# Towards the future generation of adaptive glazed building envelope.

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## Adaptive transparent building envelope technologies

The building envelope and, specifically the transparent part, can play a significant role in reducing buildings energy consumption and achieving higher level of indoor environmental quality. Its impact is quantified by Jin et al. [1], who performed a sensitivity analysis on building performance in terms of energy consumption, indoor environmental quality and whole life cost of early-stage design parameters, including façade, architectural and building services design parameters. This is summed up, as far as the influence of façade design parameters on the total energy consumption is concerned, in Figure 1. The figure shows the ranked influence on the total energy consumption (heating, cooling and lighting) of an enclosed office building located in Helsinki, London and Rome, of: a) the Window-to-Wall-Ratio (WWR); b) the U-value ($U_g$), g-value and visible transmission $\tau_{vis}$ of the transparent façade; c) the U-value of the opaque façade ($U_p$); d) the Infiltration Rate (IR). This is done according to the absolute value of the Standardized Regression Coefficients (SRC) of the global sensitivity analysis. The façade parameters pertinent to glazed facades, i.e. the U-value of the glazing ($U_g$), g-value and visible transmission $\tau_{vis}$, together with the WWR, are the ones with the largest influence on the total ideal energy consumption and the indoor environmental comfort, as well as the total life cycle costs (productivity of the occupant included).

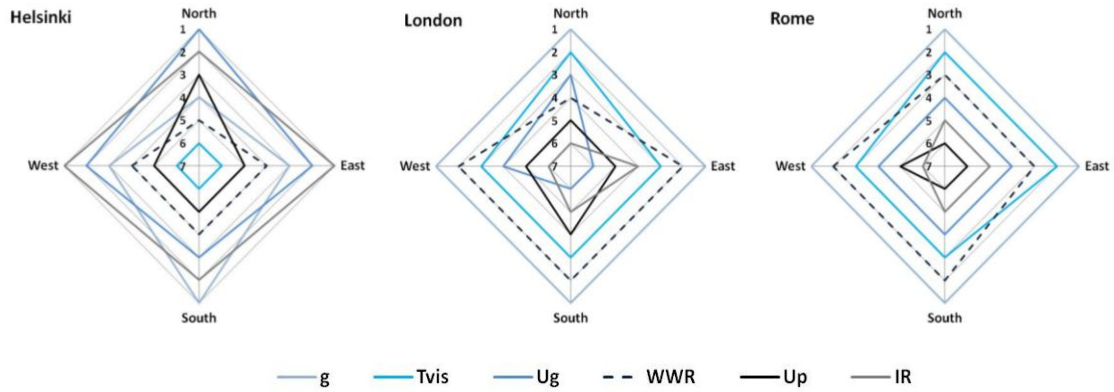

Fig 1. Influence of façade design parameters on total energy consumption of office building for different locations and orientations.

Indeed, of the various energy efficient technologies considered by IEA–ECBCS Annex 44 activity [2], adaptive technologies embedded in the building envelope, and particularly transparent ones, are considered to have the largest potential to minimize the energy consumption of buildings, such as Double Skin Facades or Advanced Integrated Façades [3], smart glazing [4] and movable solar shading [5], is considered crucial in order to achieve the Zero Energy Building (ZEB) target.

In particular smart glazing technologies are able to change dynamically their thermo-optical properties according to changing boundary conditions, i.e. external climate and internal loads (due to occupancy, lighting and equipment). The change in thermo-optical properties is either a self-triggered adaptive mechanisms (passive or smart) or it is triggered by an external stimulus (intelligent or active), and it can happen in the time scale of minutes or seconds. To the first group, technologies as thermo-chromic, thermo-tropic or photo-chromic glazing belong, these are able to change their g-value (amount of total solar radiation transmitted through the glazing) and visible transmission $\tau_{vis}$ (amount of visible radiation transmitted through the glazing) according to a change in temperature or amount of incident radiation, respectively. While in the second one, there are technologies like electro-chromic, gasochromic, light particle devices and photo-volta-chromic glazing, which instead are able to change g-value and $\tau_{vis}$ due to an imposed current. Although durability issues still need to be completely addressed, these kind of technologies are competing with other solar modulating technologies like internal and external shading devices, due to lower level of maintenance needed, absence of moving parts, higher level of automation and integration achievable. In Figure 2 the ability to modulate the g-value and $\tau_{vis}$ of some smart glazing is compared with the static thermo-optical property of state of the art double glazing units: in particular smart glazings (coloured lines) are able to vary their thermo-optical properties along the lines in the graph, while each grey dot represents the performance of a single double glazing unit (data of DGUs are taken from Window database [6] ). Moreover newer and "smarter" glazing technologies are being developed (dashed coloured lines in Figure 2): some with the main feature of being able to modulate only the infra-red part of the solar spectrum (near infrared thermo-chromics [7] and electro-chromics [8]); thermo-chromics changing transparency at lower temperatures [9]; electro-chromics that are able to modulate independently the visible and infrared portion of the solar spectrum [10].

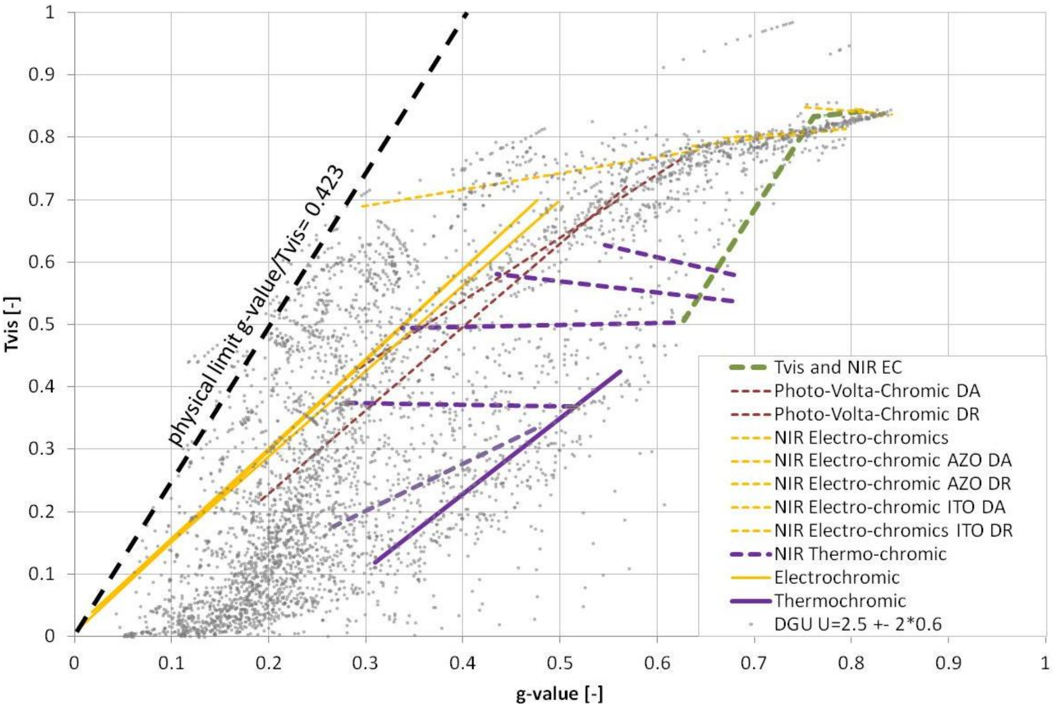

Fig 2. $T_{vis}$ and g-value of smart glazing technologies compared to standard double glazing units. The figures are sometimes based on partial optical data of smart technologies, so that the actual performance is in between a full modulating capability of the solar reflection coefficient (DR) and a full modulating capability of the solar absorption coefficient (DA).

There have been different research efforts to evaluate the benefits in terms of energy saving of adopting these latest smart glazings, as well as defining the ideal time dependent thermo-optical properties of smart glazing in general and to evaluate their impact on buildings energy consumption. But all of these study are either not supported by simulation [11] [12], or based on modelling approximations [13] [14] [15]. The aim of the present work is to present not only a method and a tool to devise the ideal/optimal range of adaptive thermo-optical properties of an adaptive glazing, but also to explicit the ideal thermo-optical properties that an ideal adaptive glazed façade must achieve, as well as its impact on the total building energy consumption.

## Simulation and optimisation of adaptive building envelope technologies

Different approaches have been used in order to define ideal/optimal time dependent building envelope properties for a certain scenario. These can be distinguished in direct and inverse methods. In the direct approach the performance of a new system/technology is characterized first; a model (or comparative experiment) is developed and the performance of such a system applied to specific cases is evaluated; finally properties of the system/technology or its control strategy are optimized to improve its performance. The direct approach appears to be ill-suited to the research issues presented above, because it evaluates a specific case of adaptive mechanisms (in terms of time scale of adaptive mechanisms and adaptive façade properties) and technology. The shortcomings of this approach are highlighted by Zeng et al. [16] who, in contrast, presents the potential of an inverse approach: the ideal value of one of the thermo-optical properties of the building envelope can be evaluated by minimizing or maximizing a cost function, which is different in the case of passive (no HVAC) or conditioned buildings, consisting in either indoor environmental comfort or energy consumption, or both of them. The main limitation of the approach of Zeng et al. [16] is that it cannot be used when multiple ideal adaptive properties need to be identified and it is hardly if not impossible to scale up.

An evolution of the inverse approach is presented by Loonen et al. [17]. The authors attempt to identify the ideal properties of an opaque façade and the optimal window-to-wall ratio *WWR,* by means of multi-objective optimisation. In this case the time horizon of the optimisation is set according to the time scale of the adaptive mechanisms, or reaction time of the façade. The optimizations are performed on a monthly basis, so that the façade is assumed to have a monthly adaptiveness, and the yearly energy consumption is taken as the some of the monthly energy consumption with different façade properties. The same approach is extended by Favoino [18] to optimize long-term adaptive glazing properties. The same approach is adopted by Goia [19] to optimize the WWR of a building and Martinez [15] to optimize several façade properties, both on an hourly basis. In all these studies the adaptive façade behaviour is approximated as the sum of the performance of different static façades, one for each month, day or hour. This method can define multiple ideal properties although solutions for small time horizons (i.e. day or hour) are not reliable, unless the results of the previous optimisations are set as the initial conditions of the optimisation on the following time horizon. This last problem can be referred to as thermal history management (THM) [20]. In a more recent work Loonen et al. [21] overcome the thermal history management problem using the building energy simulation software ESPr, by explicitly updating the states (temperatures) at the beginning of each optimisation. Moreover the time scale of the adaptive mechanisms that can be optimised is reduced to an hour, due to the ESPr capabilities of simulating dynamic thermal properties, and receding horizon control RHC (or model predictive control MPC) is used in order to ensure that the optimal time series of adaptive properties minimizes the energy consumption of the building.

In the present work the approach and the framework set by Loonen et al.[21] is extended to the building energy simulation software Energy plus, by using the capability of its Energy Management System subroutine to simulate adaptive building envelope properties. Moreover it is introduced the THM and the RHC, in order to evaluate which is the time series of adaptive properties that minimize/maximize a cost function. To achieve this Energy plus is integrated into a unique tool together with a coordination layer, Matlab, used for the thermal history management and to move the time horizon of the optimisation, and an optimisation layer, GenOpt, used to optimise the time series of the façade adaptive properties. Within this tool different level of adaptiveness can be simulated/optimised, in terms of thermo-optical properties and time scale of the adaptive mechanisms. Moreover optimal control (model predictive control) of an active building envelope system can be simulated, i.e. for an electro-chromic glazing or for a double skin facade. Figure 3 sums up all the different properties of the building envelope that can be simulated as being adaptive. Moreover different and multiple cost-function can be evaluated: total primary energy consumption, on-site net primary energy consumption (balance between energy consumption on production on site), thermal comfort, IAQ, visual comfort and overall indoor environmental quality.

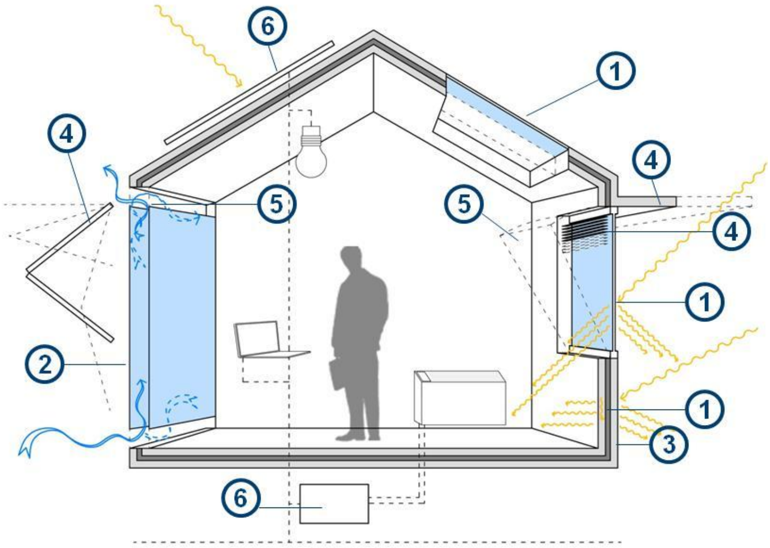

Fig 3. Adaptive building envelope (active and passive) and integrated renewable energy sources (RES) simulation capabilities of the developed tool: 1. Construction state; 2. Surface Heat Transfer Coefficient; 3. Material Surface properties; 4. Schedules; 5. Airflow Network Opening; 6. RES Generation and Storage.

## Method

As discussed above defining the ideal properties of an adaptive glazing (in terms of range and speed of adaptiveness) and evaluating its energy saving potential is useful to give directions and allocate resources for future product development. The aim of the present work is to deploy the inverse methodology presented above, by means of the Energy plus tool developed, in order to devise the set of thermo-optical properties of an ideal glazed façade and evaluate its energy saving potential in different climates and with different time scale of adaptiveness. Moreover this is not limited to optical properties (i.e. g-value and $\tau_{vis}$) but extend the concept of smart glazing also to variation of the U-value of the glazing.

At this purpose the case study of an office building located in Helsinki, London and Rome is modelled, considering a reference room with 40% WWR in the four cardinal orientation, even though only the results for the south oriented building will be presented here. The total primary energy (heating, cooling and lighting primary energy) will be used as a cost function. The performance and properties of a reference static façade R are compared with an yearly optimized one Y, a monthly adaptive M, daily adaptive D. While hourly adaptive results are presented for only 4 days in the hottest period of the year rather than for the all year and just for the London South oriented location, for the sake of brevity. The ideal adaptive properties of the adaptive glazed façade are the U-value, g-value and visible transmission $\tau_{vis}$. The ranges of variation of each single property are [min: step: max]: U-value [0.2:0.05:5.14 W/m$^2$K], g-value [0.01:0.02:0.84], $\tau_{vis}$ [0.01:0.02:0.98]). These ranges are obtained by assuming that an ideal adaptive system can change its thermo-optical properties within the full physically feasable range confined by static state-of -the-art glazings. It is important to note that these results represent the upper limit of the performance achievable by means of adaptive glazed façade and a projection of the performance achievable by means of an ideal daily adaptive glazing façade. The term ideal ,in fact, stands for an ideal range of variability, whose limits were derived theoretically, so that although physically achievable the appropriate glazing products have yet to be developed.

## Results and discussion

The results of the optimisations undertaken on the reference office building are presented in two ways: the first one shows the energy saving potential of an increasing responsive façade, while the second shows the range and variability in the adaptive properties required to achieve the largest possible energy saving. The first results, summarized in Figure 4-left, show the differences between the three climates for the South orientation, in particular it is showed the total specific primary energy consumption for the enclosed office room with the reference façade (R, according to national compliance), the *"static"* optimized solutions (*Y*) and adaptive design with different adaptive time scale, i.e. monthly (*M)* and daily (*D*). The percentages indicate the achievable energy saving compared to the R solution. The second results are showed in Figure 4-right, which represents in a 3D space of coordinates *U-value*, *g-value* and $\tau_{vis}$, the optimal state of the façade and the projections on the different planes (*U-value* - *g-value, U-value* - $\tau_{vis}$, and *g-value* - $\tau_{vis}$). The ideal state of the adaptive façade and in particular the thermo-optical properties are represented for the solutions R (black dots and grey projections), Y (green big dots and light coloured big projections), *M* (white dots and white projections) and *D* (green small dots and small light coloured projections). Only the results of Rome are showed, though they are representative of others climate and orientations in terms of shape of the domain of solutions. Results for all the façade types, orientations and locations are available, but have been omitted for brevity.

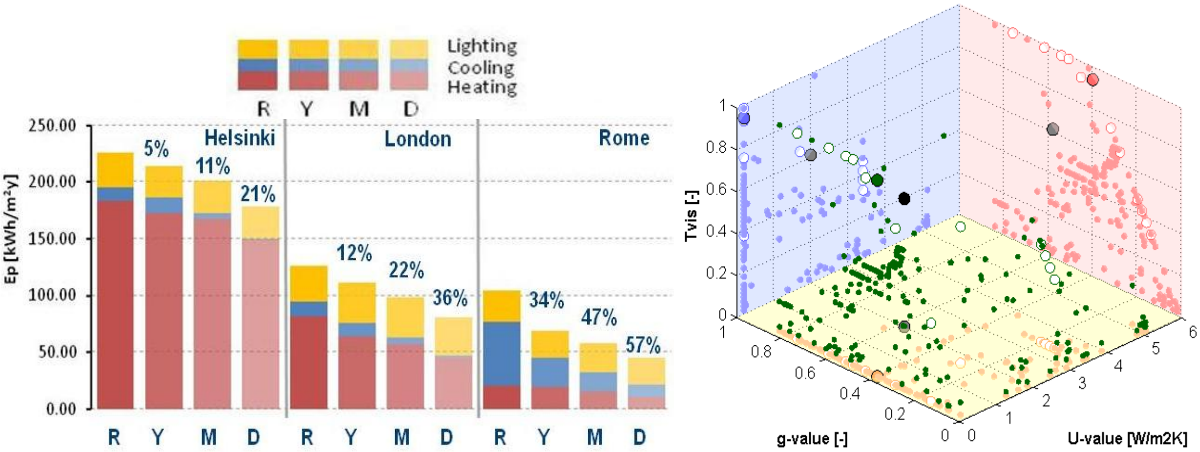

Fig. 4 left. Break up of primary energy consumption for the South oriented office buildings in the climates of Helsinki, London and Rome for the Reference façade (R), the Yearly optimized façade (Y), the Monthly adaptive (M) and the Daily adaptive façade (D).
Fig. 4 right. Thermo-optical properties of the solutions R (black dots and grey projections), Y (green big dots and green big projections), *M* (white dots and projections) and *D* (green small dots and light coloured projections).

Both R and Y façades represent state-of-the-art "static" optimised solution, and the difference between the two indicates that the reference façade is a sub-optimal solution for the specific building design and climate. Thus Y façade is a fairer reference case against which the performance of an adaptive façade may be evaluated, as it provides the highest energy saving achievable with static glazing technology. It is noticeable that the energy saving potential of adopting an adaptive façade substantially increases with the increased speed of the adaptive mechanisms. Moreover the more temperate the climate the higher the achievable energy saving in both relative and absolute terms, this is due to the fact the highest benefit in having such an adaptive façade is the reduction of cooling loads and the energy consumption for cooling purposes, which is itself reduced from 80 to nearly 100 % (from Rome to Helsinki). This is extremely important when considering a climate change scenario in which both average temperatures and temperature extremes are increasing. Although the benefits of adaptive facades can still be significant in colder climates such as Helsinki. The ideal states of Rome daily adaptive façade (Figure 4-right) for the South orientation, show different interesting results: a) it is important to select the correct constraints of the transparent façade variables, as most of the results group close to the boundaries of the variable domains; b) the most frequent solutions for the daily adaptive façade for a certain month coincide with the respective monthly adaptive solution; c) there is a consistent grouping of solutions along certain values or axis, meaning that technologies that can switch between discrete values could be designed with low loss of performance in terms of achievable energy saving; d) looking at the $\tau_{vis}$/g-value surface it can be noticed how solutions, although grouping with a high frequency close to highly spectrally selective technologies ($\tau_{vis}$/g-value higher than 2), spread nearly over the entire domain, indicating the need for a technology that is able to modulate the transmittance independently across the visible and infrared part of the solar spectrum (similarly to the technology presented in [10]), but with a wider range of variation.

The results concerning the hourly adaptive façade are shown in Fig. 5 for 4 summer days (between 19th and 22nd of July) for the South oriented reference office located in London. The climatic condition of those four days are shown on the top graph, the response of the hourly ideal adaptive façade is shown in the centre, while heating, cooling and lighting loads are shown in the bottom graph. It can be noticed how the level of adaptation of the ideal façade is able to completely eliminate the lighting loads during the day when natural light is available, minimizing at the same time the heating energy demand, which is only present for few hours in the early morning, and the cooling loads. Even though the capability of the tool to find a solution which reduces the total energy demand for those 4 days by 50% compared to the reference façade, nearly 14% more than the daily adaptive one, the solution can still be improved. In fact, due to the high level of adaptiveness (3 variables each hour) some antagonistic behaviour between the variability of the three thermo-optical property can be spotted although with similar climatic boundary conditions. In particular during daytime on the 20th and 22nd of July the U-value seems to have an opposite response than what it is expected by looking at the energy consumption and at the response of the g-value and $\tau_{vis}$.In fact the g-value and $\tau_{vis}$ of the adaptive glazing is increasing while the U-value is decreasing just before or contemporary to the presence of cooling loads.

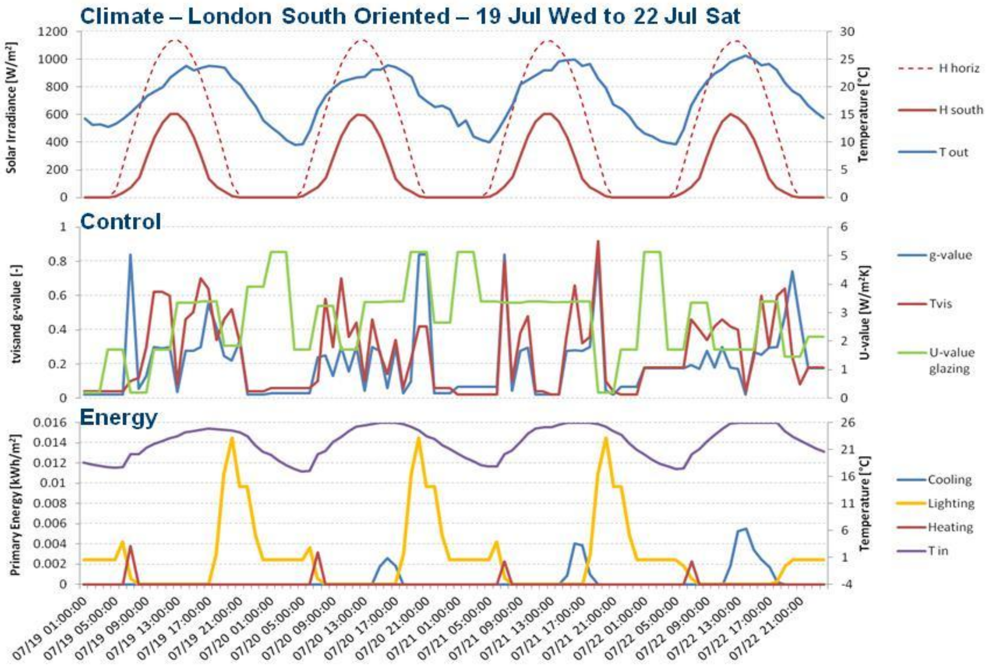

Fig 5. Hourly adaptive façade performance between 19th and 22nd of July, for London South oriented office room.

## Conclusions and future work

Adaptive building façades and particularly adaptive glazings are considered a significant step towards the improvement of the energy efficiency of buildings in order to achieve the ZEB objective. This study presented a tool and a method to identify the performance and the impact of an ideal adaptive glazing façade by means of an inverse approach, which makes use of optimization of the building total energy demand. It accounts for different time-scales of the adaptive mechanism, multiple adaptive properties and implements physical constraints of glazing façade thermo-optical performance.

It is shown that adaptive glazing can play a significant role at reducing building energy consumption in different climatic context. In general the highest decrease in energy consumption is achieved in the cooling primary energy demand of the building for all the orientations and climates. These results not only shift the limits of performance of adaptive glazing, but present a method to define the ideal set of dynamic properties and a tool that can be used to evaluate the impact of future adaptive façade systems, to optimise the design of existing and new adaptive technologies, and ultimately to define optimal control strategies in the operation of these technologies.

Future work will be focused in improving the solutions for hourly adaptive façade, extending the evaluation to the comfort domain and to reduce the computational time needed.

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