to the canyon air by ventilation. Figure 7 shows the energy loss intensity of the canyon by convection to city air, radiation to sky and transmission to building’s interior at the moment of higher exchange of the day.

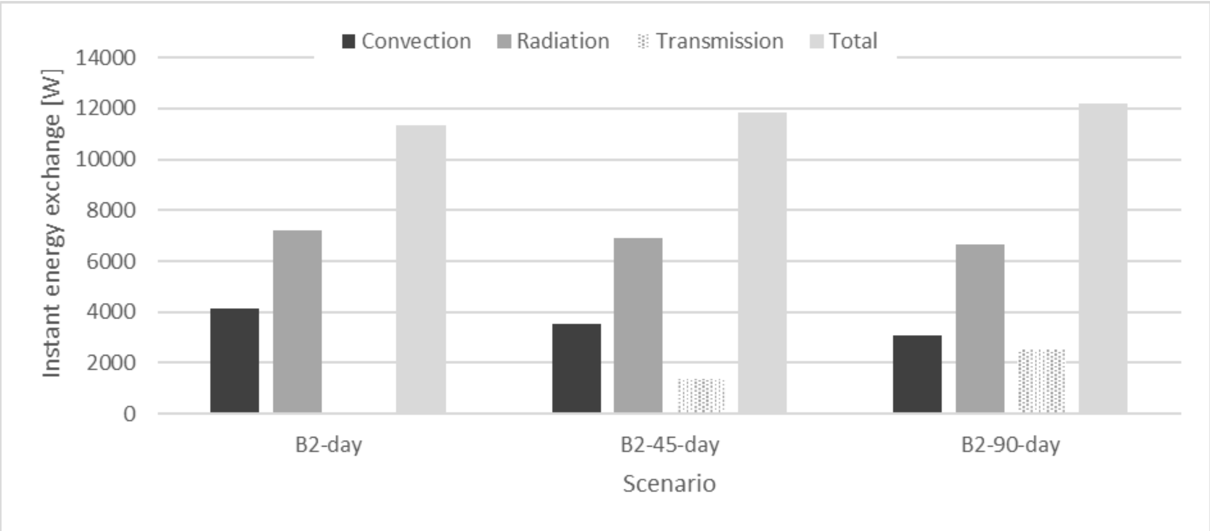


*Figure 7* *Convective, radiative, transmissive and total instant loss of energy of the canyon at the peak of intensity of total loss during the day for facades window fraction of 0, 0.45 and 0.90.*

Concerning the total energy loss of the canyon surfaces, either by convection with canyon air or by longwave radiation to the sky, the study has shown only a small difference between the three scenarios in absolute value, but has revealed a significant modification in the repartition between the mode of energy loss (energy given back to city air or radiated to the sky vault). Figure 8 shows the total energy loss from canyon surfaces for a twenty-four hour period.

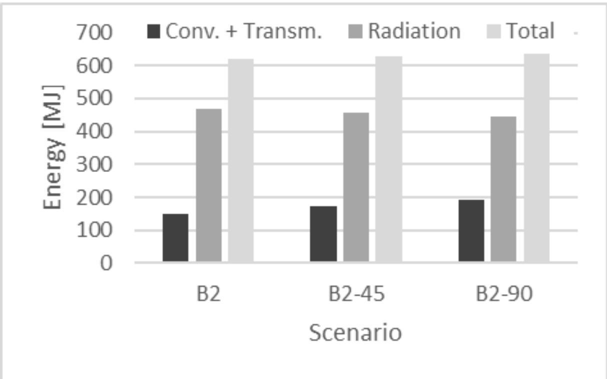


*Figure 8* *24h period energy transmitted to city air, radiated to sky and total for scenario B2, B2-45 and B2-90*

While the study has revealed only a small difference for ground temperature evolution between the three scenarios, it has shown a significant difference concerning walls temperature. In fact, by changing the reflective mode of the facades, facades with high window fraction tend to reflect more energy to the ground and less to opposite facades, resulting in a temperature difference of around 10°C higher for scenario B2 (window fraction of zero) compared to B2-90 (window fraction of 90%).

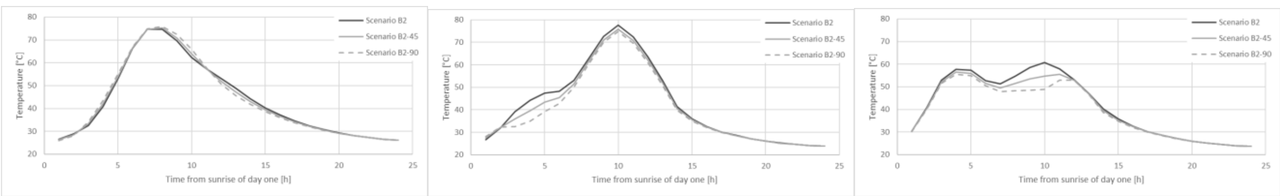


*Figure 9* *Ground, East-oriented wall and West-oriented wall temperature evolution on a twenty-four hour period for the three scenarios. (black B2, grey B2-45 and dash-grey B2-90).*

## 4. Discussion

The results first confirm the impact of facades materiality characteristics on the canyon energy balance. Indeed, while looking at the first series of results concerning the albedo value and reflective mode of facades, we can observe that canyon with high diffuse-like reflective facades might be able to reflect up to 20% of the solar incoming energy directly to the sky compared to canyon with lower albedo or with specular-like mode of reflection. Considering that all the energy directly reflected to the sky does not participate in city surfaces or air temperature elevation, this first confirm the possibility to mitigate UHI effect by modifying albedo value of facades.

When comparing the solar energy incoming to the ground, which is the part of the canyon with the lowest skyview factor and therefore the less ability to cool at night by radiation to the sky, facades with high albedo seems to worsen the situation by increasing the energy incoming on it. But when considering the part of the solar energy reflected outside the canyon and the fact that facades with high albedo tend to be cooler than facades with lower one, the impact on the daily energy balance of the ground surface is finally quite similar. Therefore, we can conclude that facades with high diffusive-like reflective albedo are a good option to mitigate UHI effect.

Concerning facades available thermal mass impact on canyon energy balance, it shows that, while facades with high thermal inertia are cooler than thinner ones, the gain on ground temperature (lower temperature) is very low during the day and might even be worst during the night. While this gain of facades temperature (lower temperature) can surely increase people comfort in open spaces by limiting the instant energy radiative transfer, this still need to be studied from the point of view of long-term balance as heavier facades tend to heat more and more on long period. Indeed, canyon with facades with high available thermal mass tend to increase the energy stored over few days, while facades with a low thermal mass are able to find an equilibrium at the end of a 24h circle, retrieving the same temperature as the city air.

Additionally, it is clearly observable that on a few days period, ground and facade temperature increase over 24h circle, meaning that the advantage they present at the beginning becomes less significant over time. This also mean that canyon with lower thermal mass are able to “cool” quite quickly when better climatic conditions occurs while “heavier” canyon requires more time to do so.

The third series of scenarios about the impact of window fraction shows at first that while the sun is visible in the sky, more energy comes to the ground, increasing people discomfort. In opposition while the sun has set, the opposite applies due to the noticeably lower temperatures of windows compared to the walls for the scenario studied. It also shows that facade walls are cooler for a part of the day for high window fraction, increasing the benefit by lowering the instant radiative exchange in the canyon.

Nevertheless, although windows can be seen as having a positive effect from the canyon energy balance point of view, the results show that while compared to the full energy balance, once the energy transmitted to the building is considered, a high window fraction tend to limit radiative exchanges with the sky and to augment the energy given back to the city air mass. Therefore, while increasing the risks of overheating for buildings and the need for cooling, it also participates to the elevation of the UHI effect.

Those results altogether confirm that facades material choice, including window fraction, have a significant impact on urban canyon energy budget. Either through the ability of materials to lower the incoming energy in the canyon, through the fact that they allow part of the canyon to cool faster or through the fact that they do not transmit energy to buildings, reflective thin and with low thermal mass opaque materials seems to be the best option to mitigate the UHI effect and therefore to limit the intensity of heatwaves.

## 5. Perspectives

The study first shows that facades materiality choice can strongly impact canyon energy balance. But while in this study every facade is considered as a 2D object, both at the building scale (no balcony, flat wall, …) and at the covering material scale (flat materials with no roughness, no third dimension for element as cladding, …) it would be interesting to adapt the model to observe the impact of the facade “roughness” or “third dimension” on energy budget within the canyon.

Keeping the spirit of this model, it would also be possible to develop a methodology which would allow to give a fast estimation of buildings impact on their direct environment, allowing to help decision makers both for new construction and refurbishment.

The use of a simple canyon model shows a real gain in the ease of use by limiting the number of parameters involved and still giving correct results validated by in-situ measurement. At this stage, it seems to be a good way to focus on elements property one by one in order to give generic rules/guide for actors of the field of construction and public policymakers. Such model could allow to asses several subject as roof materiality impact on city energy budget or to allow comparison between several strategies such as canyon materiality changes compared to traffic reduction or other generic public policy.

## Text References


[1] Harman, Ian N., Martin J. Best, and Stephen E. Belcher. 2004. “Radiative Exchange in an Urban Street Canyon.” Boundary-Layer Meteorology 110 (2): 301–16. https://doi.org/10.1023/A:1026029822517.

[2] Lienhard, John H., and John H. Lienhard. 2008. A Heat Transfer Textbook. 3rd ed. Cambridge, Mass: Phlogiston Press.xxxx

[3] Panao, Marta JN Oliveira, Helder Gonçalves, and Paulo Ferrao. 2006. “Air Flow Exchange Velocity of Urban Canyon Cavities due to Thermal Spatial Differences.” PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6-8 September 2006, January 2006.


## Main additional references used for the study


Ineichen, Pierre. 1983. “Quatre années de mesures d’ensoleillement à Genève.” University of Geneva (Switzerland).

Iqbal, Muhammad. 1983. An Introduction to Solar Radiation. Toronto ; New York: Academic Press.

Krayenhoff, E. Scott, and James A. Voogt. 2010. “Impacts of Urban Albedo Increase on Local Air Temperature at Daily–Annual Time Scales: Model Results and Synthesis of Previous Work.” Journal of Applied Meteorology and Climatology 49 (8): 1634–48. https://doi.org/10.1175/2010JAMC2356.1.