The Preparation and Implementation of a Monitoring Plan

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ABSTRACT

An essential requirement of any building performance monitoring project is the preparation and implementation of a Monitoring Plan. A Monitoring Plan describes the activities and technical requirements that must be completed and met to successfully achieve the performance evaluation goal of the field monitoring project. The Monitoring Plan is typically divided into three main sections or phases - Planning, Monitoring and Post-Monitoring. Within each phase are a number of specific actions and technical requirements, such as specifying data and instrumentation requirements, quality control procedures, one-time measurements or calculations, data analysis procedures, and documentation requirements.

KEYWORDS

Buildings, Monitoring Plan, Performance Factors, Testing, Energy Performance, One-time Measurements, Data Collection, Data Quality, Performance Evaluation, Measurement and Verification, Data Logging.

INTRODUCTION

The preparation and implementation of a Monitoring Plan is an essential element of any field monitoring project. The activities and technical requirements that must be met to successfully achieve the performance evaluation goal of the field monitoring project are described in the Monitoring Plan. The Monitoring Plan serves as a checklist of activities that must be done before, during and after the performance monitoring period.

This paper identifies the key elements that should be included in any monitoring plan for field monitoring projects. It is organized according to the three main phases of a field monitoring effort:

(1) Planning Phase
(2) Monitoring Phase
(3) Post-Monitoring Phase

The elements of each of these phases are described and discussed. These elements are common to all field monitoring projects, regardless of the number of buildings monitored or the aims of the project.

This paper focuses on the Monitoring Plan, and assumes that the goals and objectives of the field monitoring project have been carefully and completely defined prior to developing the Monitoring Plan. It also assumes that the audience for the information developed from the field monitoring has been identified, and the information this audience requires has also been defined and can be described as "performance factors." The performance factors describe the performance of the building in terms commonly used by members of the target audience.

We cannot over-emphasize the importance of carefully and fully defining the goals and objectives of the performance monitoring project. Poorly defined or stated performance monitoring goals and objectives will result in the wasted expenditure of time and money, and will not satisfactorily answer the monitoring questions. A question we ask ourselves before each monitoring project is, "To what purpose will the results be used?" This question requires that you work backwards from the audience for the results and their requirements for useful information and how you will go about the monitoring process to provide the information.

The purpose of this paper is to define the issues associated with the development and implementation of a Monitoring Plan. Specific recommendations for such things as sensor accuracy, data sampling intervals, and data storage rates are not presented, since these will change depending on the goals and objectives of the monitoring project and the methods used for data analysis.

PLANNING PHASE

The first element of the Monitoring Plan is the activities that take place prior to taking data. These are the Planning Phase activities described below.

Confirm Monitoring Objectives

The objectives or aims of the field monitoring should be defined by the principal investigator in cooperation with the client (audience for the results) during the early stages of the project. The objectives should clearly state the reasons why field monitoring is being done and what hypotheses are to be tested using the field data and analysis results. The monitoring team should read and understand the objectives of the field monitoring project as a first step in preparing the Monitoring Plan. They must also know the audience and the ways in which the data will be used.

The objective of one experiment may be to determine the amount of heating energy the passive solar design features on a group of residential buildings contribute to their space heating during the course of a year. The hypothesis is that passive solar design features provide heat to the houses during the heating season.

The objective of another experiment might be to determine whether or not buildings with passive solar heating features use less space heating energy than similar buildings without passive solar heating features. The hypothesis could be that passive solar buildings use less space heating energy than conventional buildings.

To satisfy the objective in the second example requires having information about the performance of the passive solar houses as well as about the performance of houses not considered to be passive solar heated. This example is presented because it introduces a concept that frequently arises in field monitoring projects: the need for a reference with which to compare the performance of the monitored building or buildings. The need for information about the reference should not be ignored when preparing the Monitoring Plan.

When reviewing the field monitoring objectives, the audience for whom the results of the field monitoring are intended should be understood. Included in the statement of objectives should be a statement of the audience for whom the results of the work are intended. In some cases the audience will be researchers, but in many other cases the audience will be non-technical individuals who make decisions about building construction, operation, maintenance and financing. The investigators and developers of the Monitoring Plan should know who the audience is, what information they use to make decisions, and whether or not they will use the information produced by the field monitoring project.

Confirm Performance Factor Definitions

Once the objectives of the field monitoring activities and the audience for the information are defined, a set of performance factors should be defined that will provide the audience with the information they want to know or that will influence the decisions they make. A performance factor is an index of performance of the component, subsystem or system under test, which is derived from the collected data. A performance factor should be defined in a clear, unambiguous manner easily understood by the target audience.

Performance factors include concepts such as the total auxiliary heating energy consumed by a building, the amount by which the heating energy requirements are reduced, lighting power density, etc. For influencing decision makers not directly connected with the field monitoring project, performance factors frequently involve economics. They want to know such things as, “How much did it cost to build, and what does it cost to operate?”

The responsibility of the performance evaluation team is to confirm that they understand the performance factors required and to design the Monitoring Plan so that these factors can be determined.

Develop Analysis Methodology

Three basic techniques are used for data analysis: numerical manipulation, statistical analysis, and engineering analysis. The level of analysis most appropriate for achieving the objectives of the field monitoring activities should be defined and its details established at an early stage. The details of the analysis methodology define the field data requirements.

Numerical manipulation is the most basic level of data analysis and is used to derive totals, averages, maximum, minimums, and times of the day when events in a monitored building occur. Numerical manipulation of data is very useful for understanding what happened, but not necessarily why it happened.

Statistical analysis derives relationships between two or more variables. This analysis method provides a means to identify correlations among system parameters to derive cause-and-effect relationships and performance lines or curves. It can also be used to create system models to predict events driven by one of the independent variables. These models are not useful, however, for predicting outcomes when basic parameters of the system are changed.

Engineering analysis is performed using equations and advanced engineering analysis methods. Equations are used to interpret the data and to relate data values to each other. The equations may be thermal networks or other models that describe energy balances on components, systems, or whole buildings, or to describe physical processes such as conductive, convective or radiative heat transport. Advanced engineering analysis methods are used to identify parameters of the thermal behavior that are not measured directly and to predict behavior over periods of time longer than the data collection period. Advanced engineering analysis methods may be applied to both component and whole building analysis.

Define Data Requirements

The objectives of the field monitoring project and the information requirements of the audience are used to develop the performance factors and to develop the data analysis methodology. The details of the data analysis methodology define the data requirements. It is important to follow this sequence of events so that the field monitoring project produces information, not just data.

The data collected during the monitoring period can be divided into two types. The first is the one-time measurements. These are measurements that can be taken once, then used throughout the monitoring period. The second is the continuous measurements. These include continuously varying independent parameters such as solar radiation and ambient temperature, as well as continuously varying dependent parameters such as interior temperature and auxiliary energy consumption.

The one-time measurements are important aspects of most field monitoring projects. They include single, independent measurements such as equipment capacity, connected load and, perhaps, equipment efficiency. They can also include functional relationships, such as equipment capacity or efficiency as a function of ambient temperature, or volumetric flow as a function of flow velocity.

The continuous measurements include directly measured quantities and calculated values. With the right type of data acquisition equipment, continuous measurements can be processed in real time to create time-series processed data. A good example may be energy delivered to a storage tank by an active solar heating system. The flow of energy is defined only when the pump is operating. Data acquisition equipment can sense pump operation, measure temperature differential and flow, and calculate energy delivered as a function of time.

Perform Error Analysis and Define Data Attributes
Error analysis is an extremely important part of the Monitoring Plan. The error analysis determines what levels of accuracy and resolution are required of the various components of the instrumentation system to ensure that the reported results are accurate enough to be used with confidence. The allowable measurement uncertainty for each sensor and data acquisition system (DAS) component is determined through the error analysis process.

The error analysis process can take many forms, but the most rigorous is a statistically based simulation which cascades simulated “noisy” data through all of the calculations needed to develop the final monitoring results. Once this simulation is developed, the uncertainty of the results can be easily determined. If this uncertainty level is too high, then the tolerance levels of the contributing sensors can be adjusted accordingly to reduce it. However, it must be kept in mind that the tolerance levels for individual sensors must always correspond to available and affordable sensors. The simulation results can be used to design a minimized cost DAS which provides suitable results.

Develop Instrumentation Requirements
The development of instrumentation requirements occurs in parallel with the error analysis. The specifications for the sensors and other DAS components are used to derive the limits of accuracy and expected uncertainty input to the error analysis. The specifications must take into account several factors, including the accuracy, range, response time, reliability and cost of the sensor.

The accuracy of a sensor is a measure of the uncertainty involved in any one measurement. It is typically represented as either a percent of the reading or a percent of the full-scale reading. If it is a percent of the full-scale reading, then care must be taken to account for its use in conditions other than near full-scale.

The range of a sensor includes the extent of conditions under which it will produce results to the specified accuracy. Use outside of the specified range can result in inaccurate measurements or, possibly, damage to the sensor.

The response time is the amount of time that it takes the sensor output to correspond to a change in the conditions that the sensor is measuring. It is inappropriate to measure a quickly changing process with a long response time sensor. Typically, however, building related processes occur rather slowly, and sensor response time is not usually a problem. In some circumstances, this is not the case and a fast response sensor may be required.

Reliability includes both the physical integrity of the sensor and its ability to stay within calibration. To be useful, a sensor must satisfactorily perform over the time period it takes to conduct the building performance monitoring project. It must be able to withstand all of the environmental factors imposed upon it, including weather and handling, and stay within calibration. Obviously, a sensor which is reliable for a long period of time is very desirable.

The cost of a sensor is a very important consideration in the selection process. The cost will generally go up as accuracy and reliability go up. The range is often not directly related to cost. The cost is also often directly connected to the technological approach to measuring a specific parameter. When several different technologies can be used to perform a measurement, each technology should be evaluated based on its ability to satisfy the above criteria.

The instrumentation requirements should also include methods and equipment to reduce electronic noise from entering the DAS and to protect the equipment from electrical and environmental problems. Noise reduction generally includes the appropriate grounding of the instrumentation and associated equipment. Equipment protection involves eliminating problems from electrical transients, such as voltage spikes on the electric power line, lightning induced voltages on instrumentation wires and unexpected voltages that may exist on telephone lines. All components of the DAS should be properly grounded, and transient protection devices should be installed on the power and telephone lines, and, if needed, on the sensor lines. All of the equipment should be adequately protected from the weather, as heat, water, dust, or other things may cause serious problems, including system failures and destruction of equipment.

Develop an Instrumentation Plan

The instrumentation plan contains the locations of all the sensors and other components of the data acquisition system, including communication devices, wiring, etc.. The instrumentation plan can be drawn on a floor plan of the building and should include sufficient instructions that professionals, such as licensed electricians and plumbers, will know where to install components of the system for which they are responsible according to building code or other requirements, such as labor unions.

Purchase and Configure Data Acquisition System (DAS) Equipment

The next step in the planning process is to purchase all the required components of the data acquisition system. Components of the system are frequently obtained from different suppliers, or from a company like Architectural Energy Corporation that supplies complete data acquisition systems. After the equipment is obtained, it must be configured and made ready for bench testing.

Data Acquisition System Software

Most microcomputer based data acquisition systems have standard software that allows the user to configure the equipment, and analyze and plot the collected data. The level of features and sophistication of this operating/analyzing software varies significantly. Therefore, the researcher will be required to learn to operate the software at a level to configure the sensors and data collection parameters, such as scan intervals and storage intervals, and to download, display and analyze the data. Most DAS have the ability to export data to a spreadsheet or to custom data analysis software. This enables the researcher to create custom analysis software which accepts data from the DAS standard operating software. Any custom software should be developed prior to the bench test and then thoroughly tested on the data acquisition system before the equipment is installed in the field. The operation of a data logger controlled by software should be examined to make sure that the software works properly at the end of specific time intervals when parameters in the software are reset, such as at the end of the day, month, and year.

Bench Test DAS Equipment

Prior to being installed in the field, the equipment should be tested in the office/laboratory. All functions of the equipment should be tested and the accuracy of the sensors should be verified. Some sensors may require calibration. This should be performed at this time.

Develop Quality Control Procedures and Tests

Field monitoring experiments are expensive to perform. They are generally more expensive than performing experiments in the laboratory. It is extremely important for the Monitoring Plan to include a component to ensure that quality data are collected.

Quality control procedures should be developed to ensure that the building is operating as expected and to ensure that the data collection problems are minimized. If the building is not operating as expected, the experiment will not be valid. If the data are not accurate or large amounts of data are missing, the analysis cannot be performed properly. The purpose of this activity, as part of this Monitoring Plan, is to anticipate the problems and to formulate methods of dealing with them.

Develop Documentation Requirements

The importance of documenting all phases of the field monitoring activities should not be overlooked. Three main points should be emphasized when thinking about documentation. The first is documenting the buildings and/or systems under test, the second is documenting the data, and the third is documenting the results.

Documentation for the buildings and/or systems should include complete descriptions of the building, its construction, mechanical systems, and occupancy and control patterns. Floor plans and elevations should be part of the documentation, either from construction drawings or from photographs taken at the building. Photographs (electronic images) and prints are very useful ways of documenting the building and its systems. Video technology is a useful tool for documenting the construction, features, and systems of monitored buildings.

Data must be properly labeled so that it can be easily identified by the researchers using it soon after it is collected and by others who will have interest in the data at a later date. A great deal of data can be collected in a short period of time, and unless properly labeled it has little value. Systems need to be developed as part of the Monitoring Plan to track data by name of the building, date, and time. Log (spread) sheets should be developed to comment on specific data periods when the building may have been operated in a special way for one-time tests or other purposes. Some data logger operating software has the ability to enter notes as part of the data collection record.

The data analysis process should be documented in sufficient detail that the methods used for analysis can be understood by other researchers. Processed data that is intermediate between the raw hourly data and the final results should be clearly labeled and a log kept to identify it.

Sign Monitoring Agreement with Owner and Occupant

Monitoring is generally performed in privately owned buildings. The group or organization performing the monitoring should have an agreement with the owners and occupants of the building which describes the terms under which the monitoring is performed, how the data and results will be used, what monetary compensation will be provided, what the responsibilities of occupant are for using the building, and what the responsibilities of the monitoring organization to the occupant. The agreement should describe the monitoring organization to the occupant. The agreement should describe the monitoring organization's rights to enter the building to work with the monitoring equipment and should state what, if any, equipment will be left in the building at the end of the monitoring period. The agreement should also mention the repairs for which the monitoring organization will be responsible at the end of the monitoring period.

Investigate Warranties, Licenses And Codes
Three issues should be investigated prior to installing the data acquisition equipment. The first is to determine whether or not any equipment warranties will be compromised. The second is to determine whether any codes or standards will be violated by the proposed data acquisition system and the third is to determine whether or not licensed tradesmen are required to install portions or all of the data acquisition system.

The issue of equipment warranties is most important when instrumentation is installed in mechanical equipment or appliances. Not only could the installation of the monitoring equipment void the warranty, but it may also void third party certification of the equipment (such as Underwriters Laboratories in the U.S.). This loss of certification may void insurance coverage in the case of loss, damage or injury and make the organization performing the field monitoring liable for damages.

Building codes may be violated by the installation of the data acquisition equipment. For example, current transducers that are not properly certified may be installed in electrical panels or wire that is not fire rated may be run through ductwork. In the U.S., both of these are generally violations of the building code. The personnel responsible for developing the instrumentation plan need to be aware of local code requirements.

In many instances, certain portions of the data acquisition equipment must be installed by licensed tradesmen. Licensed electricians and plumbers are frequently needed to install data acquisition system components.

Where data will be communicated out of the building via telephone, local area network or internet, care must be taken to ensure security of the communication equipment. Many building owners will not allow any connection to their communication systems; thus requiring the researcher to arrange for their own external communication channel.

Install Data Acquisition Equipment
The last step in the Planning Phase is the installation of the data acquisition system in the building. If the building to be tested is new, instrumentation wire (if required), electrical power sensors and flow meters, communication devices, and electrical power for the data acquisition equipment should be installed during construction. If the building is not new, the process of running wire (if required) and installing the sensors is more difficult. The process frequently requires licensed tradesmen for installing plumbing and electrical metering equipment. The instrumentation team is generally responsible for installing low voltage wiring, most of the sensors, and data loggers.

Central data acquisition approaches and systems have given way to portable, distributed data acquisition approaches and systems, and to portable wireless data acquisition systems. These distributed systems are synchronized in time and sampling rates, and are easily installed and operated.

MONITORING PHASE

The second element of the Monitoring Plan is the activities that take place after the data acquisition system is installed. These are the Monitoring Phase activities described below. They are divided into the pre-data collection diagnostics, the data collection, and the post-data collection diagnostics.

Pre-Data Collection Diagnostics

The pre-data collection diagnostics has two objectives. The first is to confirm that the data acquisition equipment is working properly, and the second is to confirm that the building and its systems are operating properly. These two steps are vital for a successful field monitoring project.

The process of confirming that the data acquisition system is working properly includes verifying that the sensors are producing proper readings and confirming that the data acquisition equipment works correctly in all modes, including data collection, data processing, and data transfer. The functioning of the equipment was verified during the bench tests, but should be verified again in the field.

When collected data will be transmitted to a remote server via some communication system -- telephone modem, local area network, wireless internet service -- it is essential to ensure the proper operation of this communication link. Once all data acquisition equipment has been installed, a test set of data should be collected and transmitted to verify reliable operation.

As appropriate, the operation of the sensors can be verified by comparing field data to portable standards, making sure zero values are reading correctly, and subjecting sensors to known conditions (such as an ice bath), for example, using a portable "spot watt" meter to verify values from the installed watt transducer. All sensors should work properly before data collection begins. It may be necessary to recalibrate some sensors in the field, but, in general, field calibrations should be avoided.

From our experience in monitoring the performance of many residential and commercial buildings, it is common to find problems with building construction and the installation/operation of mechanical systems. Thus, where the monitoring objective is to evaluate the proper operation of the building or specific building system, as opposed to diagnosing an operational performance problem, you may have to correct (fix) the construction or operation problem before you initiate the formal performance monitoring period. Consequently, we recommend that monitoring programs should have an activity to confirm that the building and its systems are operating as expected before data collection begins.

Data Collection

Once the data acquisition equipment and the building are operating properly, the data collection can begin. The data collection phase consists of performing one-time measurements, collecting data and performing preliminary data processing, transferring data to a central site, reviewing data for quality control, processing and analyzing the data, and finally posting the data and the results on a web site.

Many field monitoring projects aimed at determining the energy performance of buildings or their subsystems will have a requirement to perform one-time measurements. One-time measurement may include determining a building's heat loss coefficient, its infiltration rate or leakage area, the efficiency of its mechanical equipment, or connected loads, such as lighting. They may include the measurement of air flow in ducts or fluid flow in pipes. Many one-time measurements are single values, while others may be functional relationships, such as the efficiency of equipment as a function of temperature. The one-time measurements are generally performed prior to the continuous data collection since these values are needed to either process the data at the site by the data acquisition systems or to develop preliminary estimates of the performance factors.

The elements of continuous data collection are data sampling, data storage, preliminary data processing, data review and quality control, and transfer of data to a central facility. Automated data acquisition systems are capable of frequent scanning of sensors and periodic storage of average values. The intervals between sampling and storage are determined during the planning process.

Preliminary data processing is easily accomplished by computerized data acquisition systems or on a computer after the data has been transmitted out of the building. This processing can include numerical calculations, separation of data into bins, and error checking. The accuracy of field monitoring projects can be improved by performing calculations in the field that may not be correct when performed using averaged data. For instance, calculation of total heating load using measured inside and outside temperatures when the inside temperature is below the thermostat setpoint temperature is an example of the numerical calculation that can be performed most accurately in the field.

If the total power to a heat pump compressor is measured, yet the energy for cooling must be separated from the energy for heating, this is best done by separating the data into bins using logic based on another reading, such as the temperature of the supply air, or the state of a control relay. A computerized data acquisition system has the ability to separate the energy consumed by the compressor into heating or cooling.

Data review and quality control performed in real-time in the field or shortly after being received by a server are generally intended to flag errors based on upper and lower ranges for each measurement, allowable changes in a measured parameter from one stored reading to another, or maximum or minimum values at specific times of the day. Error messages can be sent to inform the operator that a problem may exist at the site. This kind of data review and analysis will trap sensor failures or identify physical changes at the site, such as debris covering a pyranometer.

Data should be transferred periodically to a central site for processing. With microcomputer based data acquisition systems, this is most commonly done via and internet connection or by telephone using a modem. The frequency with which the data are transferred will depend on the available memory or data storage capacity in the data acquisition system and the rate at which it is filled. An important reason for performing frequent transfer of data is to identify a failure of the data acquisition system as quickly as possible after it occurs. Data acquisition systems with batteries for standby power will survive most short-term power interruptions.

Once the data are received at the central facility, they should be reviewed for quality prior to using them to perform calculations. These quality control procedures should check the accuracy of the data with limits on the data or the change between readings. They should also address methods for filling data gaps, should they occur. Data gaps may be a result of problems with a sensor at the monitored building or a result of errors in the transmission of the data to the central facility.

The analysis can be performed once the data are checked for errors and determined to be suitable. As much analysis as possible should occur during the data collection period. The reason is that review of the performance factors may indicate problems with the building or with the data acquisition system which can be corrected. Waiting too long to identify such problems may mean that a great deal of time and money are spent on monitoring without being able to use all the data. Timely analysis of the data is an important step in the entire quality control process.

Some field monitoring projects will include requirements to modify the monitored building. After modifications are made, the pre-data collection diagnostics should be performed before the data collection process is begun again.

Post-Data Collection Diagnostics

After the completion of data collection, the monitoring team may want to determine whether or not the operation of the building or its systems changed during the monitoring period by performing post-data collection diagnostics. They may also want to investigate whether or not changes took place in the accuracy of the data acquisition equipment. These can be accomplished by performing diagnostics at the building, performing the one-time measurements a second time, and by checking the calibration of the data acquisition equipment. For values determined before data collection and after data collection to be significantly different, they must be outside the expected deviation of individual measurements.

POST-MONITORING PHASE

The final element in field monitoring projects is the activities which take place after the completion of the field monitoring. This is referred to as the Post-Monitoring phase.

Remove DAS Equipment and Wiring and Perform Repairs

At the completion of the monitoring period, the data acquisition is typically removed from the building, unless the building owner or manager requests that the monitoring continue as part of a continuous commissioning process. This generally includes removing the sensors, the data logger(s), and any exposed wiring. Hidden wire that was installed according to code can be left in the building. Otherwise, it should be removed. Licensed plumbers and electricians may be required to remove some of the equipment.

The monitoring team should be prepared to repair any damage that results from the monitoring, including holes in walls and ducts. Carpenters and painters may be required for this work. They should also be responsible for making sure that mechanical equipment is restored to proper working order after any sensors are removed. In some cases, an inspection by an authorized agent may be required for a company to warrant the operation of equipment.

Document Monitoring Activities

The documentation from monitoring activities can include detailed descriptions of the monitoring goals and objectives, descriptions of the monitored buildings, instrumentation plans, samples of data, and the results of the data analysis. The extent to which the monitoring is documented will depend on the specific requirements of the monitoring program. Our experience has been that documentation should be prepared by the individuals most familiar with the buildings and data. It should be prepared both during and soon after the monitoring is completed.

Prepare Reports with Results for Targeted Audience

Reports need to be prepared for the audience for whom the monitoring was performed. The reports should specifically address the information needs of the targeted audience and the performance factors developed during the data analysis should be useful for this purpose. The target audience wants information, not data, though plots of selected data can be very informative and persuasive for conveying information.

To improve the efficiency with which reports are written, they should be outlined during the Planning Phase. The outlines should be written in enough detail that they provide the framework from which the actual reports are written. Assembling this framework during the Planning Phase will help to identify information that is needed for the reports that may not have been included in the original monitoring plan and which may be difficult to obtain once the monitoring is completed.

Archive Data for Future Use

Some projects will require that data be archived for future use. The important elements of the archive are the monitoring documentation, the reports, and the hourly data. In addition, a log or system may be needed to identify the hourly data, particularly if many buildings are monitored as part of an overall project.

CONCLUDING REMARKS

The Monitoring Plan contains numerous elements and is an essential element for the successful conduct of building performance monitoring projects. The sequence of activities presented in this paper should help engineers and researchers establish the purpose for monitoring and work step-by-step to efficiently achieve the monitoring objectives.

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