RECENT ADVANCES IN SIMULATION-POWERED BUILDING SYSTEMS CONTROL

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ABSTRACT

In a simulation-powered building systems control approach, presently available control options are virtually projected onto a future time step via numeric simulation. Subsequently, the respective (performance-relevant) consequences are predicted, compared, and ranked, thus providing the basis for optimal control actions. A proof of concept for this approach has been presented in previous research. To realize the approach in a more realistic (multi-domain) control context, a series of preliminary experiments have been designed and performed in a recently established building automation test bed for simulation-powered systems control.

The paper describes the architecture and elements of the test bed as well as the design and results of the experiments. Experiences thus far suggest the feasibility and scalability of the simulation-powered control approach in a realistic setting as applied to multiple building systems for heating, ventilation, lighting, and shading.

INTRODUCTION

In a simulation-powered approach to the control of buildings' environmental systems (Mahdavi 2004), control decisions are made as follows: First, presently available control options are virtually projected onto a future time step via numeric simulation. Thereby, the building's actualized description (current building model) is regularly provided to the simulation applications together with real-time contextual information (e.g. weather conditions, sky luminance distribution) Subsequently, the respective consequences of alternative control actions (computed resulting values of pertinent performance indicators) are predicted, compared, and ranked. Figure 1 schematically illustrates this approach.

Note that in this approach, simulation is not merely used as a design and optimization support tool to virtually test the performance of buildings' environmental (HVAC) systems. Rather, the approach involves the incorporation of full-fledge numerical simulation during the run-time of building systems' operation. To our knowledge, the earliest instance of formulated ideas pertaining to real-time simulation-based building control in the building performance domain (thermal and visual indoor environmental controls) can be found in Mahdavi 1997a, 1997b. Subsequent research has substantiated this approach and provided further proof of concept mostly in terms of demonstrative implementations in lighting and shading domains (see, for example, Mahdavi 2001, 2004, 2008). However, to arrive at truly scalable solutions, sustained multi-domain implementations are necessary. Towards this end, we recently established a building automation test bed for simulation-powered systems control.

In the following sections of the paper, we first describe the test bed components and configuration, including the installed devices and the corresponding communication infrastructure. We then briefly describe the external data monitoring solution. We conclude the paper with the illustration of initial test runs and their results toward validation of a multi-domain simulation-powered building systems control approach.

TEST BED

The test bed for the integrated simulation-powered building control strategy consists of a realistic office space mock-up, located within a large-space general-use laboratory space. The test bed has a modular structure, and can be divided into two rooms (see Figures 2 to 4). Each room is equipped with two ceiling mounted luminaires, a motorized window with blind, dampers for air volume flow control, a radiant heater, and a desktop humidifier. Sensors for environmental conditions measure duct air temperature and airflow, as well as indoor air temperature, relative humidity, carbon dioxide, illuminance, and air speed. A mobile daylight emulator placed in front of the windows can be programmed to provide variable quantities of light to the spaces (Philips 2008). Figure 4 shows the physical test bed layout.

The software architecture of the test bed consists of a building model server, user interface, outdoor environment server, and a building automation controller (Figure 5). The building model server interacts through a gateway with Excel Web, a BACnet/IP-based, freely programmable building automation controller (Honeywell 2006). The field devices communicate on LON protocol. Control loops for equipment have been programmed into

Excel Web. Using BACnet protocol, the test bed variables can be accessed through a custom-built gateway by our simulation-assisted control software. Room models are kept in main memory on the building model server platform and accessed by the simulation-assisted controller, which resides on the same platform. It invokes lighting and thermal simulations for each control cycle. Simulation invocation occurs via the JavaSpaces environment (Sun Microsystems 2002). Processing-intensive simulations may be, in principle, distributed across multiple processors with JavaSpaces to minimize the load of the building model server. In the current system deployment, however, they reside on the building model server platform.

Radiance was chosen as the lighting simulation engine (Ward 1994). As existing thermal simulation engines are difficult to interface with programmatically, a node-based thermal zone model was implemented in the Matlab environment.

The performance of the simulation-assisted controller is dependent on the accuracy of the predictions of its simulator. In case of Radiance, we thus compared simulated illuminance and luminance values with corresponding measurements. Figure 6 shows, as an example, a comparison of measured and simulated horizontal illuminance levels at 10 locations in the test bed due to the operation of a luminaire. Two dimming states (100% and 60%) were considered. These results suggest a high degree of agreement between measured and simulated results.

The simulation-assisted control method was implemented for lighting, shading, ventilation and heating domains. Conceptually, the controller's decision making works as follows: At time t_i, the actual state of the building model is the starting point for the generation of candidate (alternative) options for the state of the building in a future time point t_{i+1}. In our test bed, for example, options include discrete states for shading devices, luminaires, dampers, and radiant heating devices. The options are then simulated using lighting and thermal simulation applications. Thus, values of various building performance indicators (e.g. horizontal illuminance at the workplace, illuminance distribution uniformity, glare indicators, room temperature, electrical energy use for lighting and heating, air temperatures) are computed for a future time step t_{i+1}. The prediction results are compared and evaluated based on objective functions set by building users and operators. The top ranked control state is subsequently implemented, that is, the simulation-assisted controller sends respective commands to the building automation controller via the gateway.

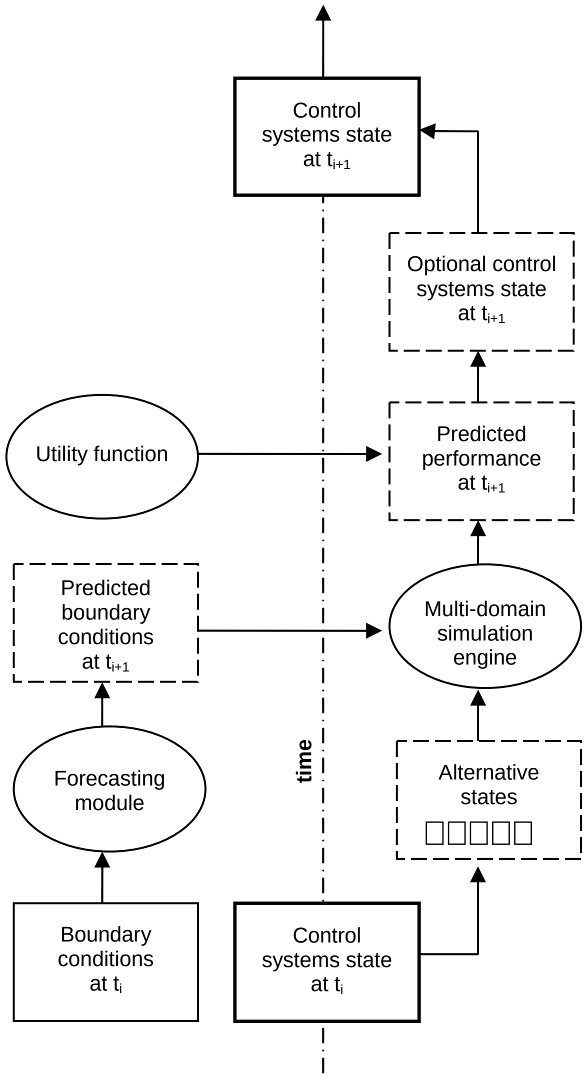

Figure 1 The schematic illustration of the simulation-assisted building systems control strategy.

Figure 2 Test bed's external view

Figure 3 Internal view of one the test bed's two rooms

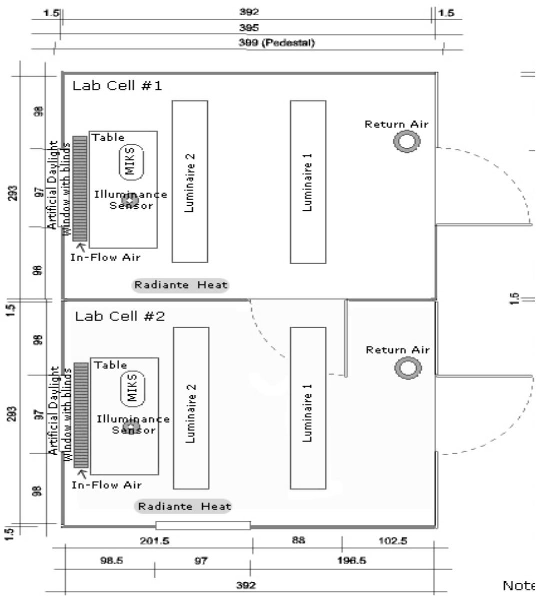

Figure 4 Test bed layout

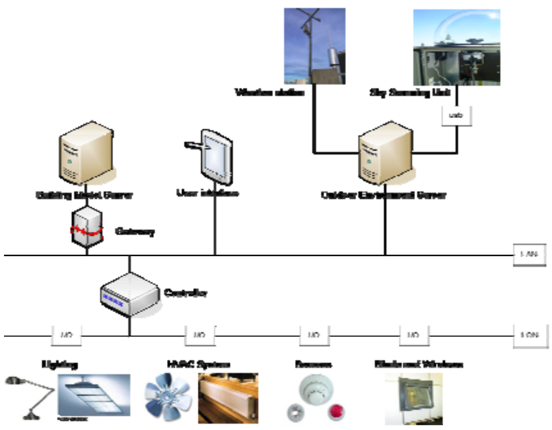

Figure 5 Communication infrastructure

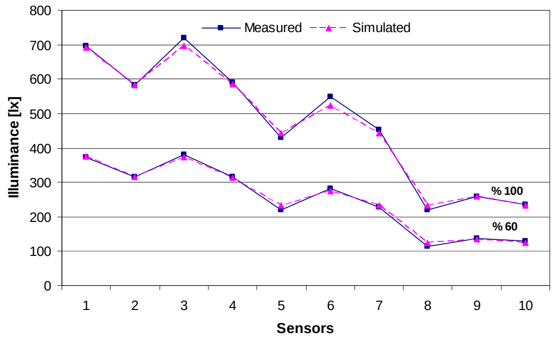

Figure 6 Measured and simulated illuminance levels in the test bed

EXTERNAL CONDITIONS

Basic local meteorological data (air temperature and relative humidity, wind speed and direction, horizontal and vertical global irradiance and illuminance) can be dynamically monitored using standard sensing equipment (weather station). However, more detailed (high-resolution) monitoring of sky radiance and luminance distribution (including cloud distribution detection) still require complex and high-cost sensing technologies. Past research efforts (Roy et al. 1998, Mahdavi and Spasojevic 2007) have demonstrated that sky luminance mapping with digital photography can provide an alternative to high-end research-level sky scanners. This approach requires, however, calibration, as the camera is not a photometric device.

We further explored the use of a digital camera with a fish-eye converter toward provision of sky luminance maps of various real occurring skies. Toward this end, we developed an original calibration method that involves simultaneous generation of digital images of the sky hemisphere and measurement of global external horizontal illuminance. For each of the regularly taken sky dome images, the initial estimate of the illuminance resulting from all sky patches on a horizontal surface can be compared to the measured global illuminance. The digitally derived luminance values of the sky patches can be corrected to account for the difference between measured and digitally estimated horizontal illuminance levels. Thereby, the difference between measured and calculated global illuminance can be assigned to a sky area associated with the sun position.

To empirically test the performance of calibrated digital sky luminance distribution mapping, we compared the illuminance predictions resulting from calibrated sky luminance maps to those resulting from respective photometric measurements (performed using an originally developed 12-sensor sky monitoring device). The results (Mahdavi and Spasojevic 2007) demonstrate that calibrated digital photography can provide a feasible technical solution toward provision of reliable high-resolution real-time sky maps (luminance distribution patterns) as part of the context input model to the simulation engine of a predictive control unit for buildings' lighting and shading systems.

INITIAL EXPERIMENT SETUP

The test bed's functional and operational performance was validated both virtually and with live experiments.

Each experiment lasted for 7 consecutive days. The live test was performed between the July 26th and August 1st, 2008. The virtual test was mainly conducted to consider outdoor weather conditions other that those prevailing during the live experiment. For this purpose, weather data from the time period between May 19th and 25th, 2008 was used. Daily occupancy intervals were defined between 8 am and 8 pm. The desired indoor air temperature was established at 23°C. The illuminance range at the work place was specified between 500 and 1000 lx. Air change rate was defined to be at least 1 h^{-1}. It was also established that natural ventilation would be used during non-occupancy hours, whereas during occupancy hours the window would be closed and only controlled ventilation would be used. The time interval for a control cycle was set at 15 minutes.

The control objective was operationalized as a weighted utility function that reflects the above considerations, as shown in eq. 1. While lighting and thermal performances are equally important in this illustrative utility function, occupant comfort has a greater weight than energy demand in each domain. The minimum air change rate is maintained at all times to ensure good indoor air quality.

$$u(E, P_{Lighting}, \Theta, P_{HVAC}) =$$

$$\left(\frac{4}{5}\cdot u_1(E) + \frac{1}{5}\cdot u_2(P_{Lighting})\right) + \frac{1}{2}\left(\frac{4}{5}\cdot u_3(\Theta) + \frac{1}{5}\cdot u_4(P_{HVAC})\right) \quad \text{(eq. 1)}$$

Where:

$u_1(E)$	Preference function for indoor illuminance E
$u_2(P_{Lighting})$	Preference function for electrical power demand $P_{Lighting}$ caused by the luminaires
$u_3(\Theta)$	Preference function for indoor air temperature Θ
$u_4(P_{HVAC})$	Preference function for electrical power demand P_{HVAC} caused by the HVAC system

Figures 7 to 11 show the preference functions that were used in the experiments. Table 1 provides a summary of considered (discrete) device states.

As in most realistic cases the numeric simulation of all possible combinations of the device states (i.e. the entire control states space) is not computationally feasible, a subset of theoretically possible device states must be selected. In the present implementation, this subset is generated following a combination of greedy search and stochastic jumps. Specifically, at each time step, the subset of devices selected for simulation includes (for each device) includes the previous state, the two "adjacent device" states, and a fourth randomly selected state.

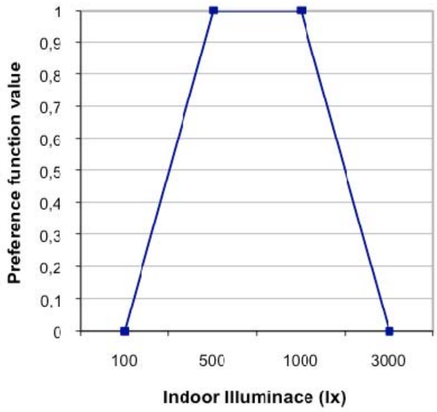

Figure 7 Preference function $u_1(E)$ for indoor illuminance

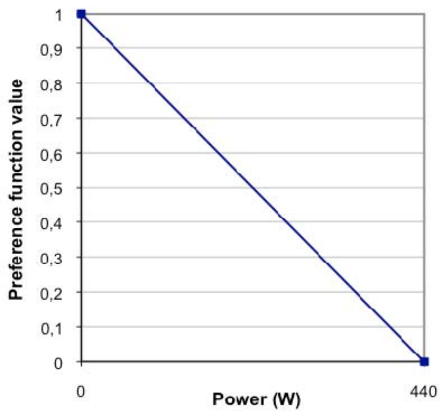

Figure 8 Preference function $u_2(P_{Lighting})$ for lighting power demand

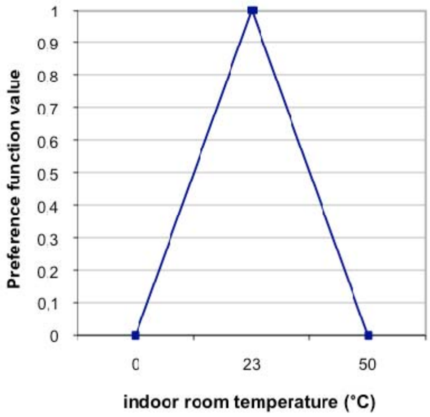

Figure 9 Preference function $u_3(\Theta)$ for indoor air temperature

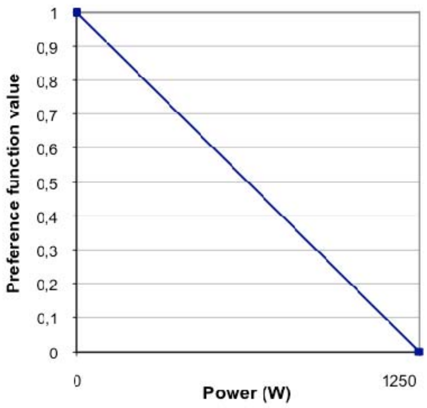

Figure 10 Preference function $u_4(P_{HVAC})$ for HVAC power demand

Table 1 – Discrete device states used in experiments

CONTROL PARAMETER	STATES
Window	0% (**closed**), 100% (**open**)
Luminaires	0% (**off**), 20%, 40%, 60%, 80%, 100% (**on**)
Blinds	0% (**retracted**), 20%, 40%, 60%, 80%, 100% (**deployed**)
Supply air damper	0% (**minimum air change level**), 10%, 20%, 30%, 40%, 50%
Supply air fan	0% (**off**), 100% (**on**)
Radiant heater	0% (**off**), 100% (**on**)

INITIAL RESULTS

Two typical days, a clear day (July 26 2008) and a cloudy day (May 21 2008) are selected from the data collected during the experiments to illustrate the capabilities of the simulation-assisted controller. The actual test was performed in the course of the clear sky day, whereas the virtual experiment was performed with the cloudy day data. In the latter case, the test bed was assumed to be adjacent to a court yard (second floor). The external test bed wall was assumed to possess a U-value of 0.2 $W \cdot m^{-2} \cdot K^{-1}$.

Outdoor illuminance and outdoor air temperature profiles of the two days are shown in Figures 11 and 15. The illuminance and device state data in Figures 12 and 16 suggests that the control system maximizes the use of daylight as opposed to artificial light. The recurrent operation of the shading device (particularly on the clear day) prevents excessive illumination and the corresponding glare risk. This is because the preference functions are defined such that natural lighting is preferred over artificial lighting. Figures 13 and 17 show utility function values for the top ranked control state.

Figure 14 shows that as long as the outside temperature is lower than the indoor temperature, the temperature difference is used to naturally cool the indoor environment. As Figure 18 illustrates, the system maintains the desired indoor temperature without the need for heating, even by an indoor-outdoor temperature difference of 10 K. Thereby, the ventilation rate (with a few exceptions in the morning hours) has been reduced to the hygienically necessary level of 1 h^{-1} (damper position 0% as per Table 1).

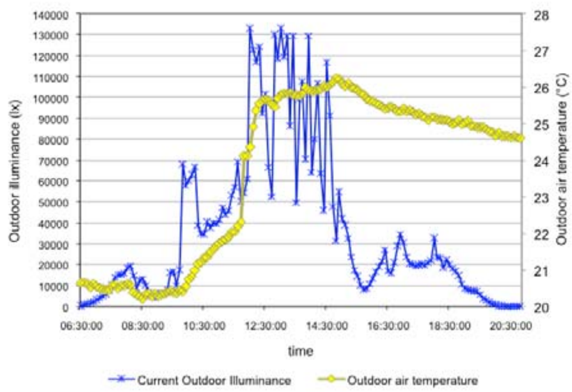

Figure 11 Clear day: Outdoor illuminance and air temperature (July 26 2008)

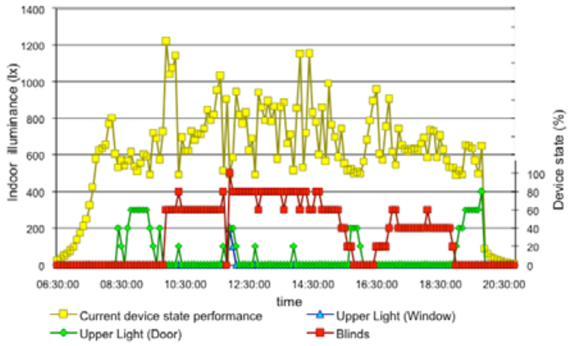

Figure 12 Clear day: Indoor Illuminance and state of individual devices (July 26 2008)

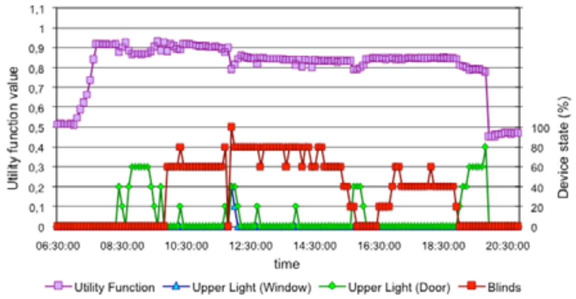

Figure 13 Clear day: Utility function for top ranked control state (July 26 2008)

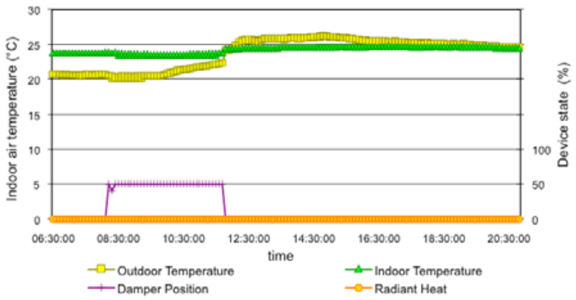

Figure 14 Clear day: Indoor/outdoor temperature and state of individual devices (July 26 2008)

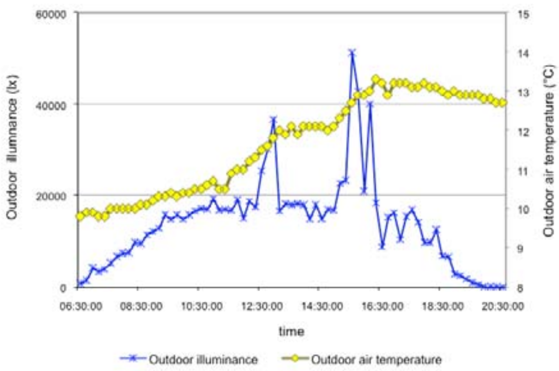

Figure 15 Cloudy day: Outdoor illuminance and air temperature (May 21 2008)

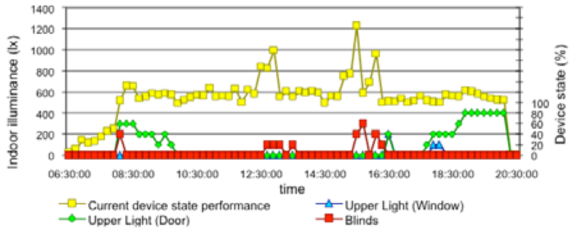

Figure 16 Cloudy day: Indoor Illuminance and state of individual devices (May 21 2008)

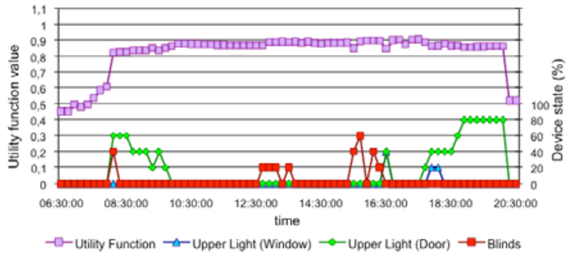

Figure 17 Cloudy day: Utility function for top ranked control state (May 21 2008)

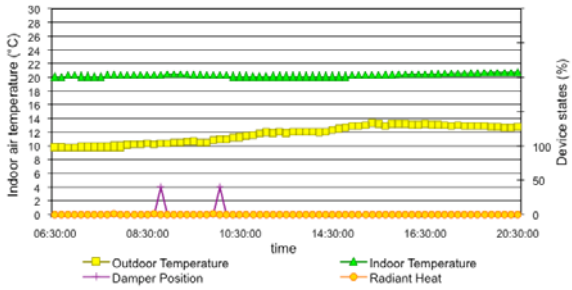

Figure 18 Cloudy day: Indoor/outdoor temperature and state of individual devices (May 21 2008)

CONCLUSION

To realize and validate a simulation-powered building systems control approach in a realistic context, a building automation test bed was designed and established. The paper described the architecture and elements of this test bed as well as the design and results of initial experiments. Experiences thus far suggest the feasibility and scalability of the simulation-powered control approach as applied to multiple building systems for heating, ventilation, lighting, and shading.

Within the framework of ongoing and future studies both in the test bed and in selected actual buildings, the performance of the simulation-powered control strategy will be further monitored, documented, and benchmarked against more conventional control methods toward preparation for wide-scale realization in the field.

ACKNOWLEDGEMENT

The research presented in this paper was supported in part by a grant from the Austrian Science Foundation (FWF), project number L219-N07.

Support was provided also by a grant from the Austrian Research Promotion Agency (FFG), Multifunctional Plug & Play Facade "MPPF" at the COMET program (Competence Centers for Excellent Technologies).

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