

Development of a Model Specification for Performance Monitoring Systems for Commercial Buildings

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ABSTRACT

The paper describes the development of a model specification for performance monitoring systems for commercial buildings. The specification focuses on four key aspects of performance monitoring:

- performance metrics
- measurement system requirements
- data acquisition and archiving
- data visualization and reporting

The aim is to assist building owners in specifying the extensions to their control systems that are required to provide building operators with the information needed to operate their buildings more efficiently and to provide automated diagnostic tools with the information required to detect and diagnose faults and problems that degrade energy performance.

The paper reviews the potential benefits of performance monitoring, describes the specification guide and discusses briefly the ways in which it could be implemented. A prototype advanced visualization tool is also described, along with its application to performance monitoring. The paper concludes with a description of the ways in which the specification and the visualization tool are being disseminated and deployed.

Introduction

Performance monitoring and building commissioning and related studies have shown that numerous operational and control problems exist in most buildings (Gillespie *et al.* 1991, Piette *et al.* 1994, Gregerson 1997, Claridge 1998). One approach to improving the identification of such problems, and hence facilitating their correction or repair, is to provide continuous performance monitoring. This approach has been shown to produce practical benefits in daily operations by allowing the identification of problems such as equipment cycling or inefficient operating strategies.

Current building control system installations typically have very limited data collection, archiving and visualization capabilities required to support performance monitoring, largely because these capabilities have not been valued and specified by design engineers. This can be seen as symptomatic of a wider disconnect between building design and operations. The project described in this paper seeks to create ‘market pull’ for performance monitoring capabilities in

commercial buildings by demonstrating the capabilities of commercially available technology from a range of different vendors, assessing the costs and benefits of employing these technologies, and developing a model specification that can be easily adapted and routinely used by a variety of organizations for both new construction and control system retrofits to specify performance monitoring capabilities that are valued by building owners and property managers.

The primary purpose of a performance monitoring system is to provide facility managers and operators with the means to assess easily the current and historical performance of a building/facility as a whole, and its significant energy consuming systems and components. A performance monitoring system includes not only the needed sensors, wiring, and data acquisition device; but also the means to calculate, display, and archive resultant metrics of performance. Such a monitoring system can be contained within an HVAC direct digital control (DDC) system, a separate energy metering system (particularly on campuses), an Energy Information System (Motegi *et al.* 2003) or a standalone system, either a conventional data acquisition system (e.g. LBNL 2006c) or a WAN-based system (e.g. Norvell 2006). The monitoring system can be installed as part of a new construction project or as part of a control system installation or upgrade project in an existing building. Current offerings from DDC vendors now include SQL data bases and improved data visualization capabilities, making a new or upgraded DDC system a viable platform for implementing a performance monitoring system. Whatever the implementation platform, a detailed, explicit specification is needed to ensure that the performance monitoring system itself performs correctly, e.g. sufficient analog to digital conversion precision, sufficient network bandwidth for archiving. It should be noted that, in general, it is not sufficient to provide a detailed specification; steps must also be taken to ensure that it is implemented correctly. These steps include making sure that the contractor has a thorough understand of what is required, installation inspection and functional testing.

Performance monitoring requires installation and programming of additional monitoring points, including measured, virtual and calculated values that are not required for control. Whole building energy, equipment power, air and water flow and local weather are among the measurements required. By themselves, these measurements can provide invaluable insight to how a building, system, or piece of equipment is operating. But, when combined together in a specific calculated value known as a performance metric, they provide building staff with the means to track building and system performance over time and to identify and diagnosis potential and current problems by comparing them with expected values or benchmarks.

The quality of any measurement is determined by the attributes of the sensor, any signal conditioning present, the infrastructure of the data acquisition system, the analog-to-digital converter, the wiring connecting them, any calibration corrections that are applied, the installation technique and field conditions. Accuracy, precision, linearity, drift or stability over time, dynamic or rate of response, range, turn-down, sample or scan rate, resolution, signal-to-noise ratio, engineering unit conversion and math functionality, data storage and retrieval frequency are all relevant to defining the quality of the measurement system and its components. The level of measurement rigor needs to be sufficient to determine the specified performance metrics and benchmarks to the required accuracy.

To make full use of the measurements, a performance monitoring system must be capable of managing, archiving, and displaying the data for interpretation. This requires reliable and effective database management and data visualization tools. Data visualization capabilities are discussed in more detail below.

The paper presents the approach adopted in the development of a performance monitoring specification that will be freely distributed at the end of the project and describes the progress to date. A draft specification was produced in collaboration with several large owners and then reviewed by a number of interested stakeholders. Case studies of the costs and benefits of different performance monitoring capabilities implemented in large commercial buildings and on campuses are currently being performed. Information from these case studies will be synthesized and disseminated in order to allow owners to make informed decisions about which performance monitoring capabilities to include as standard in their control specifications. The aim of working with large owners is to help create 'market pull' for performance monitoring while producing a specification that meets the needs of these owners – market transformation in parallel with R&D.

Benefits of a Performance Monitoring System

Monitoring main electricity and natural gas meter data enables building staff to track building electricity and natural gas use by time of day, facilitating management of peak loads and identification of unnecessary equipment operation during unoccupied periods (Price and Hart 2002). It also enables monitoring of power quality supplied to the building and power factor of building load. Monitoring chilled water plant equipment power meter data enables building staff to track and manage chiller contributions to peak load and monitor chiller health.

Monitoring building chilled water flow meter and chilled water and supply and return temperature data along with plant power enables the monitoring system to calculate the actual heating and cooling delivered by plant chillers. This information is important for a number of reasons. It is used to track and manage growth in chiller capacity requirements that can impact occupant comfort and aids in the detection of anomalous loads that increase operating costs. These measurements enable the tracking of chiller plant efficiencies, which allows the identification of more efficient operating strategies. It also enables the detection of degradations in performance that indicate the need for maintenance in order to minimize operating costs and maximize equipment life. Use of a high quality weather station provides reliable measurement of outside air temperature to enable the most effective use of free cooling, minimizing chiller use. Reliable measurement of outside wet bulb temperature enables proper cooling tower operation and maximizes chilled water plant efficiency.

Advanced data calculations and data displays provide operators with effective, standardized ways of viewing the performance of the building and the HVAC system, including comfort. Careful grouping of plots puts all the information required to monitor and, if necessary, troubleshoot, each different part of the HVAC system on a single screen. This makes it easier to spot and diagnose faults before they become problems, reducing hot and cold calls and O&M costs. The effective use of performance monitoring systems can make it easier to operate the building, freeing up stationary engineers to meet other tenant needs.

Performance Monitoring System Specifications

The *Specification Guide for Performance Monitoring Systems* (LBNL 2006a) has been written to address the capabilities discussed above and includes both detailed specifications language and higher-level guidance on the application of these specifications to a particular project. The document begins with an overview similar to that given above. To help building

owners, managers, and operators determine the level of performance monitoring appropriate for their building, performance monitoring system capabilities are then classified into three levels, Basic, Intermediate, and Advanced Diagnostics. Within each of these classes, requirements are listed for data point measurements, virtual and calculated performance metrics, and database and data visualization capabilities. Example performance monitoring requirements for the Basic Class are found in Table 1.

Table 1. Basic Recommended Performance Monitoring Requirements

| Data Displays | |
|-------------------------------|---|
| Equipment/System Graphic | Floor plan with zone temperatures; system graphic with performance data; equipment graphic |
| Data Tables | Building air handler summary table, metrics results table |
| Time Series Group Trend Plots | System performance plots |
| XY Group Trend Plots | System performance plots 1. ChW Plant Delta-T, ChW Plant tons vs. OA Temp 2. ChW Plant kW vs. ChW Plant tons 3. ChW Plant kW/ton vs. OA Temp, OA Wb Temp, ChW Plant tons 4. HVAC Power vs. OA Temp, OA Wb Temp, ChW Plant tons 5. Total Gas Flow vs. OA Temp 6. OA Temp Fraction vs. OA Damper Fraction 7. Whole Bldg Electric EUI; Whole bldg HVAC electric only EUI; Whole Bldg Natural Gas EUI, Whole Bldg Water EUI vs. Avg. Daily OA Temp |
| Data Points | |
| Measured | OA Temp; OA WB-Temp; Main Power; Main Natural Gas Flow; Main Water Flow; Chiller # Power; Other ChW plant equipment power; Plant ChW (loop #) ChWST; Plant ChW (loop #) ChWRT; Plant ChW (loop #) flow (gpm); Air handler # MA Temp, RA Temp ; SA Temp ; Air handler # SF & RF power; Air handler # flow (cfm); Zone temperatures |
| Virtual | Air Handler # OA Damper %, Return Damper %, SF Mode, SF status, ChW Valve %, SA Temp Sp, add SA-Ho Temp, SA-Ho Temp Sp, HoW Valve % if dual duct |
| Calculated – Whole Building | Avg. Daily OA Temp; Whole Bldg Peak Power; Whole Bldg Electric EUI; Whole Bldg Natural Gas EUI; Whole Bldg Water EUI; Ratio of Daily Maximum and Minimum Electric Demands |
| Calculated – Chilled Water | ChW Plant (loop #) Delta T; ChW Plant Power; ChW Loop # tons; Total ChW Plant tons; ChW Plant Efficiency (kW/ton) |
| Calculated – Supply Air | AH# Outside Air Temp Fraction; AH# Outside Air Damper Fraction; Total Air Handler Power; Total Air Handler Volume; Air Handling System Specific Power (kW/cfm) |

The document includes a series of appendices containing specifications language for acquiring the desired performance monitoring capabilities. The outline of these appendices is as follows:

- A. Glossary
- B. System Performance Capabilities and Functional Requirements
- C. Performance Metrics by Class
- D. Example Basic Level General Specifications
- E. Options and Add Alternates to Consider
- F. Other Measurements, Metrics and XY Plots to Consider

- G. Example Basic Level Specification Language Based on ASHRAE Guideline 13-2000: *Specifying Direct Digital Controls Systems*
- H. Example Graphic and Data Displays
- I. Example Point Naming Conventions
- J. Demonstration Site Case Studies (future)
- K. Selecting and Installing Instrumentation Properly (future)
- L. Verifying Accuracy Goals (future)
- M. Developing Expected Values and Benchmarks (future)

The specification guide is intended primarily to define functionality; however, it is prescriptive where necessary to ensure the required functionality is obtained with currently available industry products, e.g. certain types of sensors are allowed for particular applications. In other areas, e.g. networking, the guide only specifies functionality and does not prescribe how that functionality can be achieved.

Work to Date

General Specifications Document and Specification Guide

Development of the guide involved producing a draft general performance monitoring specification in collaboration with several large building owners. It was then reviewed by a number of interested stakeholders, including specifying engineers, manufacturers and building owners and operators. The specification was then revised and used as a resource in a number of demonstration projects. Feedback from these efforts prompted the project team to convert the general specification into a specification guide. Material was also developed and submitted to ASHRAE for inclusion in Guideline 13: *Specifying Direct Digital Control Systems*.

Demonstration Projects – Procurement and Cost/Benefit Case Studies

A number of demonstration projects involving large government and commercial buildings and campuses have been undertaken in parallel with development of the draft specifications. These demonstration projects serve two different functions:

1. Testing of the draft specification in real procurement situations.
2. Assessment of the costs and benefits of different performance monitoring enhancements

The real procurement situations included:

- Specification of instrumentation installed as part of a new chilled water plant in a medium-sized government office building.
- Specification of comprehensive performance monitoring capabilities for a replacement control system in a large government office building.
- Specification of new instrumentation and data visualization capabilities as part of a control system upgrade in a large commercial office building.

In each case, the process of providing specification language to be included in a bid package helped to focus the specification document. Review of the performance monitoring parts of the bid package by the design engineers and/or the facilities staff of the owner or property management organization resulted in a number of improvements to the specification document.

Costs and benefits are being assessed at:

- Four university campuses where additional instrumentation and/or data archiving and analysis capabilities have been installed under the UC/CSU/IOU monitoring-based commissioning program funded by the California Public Utilities Commission – further details of this program are given in Brown and Anderson (2006).
- The central plant of a government property agency where an energy information system has been installed to monitor the operation of the central plant and some of the buildings served by the central plant.
- A military base where a new control system with advanced performance monitoring capabilities has recently been installed.

Two types of cost-benefit evaluation are relevant to this project: objective and subjective. The objective assessment is of interest to policy makers, utility program designers and those owner organizations that base their technology adoption decisions primarily on detailed economic analysis. In this context, ‘subjective’ refers to an evaluation based on a combination of criteria peculiar to a particular organization. One of the aims of this project is to identify, possibly by indirect inference, what these criteria are for the different owner organizations involved in the project and to determine which enhanced performance monitoring capabilities are valued highly enough for them to be adopted as standard requirements in future new construction and control system replacement projects. Evidence from previous projects (e.g. Piette *et al.* 2001) indicates that criteria such as reduced comfort complaints and reduced time required for operators to monitor and manage the operation of the HVAC system can be as important, or more important, than reduced utility costs.

Objective assessment of the benefits of enhanced performance monitoring is not straightforward because the realization of any benefit is contingent on action being taken in response to the information generated. In the case of monitoring-based commissioning (a form of commissioning that relies on measurements from additional permanent instrumentation, ideally acted on by facilities staff), action is part of an explicit plan and the main question is what fraction of the benefits should be allocated to the performance monitoring enhancements. A further complication is that the performance monitoring enhancements can be expected to facilitate further benefits in the future. In situations where performance monitoring enhancements are installed in the absence of an explicit commissioning plan, the benefits of improved operations resulting from the detection and remedying of problems that were not previously detected can reasonably be attributed to the performance monitoring enhancements. It should be noted that the duration of the project reported here is not sufficient for formal Measurement and Verification of savings to be performed.

Technology Adoption Study

Given the project goal of creating 'market pull' for performance monitoring while producing a specification that can be adopted by a variety of owner organizations, a technology adoption study has been undertaken to better understand the issues involved in transforming the market for performance monitoring. Preliminary insights from this study are as follows.

Complex new technologies have an increased probability of failure as they emerge in the marketplace (Moore 1999). These technologies, unlike simple consumer products, frequently have a large set of users and the adoption decision is shared with many participants. For the highest probability of success, Moore recommends that target markets be examined to understand characteristics of their present behavior and likely organizational changes required for adoption. The purpose is not to merely encourage the decision to adopt a technology but to ensure its successful application.

Large public organizations with a permanent staff have been selected as the target market in a study of initial adopters of the performance monitoring specification. The study is focusing on the changes to the internal structure of one particular selected organization that would be necessary for successful adoption of performance monitoring technology. Preliminary indications are that the organization wants to adopt the technology and is willing to make organizational changes to adopt it. The organization has also expressed a willingness to consider different approaches to the procurement and maintenance of building controls, which are presently out-sourced. These approaches include a strategic partnership with a single information technology vendor that would provide system-wide expertise. Finally, staff members have expressed an interest in being trained to use the new specification but want more specific information about the required training before committing to a decision. A key factor in this organization's decision to adopt performance monitoring is its desire to gain access to, and have power over, its building control systems.

Data Visualization Prototype

One particular issue addressed by the project is that the performance monitoring capability that is most noticeably lacking from current controls vendor product offerings is high quality data visualization. The project is developing a prototype visualization tool whose capabilities can be evaluated in the field by building operators and facility managers as part of the specification development process.

The prototype visualization tool (VizTool) has been developed in two phases. The first phase involved a survey of existing visualization tools being used in the buildings industry and specification of a tool that would meet the needs of adept building operators and others who need to understand the performance of their building. The second phase, which is currently under way, involves the development of a functional prototype of the proposed visualization tool and the identification of commercialization and deployment vehicles within the buildings industry. A key specification for the VizTool is that it be open source, so that software modules might be freely adopted and deployed by control system and/or energy information system vendors. Thus, open source software tools and platforms were explored as platforms for developing the VizTool, including JFreeChart/Java, Gnuplot, CHACO and Matplotlib/Python/wxPython. Exploratory prototypical capabilities for the VizTool have been developed using two platforms -- JFreeChart/Java, and Matplotlib/Python/wxPython. At the writing of this paper, further

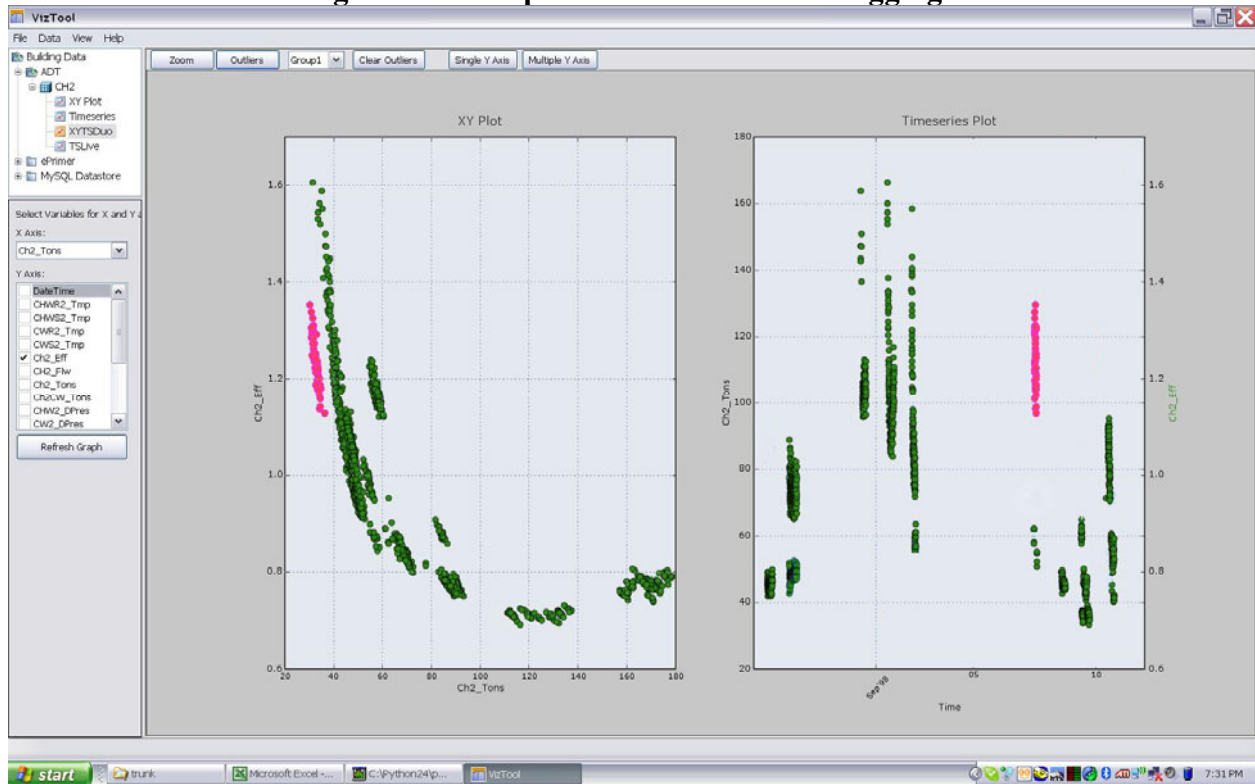
development of the VizTool prototype is under way using the Matplotlib/Python/wxPython platform.

VizTool specification. Key specification features are listed below, with the current implementation status in parentheses:

- Display data at various time intervals, down to 1-minute intervals (implemented)
- Display eight variables for up to a year (implemented)
- Zoom in on specific areas of a chart for close up views (implemented).
- Allow for more than one Y-axes scale on a plot (current implementation permits 2 Y-axes scales, and plans include capabilities for multiple Y-Axes scales).
- Generate simultaneous time series plots, XY scatter plots and ‘carpet’ plots using historical and current data (historical and current data capabilities have been implemented for time series, and development of similar capabilities is underway for X-Y scatter plots and ‘carpet’ plots.).
- Allow a high degree of user interactivity including permitting a user to:
 - Select which data variables to present on a chart, and to revise this list (implemented for selected types of charts).
 - Use the mouse to tag selected data points on one chart (e.g. “outliers” on an X-Y chart) and have the corresponding points automatically appear highlighted on other charts of the same data (e.g. time series or different X-Y chart) (basic version is implemented and is currently being revised).
- Include example templates of at least a subset of the data displays listed above in this paper in Table 1 (template displays for chillers are currently being implemented within the prototype).

Figure 1 shows an early prototypical example of the “outlier” specification feature. In the figure the user has just identified a set of data points in the X-Y scatter chart on the left. The outlier data points appear in bright pink. The data points are flagged as outliers in the database, and appear as outliers in the same bright pink in the paired timer series chart on the right. Refinements to this basic capability are now being developed within the VizTool prototype. Two refinements are for the user to be able to (1) use a “lasso” area instead of a rectangular area for identifying outliers, and (2) identify several different types of outliers within a data set.

Figure 1. Example of VizTool Outlier Tagging Feature



Deployment vehicles for VizTool. Four Use Cases are currently being explored as application vehicles for VizTool. These use cases are (1) HVAC system fault detection, (2) HVAC operator training, (3) building system monitoring and (4) data archiving. Each of these applications can benefit from effective data visualization:

1. **LBNL Automated Diagnostics Tools:** The current version of the VizTool prototype can read output files from the tools in which data records that have been identified as indicating faulty operation are flagged as “outliers.” VizTool generates charts in which these “outliers” are highlighted; an X-Y chart to illustrate the nature of the fault and a time-series chart to indicate when the fault became apparent and ceases to be apparent (e.g. if remedial action has been taken).
2. **HVAC ePrimer:** The HVAC ePrimer is a computer-based education tool intended to help students in 2-year HVAC technician courses better understand how air handling units (AHUs) operate under normal and faulty conditions. The software tool uses an accurate model of an AHU system written in SPARK (LBNL 2006b). 3-D animations that respond to the SPARK simulation allow students to analyze the operation the AHU system and components, and to engage in troubleshooting exercises to solve real-world problems. The VizTool prototype reads SPARK output files and generates X-Y scatter charts and time-series charts.
3. **Universal Translator (UT) from PG&E:** The Universal Translator (PG&E 2006) is a software tool for managing and manipulating measured building data from multiple sources. The objective is to permit the VizTool to be called from or to be embedded within the UT and this capability is being explored with the UT development team.

4. **ODBC-compatible databases:** Work is underway to enable VizTool to extract and display performance data archived in an ODBC-compatible database.

Technology Transfer

The project team is engaged on a number of fronts to see that the information developed can be used. Activities include:

- Release 1 of the draft general specification for performance monitoring systems is listed as a reference in ASHRAE's Building Performance Scoping Study dated 1/14/2006.
- Release 1 was also used to prepare an example specification focused on chilled water plant monitoring for ASHRAE Guideline Project Committee 22P: Instrumentation for Monitoring Central Chilled Water Plant Efficiency.
- Updated material, including three new annexes, *Example Specifications for DDC Based Performance Monitoring Systems*; *Example Graphic Data Displays*; and *Alternate Point Naming Convention and Example Point Names and Group Trends*, was submitted November 2005 to ASHRAE's continuous maintenance process for consideration by the Standing Guideline Project Committee 13: Specifying Direct Digital Control.
- The specification guide is to be used by ASHRAE Technical Committee 1.4 Green Controls subcommittee to help develop a reference guide for LEED.
- The specification guide is to be used to develop a metering guide for building sub-metering CSU campuses for the California State University's Mechanical Review Board. It will also be shared with participants in the California Public Utility Commission's Monitoring Based Retro-Commissioning programs.
- Material from the specification guide is being considered for use in California's Title 24 Building Energy Efficiency Standards during the 2008 standards development process.
- The current draft for the specification guide can found at <http://cbs.lbl.gov/performance-monitoring/specifications/>.

Conclusions and Next Steps

The specification produced in the project described here, while not yet in its final form, enables comprehensive monitoring of whole building and HVAC system energy and thermal comfort performance. The specification has been developed in collaboration with a number of large building owners, has been extensively reviewed by experts in the industry and is being taken up by ASHRAE and other organizations

There are a number of areas in which further activity is needed to maximize the impact of the specification and related work:

- Determine how to best tailor specifications, including summary reports for different applications
- Work with large owners to tailor specifications for their adoption
- Provide guidance on how to select and install instrumentation properly
- Survey controls vendors to assess influence of specifications on their products and follow up where further information or dialog could encourage vendors to upgrade their offerings

- Verify through-system accuracy of specified monitoring
- Document costs/benefits of specified performance monitoring
- Add LEED performance metrics (e.g., IAQ), and cost-based metrics
- Describe methods of establishing benchmarks for expected performance (whole-building/system/equipment)
- Develop & describe methods of obtaining alternative performance metrics for applications where specified monitoring points are cost-prohibitive
- Apply VizTool in as many areas as possible

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