# THE BUILDING CONTROLS VIRTUAL TEST BED – A SIMULATION ENVIRONMENT FOR DEVELOPING AND TESTING CONTROL ALGORITHMS, STRATEGIES AND SYSTEMS

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## ABSTRACT

The paper describes the design of a Building Controls Virtual Test Bed (BCVTB), a simulation environment for the development of control algorithms and strategies for the major energy systems in buildings, HVAC, lighting, active facades and on-site generation. The BCVTB is based on the whole building energy simulation program EnergyPlus and includes both the pure simulation and the hardware-in-the-loop methods of implementing the controls. For convenience and scalability, the design of the hardware-in-the-loop interface for supervisory controls uses BACnet rather than the analog interface used for local loop control. The paper concludes with a case study of the use of a prototype implementation of the BCVTB to pre-commission the building control system for the naturally-ventilated San Francisco Federal Building. A number of problems were found with the control program, demonstrating the value of the pre-commissioning and the effectiveness of the technique.

## KEYWORDS

Controls, development system, testing, hardware-in-the-loop

## INTRODUCTION

This paper describes work performed to date to develop a simulation-based tool to support the development and testing of building control systems. Applications include:

- Product Development: development and testing of new control algorithms and strategies, firmware and hardware:
    - Standard sequences of operation
    - Automated fault detection and diagnosis
    - Optimal control
- Project Work: development and testing of controls for unique, innovative, critical or high value projects for individual buildings (or chains):
    - Development of sequences of operation
    - Testing of control programs implemented in the target hardware
    - Testing of additional functionality – e.g. automated diagnostics, automated demand response

Expected benefits include:

- Shorter development time:
    - Find implementation problems prior to field testing (processing power, memory, bandwidth, addressing, interactions …)
    - Repeatable test conditions, including at the whole building level
    - Evaluate energy consumption, peak demand, comfort

The current situation is that there is little or no systematic work on the development of energy-efficient control algorithms and strategies, at least in the USA. Individual consulting engineers have generated incremental improvements and, in some cases, radical changes (e.g. Hartman 2005) but these are isolated occurrences. Testing and demonstration currently requires a series of implementations in real building projects. The lack of tools to enable testing of ideas and their implementation quickly and inexpensively is a barrier to the development and deployment of new controls technology. It is difficult to quantify these benefits, beyond noting that the process of refinement and retesting is drawn out in real buildings because of the inherent difficulty in reproducing previous conditions, so that repeat testing that takes days with a virtual building could take months, or even years, in a real building and still not achieve the same level of repeatability. The BCVTB will not completely eliminate the need for field testing but should substantially reduce the number of iterations involved, and hence the duration, of field testing. The other benefit, which is even more difficult to quantify, is that the availability of tools such as the BCVTB can be expected to stimulate development work that would not otherwise have occurred because of the cost, time and risk involved.

### Previous Work

A significant body of work on the use of simulation to evaluate HVAC control performance has been performed under the auspices of International Energy Agency (IEA) ECBCS Annex 17 (Lebrun 1992). In particular, techniques and models for use in the evaluation of the performance of both local loop and supervisory controls were developed. Control strategies were implemented in simulation and also in real, commercial, control hardware coupled to simulations of the building fabric and plant via analog interfaces (Haves and Dexter 1991, Haves *et al.* 1991, Kelly *et al.* 1991, Laitila *et al.* 1991, Vaezi-Nejad *et al.* 1991, Wang *et al.* 1994, Peitsman *et al.* 1994).

The techniques and models developed in Annex 17 were further developed, tested and documented in an ASHRAE research project (825-RP) to develop a simulation test bed for control algorithms and strategies (Haves *et al.* 1998). The test bed was built on the HVACSIM+ [1] and TRNSYS [2] component-based simulation programs; these programs are well suited to the dynamic simulation of HVAC and related equipment but are less well suited to whole building energy modeling. Some of the HVAC component models developed for ASHRAE 825-RP were extended to treat faulty behavior in order to support the development and testing of automated diagnostics (Haves 1997). The Virtual Cybernetic Building Test-bed [3] (VCBT), developed at the US National Institute for Standards and Technology is based on HVACSIM+ and has been used for testing the integration of HVAC and fire and smoke controls, BACnet conformance testing and testing of automated diagnostics for HVAC systems. A new ASHRAE research project (1312-RP) is extending the work of 825-RP to develop a simulation-based tool to evaluate fault detection and diagnosis methods for air handling units.

### Current Development Systems used by Industry

Initial discussons with prospective industry users in the United States of America indicate that general tools such as Matlab/Simulink [4] are the preferred environments for prototyping new control algorithms and strategies in the context of product development. These environments have powerful capabilities for representing prototype control algorithms and strategies but are limited in their ability to model HVAC systems and the building envelope. The main limitation of such environments in the context of this project is that it would be difficult and time-consuming to use them to model the range of systems and phenomena in buildings that affect energy performance at the level of detail required for control system development and testing. Several manufacturers expressed an interest in Modelica [5], which is a modeling language that is increasingly widely used in a variety of different industries. Some prospective users want the additional flexibility of being able to connect Matlab/Simulink to physical equipment, either in a laboratory or a real building. A comprehensive implementation sequence for development and testing is then:

1. Simulated Controls + Simulated Building
2. Simulated Controls + Real Building
3. Real Controls + Simulated Building
4. Real Controls + Real Building

## DESCRIPTION

The design of the BCVTB is based on the EnergyPlus [6] building simulation program. Use of EnergyPlus enables energy consumption, peak demand, comfort and other building-level performance metrics to be assessed. The design includes two operating modes:

1. 'Pure' simulation, in which the controls are simulated along with the building envelope and the equipment, either in EnergyPlus or in an external process
2. 'Hybrid', or 'hardware-in-the-loop', in which a simulation of the building envelope and equipment is connected through a hardware interface to real controls.

The initial implementation of the BCVTB will focus on supervisory control of HVAC, lighting, active facades and on-site generation, both at the system level and the whole-building level. This initial implementation will be capable of testing strategies that provide set-points for lower level control loops, including local loop controllers. When the control strategy is implemented outside EnergyPlus, these set-point values are most conveniently communicated digitally. The BACnet protocol will be used initially. Local loop control testing capabilities will be added by incorporating dynamic equipment models implemented in SPARK [7] into EnergyPlus.

As described in the Case Study section below, a prototype version of the BCVTB is currently being used to test the control program that implements the natural ventilation control strategy for the new San

[1] http://www.eere.energy.gov/buildings/tools_directory/software.cfm/ID=105/pagename=alpha_list
[2] http://sel.me.wisc.edu/trnsys/
[3] http://cic.nist.gov/vrml/vcbt/vcbtsim.html
[4] http://www.mathworks.com
[5] http://www.modelica.org/
[6] http://www.energyplus.gov
[7] http://simulationresearch.lbl.gov/VS/spark.html

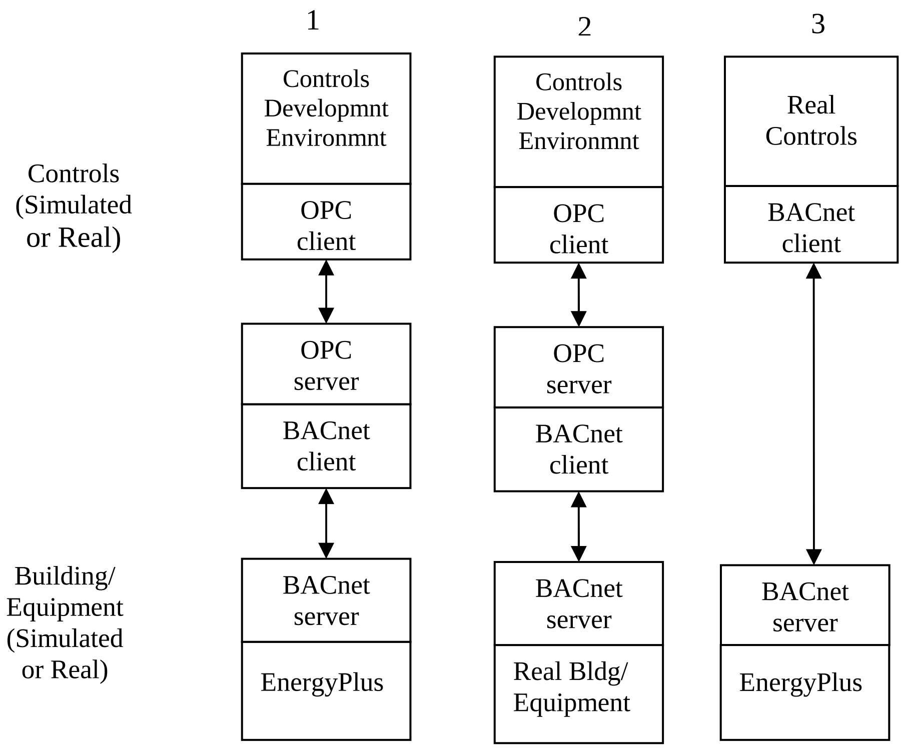


*Figure 1. Configurations of the BCVTB for different development stages.*

Francisco Federal Office Building in the actual controls hardware to be installed in the building.

**Architecture of the BCVTB**

The BCVTB will support Steps 1, 2 and 3 above using the configurations shown in Figure 1. The aim of some prospective users is to eliminate Step 2 as the capabilities and credibility of simulation improve over time.

The advantage of using OPC (OLE for Process Control[8]) as an intermediate protocol in Steps 1 and 2 is that OPC interfaces are available for at least two of the general controls development environments referred to above and there are several commercial BACnet OPC servers that appear to be suitable for use with these interfaces.

There are at least two non-commercial BACnet servers that are being evaluated for incorporation into EnergyPlus. The EnergyPlus BACnet interface will be based on the 'EMS' facility currently being implemented by the National Renewable Energy Laboratory for the next general release of EnergyPlus. The EMS facility includes an interpreter for generic line code that will allow users of EnergyPlus to input their own control strategies without having the recompile the program. The EnergyPlus BACnet interface will make use of the mapping between control points and EnergyPlus variables in the EMC facility.

The architecture for implementing Step 3 shown above is for supervisory control applications, where a digital communications interface is both more appropriate and more convenient than an analog interface. For local loop applications involving analog sensors and actuators, the configuration shown in Figure 2 is used. Within EnergyPlus, the SPARK equation-based solver is used to model equipment and sensor dynamics, drive the hardware interface (typically plug-in multifunction I/O boards) and synchronize to real time. This is the configuration currently being used to test the control system for the new San Francisco Federal Office Building (see below). Development and testing of automated diagnostics requires the modeling and simulation of the faults of interest; this involves extending current models to treat faulty behavior.

**Feedback from Potential Users**

A description of the planned capabilities of the Building Controls Virtual Test Bed (BCVTB), along with a questionnaire designed to elicit the requirements and interests of potential users, was sent to five manufacturers of controls and HVAC equipment.

Follow-up discussions were held with various individuals at each company. There was strong support for the concept of the BCVTB and the proposed approach to its design from the majority of

[8] http://www.opcfoundation.org/

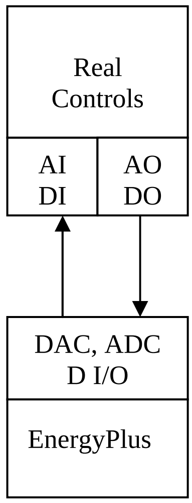


*Figure 2. BCVTB configuration for analog interfacing to local loop controls*

the companies. It is worth noting that is a diverse variety of approaches to control system development among the five companies contacted to date. For example, one company firmly expressed the requirement that the BCVTB should have the configurational flexibility to connect prototype control algorithms to real equipment, first in a laboratory and then in a real building, in order to demonstrate the robustness of a new algorithm to a skeptical product implementation department. Testing control algorithms on a simulated system or building is seen as a valuable first stage of development. Another company has the strategic goal of developing simulation technology to the point where it is a reliable substitute for physical testing for proof-of-concept, as in other industries. This is partly an issue of model fidelity and partly a question of defining appropriate boundary conditions (e.g. internal and solar loads) at the frequencies of interest.

Another difference in approach relates to hardware-in-the-loop testing. Three of the five companies considered hardware-in-the-loop testing to be extremely valuable whereas one company considers it to be of limited value. One company in particular sees hardware-in-the-loop testing as being both valuable and needed to close the wide gap between concept and implementation, allowing it to accelerate the development of control system products and other products that include embedded controls. In addition, there is an interest in developing standard control applications for standard mechanical systems that would be more efficient, more robust and less expensive to configure.

In the case of another company, the issue is whether the development of energy-efficient supervisory control strategies (the proposed initial focus of the BCVTB) is treated as product development or support for individual building design projects. This company is inclining to the latter view, which is based on the assumption that new firmware algorithms primarily affect local loop control performance and that local loop performance does not significantly affect energy performance. This assessment is not shared by one of the other companies contacted, which has identified several situations in which the low level sequence of operations has a significant effect on energy consumption.

Two companies indicated strong interest in the use of Modelica to express dynamic equipment models for use in simulation that addresses local loop control and component-level diagnostics. Consequently, the relative advantages of SPARK and ‘native’ Modelica solvers and the possibility of the Modelica language being used to express models for SPARK are currently being evaluated. The advantages of SPARK are that it is already partially integrated with EnergyPlus, it has a computationally efficient solver and it is free to the end user. The advantages of the best established of the commercial native Modelica solvers are that it provides a mature development environment for Modelica models and it has a wide user base distributed across a variety of industries. However, its numerical methods are proprietary. Benchmark comparisons of SPARK and native Modelica solvers will be performed as part of the evaluation process.

## PROTOTYPE IMPLEMENTATION

A prototype version of the BCVTB has been used to test the control program that implements the natural ventilation control strategy for the new San Francisco Federal Office Building in the actual controls hardware to be installed in the building. The open-plan spaces that comprise the majority of the office tower are naturally ventilated, with no mechanical ventilation or cooling. The building is described, along with the integrated design process used, by McConahey *et al.* (2002). The use of simulation in the design of the natural ventilation system is described by Haves *et al.* (2003) and the development of the control strategy is described by da Graça *et al.* (2003). Some of the openable windows are controlled by the building control system, which seeks to provide acceptable space temperatures during occupied periods and control the cooling of the exposed ceiling slab by nocturnal ventilation during hot periods. The natural ventilation scheme has some unusual features and so the control strategy is very different to the control strategies that any US controls contractor would be familiar with, even if they had worked on other naturally ventilated buildings. Testing the control strategy, and its implementation in the actual hardware to be used in the building, prior to occupancy was seen by the design and construction teams and the building owner was seen as a way to reduce the number and impact of controls problems that would otherwise need to be identified and addressed either in the functional testing part of the commissioning process or during occupancy.

In the prototype BCVTB, the simulation is slowed down to run in real time and is connected to control system field panels via a hardware interface consisting of digital-to-analog and analog-to-digital cards that plug in to the PC running the simulation, as illustrated in Figure 3. EnergyPlus calculates the natural ventilation air flow for the current combination of window openings and wind speed and direction and then calculates the thermal consequences of that air flow. The resulting room air and slab temperatures are then passed to instances of SPARK classes embedded in EnergyPlus that drive digital-to-analog (D/A) converters on plug-in cards in the PC. The D/A converters are connected to analog inputs on the field panels of the control system, which receive voltage signals that are equivalent to the signals received from the temperature and façade pressure difference sensors in the real building. These signals are then processed by the control system, which then generates digital raise/lower signals to for each of the window actuators to drive them more open or more closed, along with analog signals for each of the fin-tube heating elements. These signals are then sampled by another plug-in card controlled by SPARK. The window actuators have an end-to-end travel time of 15 seconds, so the raise/lower signals are sampled every 0.5 seconds and integrated using a dynamic actuator model implemented in SPARK to determine the actuator position, which is used by EnergyPlus to determine the degree of opening each window at every 15 minute zone time-step. The simulation is synchronized to real time by reading the PC clock, calculating how much real time must elapse until the simulation time and real time are equal and having the simulation process 'sleep' for the requisite amount of time.

**Example Application**

Figure 4 shows an example of the simulated performance of the naturally ventilated spaces during a period of a (typical) cool summer day in San Francisco followed by three (atypical) hot days. The control signal was generated by a custom subroutine in EnergyPlus produced as part of the process of developing the control strategy. This subroutine represents the control strategy as defined by the designers. The bottom line in the figure shows the window opening mode number (MDN), which ranges from 1, when all the windows are fully closed, to 10, when all the windows are fully open. The windows are nearly fully open during the day and nearly closed at night when the weather is mild. During hotter weather, the windows are opened just enough to provide fresh air to the occupants during the day and are fully open at night in order to pre-cool the ceiling slab and other exposed thermal mass.

Figure 5 shows the result of hardware-in-the-loop testing of an early version of the control program implemented in the hardware used in the building. The plot shows the part of the run corresponding to the first two days of the hot period shown in Figure 4, though the two runs are not directly comparable for a number of reasons. One obvious difference between the behaviors of the control system in the two runs is that, in the run with the real control system shown in Figure 5, the windows do not open during the nights following the hot days, which prevents the accumulated heat in the slab being dissipated to the environment in order to pre-cool the building. This problem was caused by a simple programming error in the implementation of the control strategy. A number of other problems were revealed by the testing, some of which resulted from miscommunications between the mechanical

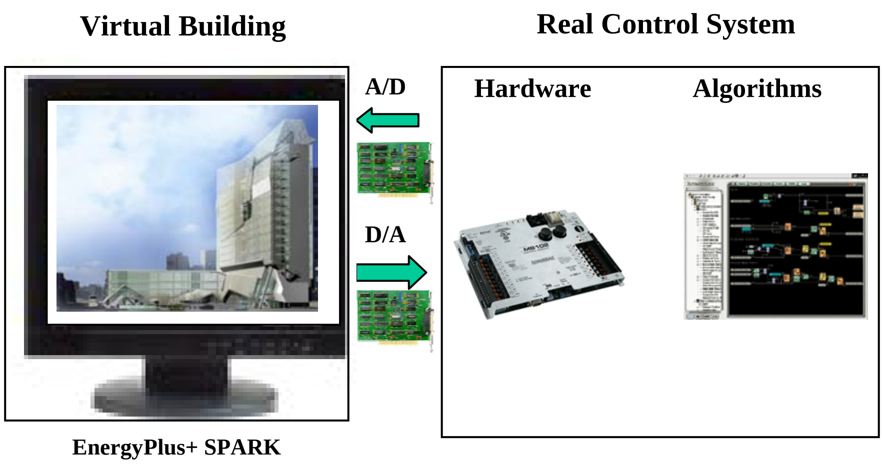


*Figure 3. Configuration of used for hardware-in-the-loop testing of local loop controls.*

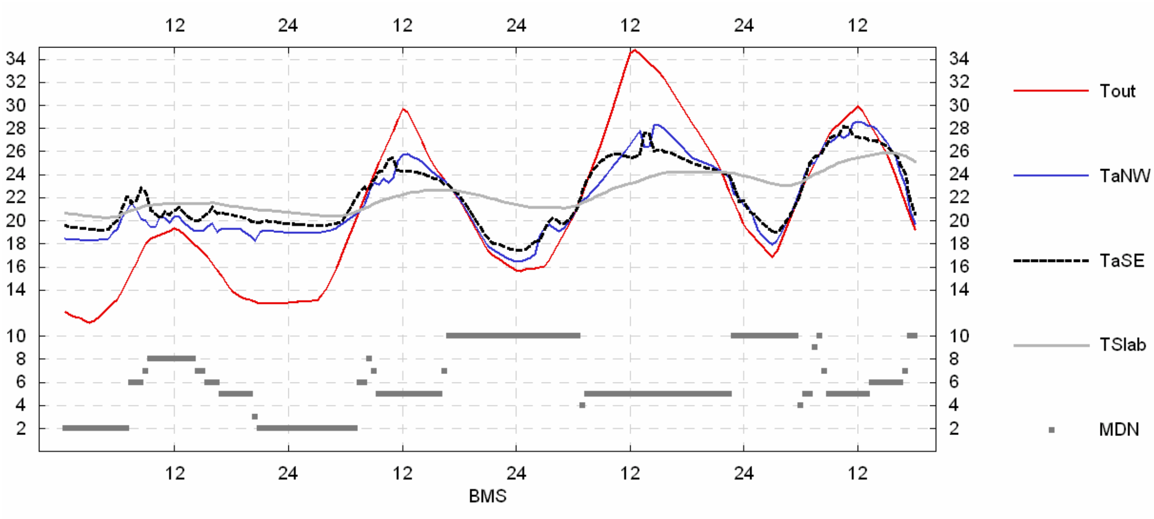


*Figure 4. Performance of the natural ventilation system using the design sequence of operations embedded in EnergyPlus. $T_{out}$ is the ambient temperature, $T_{aNW}$ and $T_{aSE}$ are the air temperatures in the perimeter zones on the north west and south east sides of the building and $T_{slab}$ is the slab temperature at the position of the control sensor. MDN is the window opening mode number, as described in the text.*

designers and the controls contractor that, in retrospect, seem almost inevitable, given the innovative nature of the design. Identifying these problems during construction, so that they could be fixed before occupancy, has avoided a number of operational problems that would have had a negative impact on thermal comfort.

Problems resulting in major impacts on performance would have been detected during functional testing or during operation, causing extra work for the contractors and/or operations staff and discomfort to the occupants until they were remedied. Problems with more subtle, yet significant, impacts on performance might have gone undetected for extended periods of time. The cumulative effect of these problems would likely have been to discourage the adoption of natural ventilation and innovative design generally.

## CONCLUSIONS

A design for a development environment for building controls has been developed, based on feedback from

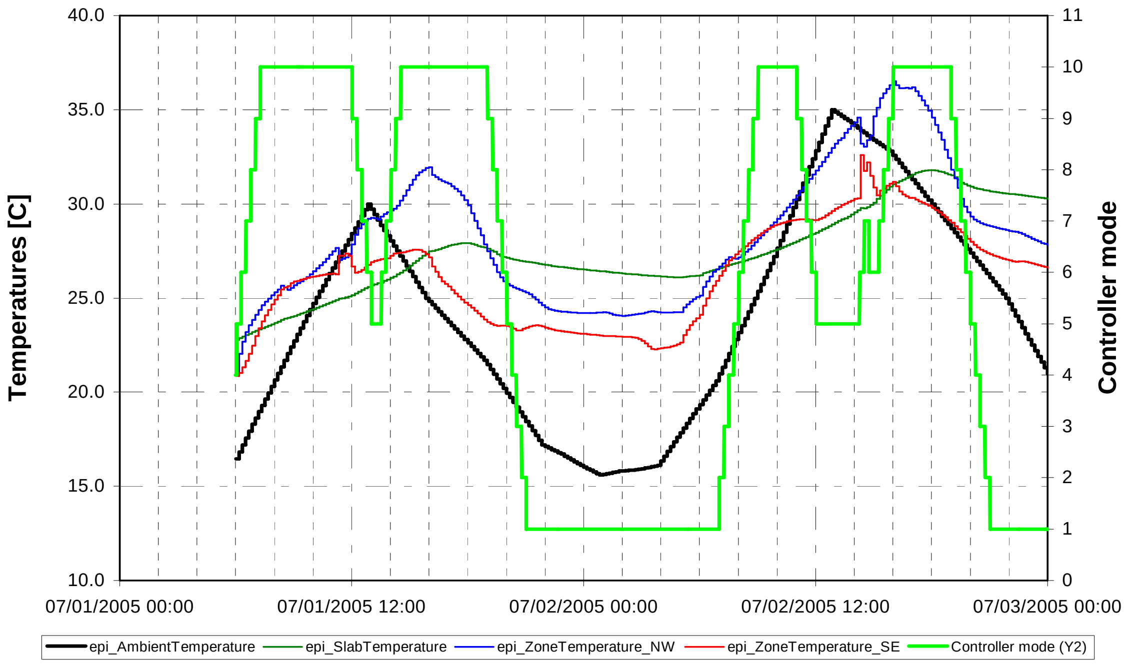


*Figure 5. Performance of the natural ventilation system using an early version of the control program implemented in the hardware used in the building and connected to EnergyPlus. Controller mode is the window opening mode number, as described in the text.*

environment will encompass implementation in both simulation, for algorithm and strategy development, and hardware-in-the-loop, for product testing and commissioning. The tools will support the development of energy-efficient supervisory control strategies, including integrated control at the whole building level, using BACnet for hardware-in-the-loop operation. Implementing the analog interface configuration will extend their applicability to local loop control. The analog interface will also support the development and testing of component-level automated diagnostics. The example of the use of a prototype version of the tools to design and test the controls for the natural ventilation system for the new San Francisco Federal Building illustrates the beneficial effect of the tools in reducing the risk involved in innovative design.

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