



International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016

## An Evolutionary Approach to Single-Sided Ventilated Façade Design

Samin Marzban<sup>a,\*</sup>, Lan Ding<sup>a</sup>, Francesco Fiorito<sup>a</sup>

<sup>a</sup>*Faculty of Built Environment, University of New South Wales, Sydney 2052, Australia*

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### Abstract

A significant portion of the carbon and greenhouse gas emissions of residential buildings in Australia is associated with energy consumption for comfort and health. This study aims to reduce the carbon emissions of residential buildings by optimizing façade design. Targeting to minimize thermal loads, mechanical ventilation will be substituted by natural ventilation, meanwhile indoor environments and appropriate visual comfort will be improved. An evolutionary approach based on a Genetic Algorithm (GA) is developed to determine a set of optimal solutions of façade design for the performance targets of ventilation efficiency, energy consumption, and visual comfort. The proposed approach comprises: an evolutionary process model; the genetic representation of single-sided façade design; genetic operation methods; and fitness functions of multi-objective performance targets as well as Pareto evaluations. The process model enables mapping of façade design options and performance targets to evolve over time. Ventilation, energy and comfort analysis of single-sided ventilation are conducted for the evaluation of the resulting performance of façade design. The expected research outcomes will improve low carbon façade design of residential buildings while reducing cooling and heating costs for the construction industry and the consumer.

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Peer-review under responsibility of the organizing committee iHBE 2016.

*Keywords:* single-sided ventilation; façade design; Genetic Algorithm (GA); energy efficiency; ventilation efficiency; thermal comfort; visual comfort; multi-c<sup>†</sup>riteria assessment; genetic representation.

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\* Corresponding author.

*E-mail address:* [s.marzban@unsw.edu.au](mailto:s.marzban@unsw.edu.au)

## 1. Introduction

Nearly 40 percent of the residential energy use in Australia is attributed to heating, ventilation and air conditioning (HVAC) systems that aim at creating a better indoor environment and maintaining health and productivity for the occupants. The huge amount of energy consumed, and the associated greenhouse gas emissions lead to the conclusion that a more sustainable approach, using renewable energy sources, is needed to provide an acceptable indoor environment in residential buildings. This suggests the need for a natural ventilation solution as an answer to decreasing unsustainable energy use and greenhouse gas emissions [1].

The efficiency of natural ventilation in providing a pleasant indoor environment and decreasing energy consumption depends on the ventilation type, commonly: single-sided ventilation (SSV) and cross ventilation (Fig. 1). Although cross ventilation is known to be more efficient, single sided ventilated buildings are the most prevalent design type in metropolitan cities. Unlike cross ventilation, wind turbulence strongly affects airflow through an opening in SSV [2]. Since this parameter is unstable, evaluating the airflow needed to provide a pleasant indoor environment is complicated, and an unsatisfactory indoor environment is more likely to happen in an SSV building.

The performance of wind-driven SSV is mostly a function of facade treatments such as vertical and/or horizontal protrusions, window type, area, location and size. All possible permutations of these parameters will create a large design space and therefore to reach an optimum combination may be costly.

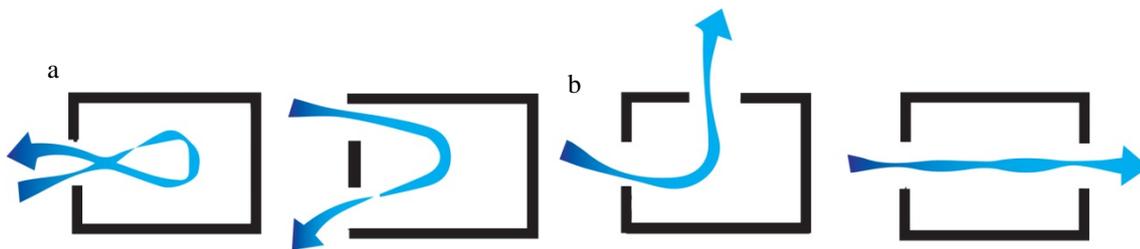


Fig. 1. (a) single-sided ventilation and cross ventilation; (b) cross ventilation

Evolutionary optimization approaches have been proven previously to be effective in resolving design and building-related problems. Such approaches are capable of handling an extremely large number of variables and potential solutions in a huge design space and they can produce unexpected optimal results [3]. The Genetic Algorithm (GA) has been introduced as one of the most powerful evolutionary optimization approaches to study natural ventilation problems [4, 5]. In a GA optimization of SSV, the vast design space of façades and their design variables can be explored and successful sets can be evolved to the next generation to ultimately converge to solutions within an acceptable range of performance targets.

In addition to ventilation efficiency, a practical SSV solution needs to satisfy objective targets of energy consumption and visual comfort. An optimum facade design for maximizing natural ventilation (very large openings as an extreme example) may satisfy natural ventilation efficiency while conflicting with visual comfort.

GA has also been a successful tool for multi-objective optimization problems. Some studies dealt with the optimization of the building envelope construction type and insulation level for walls, roofs and floors [6, 7]. A more thorough research was conducted by Magnier et al. [8] to help in the design process of low-energy buildings. The authors selected the window to wall ratio (WWR) as the single variable representing the envelope. Adding this to variables representing the HVAC system, they found the best solutions for thermal comfort and energy use based on a GA process. Caldas et al. [9] also used a GA-based process to look for optimized design solutions in terms of daylighting, heating and cooling performance. They addressed limited variables relating to windows (placement and sizing of the windows) in an office building. In addition Tuhus-Dubrow et al. [10] developed and applied a simulation tool to optimize building shape and envelope features. Wall and roof construction, foundation types, insulation levels and window types and areas are among the building envelope features that were considered in the study regarding energy use for a residential building.

Yu et al [11] studied a number of façade design variables including the window to wall ratio (WWR) for different facade orientations, and window, roof and wall heat transfer coefficients along with variables representing the overall characteristics of the building (layout plans, shape coefficient, stories and floor area). The combinations of these variables have been optimized to target thermal comfort and energy consumption. Mendez et al. [12] performed a GA-based research search to minimize lighting, heating and cooling energy requirements. The investigation was performed for an office by changing number, placement, shape and type of window and the thickness of the walls. Kasinalis et al. [13] presented a framework for the design of adaptable facades and used a GA in combination with coupled energy and daylight simulations.

Some of the studies on SSV façades have focused on ventilation and energy as the performance targets, while others tried to optimize façade design to gain comfort and minimize energy consumption. Very little has been done on façade optimization for single-sided ventilated buildings targeting ventilation, energy and visual comfort. The three performance targets are functions of a number of façade variables. Considering a set of comprehensive and realistic variables that significantly affect the three performance targets creates a huge design space that can be explored using an optimization method like GA. Using the GA-based method, the relationship between the variables that leads to high performance outcomes needs to be studied to find the best set of design variables and options.

In this study, an evolutionary approach to optimizing SSV residential buildings is developed. The evolutionary process model is developed in Section 2. In Section 3, the detailed genetic representation of facade design variables is illustrated as a part of the evolutionary model. Reproduction and discovery are argued in Section 4 as the driving mechanisms of the evolutionary model. In Section 5, multi-objective performance assessment through Pareto fronts is discussed.

## 2. An evolutionary process model to optimize single-sided naturally ventilated residential buildings

### 2.1. Definitions

Façade design information is represented using the following key components in the model:

**Genotype** - is the encoded single-sided ventilated facade design, consisting of a set of key design variables encoded as genes. It codes the design information used to produce a phenotype.

**Phenotype** - is the decoded single-sided ventilated facade design. It is produced from a corresponding genotype and is evaluated against the fitness function.

**Fitness Function** - is a measurement of the performance of the SSV facade design. It is used to measure satisfaction against the performance targets of natural ventilation efficiency, energy efficiency and visual comfort, and to determine whether an individual in a population of façade design options is selected for reproduction.

**Genetic Operation** – includes crossover and mutation. It is used to produce a new population of façade designs.

### 2.2. Development of an evolutionary process model

The evolutionary process model is presented in Fig. 2. It comprises a genetic search space of single-sided façade design, a multi-objective performance space representing fitness functions, the genetic evolutionary operations including competition for the highest performance targets, and the discovery of the relationship between key design variables that maps onto high fitnesses of the performance targets.

The process of generating the façade design solutions is conducted in the genetic search space, where façade design variables are encoded as genes. This space consists of five categories of key design variables for SSV façade:

- Openings
- Balconies
- Shadings
- Construction and insulation
- Neighbouring units

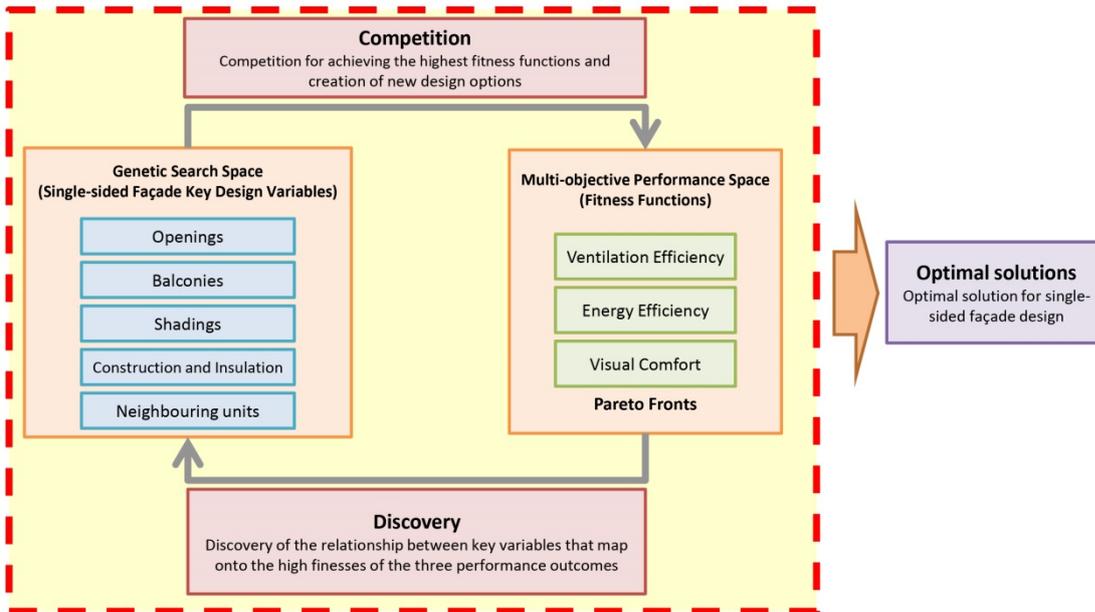


Fig. 2. framework of the evolutionary process model

The evolutionary process randomly selects a set of genes resulting in genotypes to generate a façade design population. This population is evaluated (in the multi-objective performance space) against the hierarchical fitness functions using Pareto fronts. In this space, the three multi-objective functions are ventilation efficiency, energy efficiency and visual comfort. The evolutionary process then uses competition and discovery as mechanisms for finding optimal façade design solutions. Through the competition process, different combinations of key design variables, chosen from the genetic search space, compete with each other to achieve the highest fitness functions and create new design options. The discovery mechanism locates the combinations of façade design variables recognized as the building blocks that produce high performance outcomes. At the next step the building blocks will be transferred to the next generation. This discovery process is based on genetic engineering [14] and is done to set up the relationship between key design variables and high fitness of the three performance targets, thus accelerating the evolutionary process.

The evolutionary process model considers a large search space for single-sided ventilated façade design options, and can produce unexpected optimal design solutions for improved natural ventilation efficiency, energy efficiency and visual comfort.

### 3. Genetic representation of façade design

#### 3.1. Façade design context and key variables

This study considers mid-rise residential buildings in the Australian context. Openings, balconies, shadings, construction type and neighbouring units are categories of design variables. These variables are considered by designers in the decision making process and could significantly influence natural ventilation, heating/cooling loads and visual comfort outcomes. Examples of the single-sided façade design commonly used in mid-rise residential buildings are shown in Fig. 3.

For the openings category, number, placement, typology, width, operability and sill height of the openings have been considered. Depth, width and floor to ceiling height are investigated for the balconies category. Presence or absence of the middle unit shading for each opening has been considered in the shadings category. Three

construction types (heavy, medium and light weight) and three insulation levels (R-value 2.8, 3.3 and 3.8) for each type have been taken into account.



Fig. 3. examples of single-sided façade design commonly used in Sydney mid-rise residential buildings: (a) Rhodes residential development[15]; (b) illustration of key design variables [16]

### 3.2. Encoding façade design information into the genotype

The variables in this research are either discrete (e.g. openings' typology), integer (e.g. openings' width) or binary (e.g. presence or absence of a shading) values. These variables create a five-section genotype representing openings, balconies, shading, construction type and the facades of adjacent units. Fig. 4 (a) shows an example of a genotype developed for façade design, corresponding to the mid-rise residential building example shown in Fig. 4 (b) and (c).

Table 1 presents an example of the encoded key design variables into a genotype. These genotypes are created based on a number of constraints defined for each category of variables, as below.

- **Openings:** Number of the window openings (N) assumed to be between 1 and 4 (since all the examples found in recent residential buildings in Sydney fall into this category). Opening typology (OT) is suggested by the Australian Window Association for the Sydney climate zone. The placement (P) and width (W) of openings can be changed within a range. It is assumed that each opening is either operable or fixed opening (OF), taking into account that at least one opening with a sill height (SH) of 0 m is operable.
- **Balconies:** Balcony depth (BD) is assumed to be a minimum of 2.4m as a result of the regulations in the Apartment Design Guide published by the NSW government [17]. Balcony width (BW) and floor to ceiling height (FC) are considered the same as the unit's width and height.
- **Shadings:** Existence of shading (S) will be displayed as 1 for the shading variable while 0 shows that the opening does not have any shading.
- **Construction:** To examine the building's construction, three different construction types (CT) - heavy, medium or light weight - are considered as the possible values and three insulation levels are investigated for these construction types. The minimum insulation u-value is based on the National Construction Code - Building Code of Australia (NCC2015-BCA), Volume 1 for multi-unit residential buildings (Class 2).
- **Neighbouring units:** Balconies (NB) are among the variables relating to the neighbouring units that affect the performance targets of the middle unit. The presence or absence of balconies for the neighbouring units is also taken into account.

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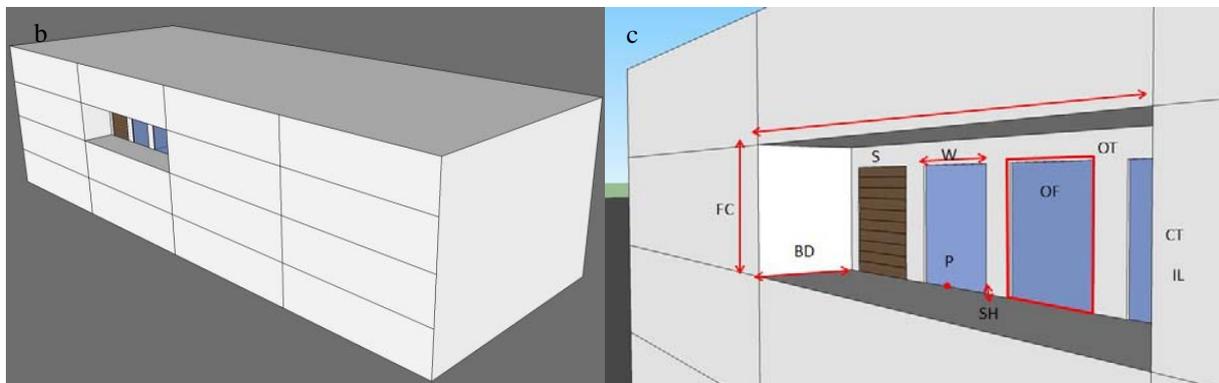
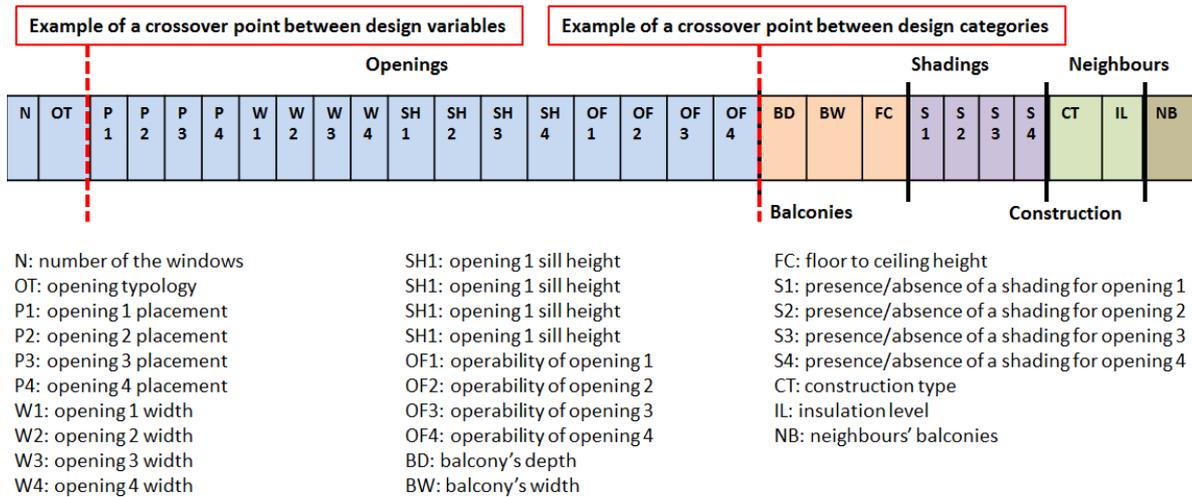


Fig. 4. (a) example of a genotype encoding design information and an example of crossover points; (b) illustration of an example of the middle unit in a mid-rise residential building; (c) illustration of key design variables

#### 4. Reproduction and discovery

Crossover and mutation are the most important parts of a genetic operation and are used for reproduction. This study considers the crossover points located between two design categories, or between design variables. Although the evolutionary process model selects these crossover points randomly for the first generation, they will be determined by the discovery mechanism in the following generations. Fig. 4(a) shows two examples of the crossover points. Through the discovery mechanism, the relationship between key design variables of the single-sided façade and the performance targets are located and evolved over time. The evolutionary process model finds the common genes in a sub-set of the façade design population and defines them as a building block. The process keeps the building blocks that map onto high ventilation, energy and daylighting outcomes throughout the evolutionary process. For example, if the combination of opening width of 1m and medium weight construction has a high fitness score, the model keeps this pattern as a building block and repeats it in a number of off-springs for the next generations.

To maintain diversity from one generation to the next, a small number of the design options will mutate. The evolutionary model changes one or more variable values in a façade design from its initial value. If the variable is a binary one, the other value will be selected. If the variable has discrete or integer values, the mutation operation randomly changes the value to one of the other defined values.

Table 1. SSV façade design variables

Category	Variable	Abbreviation in GA	Range of the variable	Upper bound	Lower bound	Step	Unit
	Number of the openings	N	1, 2, 3, 4	-	-	-	-
	Opening Typology	OT	aluminium, aluminium thermally broken, timber, uPVC, fiberglass, composite	-	-	-	-
Openings	Openings placement	P1, P2, P3, P4	-	2	0.1	0.1	m
	Openings width	W1, W2, W3, W4	-	2	0.5	0.2	m
	Sill height	SH1, SH2, SH3, SH4	0, 0.8	-	-	-	m
	Fixed or operable openings	OF1, OF2, OF3, OF4	Fixed or operable	-	-	-	-
	Balcony depth	BD	-	3.4	2.4	0.2	m
Balconies	Balcony width	BW	-	Length of the unit	-	0.2	m
	Floor to ceiling height	FC	-	Height of the unit	-	-	m
	Shading	S	Presence or absence	-	-	-	-
Construction and insulation	Construction type	CT	Light weight, medium weight, heavy weight	-	-	-	-
	Insulation level (R-value)	IL	2.8, 3.3, 3.8	-	-	-	K.m <sup>2</sup> /W
Neighbours	Neighbour's balcony	BN	Presence or absence	-	-	-	-

## 5. Multi-objective performance assessment

### 5.1. Encoding the performance targets into fitness functions

Natural ventilation, energy efficiency and thermal comfort are encoded into fitness functions to drive the evolutionary process. The multi-objective optimization problem is designed as a function “f” that maps “m” design variables to “n=4” objectives, as seen below.

$$\begin{cases} y = (y_v, y_e, y_d) \in Y \\ y_v = f_v(x), y_e = f_e(x), f_d(x) = y_d \\ f(x) = \{f_v(x), f_e(x), f_d(x)\} \\ x = (x_1, x_2, \dots, x_m) \in X \end{cases} \quad (1)$$

Where,

x is the façade design variable; X is the design space for façade design options; y is the performance target; and Y is the multi-objective performance space [18, 19]. The three performance objectives of ventilation efficiency, energy efficiency and visual comfort are defined as below.

$$f_v(x): \text{MAX ACH, while } \text{ACH} \geq 0.031 \text{ m}^3/\text{s};$$

$f_c(x)$ : MIN cooling/heating load and number of discomfort hours;

$f_s(x)$ :  $100 \text{ LUX} \leq \text{UDI} \leq 3000 \text{ LUX}$

Where,

ACH: is Air change per hour measured with  $\text{m}^3/\text{s}$  unit.

UDI: is Useful daylight illuminance or the annual occurrence of daylight illuminance across the work plane. The unit for measuring UDI is LUX [20].

- *Ventilation efficiency*

For the purpose of this study, the standard indicator for ventilation rate, ASHRAE-55 2013[21], is used. Based on the Breathing Zone Outdoor Airflow ( $V_{bz}$ ) equation in this standard, the minimum ACH for a one bedroom apartment located in NSW, Australia is  $0.031 \text{m}^3/\text{s}$ . This figure is assumed as the lower bound for the performance target of ventilation efficiency.

- *Energy efficiency and operative temperature*

The hierarchical performance target for energy efficiency is calculated by heating/cooling load at the first level and operative temperature at the next level. For operative temperature, the thermal comfort adaptive model and its extension for higher airflow velocities based on ASHRAE 55- 2013 are implemented to calculate the number of discomfort hours.

- *Visual comfort*

This study set outs to investigate visual comfort by applying the UDI-autonomous indicator based on the hypothesis that shading will prevent the eye's exposure to direct sunlight and the Daylight Glare Probability (DGP) is unlikely to happen. To investigate the validity of this hypothesis, DGP for all of the individuals in the optimal set of solutions will be evaluated to confirm that none of them causes glare for the occupants.

## 5.2. Multi-objective performance assessment through Pareto approach

The Pareto approach is adopted in order to achieve multi-objective optimization against the three defined fitness functions. It derives a set of façade design solutions (Pareto fronts) consisting of all non-dominated façade design options. The Pareto front in this research consists of a 3-dimensional space, possessing each fitness function of ventilation, energy, and visual comfort located on one axes of this space. The solutions that are found as the Pareto fronts are the façade design options that are mapped onto three defined performance targets. The fitness functions are determined by using simulation tools such as EnergyPlus [22] and Matlab. Ventilation efficiency is measured using the Air Change Rate Index, while energy efficiency and visual comfort is measured by cooling/heating load and useful daylight Illuminance index, respectively.

## 6. Conclusion and future work

This study has developed an evolutionary process model to optimize single-sided ventilated façade design in residential buildings. The genetic representation of façade design options, the genetic operation and discovery process, and the multi-criteria assessment of fitness functions have been described in this paper. The evolutionary process model enables a large search space for single-sided ventilated façade design guided by fitness functions. Running this process, possibly novel and unexpected optimal design solutions will be found for improved ventilation, energy efficiency and visual comfort.

Further study will include implementation of the evolutionary model with examples and subsequent results analyses. Implementation comprises defining the mid-rise residential building model in EnergyPlus including all of the SSV key design variables, and scripting the genotypes in Matlab. Running the evolutionary model, a set of

optimal façade design options will be generated that can deliver optimal design results to decrease carbon emissions in the residential sector.

## Acknowledgements

This paper is part of a continuing PhD research conducted at the Faculty of Built Environment, University of New South Wales (UNSW, Australia), and the Node of Excellence -Cooperative Research Centre for Low Carbon Living (CRC-LCL, Australia). This research is conceivable thanks to financial support of UNSW by the UPA (University Postgraduate Award) and the CRC-LCL (Top-up scholarship).

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