FINAL REPORT

Tools for Building Energy Asset Management (BEAM)

ESTCP Project EW-201262

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AFDD	Automatic Fault Detection and Diagnosis
AFI	Air Force Instruction
AFPD	Air Force Policy Directive
AHP	Analytical Hierarchical Process
ANOVA	Analysis of Variance
AHU	Air Handling Unit
ASHRAE	American Society for Heating, Refrigeration and Air-Conditioning Engineers
BAS	Building Automation System
BEAM	Building Energy Asset Management
BEMS	Building Energy Management System
BIM	Building Information Management
BMS	Building Management System
BOL	Beginning of Life
Btu	British thermal unit
BVM	Building Value Model
CCM	Continuous Condition Monitoring
CERL	Construction Engineering Research Laboratory (a USA Corps of Engineers organization)
CI	Condition Index
CM	Condition Monitoring
COP	Coefficient of Performance
CV	Coefficient of Variation
DOD	US Department of Defense
DOD BUILDER	The "BUILDER" Software (developed by CERL)
DOE	US Department of Energy
EAM	Enterprise Asset Management
EEB Hub	Energy Efficient Building Hub of the DOE (formerly GPIC)
E-Plus	DOE "EnergyPlus" Software
EIR	Energy Input Ratio
EOL	End of Life
ERDC	Engineer Research and Development Center (a USA Corps of Engineers organization)
FDD	Fault Detection and Diagnosis
FEMP	Federal Energy Management program
FFD	Fractional Factorial design
FMEA	Failure Modes and Effects Analysis
HASP	Health and Safety Plan
HFM	Heat Flow Modeling
HMI	Human-Machine Interface
HVAC	Heating, Ventilation, & Air Conditioning
GForge	Free web-based software for project-management and collaboration
GHG	Green House Gas

GPIC	Greater Philadelphia Innovation Cluster for Energy Efficient Buildings (Currently the EEB HUB)
IF	Improvement Factor
MOL	Middle of life
NIST	National Institute of Standards and Technology
O&M	Operations and Maintenance
PLR	Part Load Ratio
PM	Preventive Maintenance
PMV	Predicted Mean Vote
PO	Performance Objective
POC	Point of Contact
RPN	Risk Priority Number
RU	Rutgers University
SCT	Siemens Corporation, Corporate Technology
SD	Standard Deviation
SF	Supply Fan
TMY3	Typical Meteorological Year 3 – weather data for the average year (of 30)
USAFA	US Air Force Academy
VAV	Variable Air Volume

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

Military installations consist of a portfolio of buildings of various types along with the infrastructure that supports those buildings. Building energy assets can be defined as the devices, equipment, and systems that produce, transfer, and/or use energy to support occupant activities for mission accomplishment. Improper management of the complex energy assets in these buildings leads to problems. Specifically, poorly informed planning, policy, and operating decisions waste money and misallocate personnel, consume excessive amounts of energy, increase greenhouse gas emissions, shorten asset lifespan, and impede mission accomplishment. With innovative software tools, however, commanders and their subordinates at all levels of management can gain timely, practical, insightful, accurate, actionable information to maintain buildings efficiently and economically while accomplishing the assigned missions.

Building Energy Asset Management (BEAM) is an innovative software technology developed collaboratively by Siemens Corporation, Corporate Technology and Rutgers University. BEAM includes a 5-step workflow for building energy asset management: Synthesize Measure, Analyze, Plan, and Act. This process is accomplished through two main modules of the BEAM software suites: the BEAM Configuration Tool and the BEAM Runtime Tool.

This technology combines continuous condition monitoring with analytic tools for asset management. By using software installed in integration with the existing building automation systems, the facility gains real-time data regarding building energy asset conditions that enable predictive maintenance and repair actions before complaints occur. In addition, with embedded modeling and simulation engines, this software helps building operators evaluate existing asset maintenance policies and make better informed decisions. This will allow them to maintain and invest in critical "energy assets" within a building to ensure that the missions (or business objectives) are met while minimizing overall lifecycle costs.

The fundamental goal of the ESTCP-EW-201262 Demonstration Project was to show that BEAM software can address the challenges of managing building energy assets so that performance in terms of availability, reliability, and energy consumption is optimized and the building's functional objectives are fulfilled in accordance with its missions. To validate the BEAM performance objectives, we set out to answer the following key questions:

1) Can BEAM building continuous condition monitoring detect building asset faults and performance degradation and, thereby, potentially reduce or eliminate the energy wasted by operating faulty assets?
2) Can BEAM-derived optimal maintenance policies show significant lifecycle cost saving improvement over current practices at the demonstration site?
3) Can BEAM's calculation of business penalties potentially incurred in the event of failure and stoppage of energy assets provide actionable insights that inform optimal maintenance decision-making?

A demonstration of BEAM technology was conducted at the United State Air Force Academy (USAFA) located in Colorado Springs, Colorado from May 2012 to December 2013, to provide answers to the questions posed above, as well as to assess the costs and implementation issues related to the deployment of BEAM by the Department of Defense (DOD). During the 18-month project, we first customized the BEAM tools for military installations to support the "Stand Alone" mode in which BEAM software does not connect directly to a Building Automation System (BAS), thereby avoiding the necessity of network security certification. In the Stand Alone mode, BEAM receives batch BAS data periodically collected by the operator of the building automation system. We then applied BEAM to one of the campus buildings, Arnold Hall, for performance validation and cost analysis. The project started with a configuration phase when the web-based BEAM Configuration Tool was used to map the "missions" assigned to the building, to the building's assets using a model based on monetary business value. As a result, every asset considered by the project was assigned a business value, which was defined based on the loss of occupant productivity and revenue attributable to the event of an asset failure. The configuration tool was also used to generate models for automatic asset fault detection and diagnosis, energy performance monitoring, and asset performance prediction. At the end, the building information, asset information, and asset business values gathered through the BEAM Configuration Tool were further exported into a comprehensive XML-based database called the Asset Information Model.

With the asset information model, building energy model (developed and calibrated through a predecessor project), and asset reliability model in place, the BEAM Runtime phase could start. Both the project team and the building management personnel for Arnold Hall started to use the software to monitor building asset conditions on a continuous basis. Building sensor and control trending data were collected weekly and loaded into BEAM Runtime for 3 consecutive months. Several building asset faults and performance degradations were captured by the condition monitoring tool, and the conditions of the assets were updated using a 100-point metric scale named the Condition Index (CI). A sudden drop in the Condition Index alerted the facility manager of a fault or an urgent need for maintenance of the asset.

Meanwhile, the project team conducted quantitative evaluation of the existing O&M policies for Arnold Hall energy assets using the BEAM Runtime software to predict energy cost, maintenance cost, and business penalty cost associated with these policies for periods of two, five, and fifteen years. The results from the analysis were used to establish a baseline for BEAM performance validation. After that, the project team worked with the site to use BEAM software to define the optimal asset maintenance policy for each energy asset for periods of two, five, and fifteen years. The performances of the optimal asset maintenance policy and baseline maintenance policy are captured in Table 1 below. All the key performance objectives were met when using BEAM to conduct 15-year asset maintenance operation and maintenance (O&M) planning, except for performance objective (PO) IV in Availability Improvement, because the baseline for availability is already greater than 99.5%.

Table 1**:** Demonstration Results Summary

Arnold Hall SQFT (200,000 ft^2)	**2 Year's BEAM**	**5 Year's BEAM**	**15 Year's BEAM**	**Performance Objectives**
PO I: Energy Savings	8.03%	8.01%	6.61%	> 5%
PO II: Reliability Events Reduction	76.81%	88.30%	88.09%	> 20%
PO III: Energy & Maintenance Cost Savings	10.00%	11.00%	17.00%	> 15%
PO III: Penalty Cost Reduction	96.52%	99.16%	98.37%	> 15%
PO IV: Availability Improvement	0.36%	0.34%	0.33%	> 20%

PO V: Ease of Use & User Satisfaction	Willingness of facility managers to use BEAM tool for asset management	Achieved

Here we conclude that the BEAM-derived optimal maintenance policy shows significant lifecycle cost saving improvement over current practices at the demonstration site. The cost and benefit of using BEAM have been quantified, indicating a payback of investment of less than 2 years. The demonstration site facility manager, building operator, and control engineers all expressed their willingness to use the BEAM tools to monitor asset conditions and conduct energy asset management in performing their daily jobs.

1.0 INTRODUCTION

This demonstration report has been prepared for Dr. James Galvin, Environmental Security Technology Certification Program (ESTCP) Program Manager for Energy & Water, by Dr. Yan Lu, Siemens Corporation, Corporate Technology (SCT) and Dr. Mohsen Jafari, Rutgers University (RU), the Principle Investigators for ESTCP Project EW-201262. The goal of this project is to demonstrate and validate an innovative computer software system for Building Energy Asset Management (BEAM), technology designed to empower the commanders of military installations and their facilities management subordinates to better manage the operations and maintenance (O&M) activities of their buildings to accomplish their missions while increasing energy efficiency and reducing total lifecycle energy and other costs.

The building used as the demonstration test bed was Arnold Hall at the United States Air Force Academy (USAFA) in Colorado Springs, Colorado. This demonstration performed asset maintenance planning optimization by using BEAM software. In addition to validating the effectiveness of the BEAM technology, the demonstration assessed issues of costs, training, and implementation related to deployment of BEAM by the Department of Defense (DOD), including the potential for integration or coordination with DOD BUILDER and/or other programs of the Construction Engineering Research Laboratory (CERL) and other divisions of the Engineer Research and Development Center (ERDC) of the US Army Corps of Engineers.

1.1 BACKGROUND

The portfolio of buildings at a military installation consists of structures of varying construction type, age, and state of repair. These buildings are used and reassigned for an assortment of purposes at an installation. Energy assets, in general, include all devices necessary for the operation of the building that use energy for those purposes, such as HVAC and lighting systems and building envelope. Allocating limited resources of finances and personnel, the commander of an installation has the responsibility for managing the operations and maintenance (O&M) of the building energy assets under his/her command to optimize their capabilities in support of whatever missions they have been or may be assigned. In addition to primary strategic and tactical military purposes, such missions include current and lifecycle operating cost optimization, energy efficiency maximization, and greenhouse gas (GHG) or other detrimental environmental impact minimization. But the tools available to decision makers, planners, and facilities managers for understanding the dynamics of their “energy assets” are currently rudimentary. Innovative tools are needed to identify and effectively maintain critical assets in use now and for the future.

The energy efficiency of building assets begins to deteriorate as soon as they are placed in service, irrespective of whether they have been designed and commissioned for optimal performance. And such performance degradation accelerates over time as the building and the components of its systems age. Reductions in the relentless, incremental loss in the energy efficiency of existing buildings have the potential to save DOD a significant portion of the $4 billion spent annually on facilities energy consumption and to avoid the generation of greenhouse gases and other toxic waste every year. Improved O&M practices can save much of this cost and reduce environmental impacts from building operations.

1.2 OBJECTIVE OF THE DEMONSTRATION

BEAM tools enable management of buildings within a timeframe in ways that optimize energy efficiency and minimize energy and maintenance cost while fulfilling prioritized missions.

Demonstration of this technology should help DOD assess the potential for increased energy security at its installations through adoption of advanced O&M tools to be provided by BEAM:

- The BEAM technology provides military decision makers within an installation chain of command with robust analytical tools for managing maintenance policy of energy assets within their buildings so as to optimize mission accomplishment;
- These tools empower facility managers and military planners to address specific O&M issues of critical importance to them that were previously difficult or impossible to analyze effectively;
- These tools can be employed: (a) to monitor and manage the assets of energy systems in real time and (b) to assess for planning purposes existing and/or contemplated energy asset systems individually or in combination.
- The use of these tools can reduce total building energy consumption plus systems maintenance cost by 15%, while increasing the projected availability and reliability of a building's systems by 20% (see Performance Objectives). In practice, for most buildings availability and reliability are typically over 99% of the time when a long period of time is considered; therefore, an improvement of 20% using only time as a criterion may not be realistic. However, an improvement in penalty cost avoidance of that magnitude would be achievable.

1.3 REGULATORY DRIVERS

The primary drivers for this project are (i) Executive Orders: EO 13423 of 24 January 2007 and EO 13514; (ii) Legislative Mandates: Energy Policy Act of 2005 and Energy Independence and Security Act of 2007; (iii) Federal Policy: Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding (MOU) 2006; (iv) DOD Policy: Strategic Sustainability Performance Plan, Energy Security MOU with Department of Energy (DOE); and (v) USAF Policy: Air Force Energy Plan 2010.

Executive Orders: EO 13423, EO 13514

Executive Order 13514, Federal Leadership in Environmental, Energy, and Economic Performance, dated 5 October 2009, expands Executive Order 13423, Strengthening Federal Environmental, Energy, and Transportation Management, dated 24 January 2007, by making reduction of GHG emissions a priority and by requiring adoption of sustainability solutions that include achieving a building Zero-Net Energy standard.

Service Policy:
DOD for Air Force

Air Force Policy Directive (AFPD) 90-17, *Energy Management*, dated 16 July 2009 and Air Force Instruction (AFI) 90-1701, *Energy Management*, dated 16 July 2009 state the Air Force Energy Policy. Project EW-201262 directly addresses the stated intent of the Air Force Energy Strategic Plan (effective March 2013) to "Increase energy efficiency and operational efficiency for Air Force systems and processes without losing mission capabilities."

Guides: Whole Building Design Guide (http://www.wbdg.org/)
The Comprehensive Facility Operation & Maintenance Manual of the Whole Building Design Guide identifies lifecycle maintenance planning as central to current best practices.

2.0 TECHNOLOGY DESCRIPTION

BEAM is a suite of computer software tools which integrate innovative continuous condition monitoring (CCM) and energy asset management (EAM) technologies and focus on how best to maintain and invest in "critical energy assets" in a building so as to ensure that the building meets its missions (or business objectives) while minimizing lifecycle costs. Figure 1 shows the schematic of the BEAM framework. In the BEAM framework, each building is assigned missions that its occupants are tasked to accomplish, such as fire protection, air operations, administrative support, morale & welfare, recreation, education & training, etc. The energy assets – defined as assets that produce, transfer, and/or use energy to support the activities associated with mission accomplishment at a specific building – possess business values that can be measured in relation to their significance for mission accomplishment. Within the BEAM framework, the business value of each building energy asset plays key roles in the asset management process for prioritizing asset management investment and maintenance workflow. Meanwhile, the conditions of building energy assets are continuously monitored in BEAM - thereby enabling asset management decisions, whether preventive or predictive, to always be made based on the evaluation of current equipment and device conditions, including fault and energy performance. For example, the BEAM tools can be connected to building automation systems and thereby incorporate runtime asset condition monitoring into asset planning. Moreover, BEAM asset planning optimization considers not only asset investment and maintenance cost, but also the building operation cost and the potential penalty cost projected to result from a loss of asset function. These unique features of BEAM support facility managers at building, military base, and regional command levels in making better decisions for optimizing energy asset operations and investments.

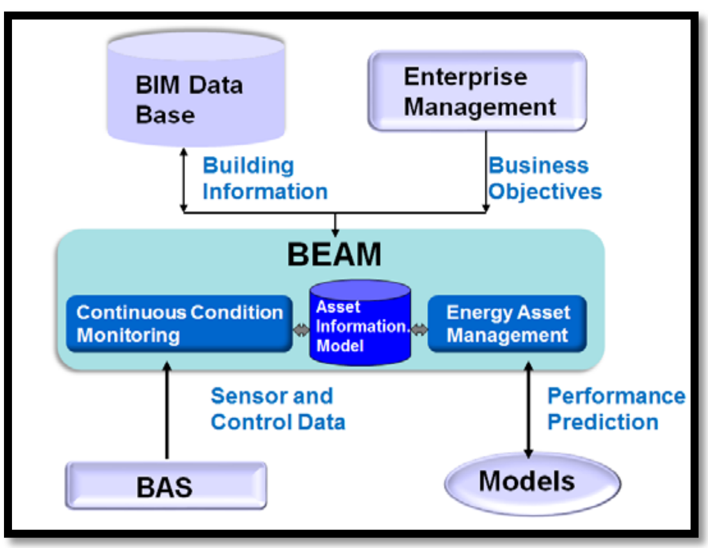


Figure 1: BEAM framework

The next subsections illustrate the details of the BEAM method, how each sub-component works, and the design of the software tool.

2.1 TECHNOLOGY OVERVIEW

BEAM Approach: BEAM technology uses a 5-step model as shown in Figure 2**.** The concept originates from Enterprise Asset Management (EAM) (Holland et al, 2005; McMullan I., 2004; Icon Group International, Inc. Staff, 2009), which has been used successfully by different sectors of the economy (e.g. power grid, transit systems, and aerospace). The 5-step model applied to building energy asset management can be outlined as a 3-phase workflow at a higher level, consisting of **Configuration**, **Planning** and **Execution** phases. During the Configuration phase, the business values of energy assets are defined based on the mapping of the building's mission to energy assets through functional zones. The typical cycle for BEAM Configuration covers months, years, or periods of time when either the building's mission or space purposing is changed. During the Planning phase, the business values of building assets are used in simulations to evaluate building operation cost and failure risks from alternative O&M policies and to generate optimal strategies. The processes and the algorithms supporting BEAM configuration and BEAM planning phases are well developed by scholars and practitioners from both academia and industry. During the Execution phase, fault detection and alarms are generated for each tracked asset through BEAM runtime software's continuous asset condition monitoring. Condition changes are assessed and displayed for the facility team to take action.

BVM Models: The Building Energy Value Models (BVM) defined during the BEAM configuration phase map the "Missions" or "Business Objectives" identified for a building to the building energy assets available and critical for the fulfillment of those objectives (Salahi, 2014). Using a combination of quantitative and qualitative techniques, "Business Value Models" identify the *Ordinal (criticality)* or *Monetary business value scores* of energy assets (through *BVM-I*, *BVM-II* and *BVM-III* as described below).

BVM-I measures criticality in ordinal terms [using a 0, 1 matrix]; BVM-II measures criticality in dollar ($) terms; BVM-III measures criticality within a seasonal context in dollar ($) terms. More specifically,

- BVM-I derives ordinal criticality scores ($\in [0,1]$) for assets by mapping a building's missions to its assets using a combination of *Analytic Hierarchy Process (AHP)* and *Failure Mode and Effects Analysis (FMEA).* Building missions are mapped to systems of assets in the building, and their criticality is evaluated through AHP. FMEA is used to associate risks or criticality of assets with their corresponding asset systems. The two models are linked to derive criticality scores for building energy assets.

- BVM-II yields monetary business value scores for assets, a model applicable to most office buildings and commercial facilities. Such business values are defined by economic loss due to failure or degradation of building assets. In BVM-II, this economic loss is estimated using the aggregated value of the building employee's productivity loss due to unavailability of an asset. (Pay structure within the military - enlisted and officer - is comparable to civilian pay scales - labor and management; so the same principles for using compensation as a proxy for productivity apply.) Common indices such as Predicted Mean Vote (PMV) and it's relation with employee's productivity through regression analysis is utilized in BVM-II. The concept of PMV and its relation to

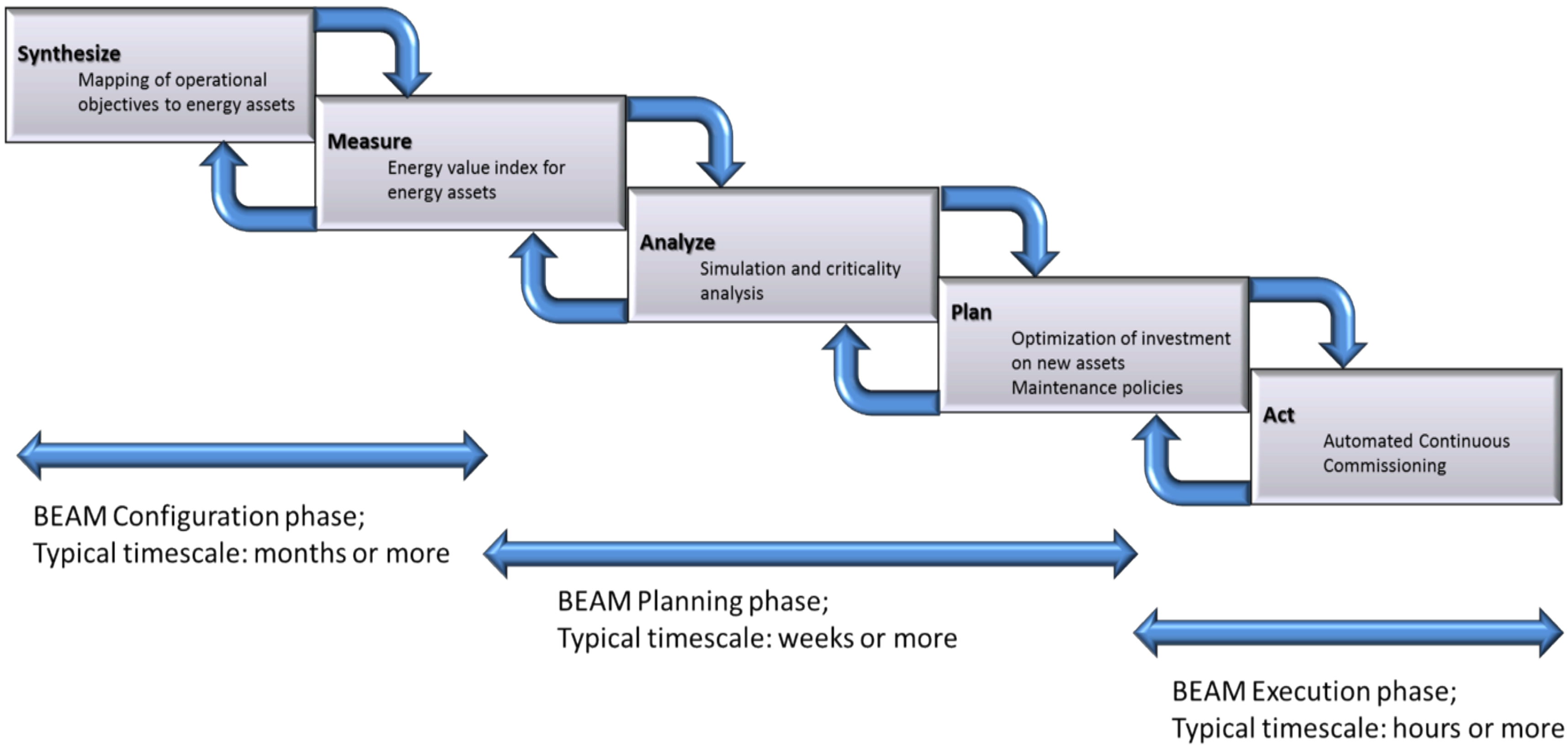


Figure 2: BEAM workflow

productivity has been extensively used in practice (Kosonen et al, 2004; Lan et al, 2011; Roelofsen, 2002).

- **BVM-III** extends BVM-II by introducing a function for seasonality, also measured in monetary terms. In addition, this model extends BVM-II to be compatible for buildings with a wider range of missions and to include calculations for the non-tangible and difficult-to-quantify consequences of asset failure, such as the need to postpone an event or accept sub-optimal conditions, thereby providing a more sophisticated model of their contribution to the business value of building assets.

Note that BVM-I can be used for any building. It is ordinal in nature and, therefore, independent of monetary considerations. In contrast, BVM-II & III use a monetary metric. Note, however, that dollar values are primarily a means for measurement; although related to monetary considerations in the real world – and usable for financial purposes – they are fundamentally measurement tools for purposes of comparative ranking and analysis. The monetary business models provide a better way than the ordinal model to optimize asset maintenance policy considering both operation/repair cost and the penalty cost from asset failures.

BVM can be applied whether or not a building is "commercially oriented" or if it is occupied or unoccupied by people. Valuation can be derived in a variety of ways. For example, the value of dormitory space can be compared to market rents for comparable housing; the value of dining facilities can be valued based on meals served (in comparison to a commercial restaurant); fitness centers can be compared to membership fees in a commercial gym. Maintenance of environmental conditions for equipment or critical processes can be subject to similar valuation methodologies.

Continuous Condition Monitoring: The Continuous Condition Monitoring (CCM) of BEAM is a module whose function is to continuously check the status of systems and assets required for the building's operation. The status of each asset and system is quantified in terms of an index called the "Condition Index." Condition Index has a value between 0 and 100, with 0 corresponding to the worst condition and 100 indicating perfect condition. To calculate an asset's Condition Index continuously, our CCM module includes three major functions:

- Automated fault detection and diagnosis (AFDD): We use runtime data from building automation systems to determine faulty HVAC parts and equipment based on a Heat Flow Model (HFM). During the fault detection phase, measured sensor and control values are used to perform estimations based on the physical properties of the system. Discrepancies of estimated and measured values are collected as a detection failure vector. Diagnosis seeks to find the most probable cause for the observed failures. In HVAC systems, the failures and faults form an "m-to-n" (matrix) relation. Our diagnosis is performed with an associative network to map the relations among failures and faults using the inherent fault simulation capabilities of the HFM nodes at runtime. The automatic fault detection generates Condition Index for the building asset detected with faults. This applies to general assets such as VAV boxes. The CIs are defined based on their faulty conditions, assuming a full functioning asset with a CI as 100, a totally failed asset with a CI as 0 and a faulty asset with a CI depending on the fault type. The details will be discussed in Section 5.

- Automatic energy asset performance estimation: We use runtime data from the building automation systems to determine the energy performance of those energy conversion devices in a building, including its chiller, fans, boiler, and other significant system components that are monitored. The condition index of this equipment is calculated as the ratio between the Expected Power Consumption and Actual Power Consumption:

$$CI = \frac{Expected\ Power\ Consumption}{Actual\ Power\ Consumption}$$

  The performance degradation can be captured by assessment of a drop in efficiency or an increase in power consumption for a particular working condition.
- Zone energy performance: BEAM CCM also monitors the energy performance of building spaces measured at zone level. The CI of a zone is defined as its energy use intensity (EUI, in kWh/square foot per year) dividing the EUI of the best performing zone.
- Condition from manual inspection: Manual condition monitoring is designed to address conditions of those components for which sensor data is not available. Manual condition monitoring may be accomplished through simple inspection or through detailed inspection and distress analysis. The frequency and procedures for inspections are matters for policy decision, presumably determined through reference to manufacturer recommendations and established industry best practices. Similar to automatic condition monitoring, the output from manual condition monitoring is an asset level Condition Index that is consistent to BUILDER's definition.

BEAM Engine: The BEAM Engine is a simulation engine, designed to explore the implications of a variety of asset maintenance policies and to identify a policy that yields minimal Total Building Cost (Mahani, 2014). Such cost minimization combines three main cost elements: (i) asset energy cost, (ii) building value loss due to asset failures (Asset Penalty Cost), and (iii) maintenance cost. Each maintenance action has a fixed cost term (based on such factors as materials cost) and a variable cost term (dependent on time duration and hourly labor cost required to perform the maintenance action). Asset Penalty Cost is defined as economic loss due to failure of an asset. This cost can be calculated using BVM. Finally, asset energy cost includes the fixed and variable costs of consuming or generating energy (e.g. electric energy and natural gas).

The BEAM engine integrates asset reliability models, performance improvement models and a building energy model to predict asset performance degradation and building energy consumption over a planning horizon for a given set of asset maintenance policies. The energy simulation takes into account such relevant factors as climate, occupancy, and system reliability. Optimal maintenance policies within budget and financial constraints can be identified through heuristic search methods based on the simulation engine.

Figure 3 shows a flow chart of every BEAM Engine simulation cycle of 1 hour. The probability of failures and energy performance degradation trend of an asset depends not only on the time elapsed since the asset's installation (actual age) but also on changes resulting from the cumulative load on the asset as well as the maintenance policies employed (Effective Age). Asset Effective Age is a function of the asset condition index generated by BEAM-CCM. The

Effective Age of assets is input to the BEAM Engine at the beginning of every cycle. Using its Asset Reliability Model, the BEAM Engine then calculates the failure probability and energy performance efficiency of the assets as a function of their Effective Ages. After that, both values are plugged into a building energy simulation to calculate building energy consumption. The BEAM reliability simulation model and building energy simulation model run in parallel, and communicate using a co-simulation platform. The Asset's Partial Load Profile is computed by the Building Energy Simulation Model and is input to the BEAM Engine's "Asset Efficiency Degradation" function, "Asset Reliability Model", and "Maintenance Optimization" model. The energy transfer or conversion efficiencies of assets are calculated based on their Partial Load Profile. Random failure events, characterized by asset availabilities, are also generated based on probability distributions. Asset performance and efficiency measures and availability indicators are then "injected" back to the Building Energy Simulation Model. The BEAM Engine then updates the asset's Effective Age and CI according to the Improvement factor (($IF \in [0,1]$) of the type of maintenance policy specified.

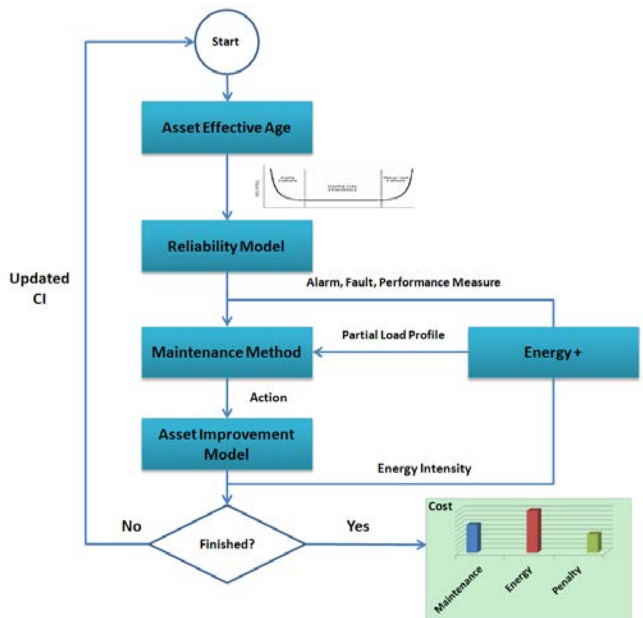


Figure 3: BEAM optimization flow chart for a 1-hour cycle

<u>Comparison to Existing Technology</u>: Although the underpinning concepts of the BEAM technology have been extensively used and developed for purposes of reliability and maintainability in industrial applications (Holland et al, 2005; Mcmullan I., 2004; Kwak et. Al, 2004; Myrefelt, 2004), BEAM is unique in its application of those concepts to building asset management. The building energy asset management (BEAM) tool differentiates itself from existing asset management software in four ways: (i) It can be integrated with building automation systems to perform runtime asset condition monitoring. (ii) It supports asset planning driven by business value. (iii) It uses combined model-based & data driven decision processes. (iv) It provides a holistic knowledge base of energy assets and their performance characteristics. These unique features support facility managers at building, military base, and regional command levels to make better decisions for optimizing energy asset operations and investments.

<u>Chronological Summary</u>: The BEAM Energy Asset Management and Continuous Condition Monitoring technologies were developed independently of each other. The Siemens Corporation, Corporate Technology (SCT) efforts to develop HVAC continuous condition monitoring have been underway for the past decade. This technology is now well advanced; it has been tested in SCT settings previously. Rutgers University's efforts to develop BEAM Asset Management have been active since 2006. However, substantial development of BEAM Asset Management was performed during 2011 in conjunction with the Energy Efficient Building Hub of the Department of Energy ("EEB-Hub," formerly "GPIC").

<u>Future Potential for DOD</u>: The proposed integrated suite of tools (BEAM) will empower DOD strategic planners, capital budgeters, facilities managers, logistical tacticians, and base commanders to design and operate more energy efficient and cost effective systems of energy assets at the single building and cluster of buildings levels of analysis. In addition to identifying flaws, weak points, critical paths, and opportunities related to the functions of energy assets within whole systems and subcomponents during normal operations, BEAM can be used for contingency planning using simulations. In emergency situations, the software can rapidly identify strategies for continuing or resuming critical functionality of energy assets under conditions where facility capabilities have been compromised by natural disaster or hostile intent. Development of the innovative system metric of asset energy performance will enable the DOD to make more sophisticated ROI calculations.

Following BEAM configuration for a single building, the BEAM software can be further developed with additional features and functions, including linkage to energy systems shared with other buildings and their energy supply chain. Facility managers and their superiors in the chain of command will have an increasingly robust and sophisticated set of tools for planning and managing the energy assets of their building portfolio from conception, design, construction, acquisition, and initial commissioning through their lifecycle to their eventual decommissioning. And, as missions and/or their timeframes or other parameters change, decision makers can use BEAM to reevaluate operations and maintenance policies by projecting their associated direct and indirect costs.

<u>Anecdotal Observations</u>: There are many success stories in private industry where the use of advanced asset management technology has led to substantial reductions (over 15%) in operation and maintenance costs, including direct energy expenditures.

2.2 TECHNOLOGY DEVELOPMENT

During the course of the project both the BEAM CCM module and the BEAM EAM engine were further enhanced by Siemens and Rutgers University respectively. BEAM CCM functionality was extended based on the existing Siemens Fault Detection & Diagnostics (FDD) technology with additional modules: Asset Energy Performance Assessment Module, Space Energy Intensity (EI) Calculator, and a Condition Index (CI) Calculator. Each of these components was customized to allow reading of the building sensor data from a CSV file in addition to the receiving data directly and continuously from a building automation system.

The BEAM EAM Engine was built based on previous research results by the Rutgers team. The BEAM Engine was developed in Matlab with an interface to read and write data to an xml based building asset information model. Energy Plus is used to simulate hourly building energy consumption which is then integrated into Matlab using a MLE+ interface developed by UPenn.

However, the major technology development efforts under the project were applied to the development of BEAM Tools.

<u>BEAM Tools</u>: Tools for BEAM include software that can enable the 5-step workflow for BEAM Configuration, Planning, and Execution phases with a focus on the energy asset systems within a building, including primarily HVAC systems, lighting, and building envelopes. There are two main modules: BEAM Configuration and BEAM Runtime, as shown in Figure 5, Figure 6 and Figure 7.

Rutgers University led the development of the BEAM Configuration Tool, which is used to map the missions assigned to a building to the building's assets based on Business Value Models: *BVM-I*, *BVM-II* or *BVM-III*. The configuration tools are also used to generate models for automatic HVAC FDD, energy performance monitoring, and building energy simulation (Energy Plus). In addition, the building information and asset information gathered through the BEAM Configuration tool generates a comprehensive XML-based database for BEAM Runtime to use, called the Asset Information Model. Figure 5 (a) shows the web-based BEAM Configuration tool for energy asset BVM value generation. Figure 5 (b) shows the results of the configuration tools.

The Siemens Corporate Technology team implemented the BEAM Runtime tool based on its Smart Energy Box (SEB) technology, which was developed during the last 10 years as an open platform to extend existing BAS functionalities. Both CCM and the BEAM Engine are implemented as plugins to the SEB. In addition, the Siemens team developed a new web-based Human Machine Interface (HMI) using Java Script and HTML5 technology. The HMI allows browsing of the assets from the Asset Information Model using the Web Server of the SEB. In addition, the user is able to import sensor data, review and detect faults, and monitor the asset Condition Index, space energy intensity and alarms. Device faults or energy performance degradations exceeding user-defined thresholds trigger alarms (Figure 6). BEAM Runtime also provides an asset-planning interface for projecting "what-if" scenarios to evaluate O&M policies or to synthesize the best O&M policy for energy conversion devices such as chillers, fans, pumps, and boilers (Figure 7).

BEAM Runtime software can run in either a "Stand Alone" or "Integrated" mode, differentiated by the connection types between the BAS and the BEAM Runtime software. For operation in the "Stand Alone" mode, the software doesn't need to communicate with BAS through BACNet. Instead, a user can upload BAS trend data daily, weekly, or bi-weekly to assess asset condition at his/her own convenience. In this way, BEAM technology presents lower security concerns to the building control network. Running in an "Integrated" mode, BEAM is integrated with the BAS system through the BACNet protocol; hence the continuous condition monitoring is fully automatic and there is no need for a user to upload data during operation. In addition, BEAM can detect and respond to faults more promptly in the "Integrated" mode.

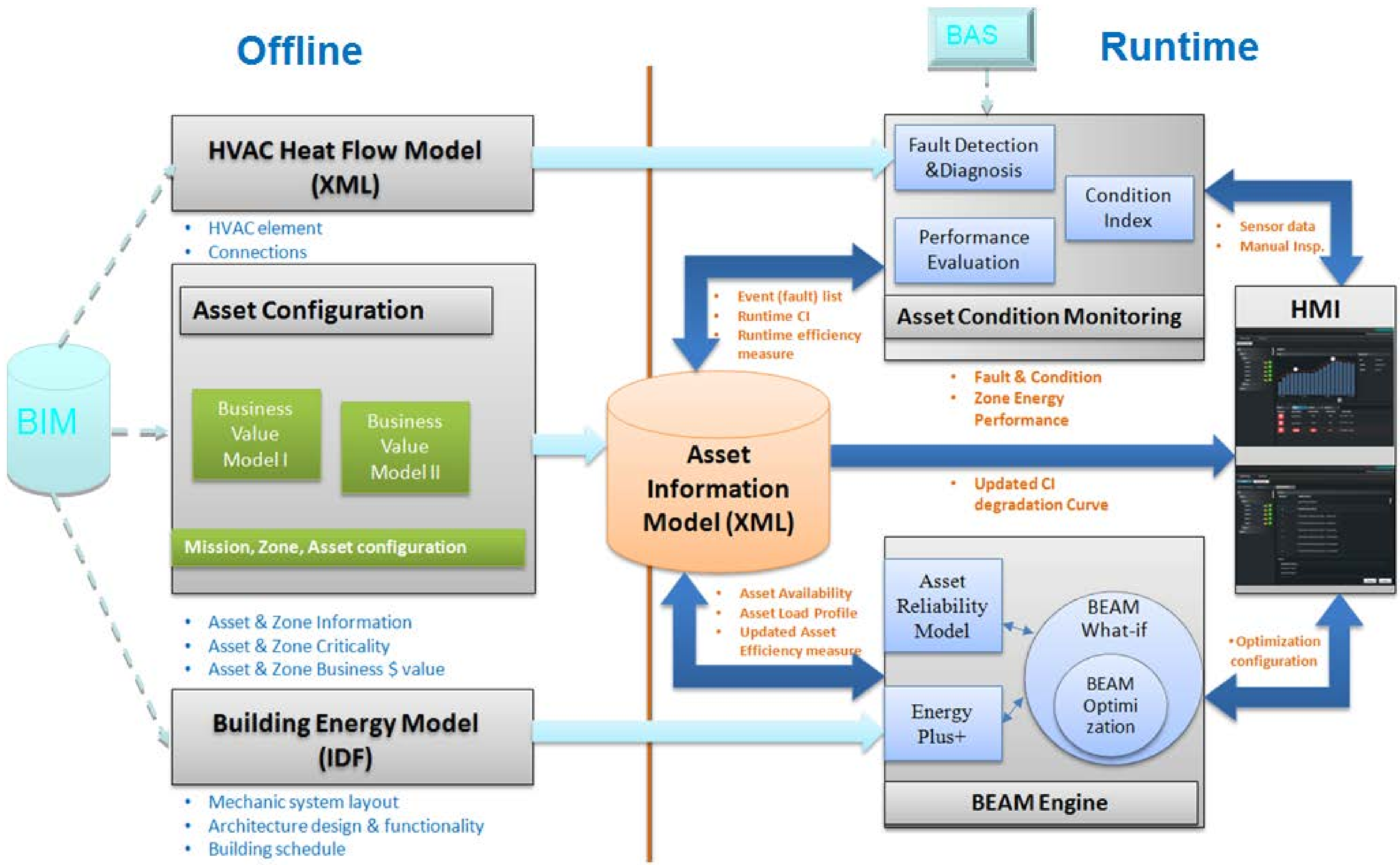


Figure 4: BEAM Software's Overall Architecture

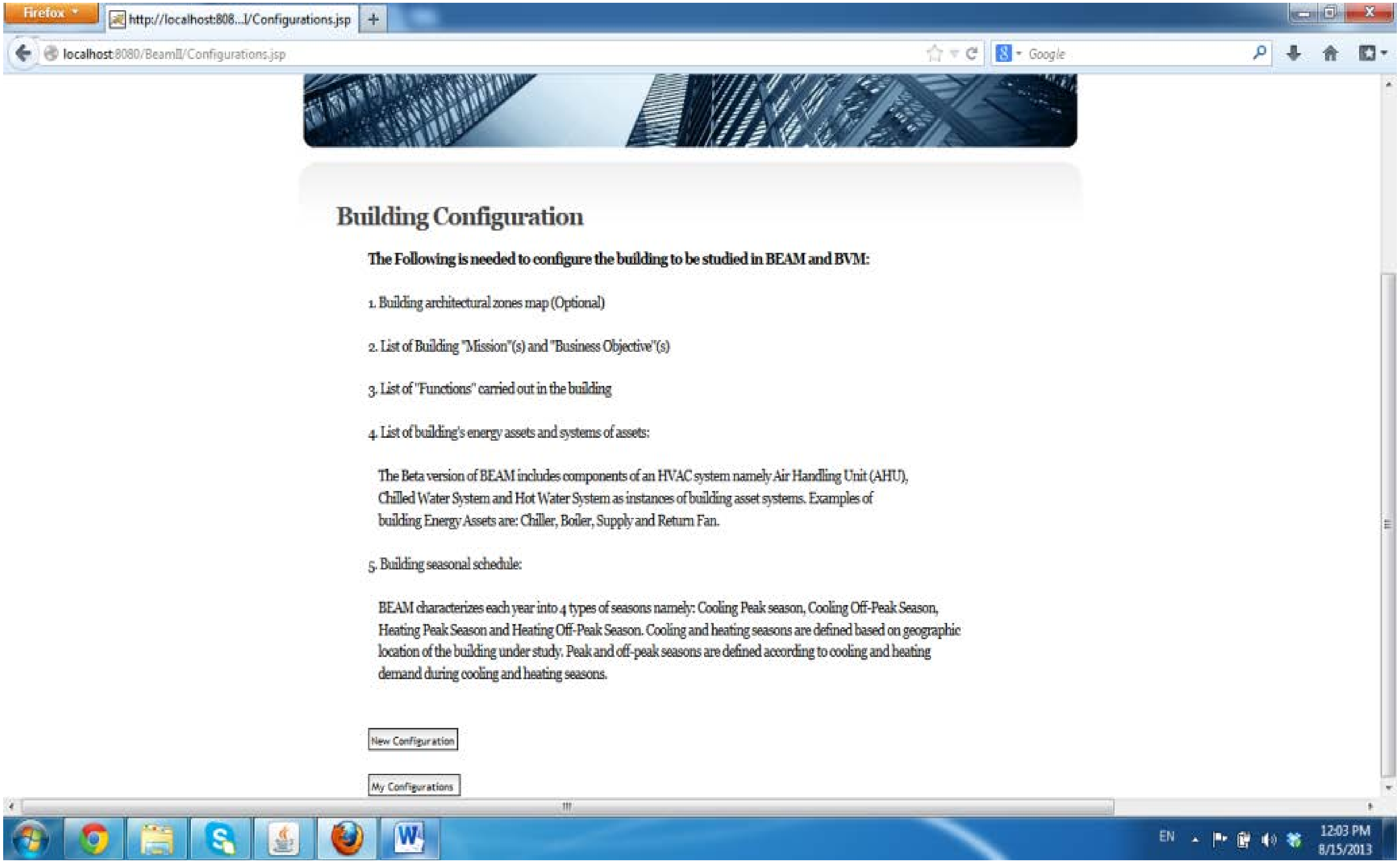


Figure 5 (a): User Interface of BEAM Configuration Tool

Final BVM-III Business Values

For Asset chiller1:
For Peak Cooling Season
$1513100.0
For Off-Peak Cooling Season
$879742.8571428572
For Peak Heating Season
$0.0
For Off-Peak Heating Season
$0.0

For Asset supplyfan1:
For Peak Cooling Season
$777200.0
For Off-Peak Cooling Season
$884514.2857142857
For Peak Heating Season
$895285.7142857143
For Off-Peak Heating Season
$1026057.1428571428

For Asset supplyfan2:
For Peak Cooling Season
$48000.0
For Off-Peak Cooling Season
$61257.14285714286
For Peak Heating Season
$49942.85714285714
For Off-Peak Heating Season
$54628.571428571435

For Asset supplyfan3:
For Peak Cooling Season
$121200.0
For Off-Peak Cooling Season
$142514.2857142857
For Peak Heating Season
$143285.7142857143
For Off-Peak Heating Season
$400057.14285714284

For Asset supplyfan4:
For Peak Cooling Season
$48000.0
For Off-Peak Cooling Season
$61257.14285714286
For Peak Heating Season
$49942.85714285714
For Off-Peak Heating Season
$54628.571428571435

For Asset supplyfan5:
For Peak Cooling Season
$0.0
For Off-Peak Cooling Season
$0.0
For Peak Heating Season
$0.0
For Off-Peak Heating Season
$0.0

For Asset supplyfan6:
For Peak Cooling Season
$331800.0
For Off-Peak Cooling Season
$355400.0
For Peak Heating Season
$288000.0
For Off-Peak Heating Season
$249600.0

For Asset supplyfan7:
For Peak Cooling Season
$60000.0
For Off-Peak Cooling Season
$76571.42857142858
For Peak Heating Season
$62428.57142857141
For Off-Peak Heating Season
$68285.71428571429

Figure 5 (b): BEAM Configuration Tool outputs

Figure 5: BEAM Configuration

Figure 6: User interface of BEAM Runtime Software - Asset Condition Monitoring

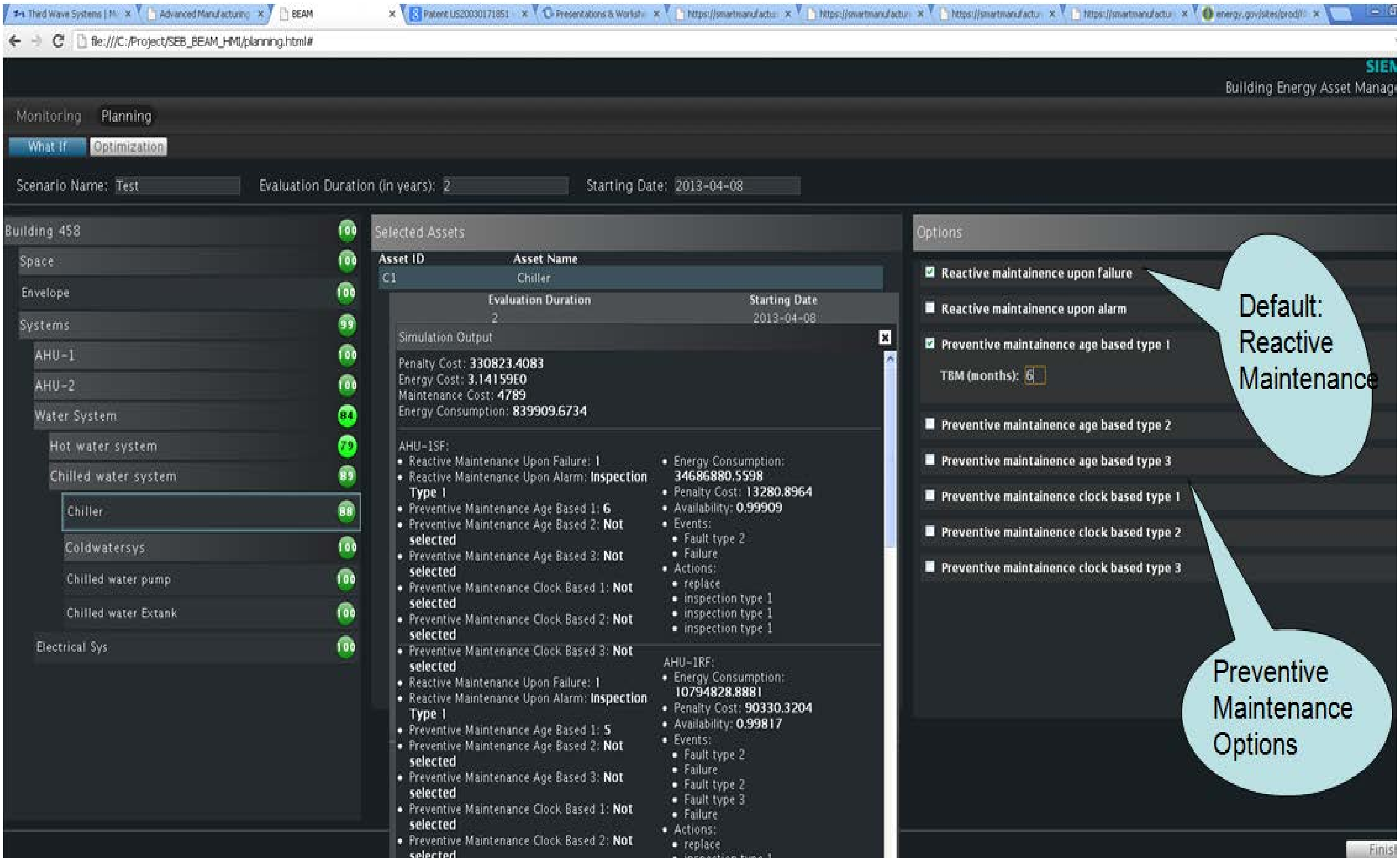


Figure **7:** User interface of BEAM Runtime Software-- Asset Management Planning

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Performance Advantages: The BEAM technology is innovative and has not been demonstrated previously. The integration of continuous condition monitoring with asset management based on asset reliability and building energy modeling is a new idea which can provide facility planners and managers with tools to optimize both asset maintenance and energy cost over short-term and long-term time horizons and to perform "what-if" analysis in response to significant unexpected events. In addition, business value driven asset planning can optimize organizational performance and better ensure accomplishment of critical missions.

The BEAM technology empowers facilities managers to manage their energy assets with live data. Cost effective building energy asset O&M policy results in equipment efficiency performance improvement which enables reductions of 15% or more in overall system energy usage. At the same time, appropriate maintenance on HVAC and other energy assets within a building is expected to extend significantly the life span of those assets.

Cost Advantages: BEAM is a software-based solution. The acquisition cost, including licensing and software installation as well as user training is expected to be low. Major costs are currently required for implementation, because the technology requires significant engineering effort during the Configuration phase, including generation of the building asset information model, reliability model, and building energy model. However, after commissioning, no maintenance is needed for BEAM. Since the software is designed to interface with the existing building automation system and support continuous commissioning, there is no need for manual data collection for purposes of asset condition assessment when the software is running in "Integrated" mode. The return on investment is expected to be within 5 years, if the building already has an existent BAS system, especially when a penalty cost is incurred during the non-availability of assets.

Performance Limitations: The BEAM tool requires supporting data on asset reliability, performance, and operating schedules. The problem of data unavailability is non-existent for new buildings. For older buildings that have kept no archives of asset information and maintenance logs, the lack of data needed for asset reliability modeling may significantly hinder the applicability of BEAM, unless data on similar assets can be obtained from the manufacturers or user groups. A scaled down version of BEAM for older buildings may be possible for purposes of generic planning for buildings of standardized construction types, particularly for structures such as Quonset huts or barracks.

BEAM technology performs planning and optimization on the basis of building simulations. The existing simulation technology (e.g., EnergyPlus) requires extensive computational time, especially when the building modeling includes sufficient details, and runs are made for several years (i.e., 4 or 5 years). A typical BEAM optimization may then take several hours of computer time to complete. While running offline, the BEAM execution time may pose practical limitations, if decisions are expected immediately or within a short time interval. Although the BEAM system is complex, its HMI has been designed so a casual user can quickly and intuitively obtain actionable information, while a power user can access more comprehensive capabilities.

Cost Limitations: A potential barrier to acceptance of BEAM technology is the time and expense required to generate all the models required by BEAM Runtime software. For example, the project team estimates that between one to three months would be required to build an EnergyPlus model for most buildings, depending on the building type, the size and complexity of the building, and the experience of the engineers who create the model. However, as we explore the potential for integrating BEAM with DOD BUILDER, we note that interoperability with DOD BUILDER could reduce BEAM engineering cost substantially. Furthermore, generation of EnergyPlus models as a routine aspect of building design by the US Army Corps of Engineers and other architectural planners within the near future is a distinct possibility.

Social Acceptance: Our military partners have been enthusiastic about the concept of BEAM, and they have been receptive to the prospective opportunity to become early adopters of the BEAM technology. However, they also advised the project team that the advanced concept in BEAM could be overwhelming to some of the civil engineering teams. We envision that well designed training is necessary for effective technology transfer. And, parallel dissemination activities are planned to educate military and civilian users and to promote the acceptance of BEAM technology.

3.0 PERFORMANCE OBJECTIVES

The Quantitative Performance Objectives [PO I, II, III, and IV] are intended to measure the savings in energy consumption, energy cost, maintenance cost, and penalty cost achievable by the BEAM technology within a specified timeframe, based on simulations. The Qualitative Performance Objective [PO V] is intended to measure the perceived benefits and utility of the technology as indicators of its potential demand from and adoption by military installation management personnel.

Due to the time limit of the project, BEAM could not be tested for a period long enough to confirm its performance. Furthermore, disturbance of the contractual business arrangements for maintenance at USAFA would be outside the scope of the project. Therefore, quantitative measurement of performance for this project was carried out using models and simulations which were validated against the baseline O&M policy using historical asset energy usage and reliability data.

Qualitative measurements of performance may therefore be particularly significant for purposes of assessing the success of this project. The BEAM technologies provide building owners and facility managers with a flexible toolset unlike any tool previously available. The extent to which military users of the technologies found BEAM worthwhile for practical applications provided indications of the future demand for and adoption of these technologies by DOD decision makers.

- **Energy Security:** The performance objectives are designed to measure the impact of BEAM technology on [1] understanding the specific energy asset needs of military installations for performance of their identified missions and [2] enhancing the reliability and availability of energy systems critical for fulfillment of those missions through [3] improved planning, policies, and management of operations and maintenance (O&M) activities. The results of such technology impacts were reflected in measurements of annual energy usage (BTU and/or kWh - PO I), asset down time (Hours - PO IV), and lifecycle costs ($ - PO III). Therefore, the performance objectives measure both directly and indirectly the ability of the technology to help O&M personnel reduce energy consumption (BTU & kWh) and allocate personnel, material, and financial resources.

- **Cost Avoidance:** The performance objectives measure both costs and benefits associated with O&M activities. By reducing both the number and severity of equipment stoppages, the BEAM technology can measurably improve building performance and lower overall costs. The metrics focused on occurrences (PO II), which relate to cost reductions, and on performance (PO I & III), which pertain to productivity improvement, may be applied to the same and/or different sets of simulated events. Others measure cost avoidance indirectly (PO I) or directly as cumulative results (PO III).

The qualitative performance measurement (PO V) does not measure cost avoidance.

- **<u>Greenhouse Gas Reduction</u>:** The Performance Objectives for EW-201262 do not attempt to measure the reduction of GHG emissions for installations or non-tactical vehicles.

Historical data has been collected to establish a baseline for the demonstration and to validate the EnergyPlus model for the site. Based on the established test bed of Arnold Hall, the demonstration can apply the Success Criteria to the Performance Objectives through simulations that assess performance improvements in relation to the baseline.

Table 2: Performance Objectives

	Performance Objective	Metric	Data Requirements	Success Criteria	15 Years Results
	Quantitative Performance Objectives (based on E+ simulation results)				
I	Building Total Energy Consumption	Energy Intensity (MMBtu/ft2 and/or kWh/ft2)	Meter readings of energy used by installation and/or utility consumption recorded by Building Automation Systems (BAS); square footage of building using energy	Establishment of a baseline of annual energy consumption of the selected building (using industry standards, designed targets, and observed performance); 5% usage reduction compared to baseline	6.6% achieved
II	Building Systems Maintenance	Number of Failure Events & Severity Level of the Failures	Maintenance logs; number of failures; severity of failures; maintenance policies; manufacturer specifications and recommendations	Reduction of number of events & severity level (using penalty cost) of occurrences by 20% (to be assessed based on simulations)	88.1% achieved
III	Building System Economic Results	Annualized and Life-cycle Costs ($)	Costs/savings for energy usage; fixed costs/savings for maintenance; variable costs/savings for maintenance; and penalty cost	Identification of 15% savings or reductions in system costs compared to baselines and/or industry standards (to be assessed based on simulations).	17% Energy and maintenance cost reduction penalty cost reduction 98.37%
IV	Building Asset Availability & Reliability	Hours	Maintenance logs; number of failures; severity of failures; maintenance policies, manufacturer specifications and recommendations (or equivalents such as work orders, etc.)	20% increase in the amount of time energy systems that are available for operation. 20% increase in the amount of time energy systems that are performing as intentionally designed (to be assessed based on simulations).	0.33% not achieved because the building had an availability of assets of more than 99%
	Qualitative Performance Objectives				
V	Ease of Use & User Satisfaction	Degree of Satisfaction	User interview	Willingness of facility manager to use BEAM tool for asset management	Achieved.

Note: After a careful evaluation on the extra modeling effort resulting from switching the demonstration site from Picatinny Arsenal to the USAFA, we decided to remove cBeam performance objectives from Table 2. However, since we chose a single building at USAFA with multiple missions and with shared service for multiple function zones, the capabilities of cBEAM can be demonstrated to some extent.

3.1 PERFORMANCE OBJECTIVES DESCRIPTIONS

PO I: Building Total Energy Consumption

- **Purpose:** Properly maintained equipment uses energy more efficiently. The purpose of PO I is to demonstrate the lifecycle cost savings in energy consumption that can be achieved through alternative maintenance policies for specific assets.
- **Metric:** Building Energy Use Intensity (MMBtu/ft2 and/or kWh/ft2 per year). DOE and American Society for Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) have developed standards for the energy intensity of different types of buildings
- **Data:** Meter readings of energy used by installation and/or utility consumption recorded by Building Automation Systems (BAS); square footage of building using energy
- **Analytical Methodology:** A baseline for total energy consumption for the demonstration site (Arnold Hall) was established from analysis of historical data. The Condition Index for critical assets and other baseline conditions was used as the initial status for purposes of simulations under a series of maintenance scenarios. After optimization by the BEAM engine, simulated results were compared between optimized alternative maintenance policies and current (reactive) maintenance procedures.
- **Success Criteria:** 5% simulated reduction in energy usage relative to a baseline of annual energy consumption of the selected building (established by using industry standards, designed targets, and observed performance).

Results: The team achieved and surpassed the expected target. The results are detailed in Section 6.

PO II: Building Systems Maintenance

- **Purpose:** The overall reliability of energy asset systems can be improved by an appropriate strategy of maintenance policies. The purpose of PO II is to demonstrate an improvement in energy system performance resulting from the adoption of the maintenance policies identified by BEAM.
- **Metric:** Number of Failure Events & Severity Level of the Failures. These metrics assess the reliability and resilience of the energy systems serving the demonstration site.
- **Data:** Maintenance logs; number of failures; severity of failures; maintenance policies; manufacturer specifications and recommendations
- **Analytical Methodology:** A history of failure and/or service problems was established and analyzed based on maintenance logs, repair tickets; parts purchase orders, emails, phone logs, and other indications of energy asset problems. A baseline rate of problem occurrence for critical assets was used as a benchmark against which simulated failure rates were measured.

- **Success Criteria:** Reduction of the Number of Events & Severity Level (using penalty cost) of Occurrences by 20%, assessed based on simulations.

Results: The project achieved and surpassed the expected target. The results are detailed in Section 6.

PO III: Building System Economic Results

- **Purpose:** The total cost of providing energy to support the mission(s) of a building consist of direct fuel costs, asset maintenance costs, and the penalty cost of losing building functionality. The purpose of PO III is the identification and measurement of each of these costs separately and in combination.
- **Metric:** Annualized and Lifecycle Costs ($)
- **Data:** Costs/savings for energy usage; fixed costs/savings for maintenance; variable costs/savings for maintenance; and penalty cost
- **Analytical Methodology:** A baseline of energy and maintenance costs was established from historical data, and penalty costs were derived by simulation. The baseline for Arnold Hall was compared to industry standards. Then simulated results were compared to the baseline to identify savings achieved by BEAM optimization.
- **Success Criteria:** Identification of 15% simulated savings or reductions in system costs compared to baselines and/or industry standards

Results: We achieved and surpassed the expected target. The results are detailed in Section 6.

PO IV: Building Asset Availability & Reliability

- **Purpose:** A cost to mission accomplishment is incurred when/if a critical function of a building is lost or diminished for a period of time. The purpose of PO IV is to increase the availability and reliability of critical energy assets.
- **Metric:** Hours of asset being unavailable and/or operating at capacity less than adequate for mission accomplishment. (Note: Scheduled time out-of-service for maintenance which does not affect the mission is not considered a factor related to availability or reliability.)
- **Data:** Maintenance logs; number of failures; severity of failures; maintenance policies, manufacturer specifications and recommendations (or equivalents such as work orders etc.)
- **Analytical Methodology:** Establish a baseline of critical asset failure and/or diminished capacity based on historical information. Compare asset availability relative to this baseline in simulations.
- **Success Criteria:** [1] Computation of 20% increase in the amount of time energy systems are available for operation, and [2] Computation of 20% increase in the amount of time energy systems are performing as designed.

Results: The reliability target was achieved, but the availability improvement of 20% increase could not be achieved because the system was already available for more than 99%. The results are detailed in Section 6.

PO V: Ease of Use & User Satisfaction

- **Purpose:** To be adopted by the military, the BEAM technology must be perceived as a practical, valuable tool for planning and setting policies for energy asset management. The purpose of PO V is to assess the reception by the demonstration site facility manager, maintenance contractor, and operations administrator of the BEAM technology in general and specifically the BVM assessment/configuration tool and the BEAM HMI.
- **Metric:** Degree of Satisfaction with the process used for interviewing and data gathering
- **Data:** User interviews with the facility manager, the building operator, and the contract service provider for Arnold Hall. A sample interview questionnaire is shown in Section 6 **Figure 25**.
- **Analytical Methodology:** Solicit the facility manager, maintenance contractor and building operator's opinions regarding the BVM assessment tool and the BEAM HMI. Discuss the use of the BEAM tool for planning and operational purposes.
- **Success Criteria:** Willingness of facility manager to use BEAM tool for asset management

Results: This performance objective was achieved. Details are available in Section 6.

4.0 FACILITY/SITE DESCRIPTION

The demonstration was conducted at the United State Air Force Academy in Colorado Springs, Colorado using Arnold Hall (Figure 8) as the test bed**.** Arnold Hall, named after General of the Air Force Henry H. "Hap" Arnold, Commanding General of the United States Army Air Forces during World War II, is the cadet social center of the United States Air Force Academy. It houses a 3,000-seat theater, a ballroom and a number of lounges, dining, and recreation facilities for cadets and visitors. The major mission of Arnold Hall is entertainment, education, and training and administration. The Arnold Hall HAVC system includes a chiller, 12 air handling units, heat exchangers and numerous exhaust fans and pumps, with total power demand of up to 400 kW. Table 3 shows the energy assets considered by this project.

Figure 8: USAFA Arnold Hall Selected for the Demonstration

Table 3: Arnold Hall Energy Assets under consideration

Asset	Type	Capacity	Served Area	Served Zone Names
Chiller	Trane	300 ton / 166KW	Whole building	Whole building
AHU-1A	VAV/Dual Duct & Deck	SF 75 HP RF 20HP	Misc.	Tax Center, Food Court, Main Kitchen, Southwest Theater Arcade, Restrooms (131,116)
AHU-1C	CAV	SF 20 HP	Auditorium	Auditorium Back-Section, Auditorium, Corridor
AHU-1D	CAV	SF 5 HP	Auditorium	Rehearsal & Dressing Room, Backstage
AHU-2	CAV	SF 20 HP	Auditorium	Auditorium
AHU-3	VAV	SF 5 HP RF 1HP	Misc.	Green Room, Workshop
AHU-4	VAV	SF 7.5HP RF 1.5HP	Misc.	Offices (177,195), Alley
AHU-5	VAV	SF 5 HP RF	Haps Lounge	Haps Lounge

		1 HP		
AHU-6	CAV	SF 20 HP RF 3 HP	Misc.	Entrance Transition, Auditorium Lobby, West Entry Hallway
AHU-7	VAV	SF 20 HP RF 5 HP	Ballroom	Ballroom
AHU-8	VAV	SF 10 HP RF 3 HP	Cadet Lounge	Cadet Lounge
AHU-9	VAV	SF 2 HP RF 1 HP	Misc.	Executive Kitchen, Offices (121,128,160), Restroom (174)
AHU-10	VAV	SF 5 HP RF 2 HP	Ballroom	Reception Ballroom Hallway
AC-1	CAV	SF 2 HP RF 1 HP	Misc.	Storage

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The United States Air Force Academy (USAFA) is a military school for officer candidates for the United States Air Force. The campus is located immediately north of Colorado Springs, Colorado. The Academy is one of the largest tourist attractions in Colorado, receiving more than a million visitors each year. The Air Force Academy sits on 18,500 acres. The demonstration was conducted in the Cadet Area (a 2,000 area facility).

- Demonstration Site Description: The Air Force Academy is a military officer's candidate school located just north of Colorado Springs. Arnold Hall is located in the 2,000 area of the base. The 2,000 area contains the buildings used most intensely by the cadet wing. All buildings in the 2,000 area are held to strict architectural integrity requirements to adhere to their original design.

- Key Operations: The demonstration is located on an air force base where military operations are continuous throughout the year across the base and in the cadet area (2,000 area). Functions of Arnold Hall can include but are not limited to military training exercises, basic training, various educational programs, military recreation, food service, and social events. These operations determine the occupancy of the building at the demonstration site.

- Command Support: The executive leadership, A7 office, approved the use of the Academy as a demonstration site and assigned resources to support the effort. Two project managers were assigned to the demonstration to ensure a successful implementation.

- Communications: USAFA has its building automation, security, and fire system on a separate network from the Air Force Non-secure Internet Protocol Router (NIPRnet).

- Other Concerns: The strong, existing relationship that Siemens Building Technology has with the Air Force Academy creates an ideal demonstration site.

- Location/Site Map: See Figure 9 below.

Figure 9: U.S. Air Force Academy Site Map

4.2 FACILITY/SITE CONDITIONS

This facility is in good operating condition; however, some renovation work was conducted at the facility during the period of this demonstration. The renovation work did not affect this demonstration in any way. All equipment listed as part of the demonstration was unaffected by any construction work. However, some temporary impact on the electricity bill of the facility could have occurred due to additional construction equipment being plugged into the building power system. We considered for the purpose of this demonstration that such impact was limited.

5.0 TEST DESIGN

Buildings have been made "smart" by installing sensors that identify and quantify physical conditions at critical points in a building's environment and equipment. And, the information from such sensors can be used to automatically and/or manually adjust equipment operations and maintenance plans. BEAM tools are designed to assist building owners/operators by providing analytic tools that leverage the latent capabilities of building automation, information management, and energy management systems for asset maintenance planning.

- Fundamental Problem: How can building energy assets be managed so that their performance (including availability and reliability) and energy consumption are optimized and the building's functional objectives are fulfilled in accordance with mission requirements?

- Demonstration Questions:

  - Can BEAM-CCM (continuous condition monitoring) detect building asset faults and performance degradation? And can BEAM-CCM reduce or eliminate the energy wasted as a result of faulty assets?
  - Can BEAM maintenance policy solutions: (i) show significant lifecycle cost saving improvement over what is already being practiced by the selected site, or (ii) be used to verify their current optimal or near optimal practices and to propose enhancements?
  - How do business penalty costs due to failure and stoppage of energy assets influence optimal maintenance decisions?

BEAM application for Arnold Hall at USAFA helped answer the questions listed above.

5.1 CONCEPTUAL TEST DESIGN

To investigate the ability of the BEAM technology to achieve the Success Criteria for the Performance Objectives, tests have been designed to measure the performance of BEAM with reference to baseline conditions in side-by-side simulations of building performance within relevant timeframes of two, five and fifteen years respectively. For purposes of conceptual test design, the simulation software used dynamic variables that change over time and interact with each other..

Tests were conducted from the perspective of the User of the BEAM tools who may be the facility manager, a maintenance supervisor, a strategic planner, a base commander, or another party.

Independent Variables: These are variables that can be manipulated or changed by or on behalf of the User. For the purpose of this conceptual test design, the independent variable is application of BEAM tools for long-term building operation and maintenance:

- **Configurable Variables:** These variables can be set and/or changed by the User during the BEAM Configuration phase (the BVM input process). Example - Missions and their importance in relationship to each other
- **Manipulated Variables:** These variables can be changed and controlled by the User during the BEAM Runtime Phase, or they may be changed by BEAM software. Example – Maintenance Policies

Dependent Variables: These variables change based upon the use of the BEAM tool:

- These are response variables to be measured. Example – kWh consumed for building operations, confirmation of the existing O&M policy, or the observation that the existing policy is inadequate.

Controlled Variables: These variables were held constant between baseline cases and designed experimental test cases to avoid influencing the independent or dependent:

- **Static Variables:** These variables are physical properties that are static, for example – Area of a Control Zone (shape and square feet);
- **Dynamic Variables:** These variables change predictably over time, for example – Degradation curve of machinery efficiency over its useful life;
- **Local Variables:** failure rates/performance degradation vs. effective age; effective age changes vs. maintenance policy

Note that patterns of Weather and Occupancy are variables that are inherently uncontrollable by the User. However, these patterns are considered "controlled variables," meaning that they were held constant in the simulations for both baseline and BEAM tests.

Table 4: Test Design Summary

Controlled Variables	Independent Variables	Dependent Variables
• Building characteristics (size, set points, etc…) • Weather pattern • Occupancy pattern • Building Missions	Use of BEAM tools vs. no use of BEAM tools	• Energy usage per asset and Energy usage for whole building • Asset Reliability & availability • Business penalty cost • Validation/rejection of baseline Asset maintenance policy

Hypothesis: To answer the questions posed above, the following hypothesis was tested:

Employing the BEAM tool leads to major improvements in asset reliability and performance, reduces building energy consumption, and supports better mission accomplishment.

The acceptance criteria for the above hypothesis were defined as following:

- BEAM optimal solutions show 5-10% reduction in energy consumption in cases of reactive baselines. In all other cases, BEAM solutions should closely confirm optimality of the existing O&M policy or identify opportunity for improvement.
- The number of failures/faults of mission critical assets logged by BEAM solutions (generated in simulations) should be less than historical or simulated logs generated under the baseline case.

As shown in the results of Section 6, the acceptance criteria for this demonstration were met.

Tests Conducted:

To test the hypothesis, we conducted the following experiments by monitoring the dependent variables to track both cost (business penalty, energy, and maintenance costs) and performance of assets using BEAM technology. We applied the BEAM tool to the Arnold Hall building:

- Used BEAM to detect asset faults and monitor asset conditions using historical data.
- Used BEAM tool's "what-if" application to evaluate in simulation O&M policies in the baseline case (e.g. current O & M practices in place for the Arnold Hall building) for periods of 2, 5, and 15 year durations.
- Used the BEAM Simulation tools to identify the optimal maintenance policy for the Arnold Hall building for periods of 2, 5, and 15 year durations.

Energy consumptions at both individual asset level and the whole building level were compared for these test cases, and are presented in Section 5.3 of this report. We also compared asset reliability and maintenance logs for these test cases.

Test Phases: Tests were executed as shown in Figure 10 below:

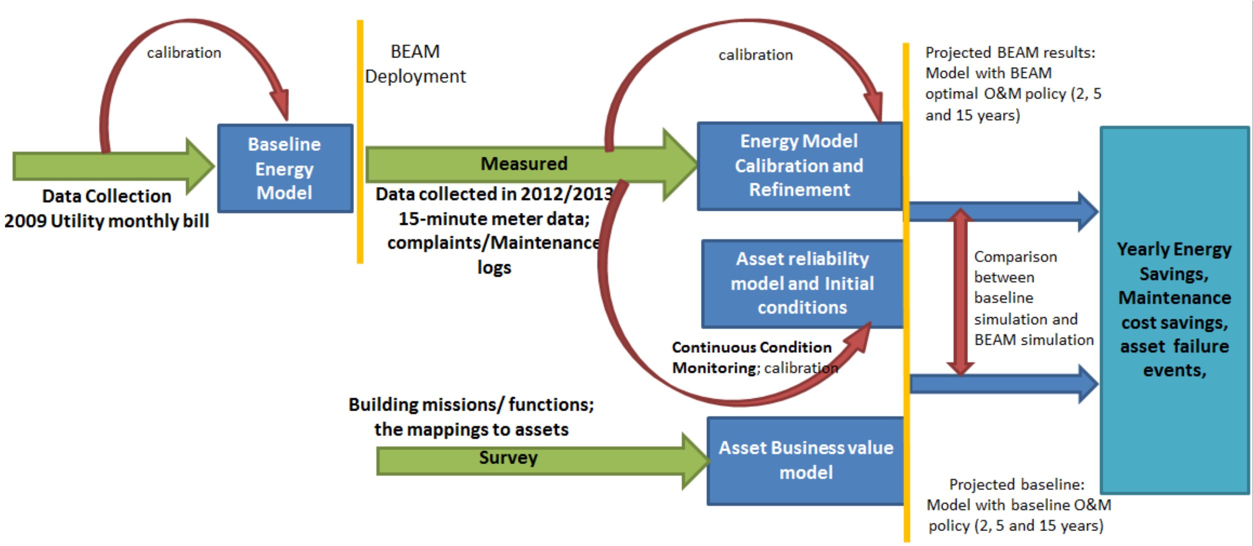


Figure 10: BEAM test phases

- **Energy Models Development:** BEAM is a model-based/data-driven technology. We were fortunate that prior to starting this project we had collected a significant amount of data about this building for another ESTCP project. The data was used principally for the development of a basic EnergyPlus model.

- **Data Collection and Model Calibration:** Fifteen minute interval building meter data were collected, for three months of heating season and three months of cooling season. With these data, the building energy model was further calibrated and refined on an hourly basis. Building asset business values were defined using the BEAM Configuration tools after interviewing the Arnold Hall building operators. Meanwhile, the building asset complaint log and maintenance history were retrieved to establish asset reliability models. All the models were calibrated using measurement data.
- **Test on BEAM-CCM:** The three months of summer building automation system trending data collected were used for BEAM CCM testing. The data were pre-conditioned and loaded into the BEAM Runtime software on a weekly basis. Building asset condition indexes were updated continuously. The results also created the initial condition of the energy assets for BEAM EAM testing**.**
- **Test on BEAM-EAM:** An "As-Is" or baseline asset O&M policy is simulated first using the BEAM Runtime software for periods of two, five, and fifteen years. Results of the simulation are the building and asset energy consumption, business penalty cost, asset reliability and validation/rejection of Asset maintenance policy. After that, the BEAM Runtime software was used to identify the optimal asset maintenance policy for each energy asset for periods of two, five, and fifteen years. The simulation results from the optimal asset O&M policy were recorded.
- **Hypothesis Validation:** By comparing the simulated results from the baseline O&M policy with the results from the optimal policy generated using BEAM, savings on energy usage, maintenance cost and building penalty cost were obtained. The hypothesis was validated.

5.2 BASELINE CHARACTERIZATION

Reference Conditions: The following data was collected and used to establish reference conditions to assess each performance objective: building temperature (*setpoints and sensor data - source: BMS*), building energy consumption data (*simulated: EnergyPlus*), interval meter data (*source: BMS*), utility rate structure and bills (*Utility Company: special contract for USAFA*), asset service contract and/or maintenance log, building event log and occupant complaint logs (*Interview of the Building Operator, the Facility Manager and the Service Contractors (EMCS, SBT)*).

Baseline Collection Period: Three-month building meter data for the cooling season and two-year maintenance log were used for the test (shown in Figure 10).

Existing Baseline Data: Arnold Hall heating season building meter data collected for another project during the 2013 winter season were used to establish the baseline.

Baseline Estimation: Both data driven and model based methodology were used to estimate the baseline of building energy use intensity, asset maintenance cost, and business penalty costs resulting from existing asset management policies.

Data Collection Equipment: There was no need to install additional hardware for data collection. This demonstration leveraged the sensors and meters from Arnold Hall's existing BAS systems.

The following baseline conditions were applied:

- **Energy baseline:** We used 2009 meter data and utility bills to establish the baseline of energy consumption and for the calibration of an EnergyPlus Model on a monthly basis (see Figure 16). The model was further calibrated using the trended meter data collected during 2012/2013 on an hourly basis. The figure below shows the model calibration for the summer time of 2013.

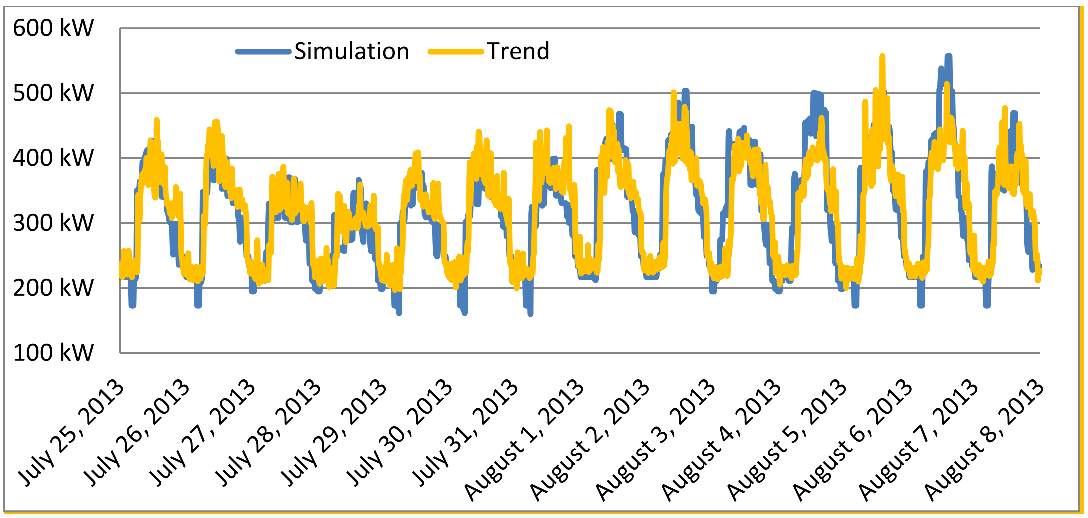


Figure 11: EnergyPlus Model Calibration for the summer of 2013

- **Maintenance policy and cost baseline:** We interviewed the USAFA facility team to understand their service contract model and to establish their baseline maintenance policy. We reviewed Arnold Hall maintenance logs from the site and the maintenance activities for each asset, and then we broke down the overall building asset maintenance cost into individual and service type-dependent itemized maintenance costs shown in Table 8.
- **Business penalty cost:** The business penalty cost baseline was established based on data collected during interviews with Arnold Hall building operator concerning the building's business activities and their corresponding economical values. The business penalty cost due to failure or degradation of building assets was calculated according to the type of the space they serve. For the office spaces, the penalty is occupants' productivity loss, which was translated to monetary impact based on their compensations. For the food service or recreational areas, daily business revenue loss is counted. Although it was not possible to get exact payment or revenue information of Arnold Hall spaces (offices, food court, lounges, ball room and auditorium), we received good estimates from Arnold Hall building operator, who has been working there for more than 30 years.

BEAM simulation baseline for lifecycle cost analysis

- **BVM model:** Input data for the BVM baseline were collected through interviews at Arnold Hall. The BVM model uses average occupancy data, building functions and their priorities depending on seasons, and salary data.

- **BEAM optimization engine:** We collected historical data on asset failures and conditions for Arnold Hall. We interviewed the facility manager to collect maintenance information, including asset maintenance policies and the resulting frequencies and duration of maintenance activities, including their types and costs.

- **Degradation of Performance of Asset**: Based on trend data collected on the site for the period of 2012-2013 we were able to compute the performance degradation of the Chiller (see Appendix B).

- For data of a stochastic nature, such as weather and occupancy, we devised a statistical sampling strategy for the baseline. For weather, we used different seasons, with each season being characterized by an average temperature and humidity profile. In order to ensure statistical rigor, we also established the standard deviation from the average baseline and included a few samples reflecting these variations. Comparison to the baseline was conducted with respect to each of these samples, and results were summarized into point and confidence interval estimates. Similarly, we characterized occupancy profiles according to seasons and functions and established an average baseline and proper standard deviations. All of these calculations have been incorporated into the EnergyPlus model of the building used for simulation of the building's energy consumption.

Reliability and Degradation Models

Most buildings are significantly net energy positive in that they consume far more energy in comparison with their optimal design conditions. This condition worsens as the age of the buildings and the age of their equipment increases (performance degradation). Increasing age also has an impact on the reliability (probability of failure) of assets. Failure probability and energy performance of the assets are related not only to the installation time (actual age) but also to the maintenance policy and cumulative load. In order to make the connection between these issues we define the new measure named "Effective Age" which is different from actual age.

Effective age

Effective Age is different from actual chronological age or clock-time age. Actual age only depends on the installation time of the component and/or its hours of operation, but the Effective Age is a function of cumulative load and the impact of both maintenance and fault experience.

Effective age and Load

Consider a component that is subjected to the loads z_1, z_2 … and z_n for the duration t_1, t_2 … and t_n. Let the acceleration factor corresponding to the load z_i be a_i. Then the effective age and actual age would be:

$$effective\ age = \sum_{i=1}^{n} a_i \times t_i \qquad (1)$$

.

$$actual\ age = \sum_{i=1}^{n} t_i \qquad (2)$$

"a_i" is the acceleration factor with value between 0 and 1. Acceleration factor is defined in [1] as a ratio of load z_i and the higher test load z_{high}. Here we define this parameter as a ratio of load z_i and the maximum possible load z_{max}. For some kind of assets, such as chiller, this ratio is named "Partial Load Ratio" (PLR). So:

$$effective\ age = \sum_{i=1}^{n} \frac{z_i}{z_{max}} \times t_i = \sum_{i=1}^{n} PLR_i \times t_i \qquad (3)$$

Effective age and maintenance improvement

Preventive maintenance is used to lengthen the useful life of an asset. By performing maintenance, we can restore the effective age (calculated based on cumulative load) of the asset. There are two possible methods to model the effective age of the asset before and after maintenance. In the first model the k-th maintenance makes an effective age reduction only with regard to the aging of the asset since (k-1)-th maintenance [2].

In the second model, each of the maintenance actions is assumed to cause an effective decrease in all of the aging that has taken place since time 0 [3].

Here we use the second model to update the effective age based on the maintenance impact. If the maintenance time is T, the effective age just after the maintenance (at time T^+) would be:

$$effective\ age_{at\ time\ T^+} = effective\ age_{at\ time\ T} \times (1 - IF) \qquad (4)$$

"IF" is the improvement factor, with a value between 0 and 1. The value of IF depends on the type of the maintenance. Better maintenance (closer to perfect maintenance) has a bigger IF, which means that after maintenance the state of the asset is closer to the "as good as new" state. Replacement is one of the corrective maintenance actions that has an IF=1.

Effective Age and Fault

Our assumption is that if a fault occurs for the asset but such fault doesn't cause failure (stoppage) in asset operation, then the energy performance of the asset worsens, the probability of failure is increases, and the CI is decreases. We can model these concepts by accelerating the asset aging. So, we can use a similar model to show the relationship between effective age and faults. If K is the time of a fault occurrence, the effective age at time K^+ would be:

$$effective\ age_{at\ time\ K^+} = effective\ age_{at\ time\ K} \times (1 + DF) \quad (5)$$

"DF" is the degradation factor which has a value between 0 and 1. A more serious fault has a larger degradation factor.

Updating Effective Age

By combining the impact of maintenance actions and faults along with the cumulative load on the effective age of the asset, we can use the following formula to update the effective age of an asset:

$$effective\ age\ (t+1) = [effective\ age\ (t) + (PLR_t \times 1)] \times (1 - IF_t) \times (1 + DF_t) \quad (6)$$

PLR_t: average partial load ratio on the asset between time t and t+1
IF_t: Improvement factor of maintenance action which takes place at time t (If there isn't any corrective maintenance action on the asset at time t, then IF_t would be 0.)
DF_t: Degradation factor of a fault that happens at time t (If no fault happens, then DF_t would be 0.)

Condition Index (CI) – Energy Performance and effective age

Performance of an asset can be considered in terms of both its functionality and its energy efficiency. Condition Index (CI) is the measure which represents the performance of the asset. Here CI is defined based on the energy efficiency of the asset. So, it is possible to measure the CI of an asset based on the energy consumption or power consumption. The CI of an asset would be:

$$CI = \frac{Expected\ Power\ Consumption}{Actual\ Power\ Consumption} \quad (7)$$

Sensors can measure actual Power Consumption, and Expected Power Consumption can be obtained from the specifications of the asset.

The energy performance of the asset degrades as a result of asset aging. We can model the age degradation based on the following equation:
:

$$Actual\ Energy\ Efficiency\ measure(effective\ age, PLR) = C^{effective\ age} \times Expected\ Energy\ Efficiency\ measure(PLR)$$

The Energy Efficiency measure depends on the asset type. For example, the Energy Efficiency measure and for a chiller is the coefficient of performance (COP) (see Appendix B).

"C" is the constant number which is associated with a particular asset type. An Expected Energy Efficiency measure is a function of the load or partial load ratio of the asset, and this function is one of the specifications for each asset.

Based on our definition for Condition Index (CI), we can formulate the CI as following:

$$CI = C^{effective\ age} \qquad (8)$$

This model helps us to find the initial value for effective age when we don't know anything about the maintenance history of the asset.

Initiating Effective age

If we measure the CI_0 of the asset at an initial time (the ratio of expected power consumption to actual power consumption, which can be measured by sensors), the initial value for effective age_0 would be:

$$effective\ age_0 = \frac{\ln(CI_0)}{\ln(C)} \qquad (9)$$

Calibrating Improvement Factor

In equation 6 we show the relationship between the "Improvement Factor" of a maintenance action (or the "Degradation Factor" of a fault) and effective age. The question remains as to how we can measure the values of these factors. Usually, maintenance experts have an informed, consensus opinion about what values are appropriate for given circumstances. For more accuracy, the maintenance expert's judgment can be used as an initial value for each of these factors; and such tentative values can then be recalibrated after a maintenance action has been taken, based on the following methodology:

1- Measure CI based on equation 7 before and after maintenance action (CI_{before}, CI_{after}) – see Appendix B
2- Calculate the effective age_{before} and effective age_{after} based on equation 9
3- Partial Load ratio can be measured during the maintenance time
4- Find the value of "Improvement Factor" (IF) based on equation 6

Degradation Function

Measurement of an asset's performance and efficiency is expected to reflect degradation due to asset aging. The Condition Index (CI), which is defined based on the energy efficiency of the asset, is the metric that represents the performance of the asset. The following function is assumed to be the energy performance degradation function of assets:

$$\text{Degradation Function:} = C^{Effective\ Age} \qquad (10)$$

"Effective Age" is measured in years, and "C" is a constant between 0 and 1. In our simulation, we assumed that C=0.85, which means that the energy performance of the asset will be decreased by 15% after 1 year (assuming the asset is without maintenance and is working constantly at maximum load). If real historical Condition Index data for several years exists, it is possible to estimate the constant "C" more accurately.

Reliability and Failure Function

The lifetime of every asset passes through three distinct periods, each of which is characterized by different failure rates [1]:

1. Beginning-Of-Life (BOL) or "Infant Mortality"
2. Middle-Of-Life (MOL) or "Useful life"
3. End-Of-Life (EOL) or "Wear-Out"

The life cycle of each kind of asset can be described by a Weibull distribution function with specific parameters. Most assets experience a rapidly decreasing failure rate in a relatively-short BOL period; a constant, low failure rate during an extensive MOL period; and an increasing failure rate at the EOL period. But, it is also possible for an asset to have an increasing failure rate in both the MOL and EOL periods [5].

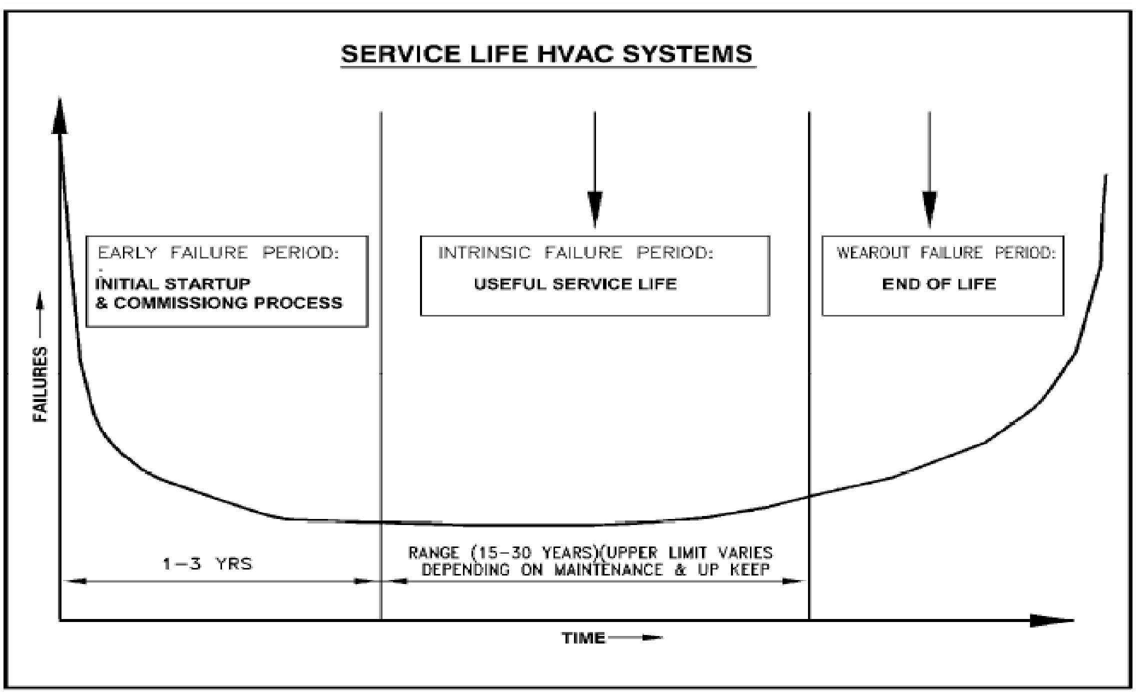


Figure 12: Bathtube curve for failure rate function

In the Arnold Hall simulation model we assumed 2 years as BOL and 20 years as MOL. So, after 22 years of age the asset will have entered its EOL period. (Note that, in order to consider the impact of maintenance actions on failure of the asset by age, we are always referring to effective age.) Also, we considered increasing the expected failure rate (with different parameters) for both MOL and EOL periods [5]. Because data on experience was not available, we assumed the same failure function for all of the assets under consideration. If the historical failure data during several years existed, it would have been possible to estimate the failure parameters with better accuracy. In the current simulation model, we assumed the following numbers for the shape parameter (β) and scale parameter (η) of the assets.

Table 5: Weibul parameters

Period	shape parameter (β)	scale parameter (η)
BOL	0.5	20,000
MOL	1.9	60,000
EOL	3.0	120,000

Note that shape parameter describes the ways the failure rate changes. A shape parameter less than 1 shows a decreasing failure rate, a shape parameter equal to 1 shows a constant failure rate, and a shape parameter greater than 1 shows an increasing failure rate.

Fault and Failure

One of the assumptions of the BEAM Reliability Model is that failures (stoppages) may result from a fault occurance [7]. Nevertheless, different type of faults that do not lead to failures are also considered in the model:

- **Fault Type 1:** The fault doesn't cause a stoppage, but it degrades the performance of the assets.
- **Fault Type 2:** The fault causes a stoppage, but it is repairable. So, the asset may be repaired after the stoppage. (The decision to repair or replace depends on the Condition Index and age of the asset).
- **Fault Type 3:** The fault causes stoppage, and it is not repairable. So, the asset must be replaced after the stoppage.

During simulations, faults were generated randomly based on Weibul probability distributions. The type of fault is also random, but following a certain distribution. In our case, the probabilities for each fault type are:

Type 1=0.2
Type 2=0.7
Type 3=0.1

If a simulated maintenance action occurs during the time period between a simulated fault and a stoppage (failure) there is an oportunity of avoiding the stoppage. The existence of such an opportunity really depends on the Type of the maintenance scheduled (cooresponding to different probability of fault detection), which will be explained later.

Failure and effective age

The probability of failure during each time interval (Δt) is given by:

$$P(Failure\ in\ [t, t + \Delta t] | No\ failure\ before\ t) = \lambda(t) \times \Delta t = \frac{f(t)}{R(t)} \times \Delta t \quad (11)$$

$f(t)$: Lifetime density function, $R(t)$: reliability function, $\lambda(t)$: hazard rate (failure rate) function.

So, failure rate can be defined as the ratio of the lifetime density function to the reliability function. If we don't consider the maintenance impact on the age of the asset, the expected number of failures (E [N]) in the interval [0, T) would be:

$$E[N] = \int_0^T \lambda(t)dt \quad (12)$$

If we consider the impact of maintenance (or fault) on the age of the asset, we have to replace the age by effective age in the failure rate function. So, the new failure rate function will be [6]:

$$\lambda_{new}(t) = \lambda(effective\ age) \quad (13)$$

Maintenance Model

BEAM considers different maintenance options. Table 6 identifies the eight options used for purposes of the demonstration:

Table 6: Maintenance Policy Options

ID	Maintenance Policy
1.	Reactive Maintenance upon Failure
2.	Reactive Maintenance upon Alarm
3.	Preventive Maintenance Type 1_Age-based
4.	Preventive Maintenance Type 2_Age-based
5.	Preventive Maintenance Type 3_Age-based
6.	Preventive Maintenance Type 1_Clock-based
7.	Preventive Maintenance Type 2_Clock-based
8.	Preventive Maintenance Type 3_Clock-based

Reactive maintenance occurs in response to an event. This event can be a failure (a breakdown) or a fault which is detected by sensors (an Alarm).

Preventive maintenance (PM) is a schedule of planned maintenance aimed to prevent future breakdowns and failures of a system that is functioning properly. Age-based maintenance actions are scheduled in response to the cumulative load on the assets, while clock-based maintenance actions are scheduled with reference to the calendar. Preventive Maintenance Type 1 through 3 provides the increasing scrutiny in inspection and tuning. In general, PM Type 3 includes all the work orders performed in PM Type 1 and 2 as well as additional inspection work orders. PM Type 2 includes all routine maintenance actions performed in PM type 1.

Each of the maintenance type listed above includes one or more alternative actions, which usually starts with an inspection and is followed by a required repair or replacement action. **Table 7** summarizes the general possible actions. In our simulation we assumed that PM Type 1 employs Inspection Type 1 with minor maintenance. PM Type 2 employs Inspection Type 2 and repair actions (including minor maintenance). PM Type 3 employs the most comprehensive inspection - Inspection Type 3 and replacement of parts and components.

Table 7: List of actions

ID	Maintenance Option
1	Inspection Type 1
2	Inspection Type 2
3	Inspection Type 3
4	Minor Maintenance
5	Repair
6	Replace

Preventive Maintenance for Chillers:

The following summarizes the details of PM types for chillers:
Type 1 includes routine “Inspection/Check” actions and requires least effort however results in lowest probability for fault detection and improvement factor. For instance, in the case of a Chiller Centrifugal, following work orders fall into PM type 1 category:

- Check oil level, add oil as necessary
- Check oil temperature
- Check unit for proper operation
- Check refrigerant charge/level, add as necessary
- Run system control test
- Check motor run hours, grease if it exceeds the threshold

Type 2 provides average level probability for fault detection due to more detailed inspection. In this type of PM, inspection is followed by routine maintenance touch-ups; therefore, the improvement factor is higher than that of PM type 1. For instance, in the case of a Chiller Centrifugal a PM Type 2 includes:

- Check sensor and mechanical safety limits; replace if necessary
- Perform Oil analysis and replace compressor oil, filters and purge unit ref filters if the analysis deems necessary
- Inspect utility vessel vent piping and safety relief valve; replace if necessary
- Inspect/clean the economizer (vane) gas line, damper valve and actuator arm

Type 3 provides the most detailed inspection (highest probability for fault detection) with the highest improvement factor and cost. This type of PM includes the list of all recommended maintenance types included in asset’s manufacturer manual (periodic maintenance). For instance in our case of Chiller, a Type 3 Preventive maintenance checklist includes:

- Compressor motor continuity check
- Check and tighten motor terminals
- Check nameplate rating

- Check condition of starter contacts
- Control circuits
- Low refrigerant temperature sensor checkout
- Leaving evaporator water temperature sensor checkout
- Leak test chiller
- Refrigerant and oil analysis for acid content
- Purge Unit
- Perform the purge system control check
- Perform purge rank check out and water removals

Preventive Maintenance Cost Model

Each action has a specific cost, improvement factor (restoration factor), and (for inspection actions only) probability for fault detection. The following Table 8 shows our assumptions about the cost, improvement factor, and fault detection probability. We assumed that these numbers are applicable for all of the considered assets. The improvement factor and cost of the Inspection Type 1 for a chiller is calculated based on the existing maintenance data for the building and the Condition Index of the asset before and after the maintenance:

Table 8: Cost of Maintenance

Action	Cost ($)	Improvement Factor (IF)	Probability of Fault detection
Inspection Type 1	100	0.054	0.15
Inspection Type 2	230	0.15	0.35
Inspection Type 3	400	0.45	0.7
Minor Maintenance	300	0.2	-
Repair	1,500	0.6	-
Replace	4,500	1	-

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

For Arnold Hall's applications at USAFA, the BEAM Runtime software was used in the "Stand Alone" mode, given concern for security considerations and recognition that the demonstration had to be conducted during a short period of time. The BEAM tool was set up both onsite and offsite.

Offsite, we received weekly trended data from the Siemens Building Automation System - Apogee installed at Arnold Hall and uploaded it to the BEAM tool, which detects asset faults, assesses equipment performance, updates the asset Condition Index, and generates alarms. The updated asset condition was then used by the BEAM Engine for testing, based on the design of experiment described above to validate each hypothesis.`

Onsite, we installed the BEAM tool on a facility manager's PC located in the control room. We trained the facility manager to use the tool for asset condition monitoring. In addition, we worked with the facility team to use BEAM for analysis of existing maintenance policies and generation of optimal maintenance strategies.

System Design: The BEAM technology leveraged existing building automation and information management systems at the demonstration site. The constituent elements of the BEAM system are described in Section 2 (Figure 1: BEAM framework). The design and layout of system components of the Arnold Hall test bed are captured by the customization processes of the asset information model for BEAM CCM and the building energy model creation process for the BEAM engine (see Appendix D for a brief description of the Arnold Hall layout and model components). The tests for the demonstration were focused on BEAM- Enterprise Asset Management (EAM) to identify the best maintenance policies for the HVAC systems of the test site.

System Depiction: Schematics and diagrams describing the BEAM workflow and runtime software architecture are provided in Section 2. Screen shots of the BEAM-HMI are also provided at Section 2 (Figure 4, Figure 5, and Figure 6). The system tested is a software tool that requires a Windows Operating System to run on a PC.

System Integration: Figure 13 shows BEAM tool's onsite and offsite setup. The key components of the demonstration are the BEAM Configuration Tool and the Runtime Tool. The BEAM configuration process for Arnold Hall was conducted mainly in Princeton. The Runtime was conducted offsite, although onsite setup is possible, as shown in Figure 13. However, for this demonstration case, instead of direct integration of the BEAM tool with the BAS system, we used a man-in-the-middle integration. The facility team from USAFA retrieved trend data from the Apogee BAS system weekly and uploaded the data to GForge for the offsite BEAM tool in the Princeton office to conduct the tests. Since the BEAM software was loosely coupled with the existing Apogee BAS system, the simulated failures generated by the software tools did not impact the existing systems.

Note: GForge is a free software fork of the web-based project-management and collaboration software. GForge provides project hosting, version control (CVS and Subversion), bug-tracking, and messaging.

System Controls: BEAM is an asset management system. For the Arnold Hall demonstration, all the controls took place within the simulation. No commands were generated from BEAM software to directly control the building HVAC equipment.

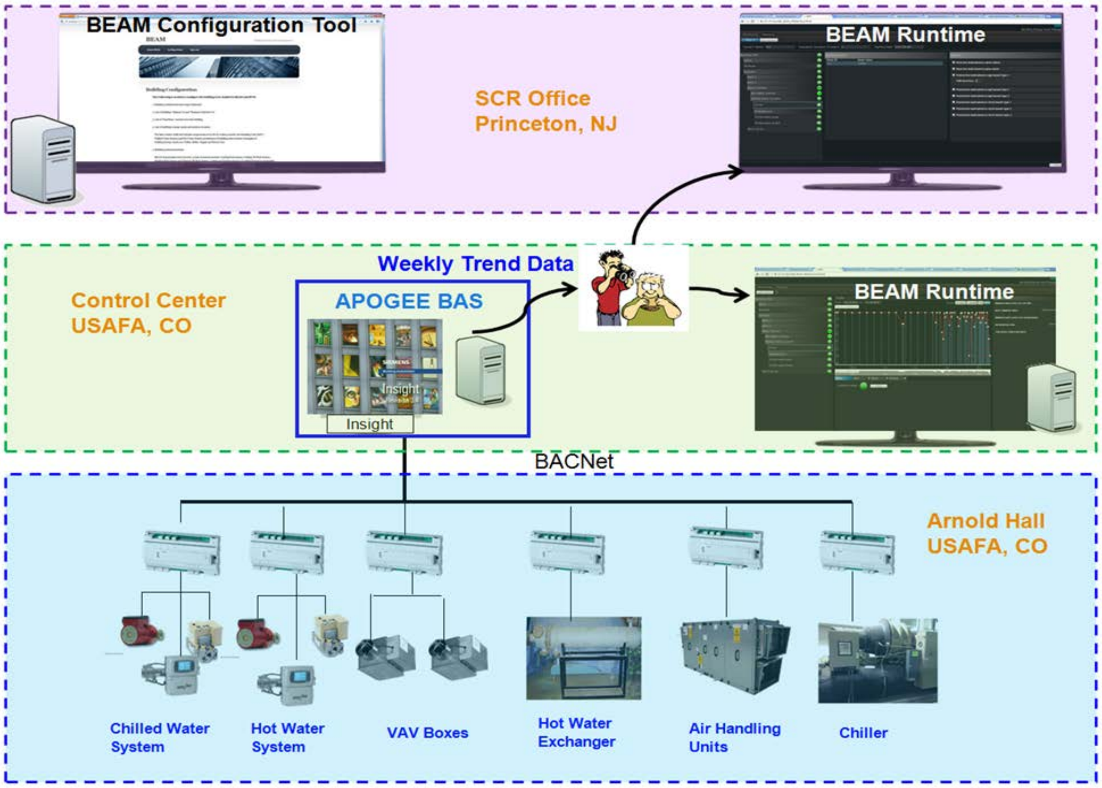


Figure 13: BEAM Demonstration Setup

Note: It is important to mention that all the building automation systems components (Chilled Water system, Hot water System, VAV boxes Hot water Exchanger Air Handling Units, Chillers) are considered in the EnergyPlus model of the building. The simulation calculates the energy consumption of all the subsystems listed on Table 3..

5.4 OPERATIONAL TESTING

We conducted an integrated assessment of BEAM technology including the following closely coupled steps: Validation of BEAM models, Execution of design of experiment, Analysis of variance, and Testing of hypothesis using output data from the design described above.

T1.1: Asset Information Model

We received a lot of information about Arnold Hall from another ESTCP project, including the zoning maps and the associated HVAC equipment. Under the current project, in addition to validating that information, we explored further and collected more details on the assets, e.g., the manufacturing data and their maintenance history. All the information was captured by an interoperable meta-data model extended from Building Information Model (BIM). In addition to the attributes defined by BIM, we also added the time series data in our asset information model to captures the asset performance and maintenance history. Figure 14 shows a tree view of such a meta- data model.

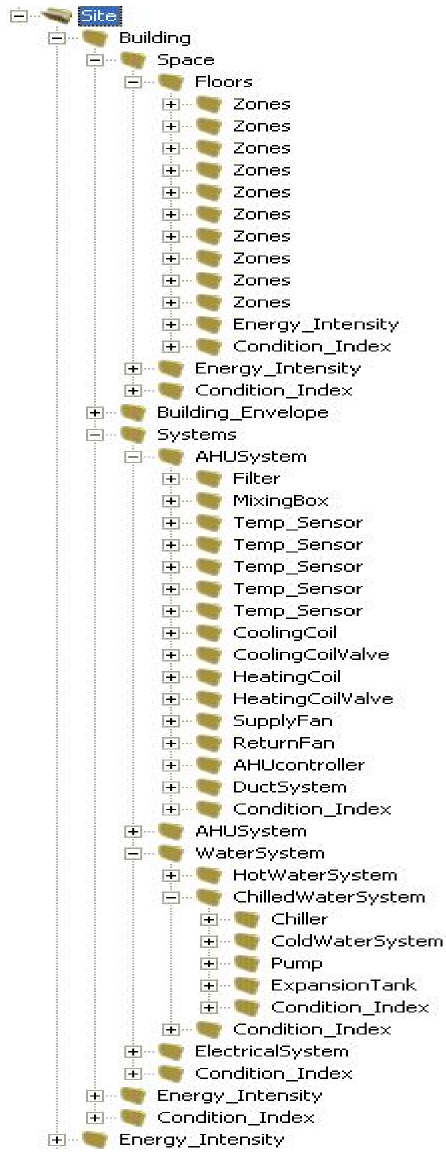
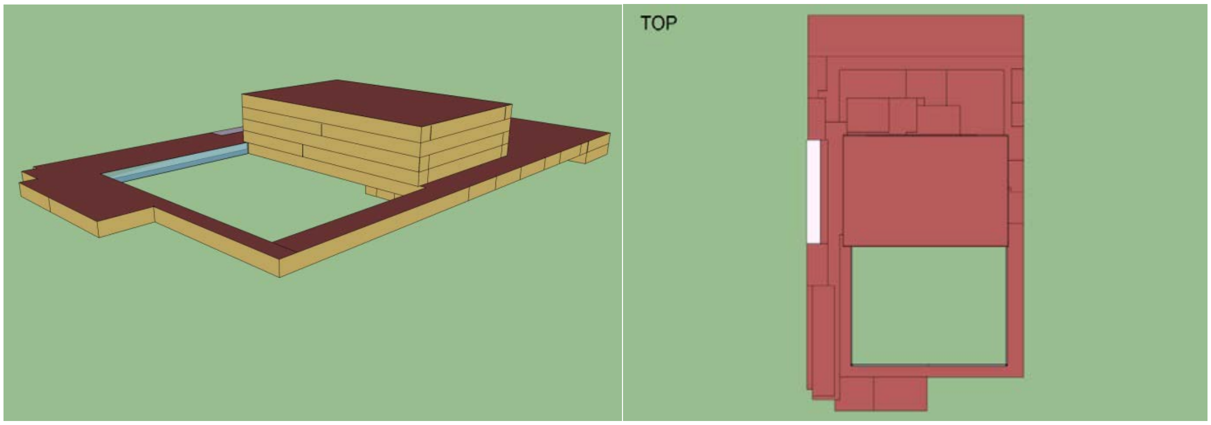


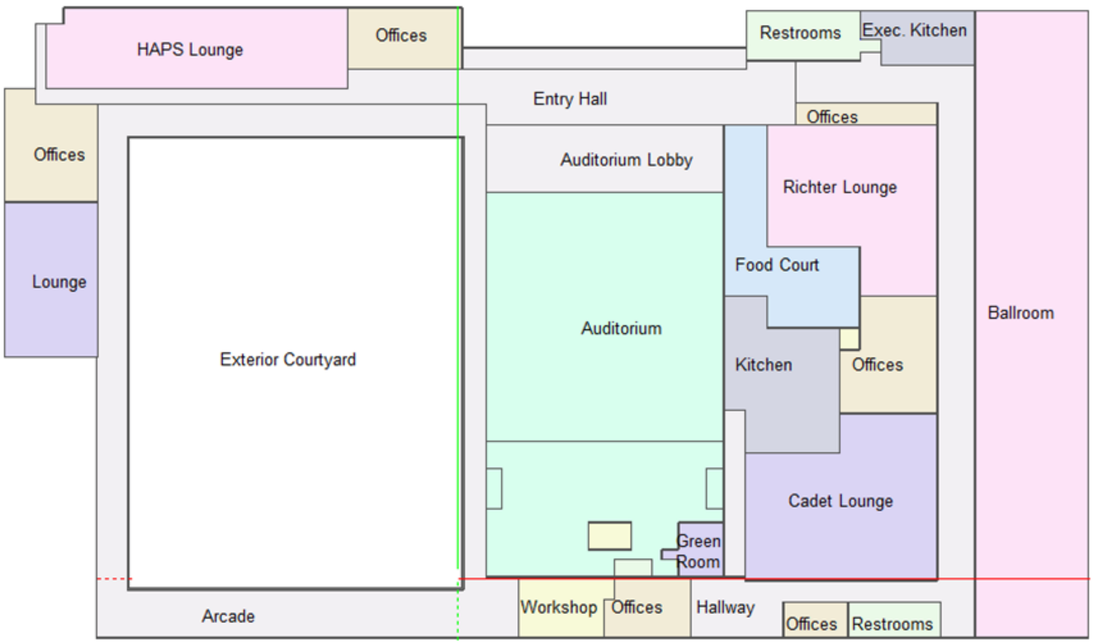
Figure 14: BEAM Asset Information Model

T1.2 & T2.2: Building energy model validation

During the course of the previous ESTCP project, we developed and calibrated an EnergyPlus Model of the Arnold Hall building. In this section, we summarize a few key aspects of that model. As shown in the pictures below, the building was modeled with four thermal zone levels. The ground level hosts most of the usable spaces (recreation, food services, administration, education and training) as shown on the floor plan of Figure 15**.**



(a): Building 3D View



(b): Ground level floor plan for Arnold Hall
Figure 15**:** Arnold Hall Building Model

The Model of Arnold Hall used for this experiment was calibrated on a monthly basis for year 2009, as shown in Table 9 and the picture below. Table 10 summarizes the validation criteria as applied.

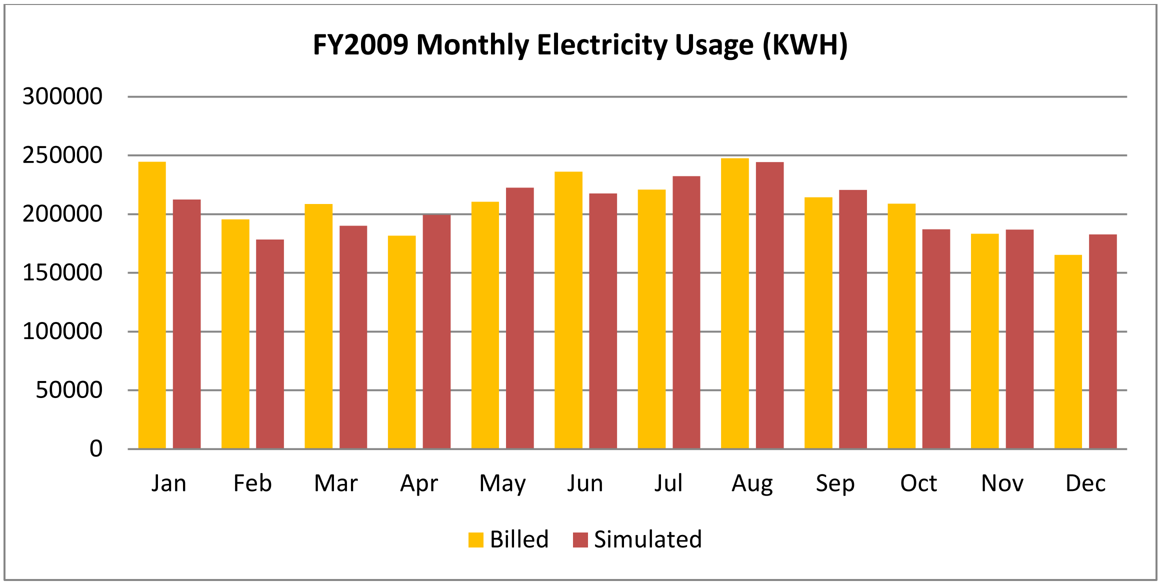


Figure 16: Monthly electricity usage calibration comparison for 2009

Table 9: Accuracy of the Electricity portion of the model

	Measured/Estimated	Simulated	Error	Relative Error
Annual Electric Energy	2,548,618 kWh	2,473,994 kWh	74,624 kWh	2.9%

For details on the EnergyPlus simulation model of Arnold Hall building see Appendix D.

Table 10: Complete Validation Results for the Simulation Model

#	**Assumption**	**Check**
1	Building construction and structure are modeled correctly	Yes
2	HVAC system is modeled correctly (configuration/layout)	Yes
3	Schedules of occupancy, lighting and plug-loads are stable and modeled correctly	Yes (No plug load models)
4	Excess energy consumption profile matches measurement	Error less than 3%
5	Behavior of major HVAC equipment matches measurement	we used simulation
6	Equipment failure and degradation are modeled correctly	Yes see appendix B.

T1.3: CCM model validation

The models for asset continuous condition monitoring include two parts: the equipment fault models which were represented by a bunch of rules, and the asset performance models which were defined as the ratio between the expected power consumption and the actual power consumption. We applied the air handling unit performance assessment rules (APAR) rules and the VAV Box Performance Assessment Control Charts (VPACC) developed by National Institute of Standards and Technology (NIST) (Schein 2006) to detect HVAC faults. Each rule is expressed as a logical statement that, if true, indicates the presence of a fault. The threshold parameter of each rule was identified for Arnold Hall application and validated based on the building automation system trending data collected in the summer of 2013. The energy performance models of chillers and fans were developed based on the asset coefficient of performance (COP) curve measurement and calibrated with building automation system trending data (please refer to Appendix B for details).

T1.4: Building Value Model validation

We applied BVM III model to Arnold Hall based on the interview results with the building operator. The details regarding this model are presented in Appendix D.

T2.1: Use of BEAM to conduct asset fault detection and performance evaluation

Three months of Arnold Hall BAS data were collected and fed into the BEAM Runtime Tool for asset fault detection and energy performance evaluation on a weekly basis. Quite a few faults were detected. For example, the heating coil of AHU 1A (a dual deck air handling unit) was detected to be switched on from July 1 to July 7 in Cooling mode. Similar behaviors were observed on AHU 1D and AHU 5 in August 2013. It was also detected that the mixed air temperature (MAT) of AHU 7 didn't follow the set point of MAT, which indicated a damper-stuck fault. All the faults detected were reported back to the facility and the faulty HVAC components were fixed accordingly. In addition to the fault detection, the BEAM Runtime tool also provided energy performance evaluation. The details can be found in Appendix B.

T2.3 & 2.4: Run "what-if" analysis on baseline O&M policies and BEAM optimization on Arnold Hall asset management

The BEAM what-if function was used to evaluate O&M policies in the baseline case (i.e. current O&M practices in place for the Arnold Hall building) for periods of 2, 5, and 15 year durations.

Table 11 shows the current maintenance policies of the building which were mapped to the Maintenance Policy Options in the BEAM tool.

Table 11: Baseline Maintenance Policy

Asset	Baseline Maintenance Policy
Chiller	-Monthly Preventive Maintenance Type 1 in Cooling Season -Annually Preventive Maintenance Type 2 at the beginning of cooling peak season
Supply Fans (1-13)	-Semi-Annual Preventive Maintenance Type 2

The BEAM Optimization function was used to identify the optimal maintenance policies for the Arnold Hall assets for the same periods of 2, 5 and 15 years respectively. One set of the coefficients used by the optimization function is the average partial load ratio (PLR) in each season for each asset. To determine this set of coefficients, the EnergyPlus model of the Arnold Hall building was executed offline. The following **Table 12** shows this set of coefficients.

Table 12: “Seasonal PLR” for each asset

Asset	Cooling Season PLR	Heating Season PLR
Chiller	0.476	0.104
SF1 (Supply Fan 1)	0.455	0.444
SF2	0.979	0.965
SF3	0.979	0.967
SF4	0.979	0.964
SF5	0.979	0.974
SF6	0.568	0.585
SF7	0.668	0.604
SF8	0.979	0.974
SF9	0.401	0.405
SF10	0.977	0.953
SF11	0.677	0.489
SF12	0.899	0.885
SF13	0.973	0.948

As the results of the off-line runs show, the load on the chiller in the cooling season is much more than the load on it in the heating season; but, for most of the supply fans, the loads in the cooling season and the heating season are very close to each other.

The recommended optimal maintenance policy for each asset in each season of each year from T2.4 is described in Appendix C. Here we summarize the simulated results and comparisons between the baseline policies and optimal policies.

Two Years Simulation Results

The what-if application was run with the current maintenance policies over 4 replications. Since we repeated the simulation four times, the average energy consumption for two years, standard deviation (SD) of energy consumption, and the Coefficient of Variation, which is defined as the ratio of SD to the average, are shown in this Table 13. The coefficients of variation (CV) are very small; therefore, we can claim that the results of energy consumption are repeatable. Table 14 shows the two-year simulated energy consumption results of all the assets under optimal maintenance policies. Table 15 and Figure 17 compares all the costs related to the baseline policies and the optimal policies, including energy cost, maintenance cost and business penalty cost. Figure 18 and 19 compare the performance degradations of the chiller and an air handling unit over two years. The results showed that the BEAM optimal maintenance polices are superior to the baseline policies from all of the three aspects.

Table 13: Baseline Energy Consumption for two years simulation

Asset	Energy (kWh) (Mean)	Energy Standard Deviation (SD)	Energy Coefficient of Variation-(CV)
Chiller	215,422	12,455	0.058
SF1	57,651	1,628	0.028
SF2	24,153	738	0.031
SF3	4,426	127	0.029
SF4	24,441	1,507	0.062
SF5	1,332	93	0.070
SF6	6,940	374	0.054
SF7	4,255	284	0.067
SF8	27,506	1,847	0.067
SF9	15,353	1,251	0.082
SF10	7,040	636	0.090
SF11	1,788	47	0.026
SF12	3,542	356	0.100
SF13	2,834	152	0.053
Total	396,684	12,192	0.031

Table 14: Optimal Energy Consumption and Savings for two years Simulation

Asset	Energy (kWh)	Saving (%)
Chiller	196,839	8.63
SF1	52,720	8.55
SF2	23,028	4.66
SF3	4,347	1.78
SF4	23,036	5.75
SF5	1,242	6.74
SF6	5,902	14.96
SF7	3,862	9.25
SF8	26,044	5.31
SF9	13,628	11.23
SF10	6,393	9.19
SF11	1,690	5.45
SF12	3,380	4.58
SF13	2,713	4.28
Total	364,825	8.03

Table 15: Comparison Baseline V’s Optimal Solution for Two-Year Simulation

	Base Line	BEAM	BEAM/Baseline (%)
Energy (kWh)	396,684	364,824	92%

Penalty ($)	7,119,311	248,042	3%
Maintenance Cost ($)	87,785	78,200	89%

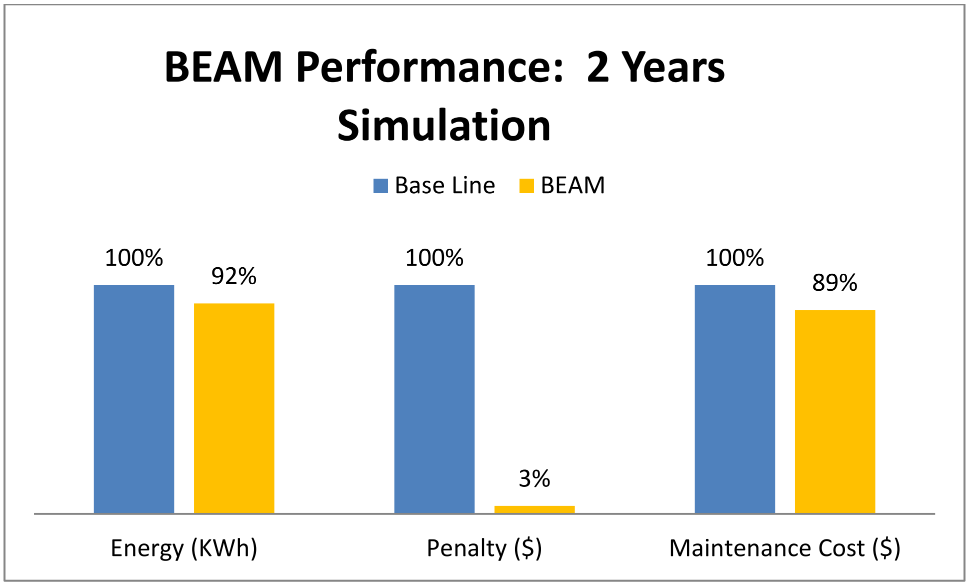


Figure 17**:** Comparison of the Baseline vs. the Optimal Solution for Two-Year Simulation

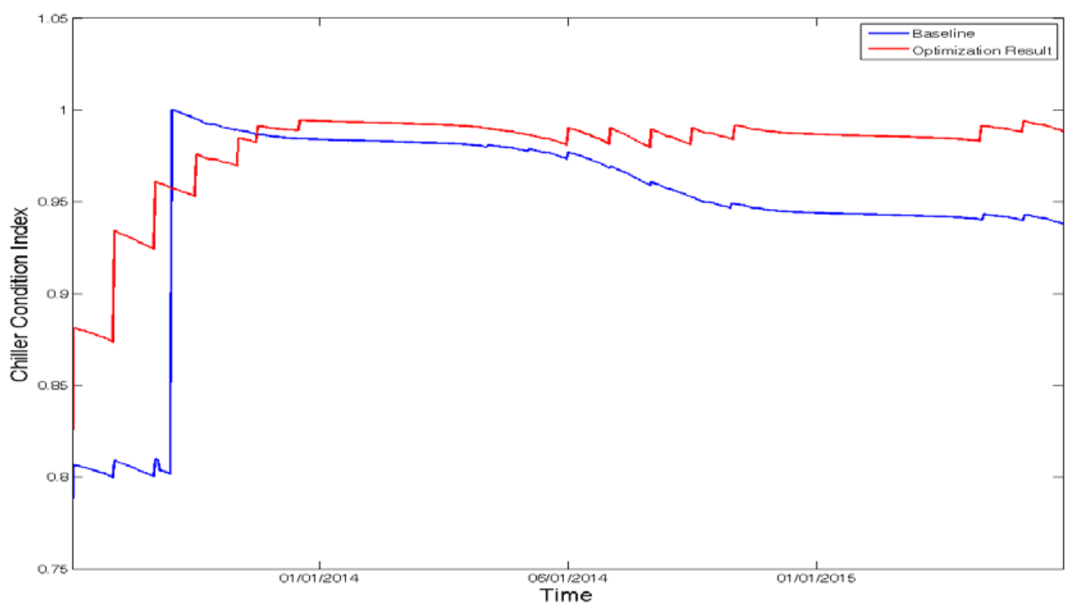


Figure 18: Chiller Condition Index Comparison for Two-Year Simulation

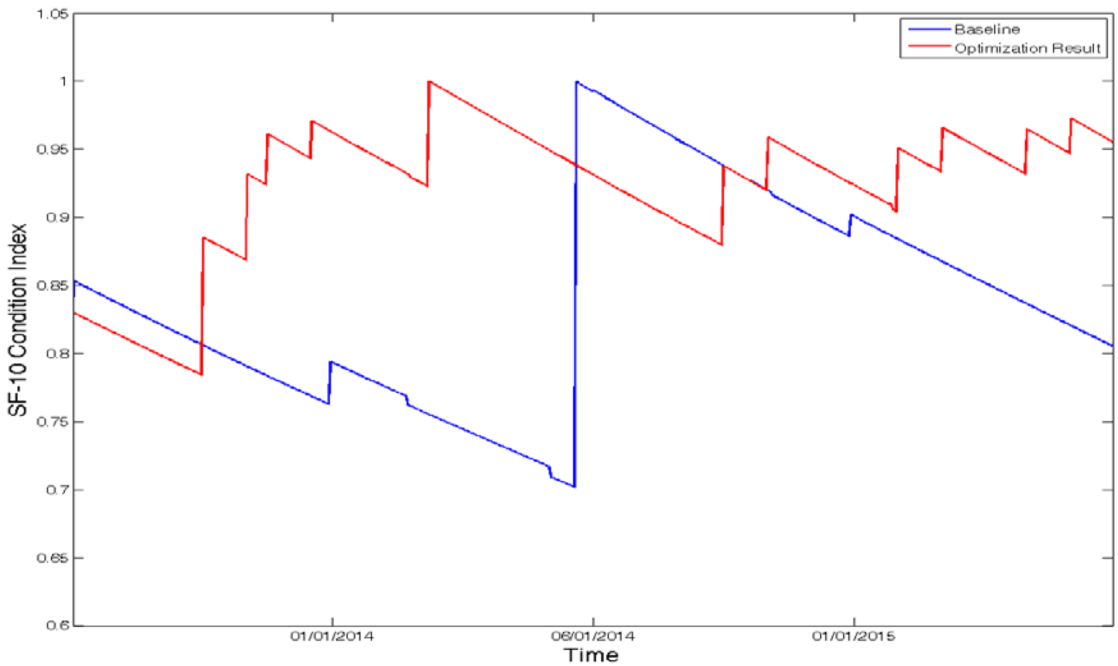


Figure 19: Condition Index of SF-10 (Two-Year Simulation)

Remark:
Note that the initial condition of the simulation is the same for both the baseline and optimization. The offset observed at the origin of the time axis is due to time scaling because as soon as we apply BEAM recommended maintenance policies, the CI changes in the first hours or days, therefore the sudden jump in CI.

Five Years Simulation Results

We repeated the same tests for five year simulation for both the baseline maintenance policies and the BEAM generated policies. Table 16 and Table 17 show the simulated energy consumption of each asset. Adoption of the policies recommended by the BEAM optimization function was projected to reduce the total energy consumption of the assets under consideration by 8%.

Table 16**:** Energy Consumption Results for Baseline Case for Five Years

Asset	Energy (kWh) (Mean)	Energy – kWh Standard Deviation (SD)	Energy coefficient of variation (CV)
Chiller	531,130	20,118	0.04
SF1	143,408	5,301	0.04
SF2	61,715	1,847	0.03
SF3	11,675	343	0.03
SF4	60,547	2,205	0.04
SF5	3,362	78	0.02
SF6	16,120	497	0.03

SF7	10,723	257	0.02
SF8	67,696	2,002	0.03
SF9	37,481	800	0.02
SF10	17,600	226	0.01
SF11	4,597	154	0.03
SF12	8,928	259	0.03
SF13	6,930	49	0.01
Total	981,913	18,651	0.02

Table 17: Simulated Energy Savings per Asset using Optimal Policies for 5 Years

Asset	Energy (kWh)	Saving (%)
Chiller	488,016	8.12
SF1	131,733	8.14
SF2	56,327	8.73
SF3	10,516	9.93
SF4	56,323	6.98
SF5	3,156	6.13
SF6	14,735	8.59
SF7	9,755	9.03
SF8	63,678	5.94
SF9	33,994	9.30
SF10	15,963	9.30
SF11	4,222	8.16
SF12	8,250	7.60
SF13	6,635	4.26
Total	903,303	8.01

The optimization results listed in Table 18 indicate that adoption of the recommended policies would reduce not only the total energy consumption of the assets under consideration but also the number of failures (total penalty cost) experienced for those assets. Figure 20 show the cost elements of the baseline scenario in comparison with the optimization scenario.

Table 18: Cost Elements (Five-Year Simulation)

	Base Line	BEAM	BEAM/Baseline (%)
Energy (kWh)	981,913	903,302	92%
Penalty ($)	15,950,721	133,900	1%
Maintenance Cost ($)	202,612	173,300	86%

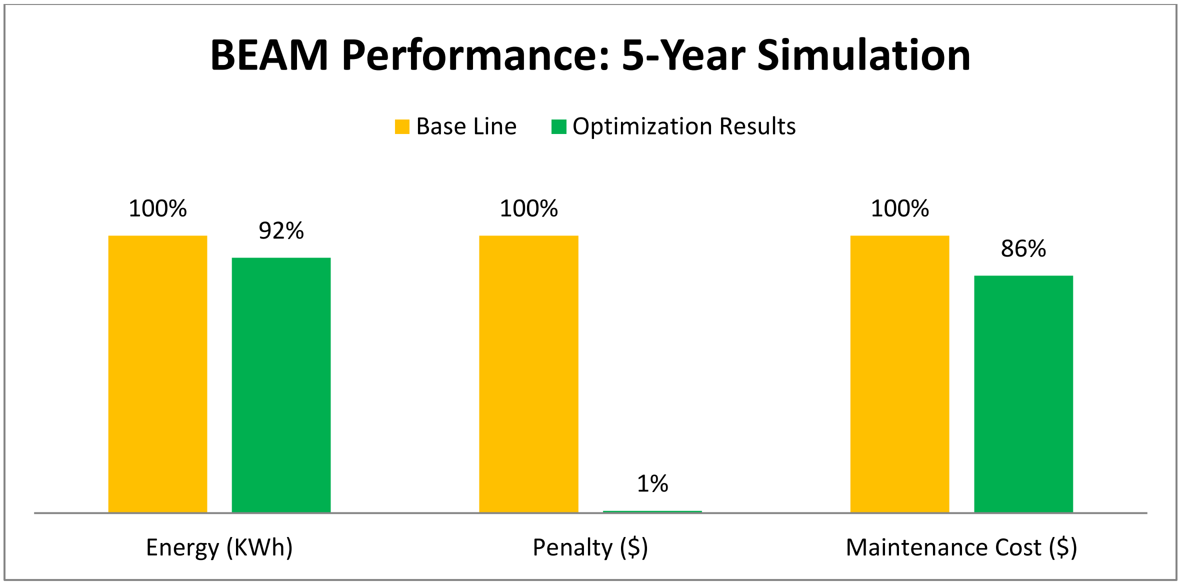


Figure 20: Cost Elements (5-year simulation)

Figure 21 and Figure 22 show the condition indexes of the chiller and Supply Fan 10 (SF-10) during the five years.

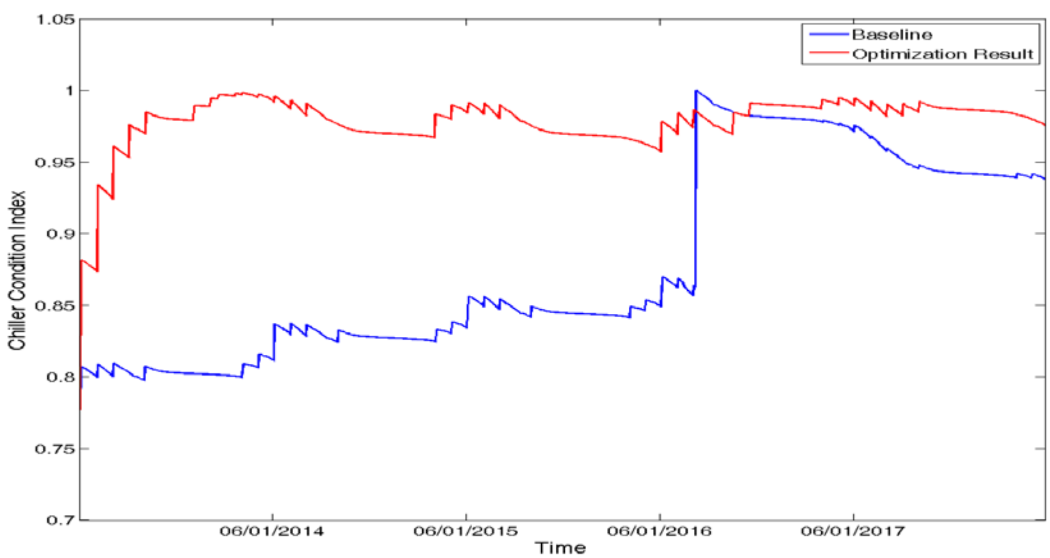


Figure 21: Chiller Condition Index (five-year simulation)

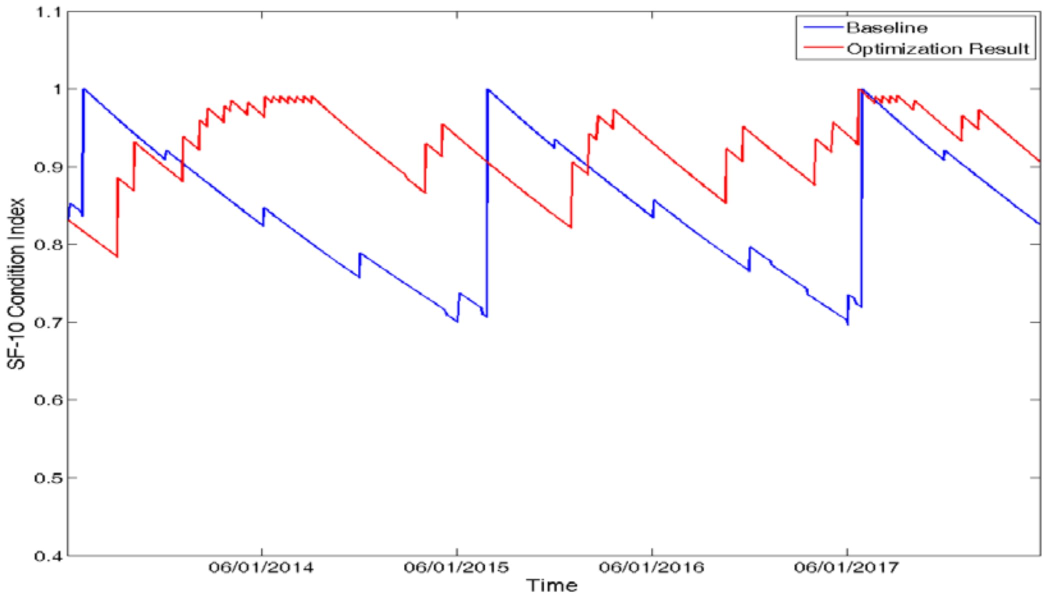


Figure 22: Supply Fan 10 (SF-10) Condition Index (five-year simulation)

As shown in Figure 21, in the baseline case a huge jump in Condition Index (CI) of the chiller is projected on July-2016. This jump is the result of a chiller failure following by a replacement or an overhaul. The same improvements in the SF-10 Condition Index are shown in Figure 22, depicting that in the baseline scenario, SF-10 fails 3 times during the 5 year simulation. Table 19 and 20 list the preventive maintenance activities and failure events of the chiller projected for each scenario (baseline and optimization). As explained in Section 5.2, a preventive maintenance activity always comprises an inspection followed by repair/replacement actions. PM Type 3 employs the most comprehensive inspection and repair actions. That is why the asset condition is higher in BEAM O&M case because it employs PM Type 3.

Table 19: Actions List for Five-Year Simulation

Baseline – Actions list for chiller	Optimization - Actions list for chiller
PM Type2 @ 2013-6-1	PM Type3 @ 2013-6-1
PM Type1 @ 2013-7-1	PM Type3 @ 2013-7-1
PM Type1 @ 2013-8-1	PM Type3 @ 2013-8-1
PM Type1 @ 2013-10-2	PM Type3 @ 2013-9-1
PM Type1 @ 2014-4-1	PM Type3 @ 2013-10-1
PM Type1 @ 2014-5-1	PM Type3 @ 2014-1-1
PM Type2 @ 2014-6-1	PM Type3 @ 2014-2-1
PM Type1 @ 2014-7-1	PM Type3 @ 2014-4-1
PM Type1 @ 2014-8-1	PM Type3 @ 2014-5-1
PM Type1 @ 2014-10-2	PM Type3 @ 2014-6-1
PM Type1 @ 2015-4-5	PM Type3 @ 2014-7-1
PM Type1 @ 2015-5-5	PM Type3 @ 2014-8-1
PM Type2 @ 2015-6-1	PM Type3 @ 2015-4-1
PM Type1 @ 2015-7-1	PM Type3 @ 2015-5-1
PM Type1 @ 2015-8-1	PM Type3 @ 2015-6-1
PM Type1 @ 2015-10-2	PM Type3 @ 2015-7-1
PM Type1 @ 2016-4-5	PM Type3 @ 2015-8-1
PM Type1 @ 2016-5-5	PM Type3 @ 2016-6-1
PM Type2 @ 2016-6-1	PM Type3 @ 2016-7-1
PM Type1 @ 2016-7-1	PM Type3 @ 2016-8-1
PM Type1 @ 2014-8-1	PM Type3 @ 2016-9-1
PM Type1 @ 2016-10-2	PM Type3 @ 2016-10-1
PM Type1 @ 2017-4-5	PM Type3 @ 2017-4-1
PM Type1 @ 2017-5-5	PM Type3 @ 2017-5-1
PM Type2 @ 2017-6-1	PM Type3 @ 2017-6-1
PM Type1 @ 2017-7-1	PM Type3 @ 2017-7-1
Repair @ 2016-7-13	PM Type3 @ 2017-8-1
PM Type1 @ 2017-8-1	PM Type3 @ 2017-9-1
PM Type1 @ 2017-10-2	PM Type3 @ 2017-10-1
PM Type1 @ 2018-4-5	
PM Type1 @ 2018-5-5	

Table 20: Events List for Five-Year Simulation

Baseline – Events list for chiller	Optimization - Events list for chiller
Fault Type 2 @ 2016-7-8 Failure @ 2016-7-13 (stoppage)	None

15-Year Simulation Results

Similar to two- and five-year simulations, we conducted simulations for a period of 15 years. It is assumed that for most energy assets in the building fifteen years is a lifetime. The simulation results below show that, not only we save energy and maintenance cost for a longer period of time but also, we avoid any catastrophic failure of equipment. By avoiding failure of equipment, we save penalty cost. Note that by using preventive maintenance as suggested by BEAM the facility manager can exploit the pre-planned downtime of the building to do some major maintenance without affection users comfort or building availability.

Table 21: Energy Consumption Results for Baseline Case for 15-Year Simulation

Asset	Energy (kWh) (Mean)	Energy (SD)	Energy (CV)
Chiller	1,550,718	18,517	0.01
SF1	430,542	8,170	0.02
SF2	182,239	2,334	0.01
SF3	34,091	719	0.02
SF4	175,195	3,167	0.02
SF5	9,988	66	0.01
SF6	48,378	883	0.02
SF7	31,691	603	0.02
SF8	206,445	4,726	0.02
SF9	111,622	1,794	0.02
SF10	51,846	1,266	0.02
SF11	13,683	289	0.02
SF12	26,757	618	0.02
SF13	20,733	506	0.02
Total	2,893,928	24,152	0.01

Table 22: Optimization results with optimization for 15 years simulation

Asset	Energy (kWh)	Saving (%)
Chiller	1,456,594	6.07
SF1	393,747	8.55
SF2	169,273	7.11
SF3	31,560	7.42
SF4	169,767	3.10
SF5	9,482	5.07
SF6	44,063	8.92
SF7	29,085	8.22
SF8	191,946	7.02
SF9	101,672	8.91
SF10	47,973	7.47
SF11	12,617	7.79
SF12	24,907	6.91

SF13	20,084	3.13
Total	2,702,769	6.61

Table 23**:** Baseline vs. Optimization for 15-Year Simulation

	Base Line	**BEAM**	**BEAM/Baseline (%)**
Energy (kWh)	2,917,574	2,702,769	93%
Penalty ($)	36,393,171	593,842	2%
Maintenance Cost ($)	676,300	503,800	74%

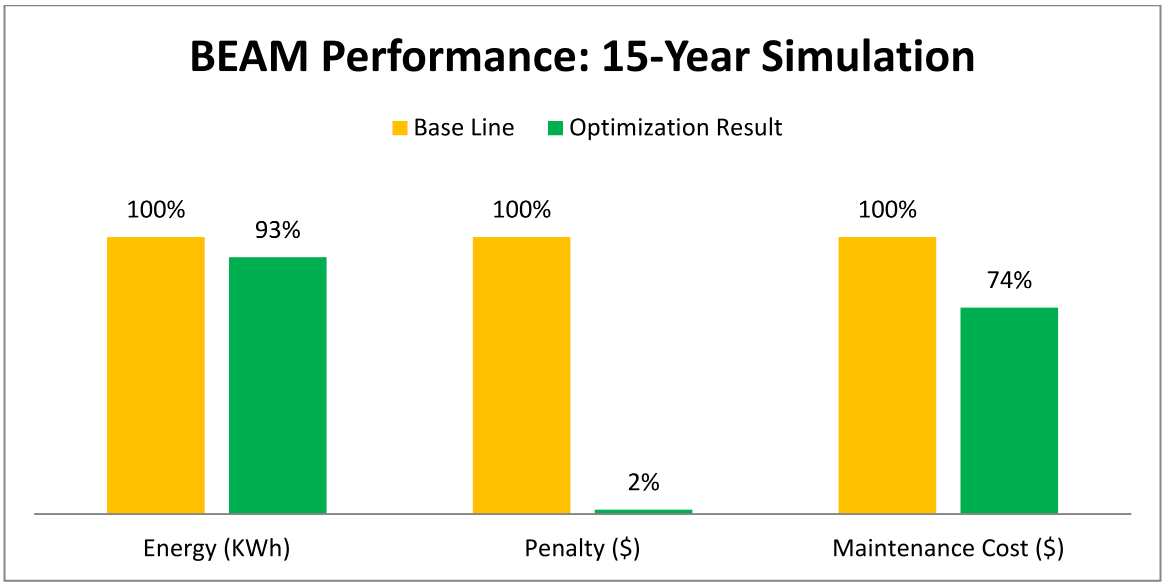


Figure 23: Comparison Baseline vs. Optimization for 15-Year Simulation

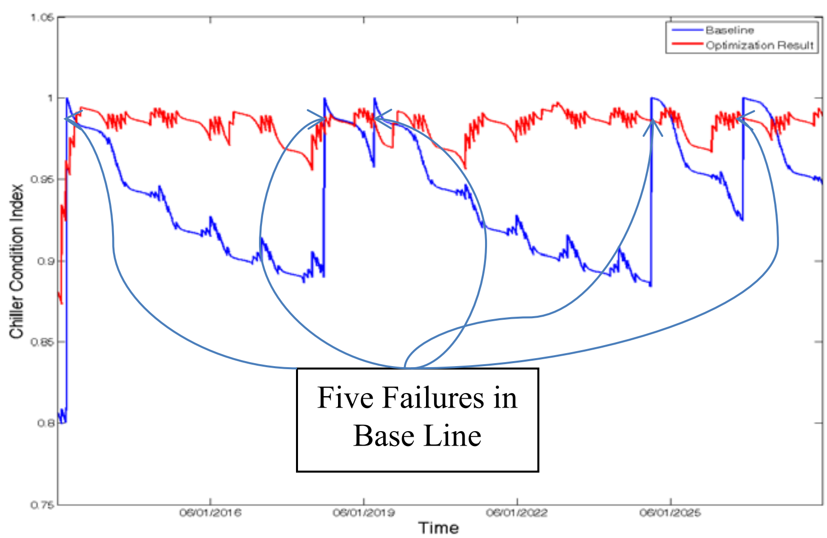


Figure 24: Chiller Condition Index for 15-Year Simulation

Technology Transfer or Decommissioning: Siemens Building Technology is already servicing USAFA and is conducting the technology transfer to the Academy. With regard to decommissioning, BEAM software can be easily removed from the facility team's PC through a un-installation function that the software tool provides.

5.5 SAMPLING PROTOCOL

Data Description: In our experiments, the reactive maintenance type is selected for all assets by default. In addition, we considered the six different types of preventive maintenance policy shown on Table 38 in Appendix C. All the tests were conducted by using the same BVM penalty cost per unit of time loss for each asset, as computed with the BVM tool and presented on Table 59: Seasonal BVM values in Appendix D. For each test, we collected statistics on energy usage per asset and for the whole building from EnergyPlus. Optimal maintenance policies and corresponding maintenance schedules were retrieved from the BEAM engine. No special arrangements were made for data backups or storage, since all outputs are repeatable using simulations.

Data Collection: For the trending data and utility data collection, Table 24 below summarizes the types, the sampling rates used, data collectors, and storage.

Table 24: Sampling Protocol

ID	Data Description	Data Collector(s)	Data Recording Method	Frequency	Data storage
1	Building operation data (trend)	Siemens (Apogee)	Automated	15 minutes	GForge
2	Meter data	Siemens (Apogee)	Automated	15 minutes	GForge
3	Occupancy scheduling	USAFA	Manual	Variable	GForge
4	Utility data	USAFA	Manual	Monthly	GForge
5	Maintenance data	USAFA	Manual	Monthly	GForge
6	Complaints	USAFA	Manual	Monthly	GForge
7	Building Energy Simulation	Rutgers	Automated	Variable	GForge

5.6 SAMPLING RESULTS

The experimental testing was conducted using simulations. The energy usage simulation was based on hourly intervals for EnergyPlus model computations. For the EnergyPlus model calibration meter, 15-minute interval data were used.

6.0 PERFORMANCE ASSESSMENT

BEAM assessments were carried out mainly by using simulations provided by the BEAM Runtime software and through statistical analysis of output results for test combinations identified by the design of experiment. As indicated in Section 5, steps to model and data validation, accuracies of inputs and the proper design of experiment with sufficiently sized fractional factorial design and statistically sufficient runs of simulations guaranteed the accuracy of performance data. A large number of simulation runs, each conducted over sufficiently long periods of time, can reduce the impacts of human subjectivity on the conclusions derived from a test.

Although the performance assessment of the BEAM technology did not involve direct lifecycle analysis of separate energy assets, the output of BEAM optimization provides indirect analyses of the lifecycle costs for building energy assets. Usually, the lifecycle of a building is much longer than the lifecycle of its individual assets. Moreover, individual assets have different lifecycles. Nevertheless, lifecycle cost and benefit approximation using BEAM analysis can be achieved by extending the planning period so that the full life of a majority of a building's assets is included.

PO I: Building Total Energy Consumption

The results of the experiment on Table 25 show clearly in simulation that, the use of BEAM can lead to energy savings beyond the target of 5% set for this demonstration. The simulation results for the 2, 5, and 15-Years' time horizons demonstrate respectively 8.03%, 8.01%, and 6.61% reduction in energy usage relative to the baseline of annual energy consumption at the demonstration site.

Table 25: Performance Objective I Results Summary

Arnold Hall SQFT ($200,000\ ft^2$)	**2 Years**		**5 Years**		**15 Years**	
	Baseline	BEAM	Baseline	BEAM	Baseline	BEAM
Energy (kWh)	396,684	364,824	981,913	903,302	2,893,928	2,702,769
Energy Intensity (kWh/ft^2)	1.98	1.82	4.91	4.52	14.47	13.51
Savings (%)		8.03%		8.01%		6.61%

PO II: Building Systems Maintenance

The simulation results for the 2, 5, and 15-Years' time horizons indicate respectively 76.81%, 88.30%, and 88.09% reduction in reliability events relative to the baseline. These results exceeded the Success Criteria target of a 20% reduction.

Table 26: Performance Objective II results Summary

	Assets	2 Years		5 Years		15 Years	
		Baseline	BEAM	Baseline	BEAM	Baseline	BEAM
Fault and reliability events	AHU-1A	2.00	0	4.25	0	12.00	0
	AHU-1C	1.50	0	3.50	0	10.75	1
	AHU-1D	1.75	0	4.00	1	10.75	1
	AHU-2	1.25	0	3.50	0	10.75	0
	AHU-3	1.00	2	2.00	2	6.25	5
	AHU-4	1.00	0	3.50	0	9.75	0
	AHU-5	1.50	1	3.00	1	9.50	5
	AHU-6	1.50	0	3.50	0	10.50	0
	AHU-7	1.00	0	3.50	0	10.25	0
	AHU-8	1.75	1	3.50	1	10.00	3
	AHU-9	2.00	0	3.50	0	10.75	0
	AHU-10	1.75	0	3.50	0	10.25	0
	Chiller	1.25	0	1.50	0	4.50	0
Number of Reliability Events		19.25	4	42.75	5	126	15
Reliability Events Improvement (%)			76.81%		88.30%		88.09%

PO III: Building System Economic Results

Table 27: Performance Objective III Results Summary

	2 Years		5 Years		15 Years	
	Baseline	BEAM	Baseline	BEAM	Baseline	BEAM
Energy cost	$79,336	$72,964	$196,382	$180,660	$583,514	$540,553
Maintenance cost	$87,785	$78,200	$202,613	$173,300	$676,300	$503,800
Sub-Total	$167,121	$151,164	$398,995	$353,960	$1,259,814	$1,044,353
Savings (%)		10%		11%		17%
Penalty Cost	$7,119,311	$248,042	$15,950,721	$133,900	$36,393,171	$593,843
Savings (%)		96.52%		99.16%		98.37%

The simulation results for the 2, 5, and 15-Year time horizons show respectively 10%, 11%, and 17% reduction in Energy and Maintenance combined costs reduction relative to the baseline, while the penalty cost is showing respectively 96.52%, 99.16%% and 98.37% reductions. The cost savings for energy cost and maintenance costs over 15 year period are in the range of the target set for this demonstration which is 15% savings. However, we have to use caution about interpreting the performance in terms of penalty cost savings because the evaluation of the penalty cost itself can be somewhat subjective, as was previously mentioned at the beginning of this section.

PO IV: Building Asset Availability & Reliability

Table 28: Performance Objective IV results Summary (in %)

	Assets	2 Years		5 Years		15 Years	
		Baseline	BEAM	Baseline	BEAM	Baseline	BEAM
Availability	AHU-1A	0.99452	1	0.995342	1	0.995616	1
	AHU-1C	0.99589	1	0.996164	1	0.996073	0.999635
	AHU-1D	0.99520	1	0.995616	0.998904	0.996073	0.999635
	AHU-2	0.99657	1	0.996164	1	0.996073	1
	AHU-3	0.99726	0.994521	0.997808	0.997808	0.997717	0.998174
	AHU-4	0.99726	1	0.996164	1	0.996438	1
	AHU-5	0.99589	0.99726	0.996712	0.998904	0.996530	0.998174
	AHU-6	0.99589	1	0.996164	1	0.996164	1
	AHU-7	0.99726	1	0.996164	1	0.996256	1
	AHU-8	0.99520	0.99726	0.996164	0.998904	0.996347	0.998904
	AHU-9	0.99452	1	0.996164	1	0.996073	1
	AHU-10	0.99520	1	0.996164	1	0.996256	1
	Chiller	0.99143	1	0.99589	1	0.995890	1
Minimum Assets Availability (%)		99.14%	99.45%	99.53%	99.78%	99.56%	99.82%
Maximum Assets Availability (%)		99.73%	100.00%	99.78%	100.00%	99.77%	100.00%
Average Assets Availability (%)		99.55%	99.92%	99.62%	99.96%	99.63%	99.96%
Improvement of Average Assets availability (%)			0.36%		0.34%		0.33%

Table 29: Performance Objective IV Results Summary (in hours)

	Assets	2 Years		5 Years		15 Years	
		Baseline	BEAM	Baseline	BEAM	Baseline	BEAM
Availability (h)	AHU-1A	17,424	17,520	43,596	43,800	130,824	131,400
	AHU-1C	17,448	17,520	43,632	43,800	130,884	131,352
	AHU-1D	17,436	17,520	43,608	43,752	130,884	131,352
	AHU-2	17,460	17,520	43,632	43,800	130,884	131,400
	AHU-3	17,472	17,424	43,704	43,704	131,100	131,160
	AHU-4	17,472	17,520	43,632	43,800	130,932	131,400
	AHU-5	17,448	17,472	43,656	43,752	130,944	131,160
	AHU-6	17,448	17,520	43,632	43,800	130,896	131,400
	AHU-7	17,472	17,520	43,632	43,800	130,908	131,400
	AHU-8	17,436	17,472	43,632	43,752	130,920	131,256
	AHU-9	17,424	17,520	43,632	43,800	130,884	131,400
	AHU-10	17,436	17,520	43,632	43,800	130,908	131,400
	Chiller	17,424	17,520	43,596	43,800	130,824	131,400

The success criterion of this performance objective was set too high for several reasons:

1. If an asset in unavailable for more than 20% of the time, the asset will probably be replaced. Therefore, a 20% increase in availability is not reasonably achievable.
2. As shown in Table 28, assets for this particular building are already available more than 99% of the time; therefore any improvement will be miniscule.

Since in the case of BEAM, maintenance is pre-planned, it can be done during off periods where the asset is not needed or can be taken offline with minimal negative impact on the user. Therefore, we assume that maintenance with BEAM planning will not result in downtime when the asset is needed therefore no impact on availability.

In conclusion, for this building, the improvement in availability is not substantial.

PO V: Ease of Use & User Satisfaction

PERCEIVED USEFULNESS		1	2	3	4	5	6	7		NA
1. Using the system in my job would enable me to accomplish tasks more quickly	unlikely	○	○	○	○	●	○	○	likely	○
2. Using the system would improve my job performance	unlikely	○	○	○	●	○	○	○	likely	○
3. Using the system in my job would increase my productity	unlikely	○	○	○	●	○	○	○	likely	○
4. Using the system would enhance my effectiveness on the job	unlikely	○	○	○	○	●	○	○	likely	○
5. Using the system would make it easier to do my job	unlikely	○	○	○	○	●	○	○	likely	○
6. I would find the system useful in my job	unlikely	○	○	○	○	●	○	○	likely	○
PERCEIVED EASE OF USE		**1**	**2**	**3**	**4**	**5**	**6**	**7**		**NA**
7. Learning to operate the system would be easy for me	unlikely	○	○	○	○	○	●	○	likely	○
8. I would find it easy to get the system to do what I want it to do	unlikely	○	○	○	○	○	●	○	likely	○
9. My interaction with the system would be clear and understandable	unlikely	○	○	○	○	●	○	○	likely	○
10. I would find the system to be flexible to interact with	unlikely	○	○	○	○	○	●	○	likely	○
11. It would be easy for me to become skillful at using the system	unlikely	○	○	○	○	○	●	○	likely	○
12. I would find the system easy to use	unlikely	○	○	○	○	○	●	○	likely	○
		1	**2**	**3**	**4**	**5**	**6**	**7**		**NA**

List the most **negative** aspect(s):

1. Initial setup, information collection could be time consuming
2. keeping the database updated
3.

List the most **positive** aspect(s):

1. Predictive maintenance
2. Less downtime and faults
3. Cost effective

Figure 25: Survey result from the facility manager (EMCS-Chief)

Comments:

This person is likely to install and operate the BEAM tool set. Therefore his opinion carries heavy weight. He sees a lot of positive aspects to the BEAM tools.

PERCEIVED USEFULNESS		1	2	3	4	5	6	7		NA
1. Using the system in my job would enable me to accomplish tasks more quickly	unlikely	○	○	○	○	○	○	○	likely	●
2. Using the system would improve my job performance	unlikely	○	○	○	○	○	○	○	likely	●
3. Using the system in my job would increase my productity	unlikely	○	○	○	○	○	○	○	likely	●
4. Using the system would enhance my effectiveness on the job	unlikely	○	○	○	○	○	○	○	likely	●
5. Using the system would make it easier to do my job	unlikely	○	○	○	○	○	○	○	likely	●
6. I would find the system useful in my job	unlikely	○	○	○	○	○	○	○	likely	●
PERCEIVED EASE OF USE		**1**	**2**	**3**	**4**	**5**	**6**	**7**		**NA**
7. Learning to operate the system would be easy for me	unlikely	○	○	○	○	○	●	○	likely	○
8. I would find it easy to get the system to do what I want it to do	unlikely	○	○	○	○	○	○	●	likely	○
9. My interaction with the system would be clear and understandable	unlikely	○	○	○	○	○	○	●	likely	○
10. I would find the system to be flexible to interact with	unlikely	○	○	○	○	○	○	○	likely	●
11. It would be easy for me to become skillful at using the system	unlikely	○	○	○	○	○	○	●	likely	○
12. I would find the system easy to use	unlikely	○	○	○	○	○	○	●	likely	○
		1	**2**	**3**	**4**	**5**	**6**	**7**		**NA**

List the most **negative** aspect(s):

1. N/A
2.
3.

List the most **positive** aspect(s):

1. Live data of the system. be informed in advance of complains
2. Repair could be done before complains.
3. Quicker isolation of the problem

Figure 26: Survey result from the building operator of Arnold Hall

Comments:

This person is not using any of the building automation and control software; however, he deals with complaints of the building users. That is why he didn't give opinion on the usability of the software. But he is showing a significant interest on the outcomes of using tools such as the monitoring tool that can help anticipate maintenance and avoid failure of equipment. Rapid identification of faults or failure and their possible causes can be a major improvement for the management of the building. He finds that the tools could be very useful for him.

7.0 COST ASSESSMENT

The team used the NIST Handbook 135 approach to develop a life cycle cost analysis of the project using rules established in the *Life-Cycle Costing Manual for the Federal Energy Management Program.* For example, the team used the actual energy price at the building site and calculated the Savings-to-Investment ratio and Adjusted Rate of Return in addition to ROI. The team also used NIST's *Building Life Cycle Cost* computer program and referenced *Present worth Factors for Life-Cycle Cost Studies in the Department of Defense.*

Life-Cycle Cost Table: Table 30 highlights the data, relevant to the BEAM technology, tracked by the project team during the demonstration. The objective is to estimate life cycle costs at full scale operation.

Table 30: Detail Elements of Cost Model of BEAM Technology

Cost Element	**Data Tracked During the Demonstration**
Hardware capital costs	Acquisition cost of a PC required for BEAM Tool installation; additional sensor installation for asset condition monitoring
Software costs	Licensing costs of BEAM software; optional BACNet server license
Commissioning cost	1) Engineering effort of building and asset information gathering 2) Engineering effort of Model development 3) Engineering effort of Model calibration 4) Engineering effort of Building Automation System Point configuration and trending 5) Engineering effort of Network configuration and testing (optional, only applied to "Integrated" Mode) 6) Engineering effort of BACNet point configuration (optional, only applied to "Integrated" Mode)
Facility operational costs	Operational Data Collection: 1) Trending data retrieval from building automation system (Siemens Apogee); 2) interval meter data; 3) Failure reported and complaint logs 4) Maintenance activity and cost data 5) Utility rate and bills Test Data 1) Faults detected by BEAM-CCM from trend data 2) Asset CI s updated by BEAM-CCM from trend data Simulation data: 1) Energy consumption (gas and electricity) /peak load and energy cost with BEAM implementation vs. current practice. 2) Penalty Cost based on business value with BEAM implementation vs. current practice.
Maintenance	1) Engineering effort to solve BAS trending errors 2) Maintenance cost with BEAM implementation vs. current practice.
Hardware lifetime	1) No lifetime cost on BEAM software 2) Computer replacement cost 3) Optional cost of meter/sensor performance degradation

Cost Element	Data Tracked During the Demonstration
Operator training	Estimate of training costs
Salvage Value	Estimate of end-of-life value less removal costs (estimated zero)

Life-Cycle Cost Timeframe: Because HVAC systems are one of the primary systems monitored and managed by BEAM, and because a typical HVAC life cycle is assumed to be 15 years, the life cycle of 15 years will be applied to the LCCA.

Table 31: BEAM software Cost/Savings and Return on Investment (ROI)

BEAM Software	2 Years	5 Years	15 Years
Total Cost	$92,930	$93,890	$128,910
Energy & Maintenance cost Saving	$15,957	$45,035	$215,461
Energy and Maintenance ROI	-83%	-52%	67%
Penalty Cost Savings	$6,871,269	$15,816,821	$35,799,328
Penalty Cost ROI	7294%	16746%	21094%

As Table 31 above shows, it is clear that over the life cycle of the assets (15 years) using BEAM leads to a 67% ROI resulting from Energy and Maintenance cost savings, assuming that the energy price and labor rate remain constant during that time period, which is unlikely. If we assume some increase of the energy price cost and labor rate, the saving will even be higher. The major savings are in the penalty cost, as shown. In fact, Table 31 above tells us that by using BEAM tools we increased significantly the availability and the capability of the building to achieve its mission(s).

7.1 COST MODEL

In **Table 32** below, we list all the cost elements contributing to the implementation of the BEAM tools at a given site. The hardware is comprised of two industrial computers from Siemens called "Siemens Industrial Box-PC," off-the-shelf standard Ethernet cables and router or switch or a hub, a laptop. The software components and the process of implementing them are as follows:

1) The first step is the building assets audit, which can be accomplished in a day, as indicated in Table 32.
2) The collection and review of maintenance logs, we estimated 2 days of work.
3) The configuration of the BACNet points. In a building that already has BACNet points configured this task can be skipped.
4) The following steps involve the development of models:
    - Building EnergyPlus Model Development (estimate 8 weeks)
      Note: this is an estimate based on the model development effort under another ESTCP project and the previous building model development effort for Picatinny Arsenal. However, the level of details of the given model is not necessary for BEAM use.
    - Business value Modeling (estimated at 2 weeks)

- FDD Heat Flow/Rule Modeling (estimated at 4 weeks)

5) Integration and system testing (estimated at 1 week)
6) Commissioning (estimated at 1 week)
7) System maintenance (We estimated that for the first two years no maintenance will be needed. But after five years some changes to the buildings should be anticipated that could require some adjustment to the different models.)

Table 32: Actual Cost Model for BEAM Technology

BEAM Software			2 Years		5 Years		15 Years	
Type	Description	Cost	Qty	Cost	Qty	Cost	Qty	Cost
Total Cost				$92,930		$93,890		$128,910
Hardware	Siemens Industrial Box-PC - 1 box	$2,900	1	$2,900	1	$2,900	2	$5,800
	network cables 3	$10	3	$30	3	$30	3	$30
	Industrial Hub - 1 for the group	$100	1	$100	1	$100	2	$200
	Monitoring station - 1 dedicated laptop computer for the logical group	$500	1	$500	1	$500	2	$1,000
Software and commissioning	- Building asset audit (1 day) - Maintenance log Collection and review (2 days) - Configuration of BACNet (2 days) Total (1 week@ $4800)	$4,800	1	$4,800	1	$4,800	3	$14,400
	Integration and system testing (1 week@$4800)	$4,800	1	$4,800	1	$4,800	1	$4,800
	First installation - (1 week @ $4800)	$4,800	1	$4,800	1	$4,800	1	$4,800
	System yearly maintenance/upgrade once every 5 years -(1 day@ $960)	$960	0	$0	1	$960	3	$2,880
	License BEAM Condition Monitoring	$2,500	1	$2,500	1	$2,500	1	$2,500
	SEB License	$2,500	1	$2,500	1	$2,500	1	$2,500
	Building EnergyPlus Model Development 8 weeks (1 week@ $5000)	$40,000	1	$40,000	1	$40,000	1	$40,000
	Business value Modeling 2 weeks (1 week @ $5000)	$10,000	1	$10,000	1	$10,000	3	$30,000
	FDD Heat Flow Modeling 4 weeks (1 week@$5000)	$20,000	1	$20,000	1	$20,000	1	$20,000

7.2 COST DRIVERS

The main cost driver of this technology is the development of the different models necessary to simulate long term perspectives of different maintenance policies and "what-if" scenarios. The secondary cost element is the update of these models in case significant changes to the building occur. One challenge for the building managers could be finding qualified resources to update these models and run simulation of new "what-if" scenarios for a long period after the commissioning.

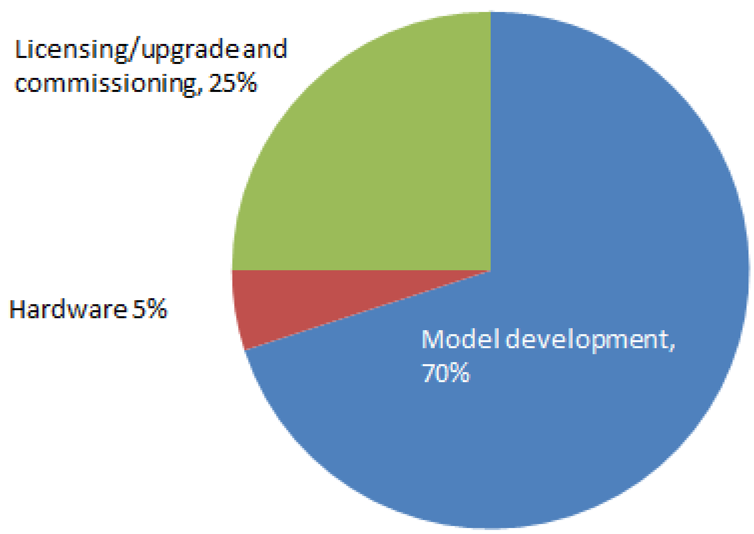


Figure 27: BEAM cost distribution

Table 33: Cost of BEAM technology by category over lifetime

	Cost	Cost Proportions
Hardware	$7,030	5%
Licensing/upgrade and commissioning	$31,880	25%
Models Development	$90,000	70%

7.3 COST ANALYSIS AND COMPARISON

As the figure above indicates, the main cost driver of the BEAM technology is the development of models used to simulate different maintenance polities. Fortunately this cost is likely to be a onetime expense for most buildings considering that major upgrades of buildings are not a regular occurrence. Furthermore, most assets considered by BEAM have a life time of 15 years or more. In a bottom-line analysis, over a 15 year lifetime we see that despite the significant cost of implementation of the BEAM software, the return on investment (ROI) is good in direct savings on energy and maintenance cost.

Table 34: BEAM Lifetime cost comparison

BEAM Software	15 Years
BEAM Total Cost	$128,910
Energy & Maintenance cost Saving	$215,461
Energy and Maintenance ROI	67%
Penalty Cost Savings	$35,799,328
Penalty Cost ROI	21,094%

We choose not to aggregate penalty costs saving with energy and maintenance costs savings because, in general, penalty costs are shouldered by the users of the building and not by the building management. The penalty costs savings computed may seem unrealistic. The way to interpret this data is to consider it as a potential loss of productivity of occupants of the building due to non-availability of the building. In reality, in most cases the occupants of the building may move their activities temporarily in other venues. For example: work from home, move the meeting in another building, reschedule the meeting etc. In the end, the real penalty cost may be less than shown in Table 34 above. In any case, any additional cost saving on top of the direct energy and maintenance costs savings is a plus for the BEAM technology.

8.0 IMPLEMENTATION ISSUES

As described previously in the document, the actual use of this technology is straightforward after commissioning. The challenges are the following:

1) The development of models (building model, FDD Heat Flow Model, Business Model) used to simulate the "what-if" scenarios.
2) Maintenance logs may not be available or will be incomplete.
3) The subjectivity of the data due to the fact that some of the data used in developing the models is a result of interviewing people involved in the building as occupants, maintenance technicians, or facility managers.
4) After commissioning, if significant changes are made to the building such as remodeling, replacement of equipment, addition of equipment, the facility manager could find it challenging to update the models and rerun the simulations to adjust the maintenance policy.

Being unable to run the BEAM tool in integrated mode is also an issue. But we believe that this issue can be overcome by adding security software to the tool chain as we previously did in another ESTCP project at the same site. However, data from the building operator is being obtained in the form of CSV file.

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APPENDICES

Appendix A: Points of Contact

Table 35: Points of Contact

Point of Contact	Organization	Phone & E-mail	Role in Project
Dr. Yan Lu	Siemens Corporation, Corporate Technology	yanlu@siemens.com 609-734-3549	PI
Sue DeMeo	Siemens Corporation, Corporate Technology	susan.demeo@siemens.com 609-734-4469	Business Contact
Thomas Gruenewald	Siemens Corporation, Corporate Technology	thomas.gruenewald@siemens.com 609-734-3546	PM
Dr. Mohsen Jafari	Rutgers University	jafari@rci.rutgers.edu	PI
Larry Lawrence	US Air Force Academy	Larry.lawrence@us.af.mil 719-333-1447	Site Support

Appendix B: Arnold Hall Chiller Degradation

Introduction

Arnold Hall has two chillers – CH01 and CH02. CH02 has been down for many years. Trend data for CH01 is available for the period 10/04/2012-10/24/2012 and 06/24/2013-08/17/2013. The performance of CH01 was calculated for these periods; significant degradation has been noticed.

COP calculation

The chilled water supply and return temperature, and the chiller power consumption are trended, with a 15-minutes sampling interval. The chilled water flow is not available. However, the primary chilled water pump is constant speed drive rated at 600 GPM. Therefore, it is reasonable to assume the chilled water has 500 GPM constant flow rate if we assume that the pump runs between 75% (450 GPM) and 90% (540 GPM) capacity. Then, the cooling output can be calculated as:

$$P_{cool} = \rho M \left(T_{CHWRT} - T_{CHWST} \right)$$

where, $\rho = 0.1465 \dfrac{KW}{GPM\,^{\circ}F}$ is the specific heat of chilled water;

and, $M = 500\,GPM$

The instantaneous COP can be calculated as:

$$COP = \frac{P_{cool}}{P}$$

Instantaneous COP needs to be adjusted by corresponding condenser water entering temperature (CWST). **Table 36** from manufacturer document gives the part load power at reduced CWST.

Table 36: Chiller power reduction at reduced CWST

Percent Load	KW (CWST=85°F)	KW	A	CWST (°F)
100%	166.56	166.56	1.00000	85
90%	148.09	145.06	0.97954	81
80%	133.79	128.52	0.96061	77
70%	119.88	113.17	0.94403	73
60%	106.61	98.81	0.92684	69
50%	93.36	85.24	0.91302	65
40%	79.8	73.05	0.91541	65
30%	66.14	60.23	0.91064	65
20%	51.63	46.71	0.90471	65

The relation between adjusting factor, A = $KW/KW_{CWST=85°F}$, and CWST can be fitted using a second order polynomial equation.

$$A = f(CWST) = 3.228\times10^{-5}CWST^2 - 4.078\times10^{-4}CWST + 0.8011$$

$$COP_{adj} = A \cdot COP$$

Figure 28: **CH01 COP** shows the adjusted COP change.

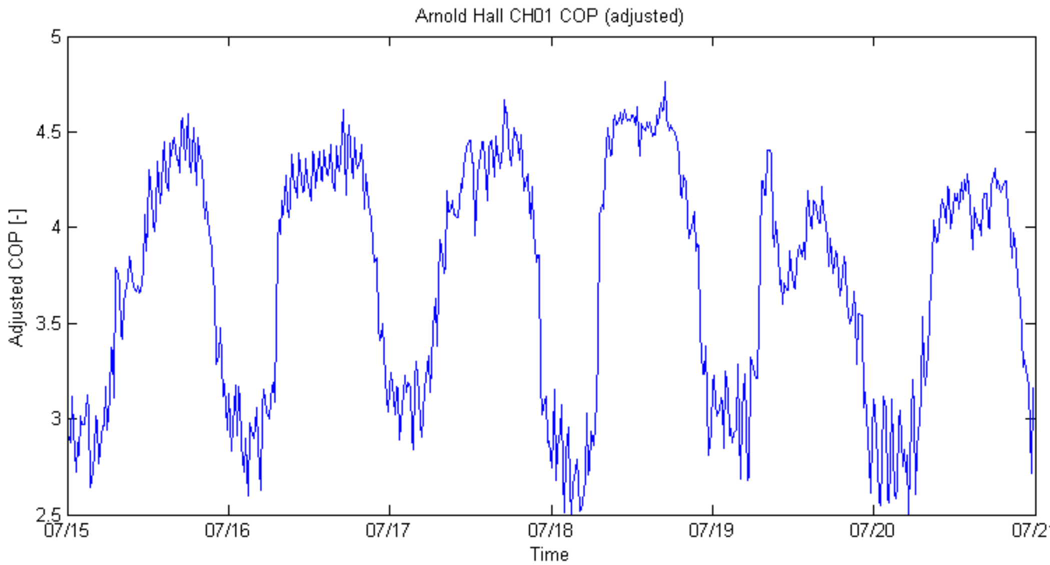


Figure 28: CH01 COP

PLR Calculation

The chiller has rated cooling capacity 300 Ton. That is equivalent to 1055 KW.
Then the chiller part load ratio (PLR) can be calculated as

$$PLR = \frac{P_{cool}}{P_{cool\ capacity}}$$

Figure 28 is the plot of instantaneous COP against PLR. The downward shift of data points is remarkable.

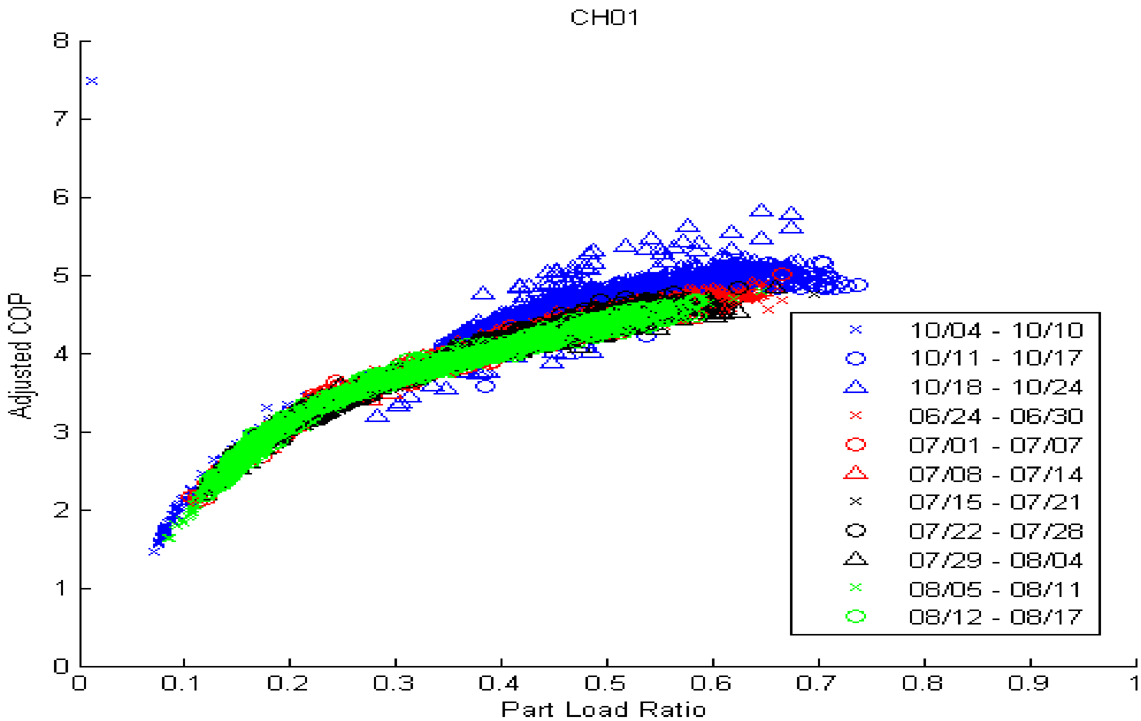


Figure 29: CH01 adjusted COP-PLR scatter plot

Curve fitting and CI calculation

Chiller performance is characterized by its COP-PLR curve. The reference performance data is provided by the manufacturer (Table 37).

Table 37: Chiller reference performance (CWST=85°F)

Percent Load Ratio	COP
100%	6.33
90%	6.41
80%	6.31
70%	6.16
60%	5.94
50%	5.65
40%	5.29
30%	4.79
20%	4.09
19%	4.00

Conventionally, a polynomial equation of power 4 is used to fit COP-PLR curve. The fitted curve is shown as following:

$$COP_{ref} = f(PLR) = -10.91PLR^4 + 28.03PLR^3 - 29.67PLR^2 + 17.27PLR + 1.61$$

Assume chiller performance curve at any time is in the form of

$$COP_{adj} = COP_{ref} CI / 100$$

The fitted curves are shown in Figure 30, and corresponding CI's are shown in Figure 31.

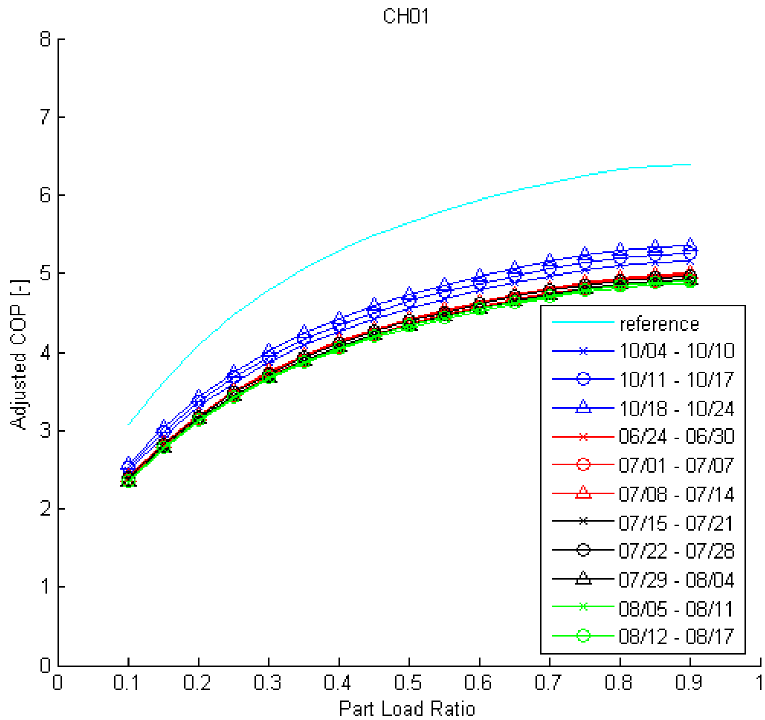


Figure 30: CH08 fitted performance curve

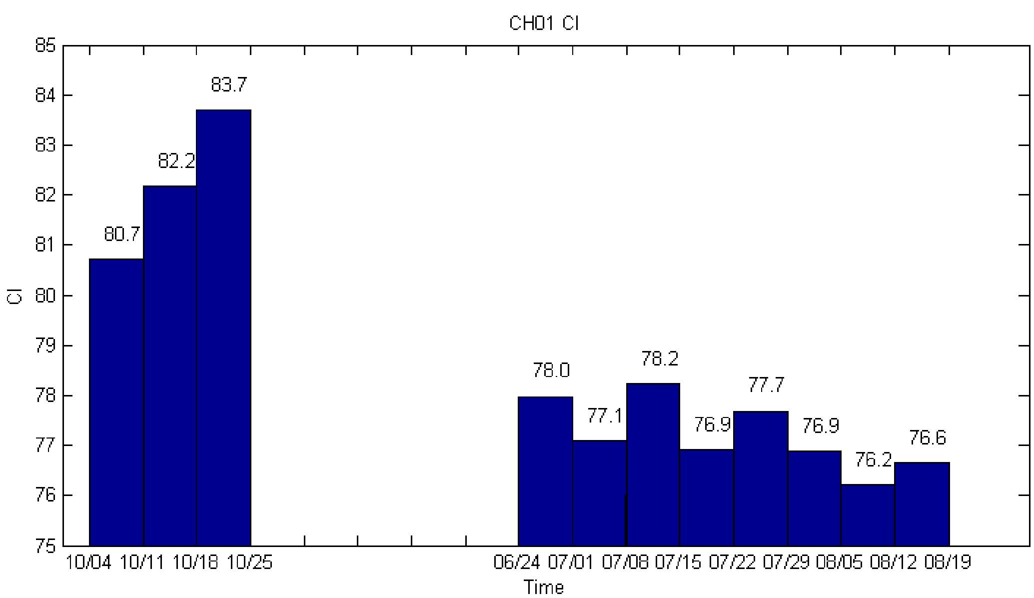


Figure 31: CH01 CI

Appendix C: Optimization Recommended Policies

We considered two different frequencies for each preventive maintenance policy option. Consequently, 12 (=6*2) maintenance options were studied. The "what-if" analysis representing base line case and the optimization ran for 2, 5 and 15 year durations each. For each duration selection, the simulation/co-simulation (with failure generating probability distribution for assets) ran several times (3 or more). This is to ensure that statistically sufficient variations are observed within these runs.

Table 38: Maintenance Policy Options

ID	Description
9.	Reactive Maintenance upon Failure
10.	Reactive Maintenance upon Alarm
11.	Preventive Maintenance Type 1_Age-based ^^^
12.	Preventive Maintenance Type 2_Age-based ^^^
13.	Preventive Maintenance Type 3_Age-based *** ^^^
14.	Preventive Maintenance Type 1_Clock-based ###
15.	Preventive Maintenance Type 2_Clock-based ###
16.	Preventive Maintenance Type 3_Clock-based *** ###

*** Preventive Maintenance Type 3 is the category with the most detailed actions and the highest improvement factor.
^^^ Age-based maintenances are scheduled based on the cumulative load on the assets.
Clock-based maintenances are scheduled based on the calendar.

Two years Optimization results:

Table 39: Year One of Two

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month1 month	preventive maintenance clock based type 3 every 1 months	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance	Reactive	preventive	Reactive

	age based type 3 every 1 month	maintenance	maintenance clock based type 3 every 1 month	maintenance
SF5	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 40: Year two of two

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance

SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance

SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 41: Year One of Five

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1	preventive maintenance	preventive maintenance	Reactive maintenance

	month	clock based type 3 every 1 month	clock based type 3 every 1 month	
SF9	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 42: Year Two of Five

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1	Reactive maintenance	preventive maintenance	Reactive maintenance

	month		clock based type 3 every 1 month	
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 43: Year Three of Five

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1	Reactive maintenance	preventive maintenance	Reactive maintenance

	month		clock based type 3 every 1 month	
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 44: Year Four of Five

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2	Reactive maintenance	Reactive maintenance	Reactive maintenance

	month			
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 45: Year Five of Five

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1	Reactive maintenance	preventive maintenance	Reactive maintenance

	month		clock based type 3 every 1 month	
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 46: Year 6/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance

SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 47: Year 7/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1	Reactive maintenance	preventive maintenance	Reactive maintenance

	month		clock based type 3 every 1 month	
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 48: Year 8/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type	Reactive maintenance

			3 every 1 month	
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 49: Year 9/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type	Reactive maintenance

			3 every 1 month	
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 50: Year 10/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2	Reactive maintenance	Reactive maintenance	Reactive maintenance

	month			
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 51: Year 11/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance	Reactive	preventive	Reactive

	age based type 3 every 1 month	maintenance	maintenance clock based type 3 every 1 month	maintenance
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	Reactive maintenance	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 52: Year 12/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance

SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance

SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 53: Year 13/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF3	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance

SF10	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF13	Reactive maintenance	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 54: Year 14/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF3	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF4	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type	Reactive maintenance

			3 every 1 month	
SF7	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	Reactive maintenance	preventive maintenance clock based type 3 every 1 month	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Table 55: Year 15/15

Asset	Cooling Peak	Cooling off-Peak	Heating Peak	Heating off-Peak
Chiller	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF1	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF2	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF3	preventive maintenance clock based type 3 every 1	preventive maintenance	Reactive maintenance	Reactive maintenance

	month	clock based type 3 every 1 month		
SF4	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF5	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF6	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF7	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance
SF8	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF9	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF10	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF11	preventive maintenance clock based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF12	preventive maintenance age based type 3 every 1 month	preventive maintenance clock based type 3 every 1 month	Reactive maintenance	Reactive maintenance
SF13	preventive maintenance clock based type 3 every 2 months	Reactive maintenance	Reactive maintenance	Reactive maintenance

Appendix D: Building Energy Simulation model

The EnergyPlus model was built to run what-if (baseline case) and optimization scenarios. The following components were included in the EnergyPlus model of Arnold Hall.

Building Zones

41 zones were identified during the development of the building energy simulation model. Most zones are located at the Main Level (Ground Level). The ballroom has one zone in the basement level, and the auditorium has more zones at Levels 1~4. The zone map for the Main Level (Ground Level) is shown in the following figure.

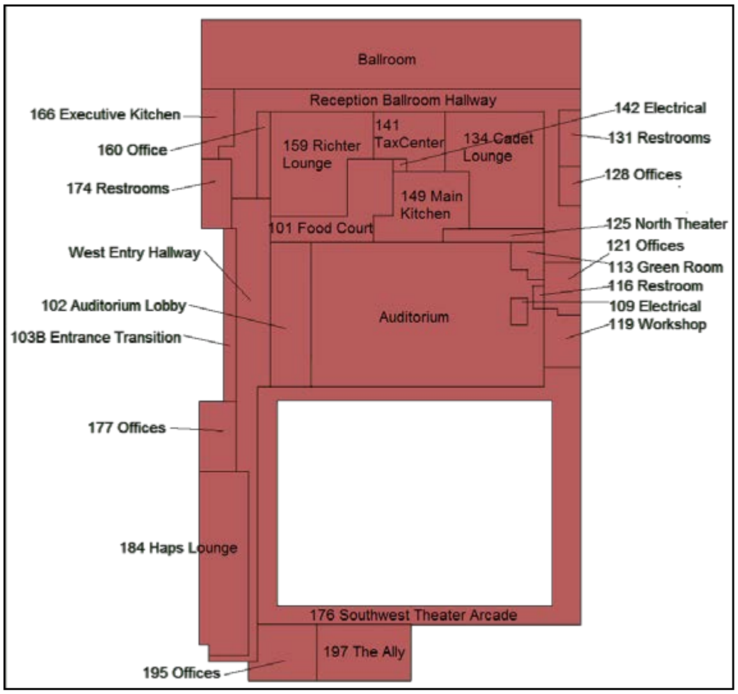


Figure 32: Zone Map - the Main Level (Ground Level)

Plants

The heating water for Arnold Hall is provided by a central plant within the same USAFA campus. However, in the simulation, a natural gas boiler is modeled as an equivalent surrogate. This boiler has nominal capacity of 478.9KW and nominal thermal efficiency of 0.89. There are two 300-ton chillers providing chilled water to both Arnold Hall and one adjacent building (Harmon Hall). Metering that measures the flow to and from the Harmon branch is not available. In the simulation, an electric chiller is modeled as an equivalent surrogate. The simulated chiller has reference capacity of 703.3KW and reference COP of 5.5. There are two cooling towers providing condenser water. In the simulation, one cooling tower is modeled as an equivalent surrogate.

Air Handling Units

Twelve (12) air handling units have been identified as providing conditioned air to the zones. The correlation between zones and AHUs is summarized in Table 56.

Table 56: Air Handling Units

AHU	Type	Served Area	Served Zone Names
AHU-1A	VAV/Dual Duct/Dual Deck	Misc.	Richter Lounge, Tax Center, Food Court, Main Kitchen, Southwest Theater Arcade, Restrooms(131,116)
AHU-1C	CAV	Auditorium	Auditorium Behind, Auditorium, Corridor
AHU-1D	CAV	Auditorium	Rehearsal & Dressing Room, Backstage
AHU-2	CAV	Auditorium	Auditorium
AHU-3	VAV	Misc.	Green Room, Workshop
AHU-4	VAV	Misc.	Offices (177,195), Ally
AHU-5	VAV	Haps Lounge	Haps Lounge
AHU-6	CAV	Misc.	Entrance Transition, Auditorium Lobby, West Entry Hallway
AHU-7	VAV	Ballroom	Ballroom
AHU-8	VAV	Cadet Lounge	Cadet Lounge
AHU-9	VAV	Misc.	Executive Kitchen, Offices (121,128,160), Restroom(174)
AHU-10	VAV	Ballroom	Reception Ballroom Hallway

For each air-handling unit in the simulation, 1 supply fan and 1 return fan are modeled.

Appendix E: Business Value Model (BVM)

BEAM Configuration maps the missions assigned to a building to the building's assets based on Business Value Models: *BVM-I*, *BVM-II* or *BVM-III*. The following **Table 57** lists data assumptions for the BVM model. Some data are input based on information received from the building owner/operator, which were obtained through the interview process.

Table 57: BVM Data Assumptions

#	Assumption	Description	Data/Model Source
1	Productivity loss or business value loss due to asset failure: Quantifiable Economic Consequence of Asset Failure (Loss)	Building occupants' productivity as well as activities performed in the building are correlated with performance of building energy assets such as components of HVAC system namely chiller, supply and return fans; thus, any deviation from optimal performance of such components (including asset failures) results in loss of productivity or business value gained through activities held in the building. This concept is used in defining consequence of asset failure in monetary terms. (i.e. Asset Business Value in BVM-II & -III)	BVM Survey Questionnaires
2	Building Zoning: Thermal zoning concept	In order to effectively map building missions to energy assets, zoning is performed based on thermal zoning (Control Zones) concept used in building energy simulation. Control Zones (zones with independently controlled equipment) are defined based on placement of Air Terminal Units (i.e., VAV boxes) within the building.	Building Simulation Model (EnergyPlus Model)
3	Building Mission/Business Objectives and Functions	Building missions are accomplished through various functions carried out in building zones. Functions performed across the building can be defined according to functional zones within the building. Functional zones are defined based on the type(s) of activities performed in them. Each functional zone may be operational for one or more mission.	BVM Survey Questionnaires

#	Assumption	Description	Data/Model Source
4	Seasonality	4 seasons are considered in BVM-III business value calculation: Peak Cooling, Off-Peak Cooling, and Peak Heating & Off-Peak Heating. Peak and Off-Peak seasons are defined based on cooling and heating demands. Such seasons include various intensive and un-intensive occupancy patterns throughout the year.	BVM Survey Questionnaires
5	Duration of Asset Unavailability Due to Failure (Loss)	This duration is defined in days. This number is used to derive monetary consequence per failure of assets.	BVM Survey Questionnaires or default unavailability duration
6	Polynomial Regression Function between Relative Productivity and PMV in BVM-II.	It is assumed that office work consists of typical office tasks such as typing, proof reading, etc…; Thus the function introduced by Lan et al. 2011, can be used: $RP = -0.0351PMV^3 - 0.5294PMV^2 - 0.215PMV + 99.865$	Regression function from Lan et al., 2011
7	Employees' Annual Income or Income Contribution as Reference for Economic Loss Due to Productivity	It is assumed that since employees are hired to produce value for the organization, their average annual income may be used to approximate an economic value for loss of productivity due to asset failure	BVM Survey Questionnaires
8	Risk Priority Number (RPN): FMEA's risk measure used in BVM-I for asset criticality score calculation.	In order to define criticality of an asset such as supply fan to performance of its associated asset system (AHU), FMEA's RPN $\in [0,100]$ is used which is defined based on assets fault types, each fault's occurrence probability $\in [0,10]$ & each fault's consequence on performance of asset system $\in [0,10]$	Historical data on asset faults, BVM Survey Questionnaires

According to the seasonality concept in BVM model Peak and off-Peak seasons are defined based on cooling and heating demands. Table 58 shows the start date and end date for each defined season.

Table 58: Seasons Start date and End date

Season	Start Date	End Date
Cooling season	April - 1	October - 15
Cooling Peak season	June - 1	August - 31
Heating season	October - 16	March - 31
Heating Peak season	December - 1	February - 15

Note that, as Table 58 shows, in the cooling season we consider two cooling off-peak seasons, one of them before cooling peak season (April-1 to May-31) and the other one after cooling peak season (September-1 to October-15). The same approach is taken for the heating season.

Based on the inputs received from users about average annual income for task related zones, average business value gained through activities in non- task related zones and duration of asset unavailability due to failure (in days), business value for each asset is calculated. The following table shows these values which are used as penalty cost per failure for the assets.

Table 59: Seasonal BVM values

Asset	Cooling Peak($)	Cooling off-Peak ($)	Heating Peak ($)	Heating off-Peak ($)
Chiller	4,406,350	2,566,336	0	0
SF1	995,800	1,159,943	1,019,021	954,514
SF2	85,800	99,943	168,771	288,514
SF3	7,800	9,086	15,343	26,229
SF4	85,800	99,943	168,771	288,514
SF5	0	0	0	0
SF6	65,520	76,320	64,440	56,160
SF7	0	0	0	0
SF8	449,800	523,943	482,021	486,514
SF9	46,800	54,514	92,057	157,371
SF10	126,100	146,886	248,043	424,029
SF11	481,520	560,891	524,726	543,017
SF12	296,400	345,257	296,629	267,086
SF13	0	0	0	0

As you see chiller has the most business value which is reasonable since chiller is serving all of the 41 zones of the building. So the failure of chiller in cooling season will impact the functionality of whole building.

Appendix F: BEAM Configuration Tool User Manual

BVM tool User Manual

USAFA Arnold Hall Case Study

Pre-Requisites

- Firefox browser is the preferred browser for BVM tool application.
- Apache Tomcat 7.0 has been started.
- Copy “BeamIII_3_3.war” into the webapps folder of Apache Tomcat, (in my machine, it is
  C:\Program Files\Apache Software Foundation\Tomcat 7.0\webapps) and rename it as “BeamII.war”;
- Use IP address http://localhost:8080/BeamII/ to load the BVM tool.

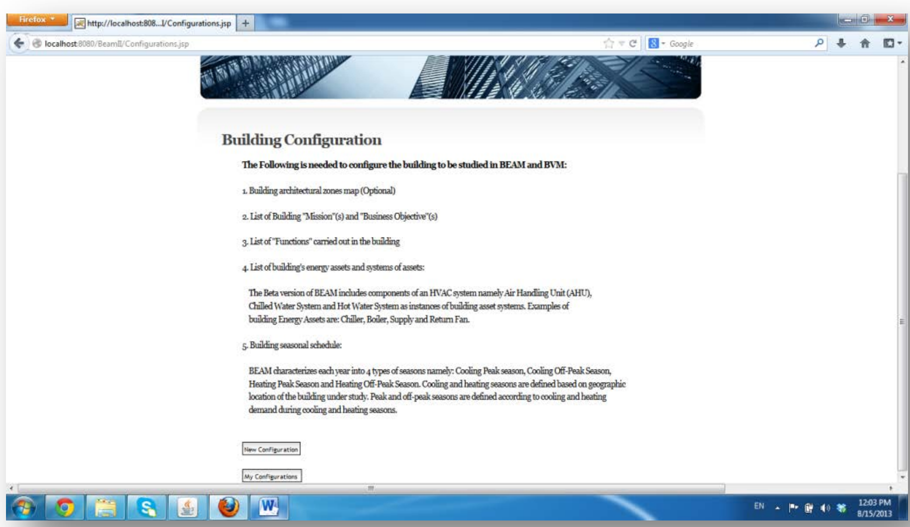
Step1: BVM tool log in

User name: beam
Password: beam

Note: this user name and password cannot be changed.

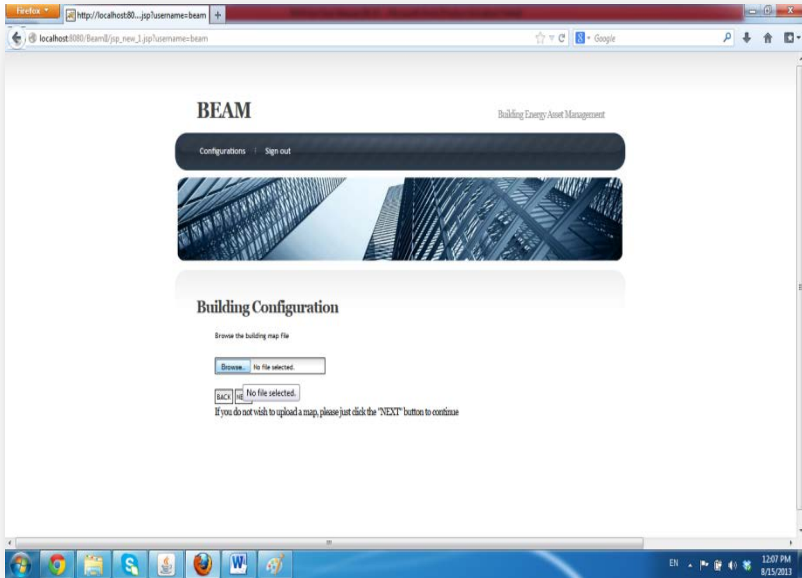
Step2. Building Configuration

Click “New Configuration” to start configuration process
Click “My Configuration” to load a previously existing configuration
Here, we click “New Configuration” to start a new configuration process. Here we use Arnold Hall as an example.



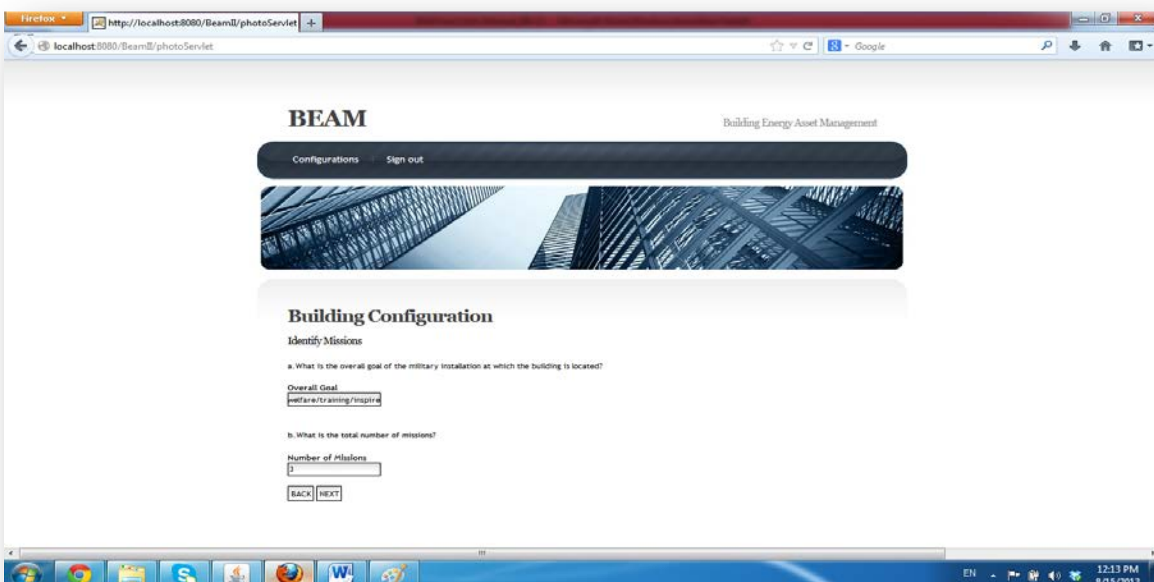
Step 2.1: Browse building zone map
Notes:

- Zone maps should be in *.png format
- No error occurs if no map is uploaded



Step 2.2: Identify Goal of military installation and Number of Missions

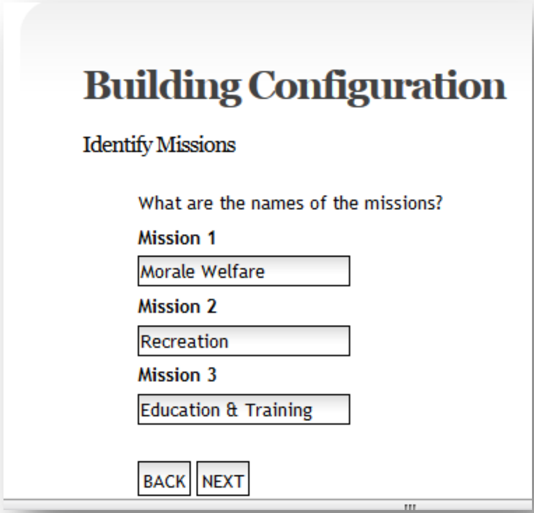
Type "welfare/training/inspire" as the overall goal and "3" as the number of missions.



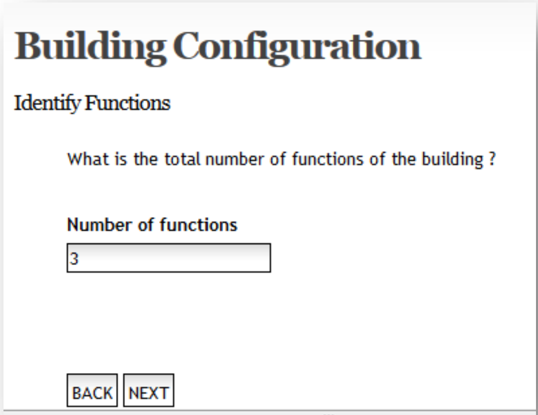
Notes:

- "Overall Goal" is a text indication high level purpose of the building.
- "Missions" are specific business objectives which ensure realization of building "Overall Goal".
- Suggested number of missions for USAFA Arnold hall: 3 Missions

Step 2.3: Identify Missions (Input three missions indicated below)



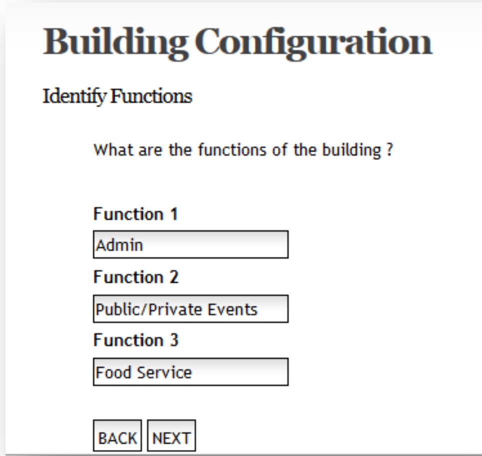
Step 2.4: Identify Functions



Notes:

- Functions are set of actions carried out in the building zones that help accomplish individual building "Missions".
- BVM3 tool supports 3 types of functions. (since it is defined specifically for USAFA Arnold hall)
- If more than 3 functions are defined no error is generated; however the tool automatically reads and uses only the first 3.

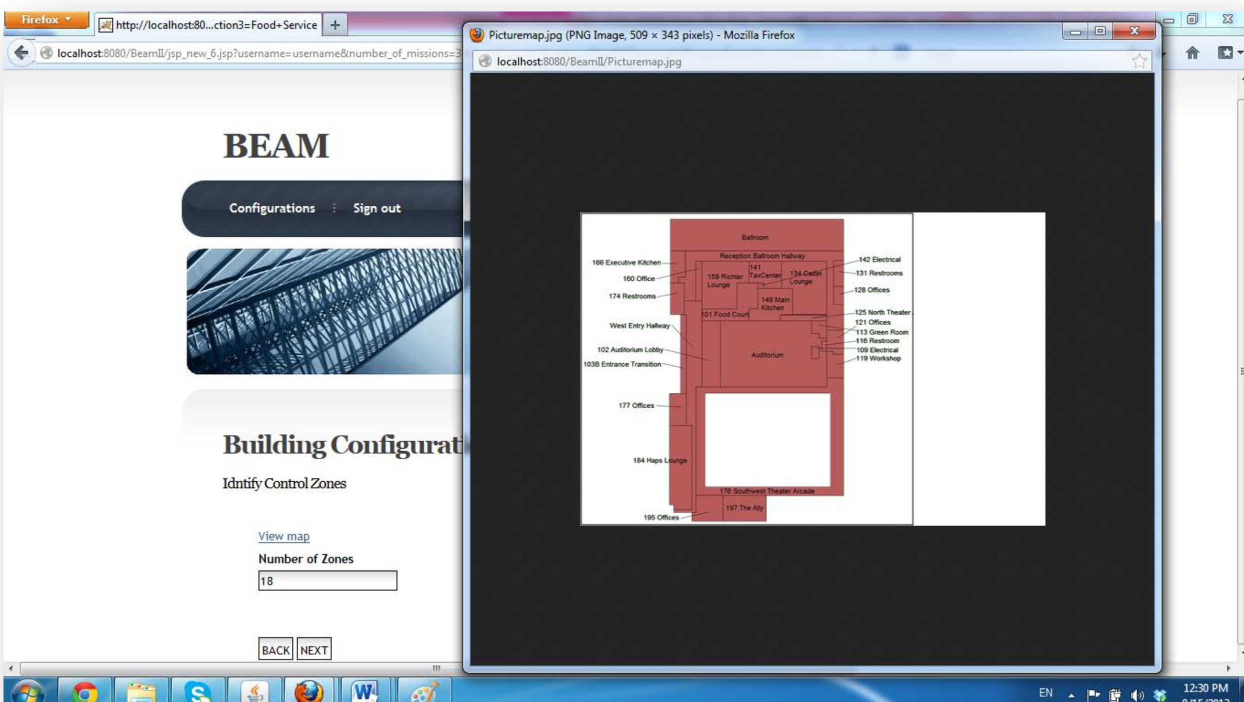
Step 2.5: Identify Function names



Notes:

- The sequence of data entry is important here. In other words, always use "Admin" as first and "Food Service" as last "Function" input. Since the BVM3 questionnaires are designed according to this sequence. The question types are different for each "Function" type.

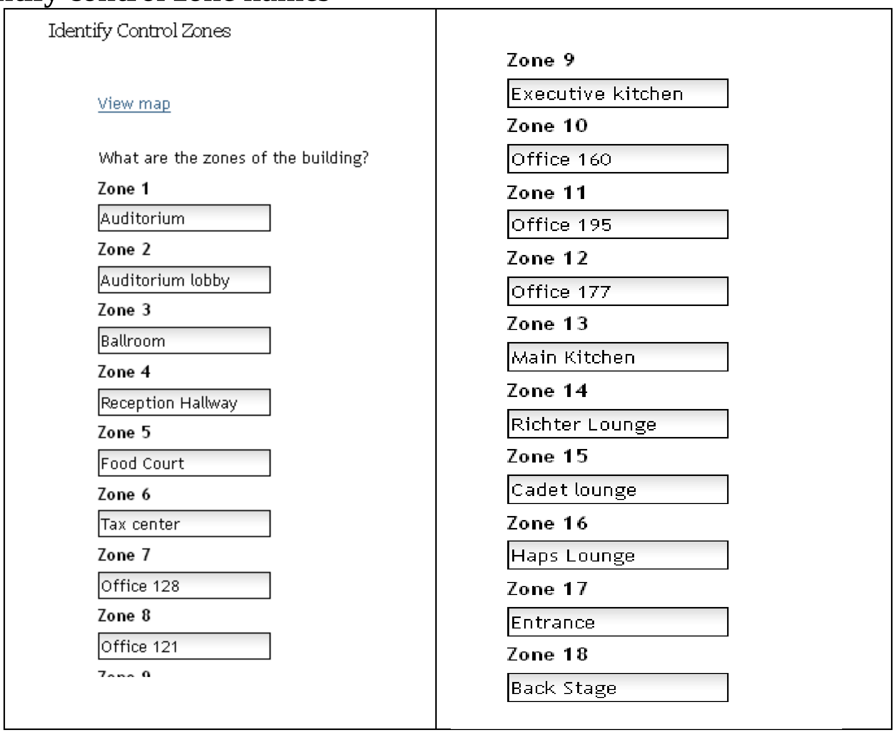
Step 2.6: Identify control zones



Notes:

- If in step 2.1 building map was uploaded, user can view this map now by clicking “View Map”
- Suggested number of zones for USAFA : <u>18 zones</u>

Step 2.7: Identify control zone names



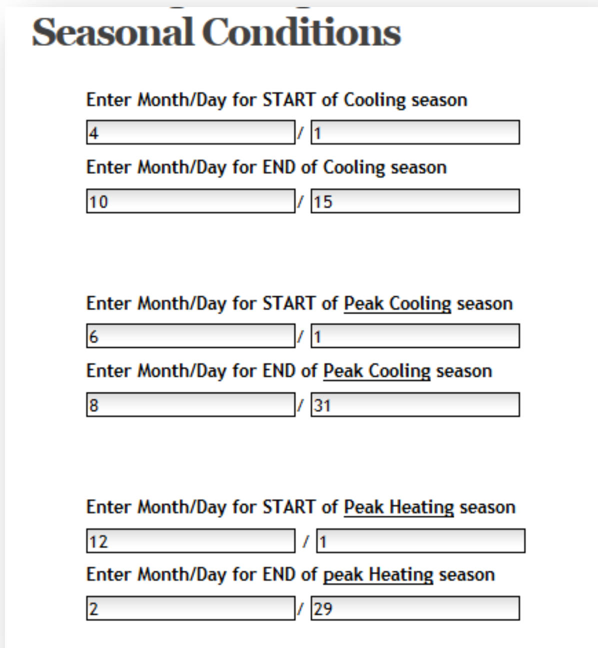
A complete list of zones for USAFA and the associated asset systems is listed in **Table 60** below. **Table 60** is also going to be used in step 3.12 for zone asset Association.
The data entry is in no particular order. Click NEXT to proceed.

Table 60: List of zones, associated asset systems and functions assigned

Zone Name	Associated asset System	Associated Functions
Auditorium lobby	Chilled Water System, AHU-6	Public/Private Events
Auditorium	Chilled Water System, AHU-1C, AHU-2	Public/Private Events
Ballroom	Chilled Water System, AHU-7	Public/Private Events
Reception Hallway	Chilled Water System, AHU-10	Public/Private Events
Food Court	Chilled Water System, AHU-1A	Food Service
Tax center	Chilled Water System, AHU-1A	Admin
Office 128	Chilled Water System, AHU-9	Admin
Office 121	Chilled Water System, AHU-9	Admin
Executive kitchen	Chilled Water System, AHU-9	Food Service
Office 160	Chilled Water System, AHU-1A	Admin
Office 195	Chilled Water System, AHU-4	Admin

Office 177	Chilled Water System, AHU-4	Admin
Main Kitchen	Chilled Water System, AHU-1A	Food Service
Richter Lounge	Chilled Water System, AHU-1A	Public/Private Events
Cadet lounge	Chilled Water System, AHU-8	Public/Private Events
Haps Lounge	Chilled Water System, AHU-5	Public/Private Events
Entrance	Chilled Water System, AHU-6	Admin
Back Stage	Chilled Water System, AHU-1D	Public/Private Events

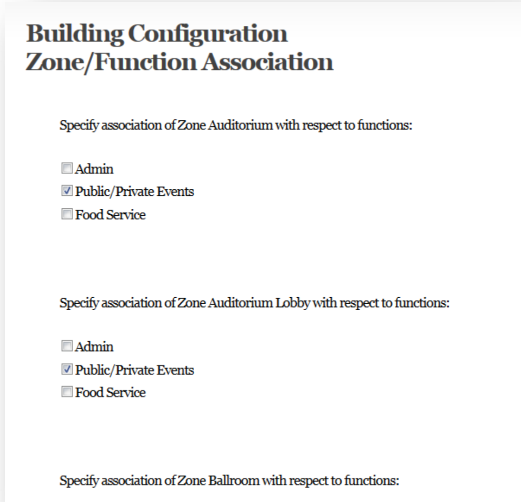
Step 2.8: Building seasonal conditions (please input the following data and click NEXT):



Notes:

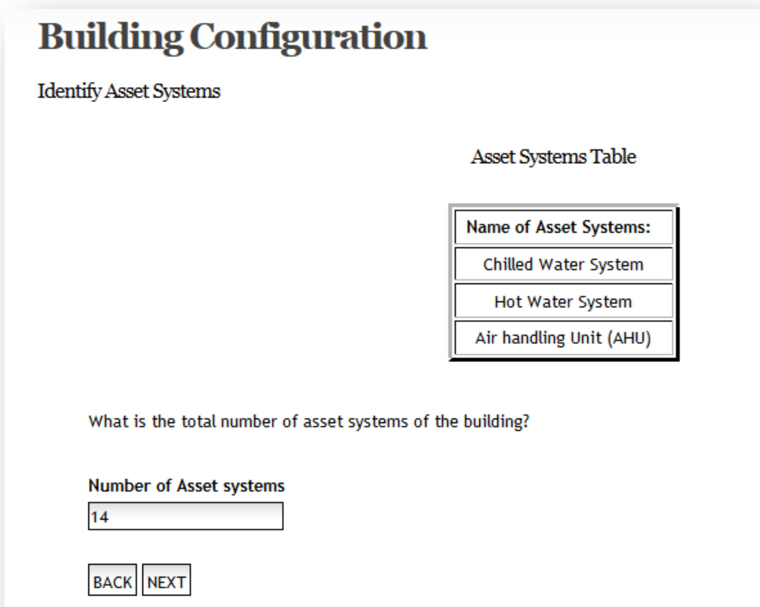
- Dates should be input as displayed for instance 4-1 for April 1st NOT 04-01

Step 2.9: Zone/Function Association



Notes: More than 1 "Function" can be associated with each zone; therefore more than one box can be marked for each zone. Please use **Table 60** to associate each zone with its functions.

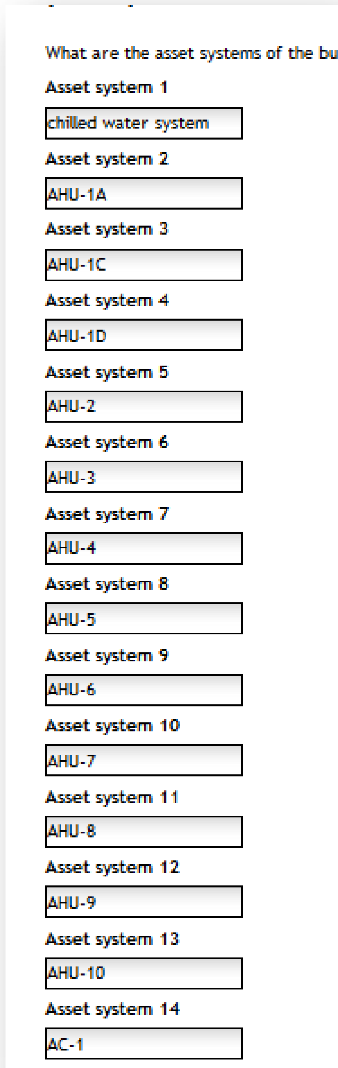
Step 2.10: Identify Asset Systems



Notes:

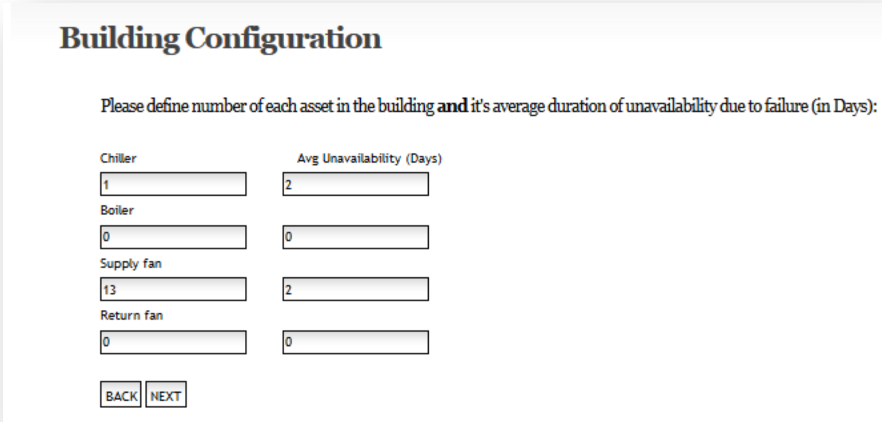
- The Assets systems supported in BVM tool are the ones listed in the Asset Systems Table in the above snapshot for Step 2.10.
- Number of Asset systems in USAFA Arnold Hall=14

Step 2.11: Identify Asset System Names and click NEXT



Note: The data entry does not have particular order

Step 2.12:
Number of each asset in the building and average duration of unavailability due to failure



Notes:

- Average Unavailability is in days
- If an asset does not exist in a building inputs are zero.

Step 2.13: Asset-Asset System Association.
The Following **Table 61** can be used for USAFA associations:

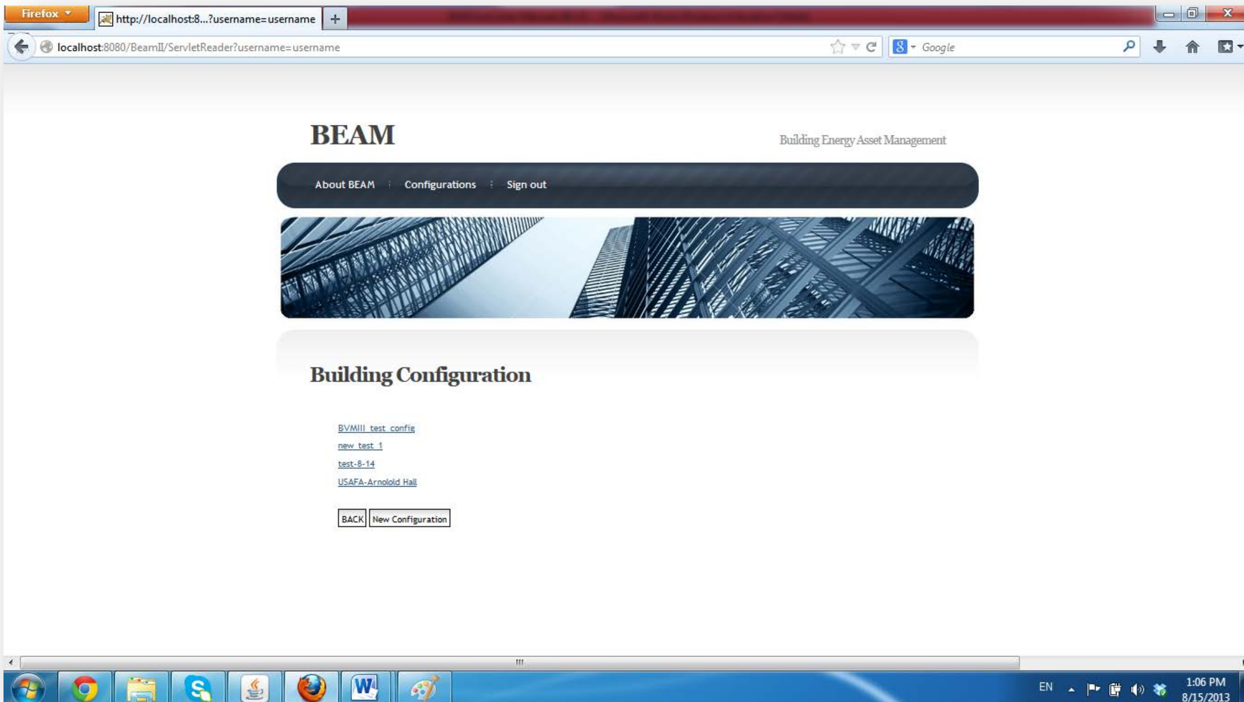
Table 61: Asset System/Asset Association

Asset System	Asset
Chilled Water System	chiller1
AHU-1A	supply Fan1
AHU-1C	supply Fan2
AHU-1D	supply Fan3
AHU-2	supply Fan4
AHU-3	supply Fan5
AHU-4	supply Fan6
AHU-5	supply Fan7
AHU-6	supply Fan8
AHU-7	supply Fan9
AHU-8	supply Fan10
AHU-9	supply Fan11
AHU-10	supply Fan12
AC-1	supply Fan13

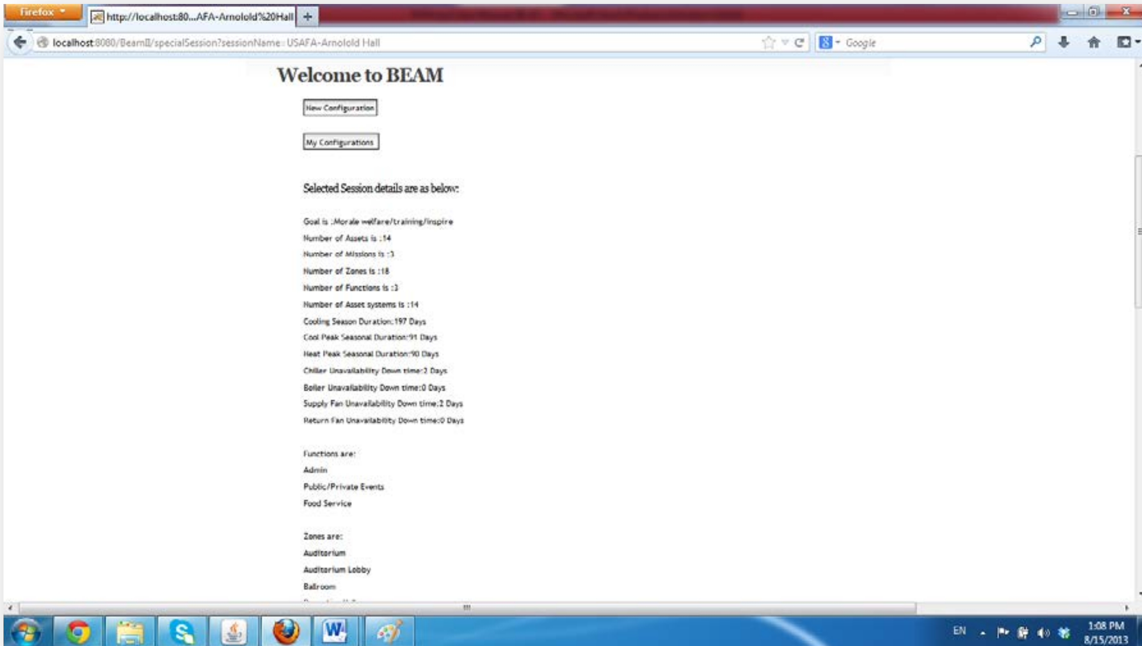
Step 2.14:
Assign a configuration name (say "Beam_Test_8_17") and save the configuration.

Step 3: Using BVM questionnaires (BVM-I, -II or –III)

Step 3.1:
User can build a new configuration or choose to upload and use the already saved configuration from the list. Here **we will upload** "Beam_Test_8_17" just saved by clicking "My Configurations". Snapshot below shows the configurations saved on a machine at RU. Click the displayed link "Beam_Test_8_17" in the next window.

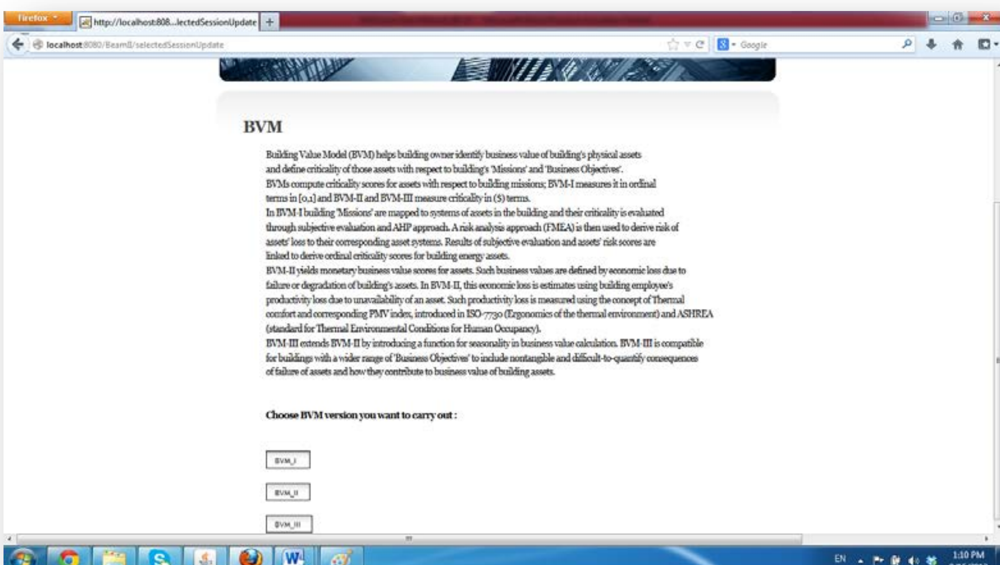


Step 3.2:
Upon choosing a configuration, the data saved for the configuration is displayed to the user, see Example snapshot below):

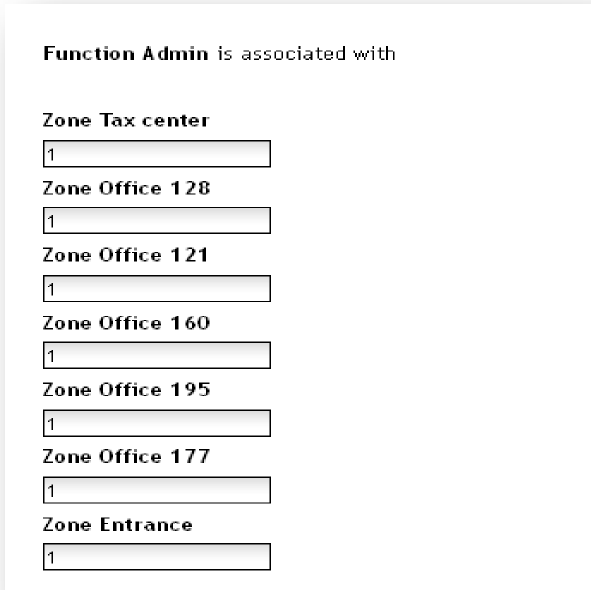


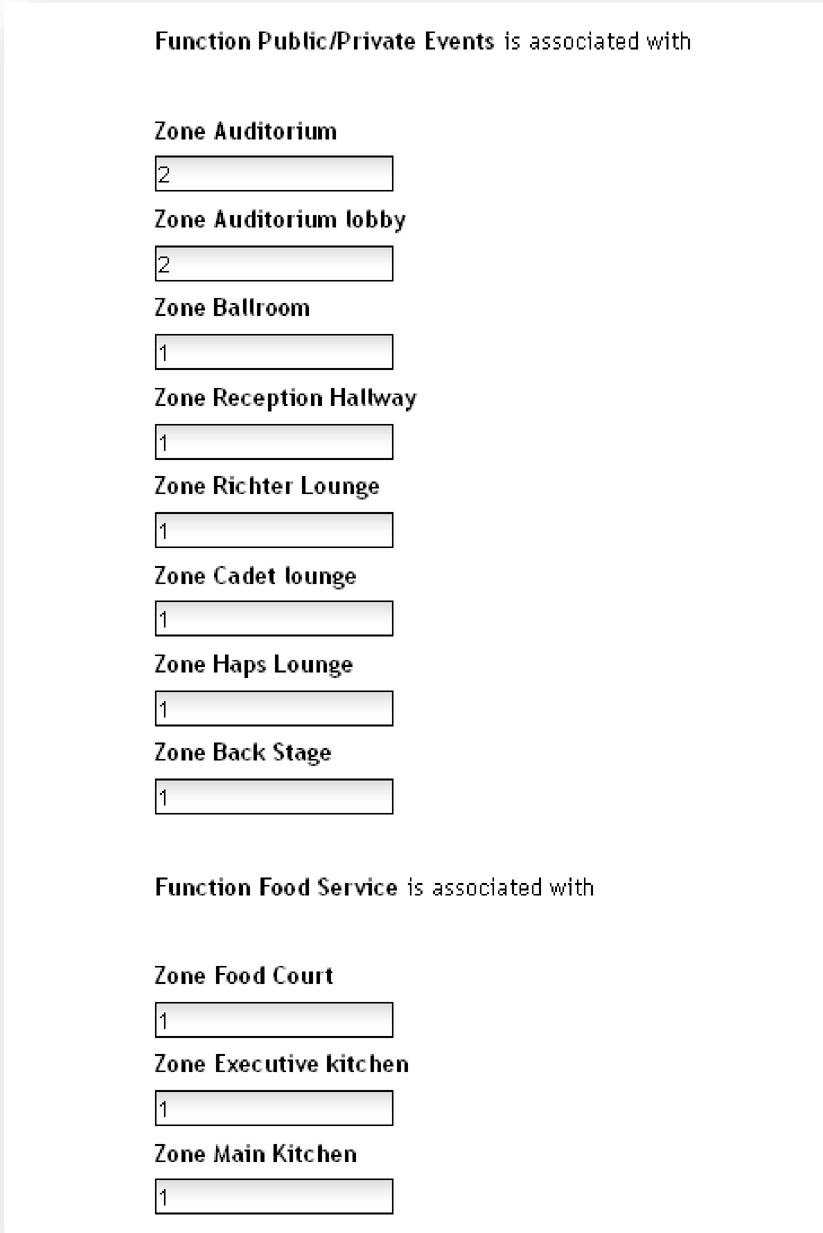
The user then can click the "Use these values for BVMs" button (please scroll to the bottom) to use the values in configuration for BVM questionnaire.

Step 3.3:
User can choose to select either BVM-I, -II or III by clicking on the buttons:



Step 3.4: for USAFA, BVM-III is going to be selected:
In this step the number of intensive occupation periods for zones associated with each function is defined. For instance an "Auditorium" can have 2 intensive occupation periods. One in summer and one in winter: Input "2" in the zone Auditorium and Zone Auditorium Lobby, input "1" in all other zones.




Function Public/Private Events is associated with

Zone Auditorium

2

Zone Auditorium lobby

2

Zone Ballroom

1

Zone Reception Hallway

1

Zone Richter Lounge

1

Zone Cadet lounge

1

Zone Haps Lounge

1

Zone Back Stage

1

Function Food Service is associated with

Zone Food Court

1

Zone Executive kitchen

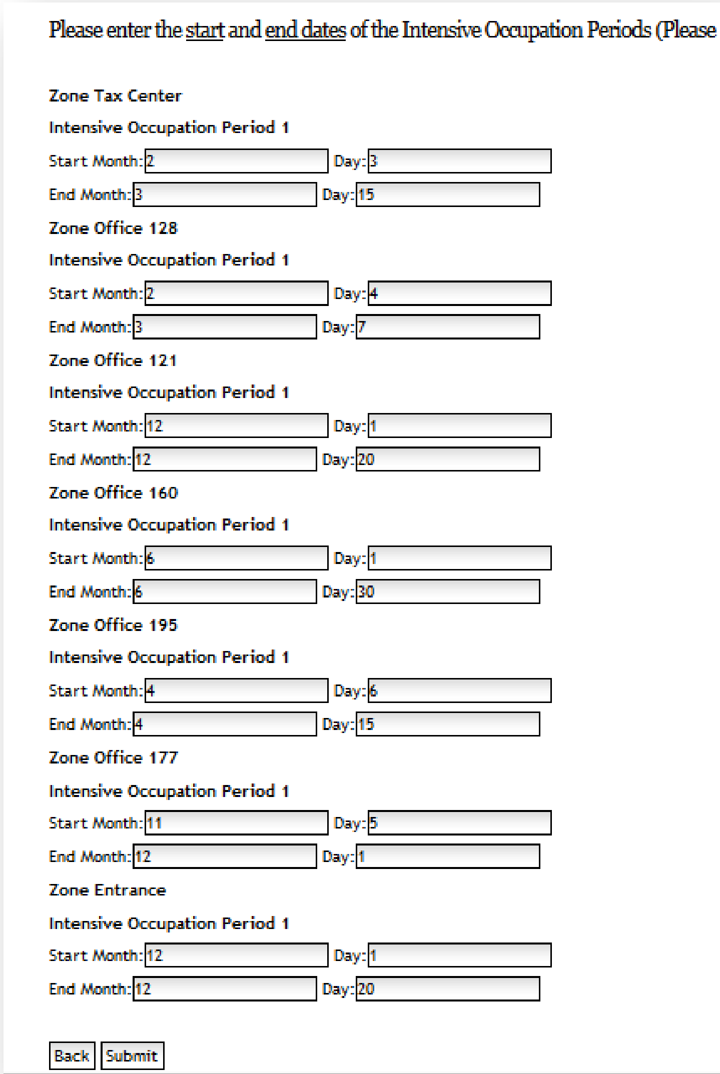
1

Zone Main Kitchen

1

Steps 3.5 & 3.6 are questionnaire specific to zones associated with “Admin Function”

Step 3.5: Intensive occupation period for zones associated with “Admin Function”


Please enter the start and end dates of the Intensive Occupation Periods (Please I

Zone Tax Center
Intensive Occupation Period 1
Start Month: 2 Day: 3
End Month: 3 Day: 15

Zone Office 128
Intensive Occupation Period 1
Start Month: 2 Day: 4
End Month: 3 Day: 7

Zone Office 121
Intensive Occupation Period 1
Start Month: 12 Day: 1
End Month: 12 Day: 20

Zone Office 160
Intensive Occupation Period 1
Start Month: 6 Day: 1
End Month: 6 Day: 30

Zone Office 195
Intensive Occupation Period 1
Start Month: 4 Day: 6
End Month: 4 Day: 15

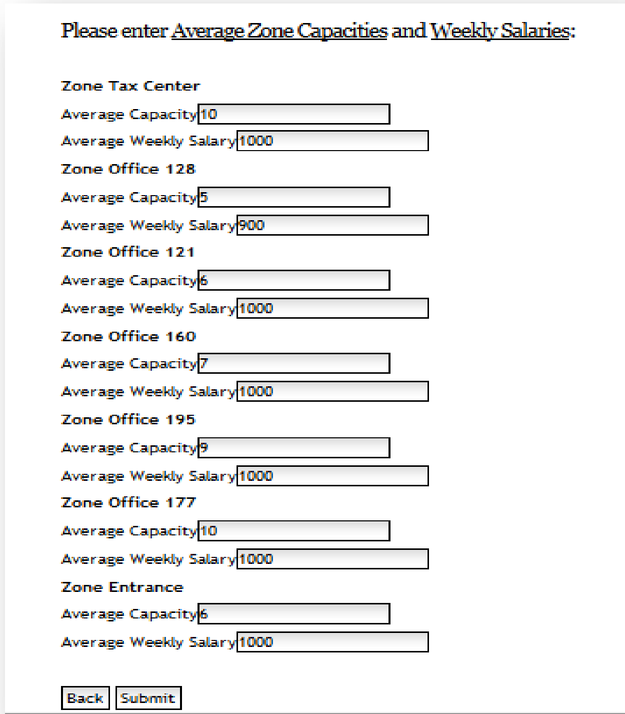
Zone Office 177
Intensive Occupation Period 1
Start Month: 11 Day: 5
End Month: 12 Day: 1

Zone Entrance
Intensive Occupation Period 1
Start Month: 12 Day: 1
End Month: 12 Day: 20

Back Submit

Note: follow instructions in step 2.8 for date entry

Step 3.6:
Average Weekly Salary and Average Zone capacity for zones associated with "Admin Function":


Please enter Average Zone Capacities and Weekly Salaries:

Zone Tax Center
Average Capacity 10
Average Weekly Salary 1000
Zone Office 128
Average Capacity 5
Average Weekly Salary 900
Zone Office 121
Average Capacity 6
Average Weekly Salary 1000
Zone Office 160
Average Capacity 7
Average Weekly Salary 1000
Zone Office 195
Average Capacity 9
Average Weekly Salary 1000
Zone Office 177
Average Capacity 10
Average Weekly Salary 1000
Zone Entrance
Average Capacity 6
Average Weekly Salary 1000

Back Submit

Notes:

- Salary is in dollars
- The numbers are dummy numbers and NOT USAFA data.

Steps 3.7& 3.8 are questionnaire specific to zones associated with “Public/Private Events Function”

Step 3.7:
Similar to step 3.5, intensive occupation periods are defined for zones Associated with “Public/Private Events Function”. Snapshot below shows part of the data entry and not the complete zones.
Data are dummy numbers and NOT USAFA data

Zone Auditorium

Intensive Occupation Period 1

Start Month: 12 Day: 24

End Month: 1 Day: 5

Zone Auditorium

Intensive Occupation Period 2

Start Month: 8 Day: 1

End Month: 8 Day: 15

Zone Auditorium lobby

Intensive Occupation Period 1

Start Month: 4 Day: 1

End Month: 6 Day: 31

Zone Auditorium lobby

Intensive Occupation Period 2

Start Month: 12 Day: 24

End Month: 1 Day: 5

Zone Ballroom

Intensive Occupation Period 1

Start Month: 12 Day: 23

End Month: 1 Day: 5

Zone Reception Hallway

Intensive Occupation Period 1

Start Month: 3 Day: 1

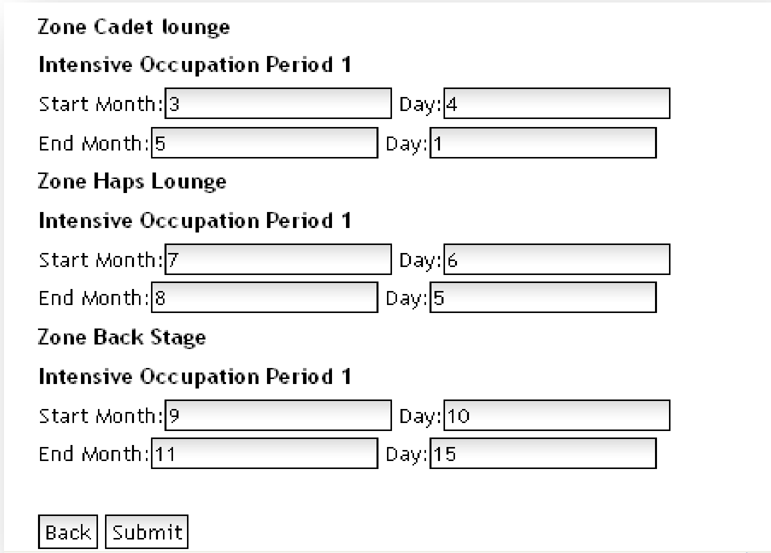
End Month: 5 Day: 20

Zone Richter Lounge

Intensive Occupation Period 1

Start Month: 6 Day: 1

End Month: 8 Day: 20



Zone Cadet lounge

Intensive Occupation Period 1

Start Month: 3 Day: 4

End Month: 5 Day: 1

Zone Haps Lounge

Intensive Occupation Period 1

Start Month: 7 Day: 6

End Month: 8 Day: 5

Zone Back Stage

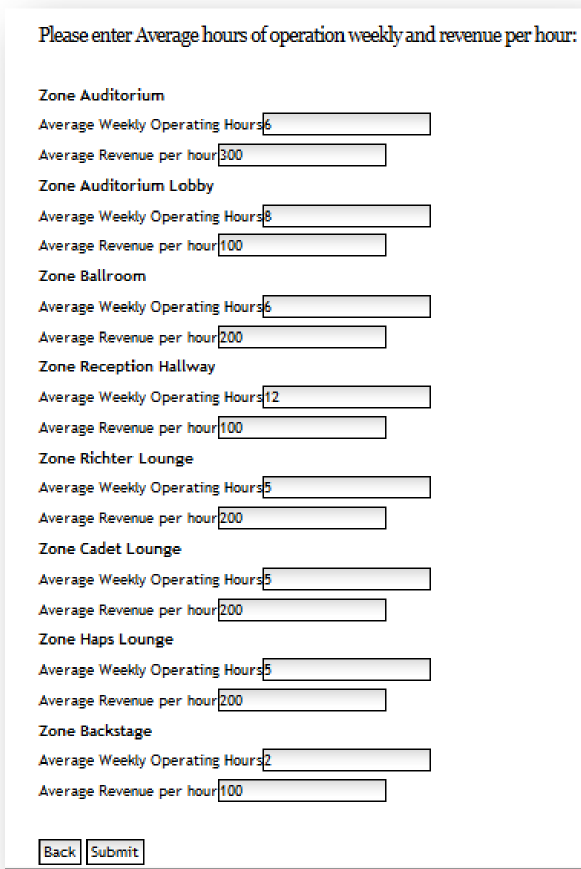
Intensive Occupation Period 1

Start Month: 9 Day: 10

End Month: 11 Day: 15

Back Submit

Step 3.8: "Average hours of operation" and "revenue per hour" for zones Associated with "Public/Private Events Function".



Please enter Average hours of operation weekly and revenue per hour:

Zone Auditorium

Average Weekly Operating Hours 6

Average Revenue per hour 300

Zone Auditorium Lobby

Average Weekly Operating Hours 8

Average Revenue per hour 100

Zone Ballroom

Average Weekly Operating Hours 6

Average Revenue per hour 200

Zone Reception Hallway

Average Weekly Operating Hours 12

Average Revenue per hour 100

Zone Richter Lounge

Average Weekly Operating Hours 5

Average Revenue per hour 200

Zone Cadet Lounge

Average Weekly Operating Hours 5

Average Revenue per hour 200

Zone Haps Lounge

Average Weekly Operating Hours 5

Average Revenue per hour 200

Zone Backstage

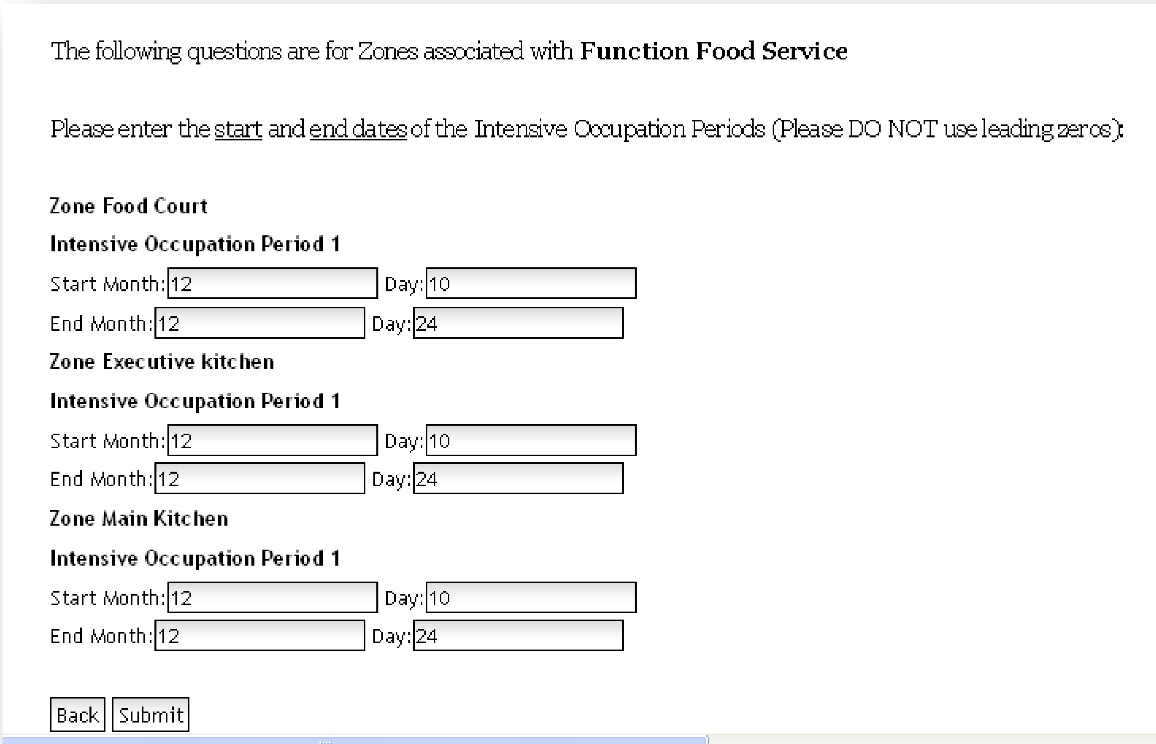
Average Weekly Operating Hours 2

Average Revenue per hour 100

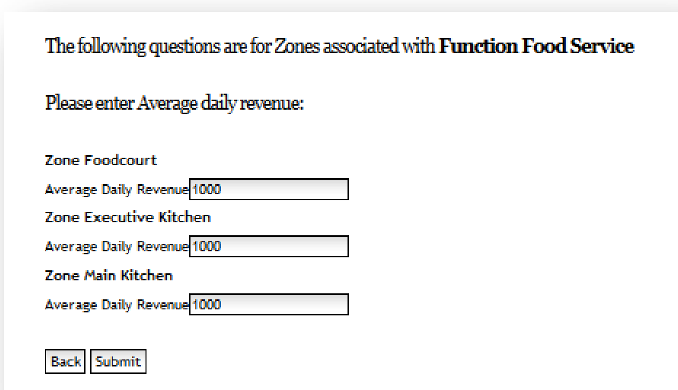
Back Submit

Steps 3.9& 3.10 are questionnaire specific to zones associated with "Food Service Function"

Step 3.9:
Similar to step 3.5 & 3.7, intensive occupation periods are defined for zones Associated with "Food Services Function". Snapshot below shows part of the data entry and not the complete zones.
Data are dummy numbers and NOT USAFA data



Step3.10: "Average daily revenue" for zones Associated with "Food service Function".



Step3.11: Zone/Asset Association:

Please use **Table 62** below for zone asset association for USAFA, based on the configuration defined in step 2. Click NEXT.

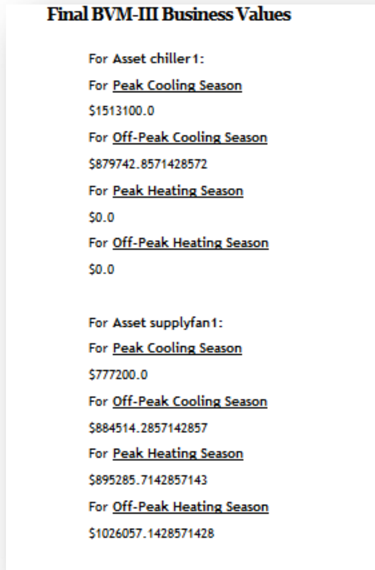
Table 62: Zone Asset Association

Zone Name	Associated asset System
Auditorium lobby	Chiller1, Supply fan 8
Auditorium	Chiller1, Supply Fan 2, Supply Fan 4
Ballroom	Chiller1, Supply Fan 9
Reception Hallway	Chiller1, Supply Fan 12
Food Court	Chiller1, Supply Fan 1
Tax center	Chiller1, Supply Fan 1
Office 128	Chiller1, Supply Fan 11
Office 121	Chiller1, Supply Fan 11
Executive kitchen	Chiller1, Supply Fan 11
Office 160	Chiller1, Supply Fan 1
Office 195	Chiller1, Supply Fan 6
Office 177	Chiller1, Supply Fan 6
Main Kitchen	Chiller1, Supply Fan 1
Richter Lounge	Chiller1, Supply Fan 1
Cadet lounge	Chiller1, Supply Fan 10
Haps Lounge	Chiller1, Supply Fan 7
Entrance	Chiller1, Supply Fan 8
Back Stage	Chiller1, Supply Fan 3

More than one asset can serve one zone so multiple boxes can be marked for each zone.

Step 3.12:

Asset seasonal Business Values are displayed. The Business Values should be non-negative. If any of the assets are not associated with any zone defined in the configuration the Business Value will be zero. Example: Supply fan 5's business Value in this example is zero since Supply fan 5 (Associated with AHU-3) is not associated with any zone in configuration. The same condition holds for Supply fan 13(Associated with AC-1). Also, you can find BVM3.xml data



file in the Apache Tomcat installation

For Asset supplyfan2:

For Peak Cooling Season

$48000.0

For Off-Peak Cooling Season

$61257.14285714286

For Peak Heating Season

$49942.85714285714

For Off-Peak Heating Season

$54628.571428571435

For Asset supplyfan3:

For Peak Cooling Season

$121200.0

For Off-Peak Cooling Season

$142514.2857142857

For Peak Heating Season

$143285.7142857143

For Off-Peak Heating Season

$400057.14285714284

For Asset supplyfan4:

For Peak Cooling Season

$48000.0

For Off-Peak Cooling Season

$61257.14285714286

For Peak Heating Season

$49942.85714285714

For Off-Peak Heating Season

$54628.571428571435

For Asset supplyfan5:

For Peak Cooling Season

$0.0

For Off-Peak Cooling Season

$0.0

For Peak Heating Season

$0.0

For Off-Peak Heating Season

$0.0

For Asset supplyfan6:

For Peak Cooling Season

$331800.0

For Off-Peak Cooling Season

$355400.0

For Peak Heating Season

$288000.0

For Off-Peak Heating Season

$249600.0

For Asset supplyfan7:

For Peak Cooling Season

$60000.0

For Off-Peak Cooling Season

$76571.42857142858

For Peak Heating Season

$62428.57142857141

For Off-Peak Heating Season

$68285.71428571429

For Asset supplyfan8:

For Peak Cooling Season

$171600.0

For Off-Peak Cooling Season

$214400.0

For Peak Heating Season

$174800.0

For Off-Peak Heating Season

$191200.00000000003

For Asset supplyfan9:

For Peak Cooling Season

$74400.0

For Off-Peak Cooling Season

$94285.71428571428

For Peak Heating Season

$75942.85714285713

For Off-Peak Heating Season

$81942.85714285716

For Asset supplyfan10:

For Peak Cooling Season

$60000.0

For Off-Peak Cooling Season

$76571.42857142858

For Peak Heating Season

$62428.57142857141

For Off-Peak Heating Season

$68285.71428571429

For Asset supplyfan11:

For Peak Cooling Season

$313500.0

For Off-Peak Cooling Season

$378142.85714285716

For Peak Heating Season

$360185.71428571426

For Off-Peak Heating Season

$598571.4285714286

For Asset supplyfan12:

For Peak Cooling Season

$72000.0

For Off-Peak Cooling Season

$91885.71428571428

For Peak Heating Season

$74914.28571428572

For Off-Peak Heating Season

$81942.85714285716

For Asset supplyfan13:

For Peak Cooling Season

$0.0

For Off-Peak Cooling Season

$0.0

For Peak Heating Season

$0.0

For Off-Peak Heating Season

$0.0

Appendix G: BEAM Runtime Tool Installation & User Manual

Runtime Tools for Building Energy Asset Management (BEAM)

BEAM Setup

Prerequisites Software

Install .NET libraries

Need to install the following updates on top of .NET3.5 Framework

- ADO.NET Data Services Update for .NET Framework 3.5 SP1 for Windows 2000, Windows Server 2003, Windows XP, Windows Vista and Windows Server 2008

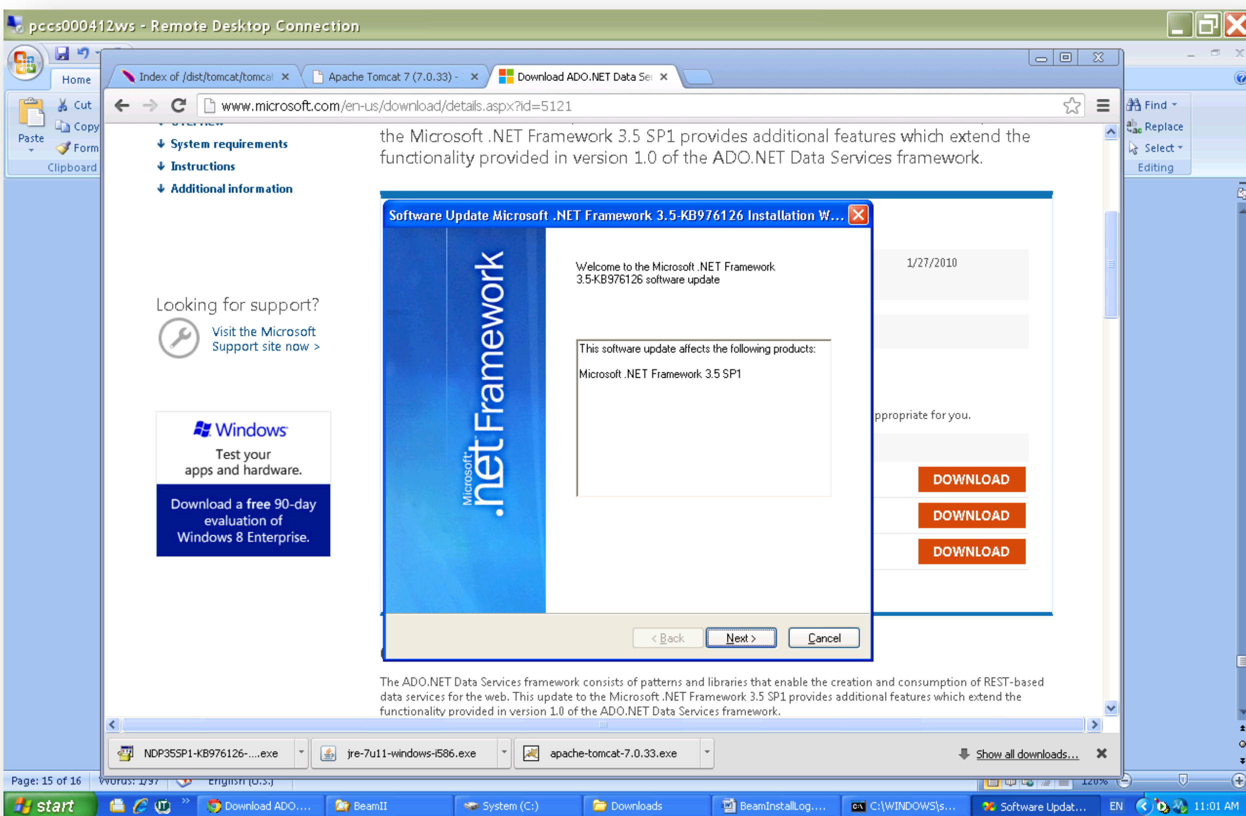
 http://www.microsoft.com/downloads/en/details.aspx?displaylang=en&FamilyID=4b710b89-8576-46cf-a4bf-331a9306d555

- Microsoft Visual C++ 2010 Redistributable Package (x86)

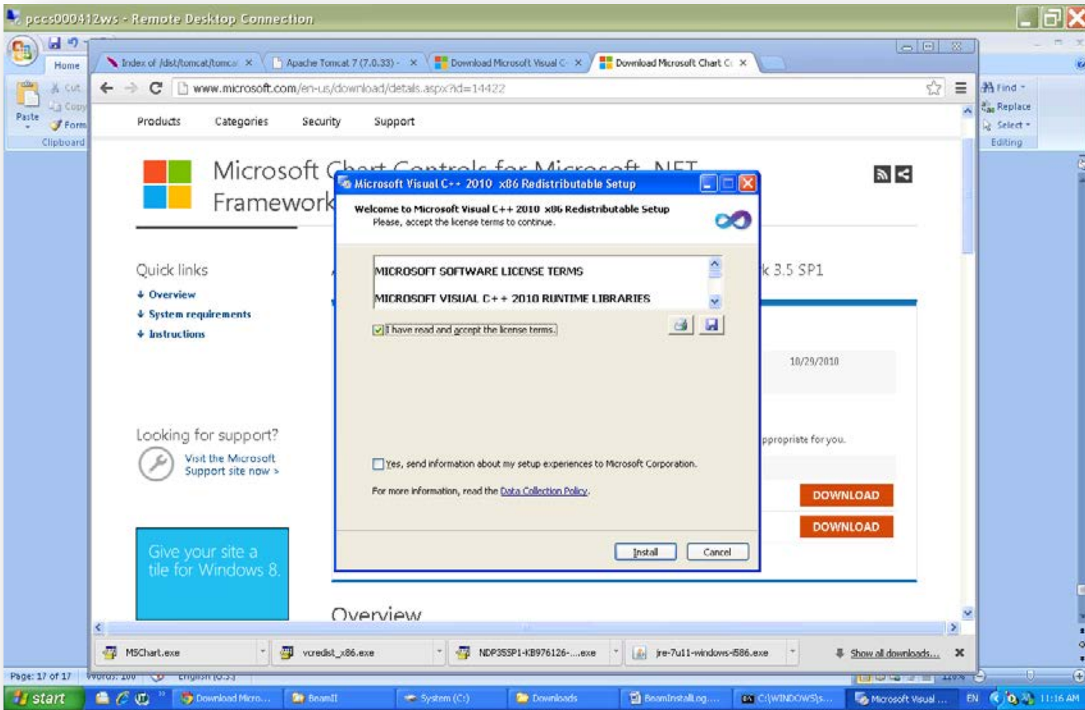
 http://www.microsoft.com/downloads/en/details.aspx?FamilyID=a7b7a05e-6de6-4d3a-a423-37bf0912db84

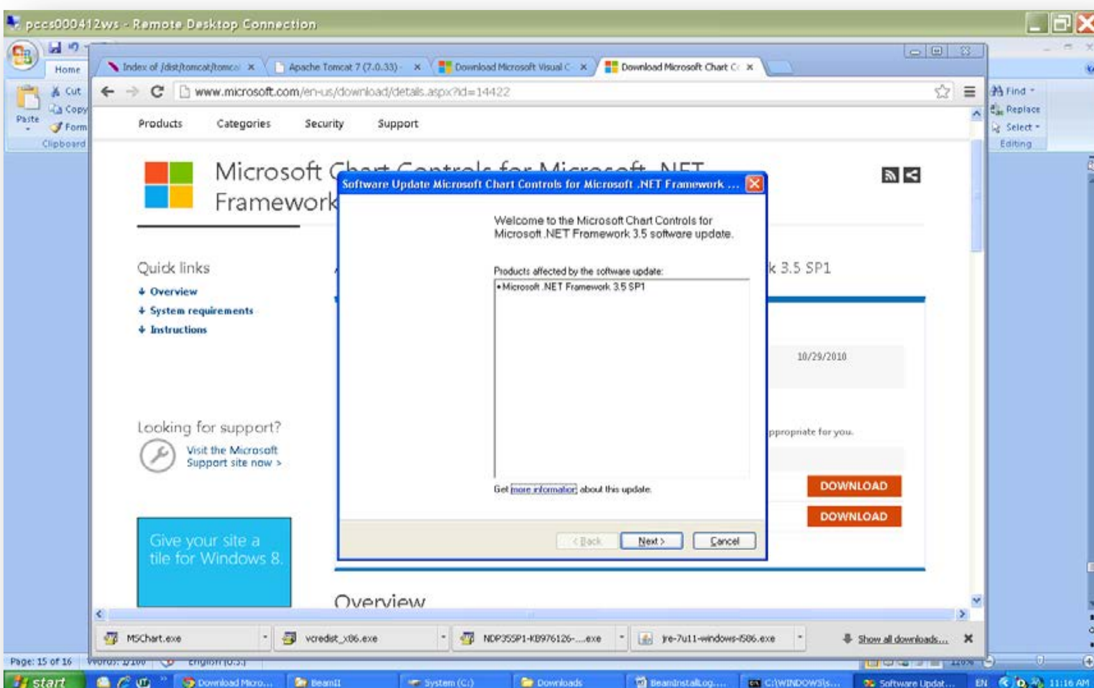
- Microsoft Chart Controls for Microsoft .NET Framework 3.5

 http://www.microsoft.com/downloads/en/details.aspx?FamilyID=130f7986-bf49-4fe5-9ca8-910ae6ea442c

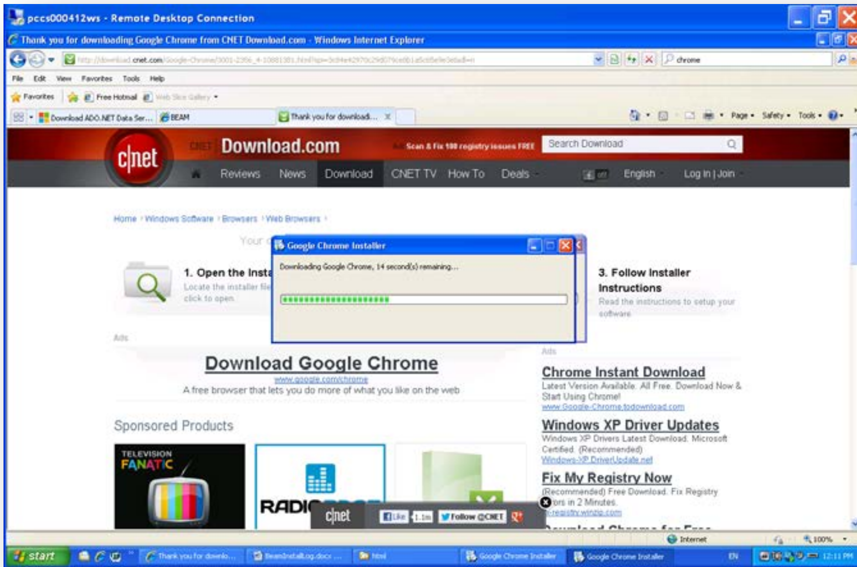


Only install vcredist_x86.exe



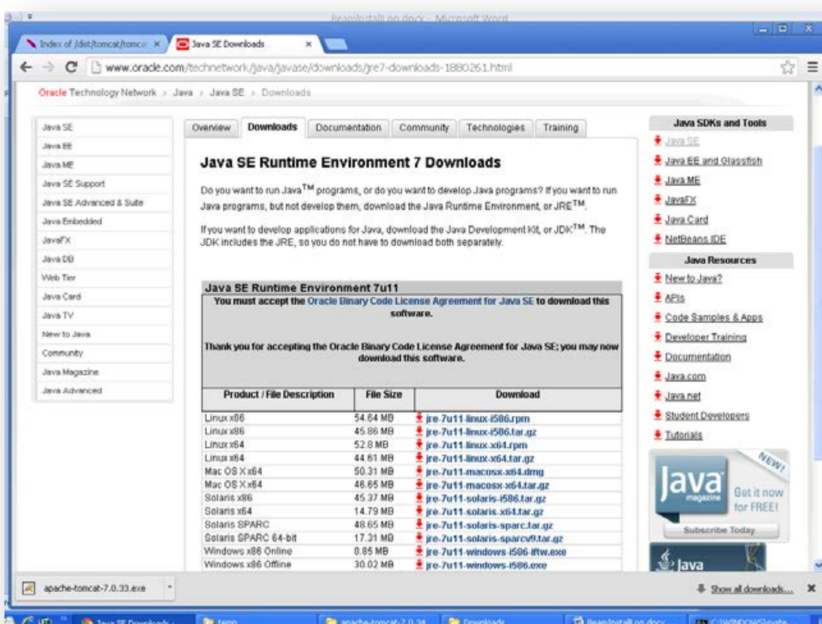


Install Google Chrome
Download Chrome from CNET and run setup



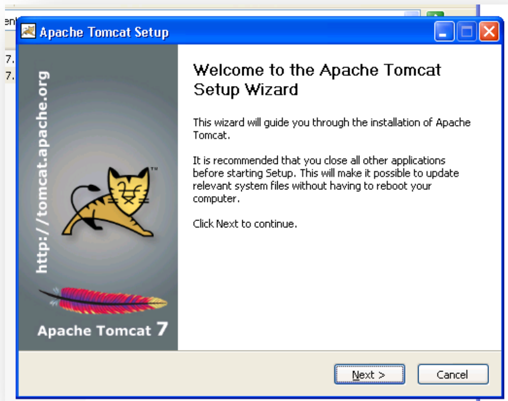
Install Java JRE 6.0 or above

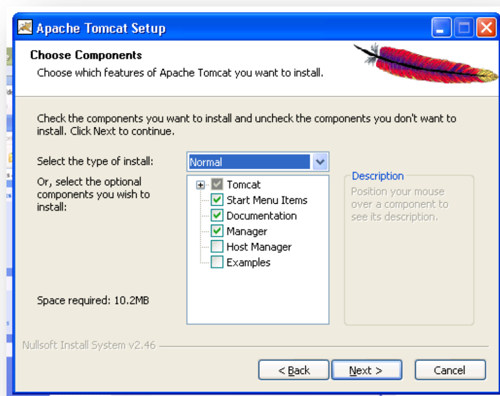
Download from http://www.oracle.com/technetwork/java/javase/downloads/index.html, choose “Windows x86 Offline”

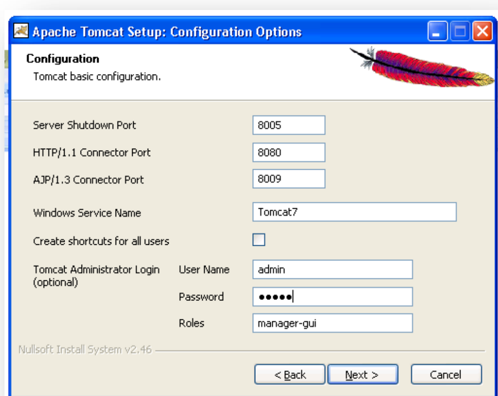


Install Apache Tomcat

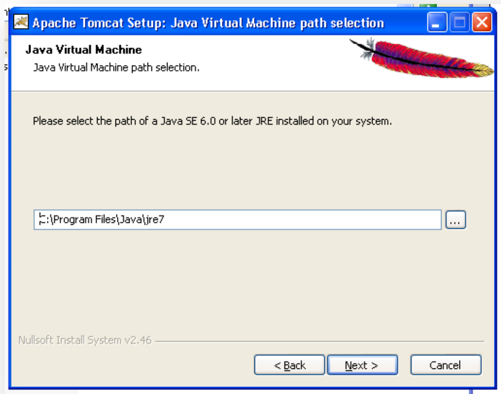
Download apache tomcat from http://archive.apache.org/dist/tomcat/tomcat-7/v7.0.33/bin/

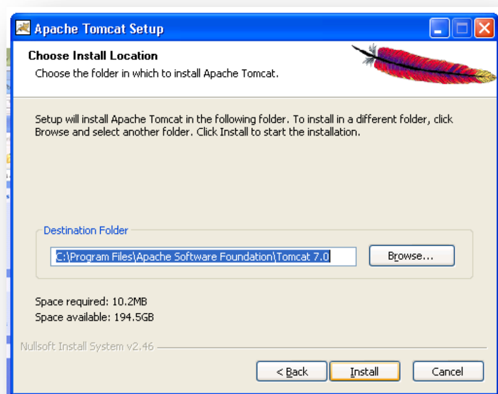


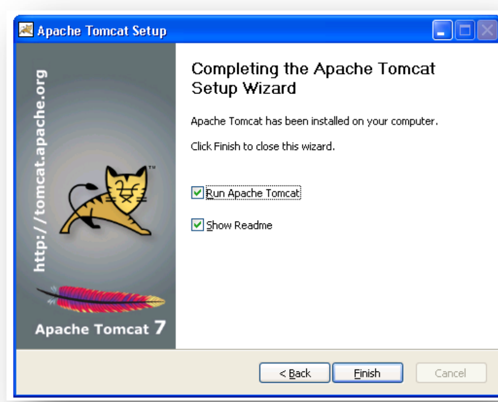




User Name: admin
Password: admin



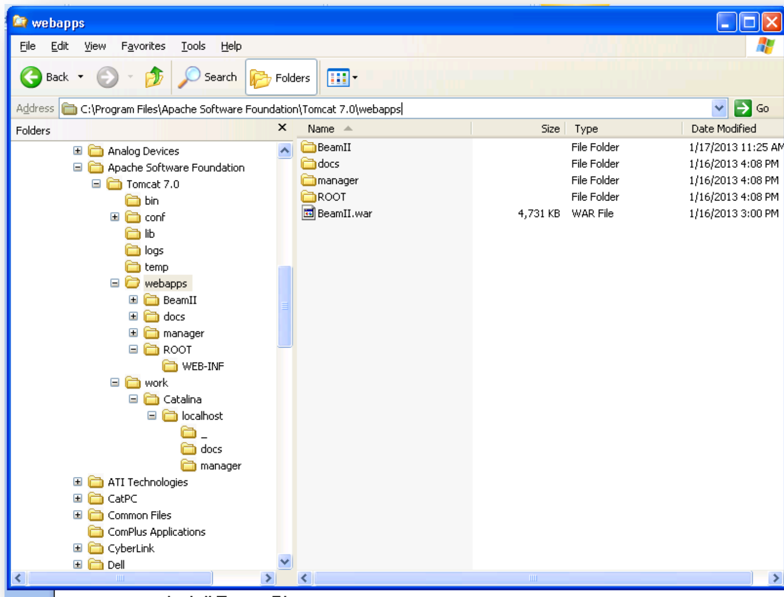




Setup BEAM Configuration Tool

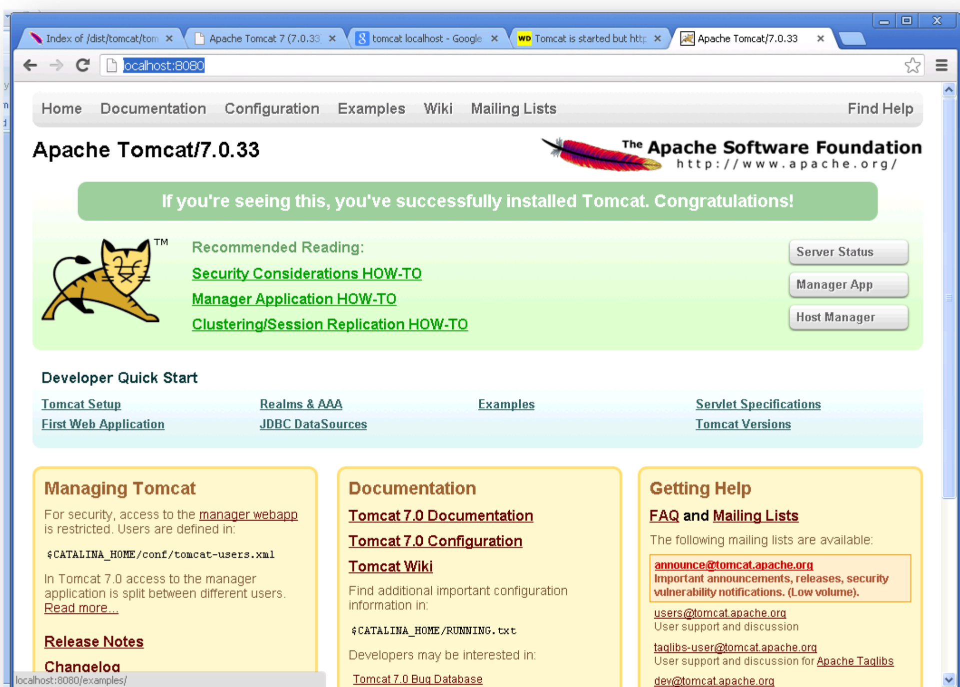
Copy “BEAMIII.war” to C:\Program Files\Apache Software Foundation\Tomcat 7.0\webapps

A folder named BEAMIII is generated automatically



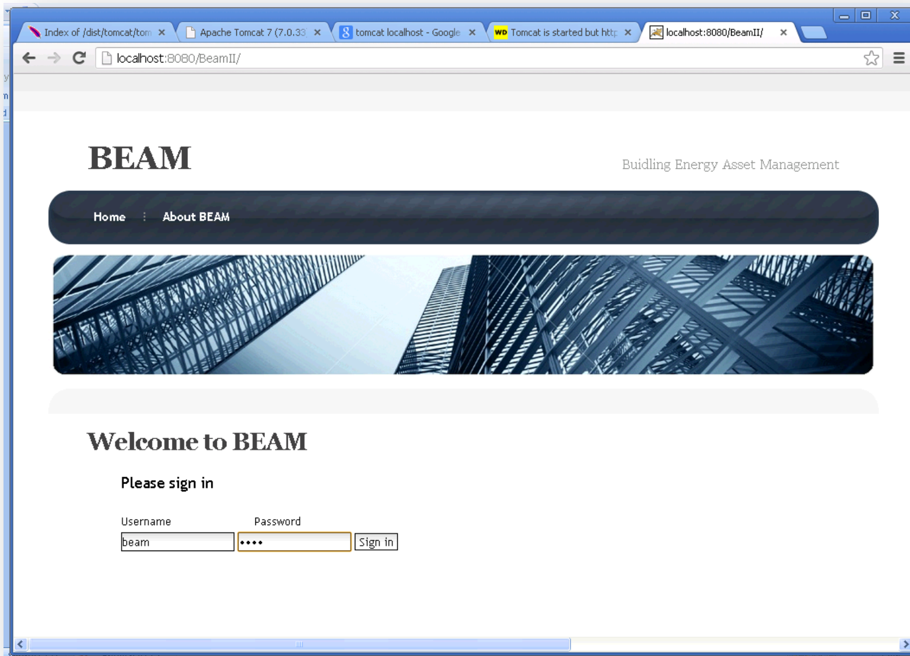
Test BEAM Configuration Tool

Startup Chrome browser and type in Localhost:8080 in the address bar. The browser windows should look like the screenshot below.



Startup BEAM Configuration Tool

Startup Chrome browser and type in URL http://localhost:8080/BeamIII/ (case sensitive)

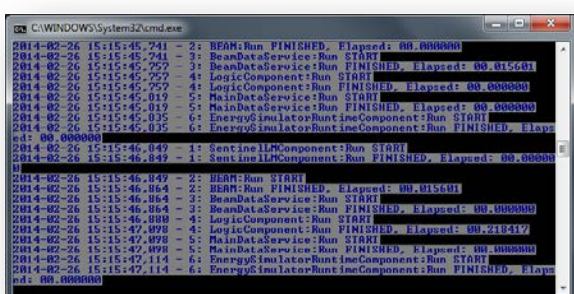


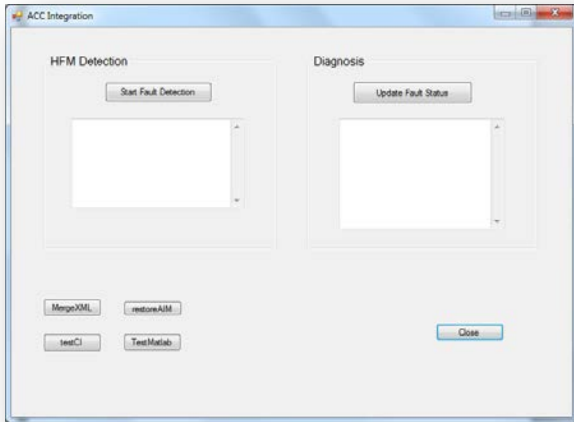
User Name: beam
Password: beam

Startup BEAM Runtime and Runtime HMI

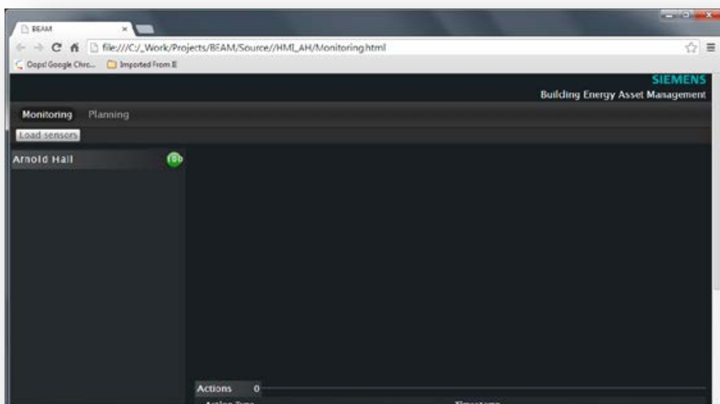
Start the beam runtime by starting the ArnoldHall_1.StartSEB.bat as administrator.

1) Right click on ArnoldHall_1.StartSEB.bat
2) Select "Run as Administrator" from the context menu
3) Two windows like shown below will show up

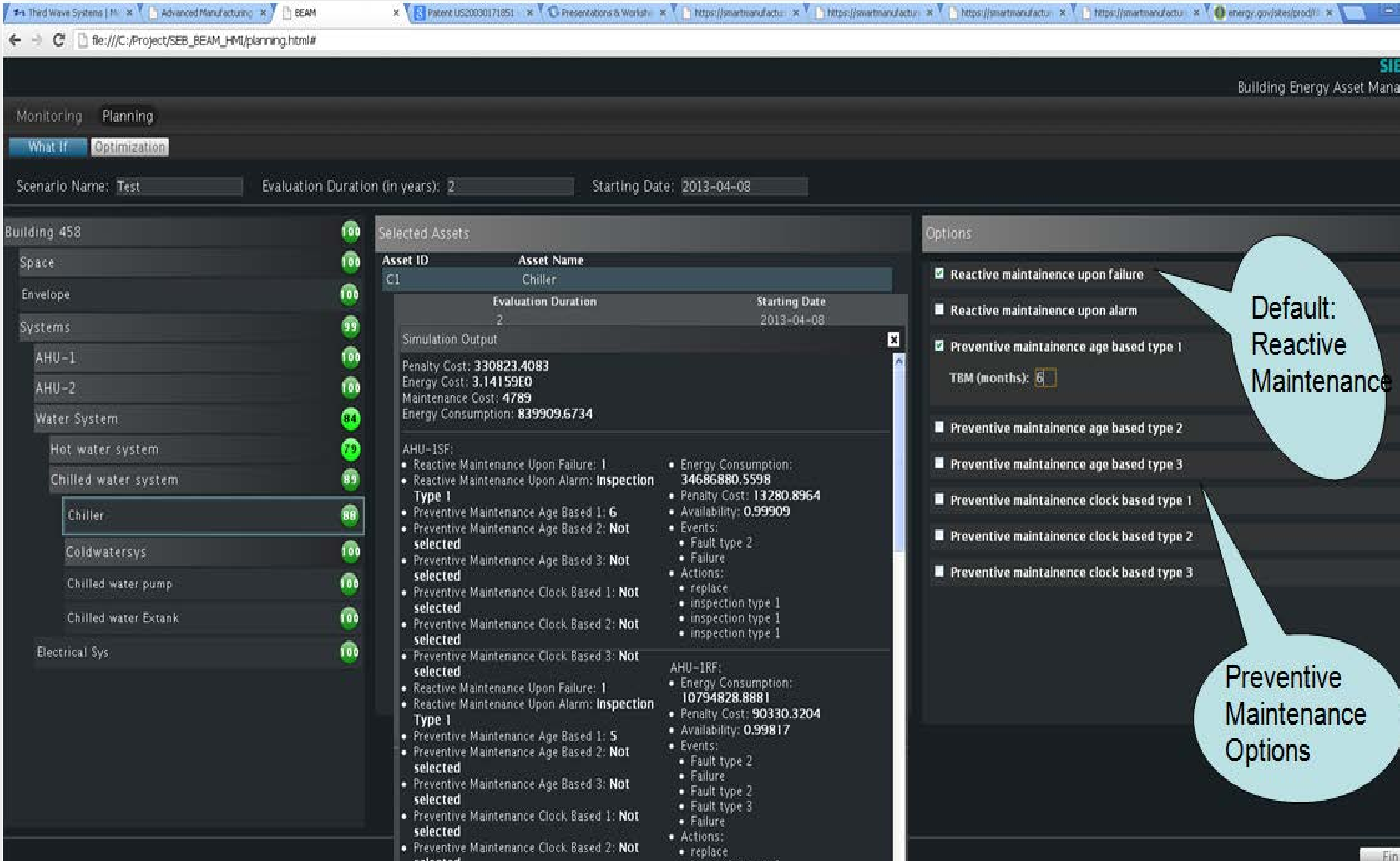




Now start the BEAM Runtime HMI by double clicking the ArnoldHall_2.StartBEAM.bat file. The Chrome browser window with the BEAM HMI should be visible like shown below



BEAM Condition Monitoring Main Screen



BEAM Condition Monitoring main Screen (suite)

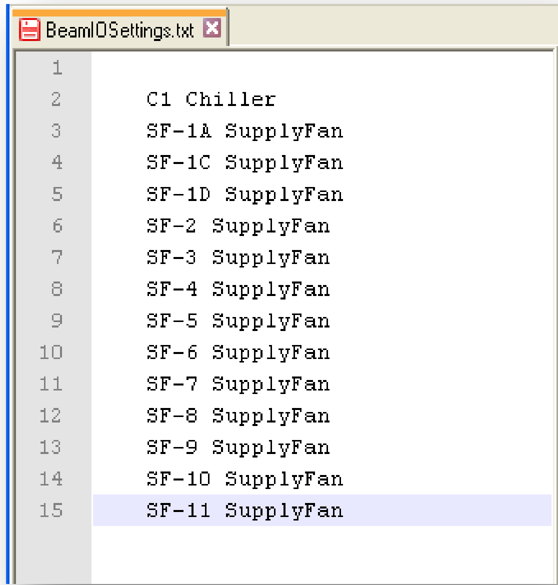
BEAM Limitations
Due to the current BEAM architecture and data model design, there are three limitations Users should keep in mind during their stage of configuration:

Limitation One:
When specifying the season dates, the users should go to the asset model file “asset.xml” (located at \\BEAM_HOME\Resources\ArnoldHall\ ), here BEAM_HOME represents the path where all BEAM binaries located. It is where the users input their season dates (with the node x-path as “//Site/BEAM_Optimization/ Building_Considered/Seasnos”):

```xml
<BeamEngineMode>Optimization</BeamEngineMode>
<BEAM_Optimization Total_Budget="300000" Status="Ready">
  <Building_Considered Name="Arnold Hall" ID="ArnoldHall">
     <Seasons ID="Season" Name="Seasons">
      <Cooling StartDate="4-1" EndDate="10-15">
        <CoolingPeak StartDate="6-1" EndDate="8-30" />
      </Cooling>
      <Heating StartDate="10-16" EndDate="3-31">
        <HeatingPeak StartDate="12-1" EndDate="2-15" />
      </Heating>
    </Seasons>
    <BEAM_Analysis>
```

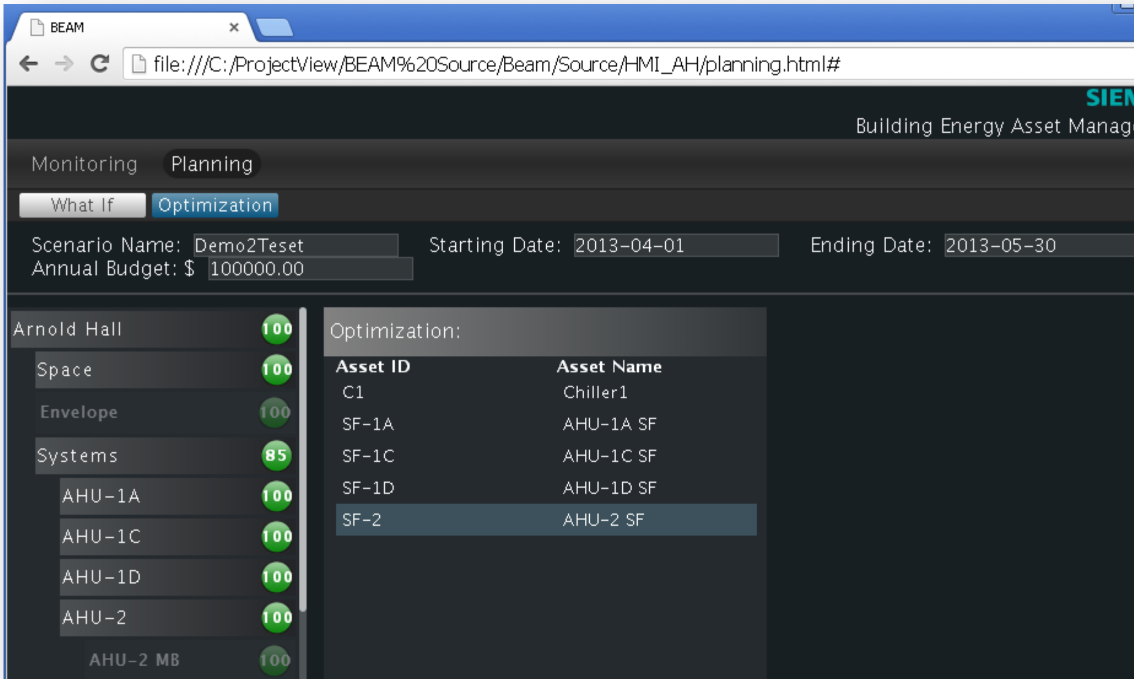
The BEAM Runtime automatically write these seasonal dates into the actual asset info model xml file “AssetInfoModel.xml” (located at \\BEAM_HOME\Resources\ ) in the same node path;

Limitation Two:
When selecting assets for BEAM optimization or what-if simulation, the order that users select each asset matters as the BEAM runtime read and write input and output data according to a Beam OS Settings configuration file (see the following).




```
C1 Chiller
SF-1A SupplyFan
SF-1C SupplyFan
SF-1D SupplyFan
SF-2 SupplyFan
SF-3 SupplyFan
SF-4 SupplyFan
SF-5 SupplyFan
SF-6 SupplyFan
SF-7 SupplyFan
SF-8 SupplyFan
SF-9 SupplyFan
SF-10 SupplyFan
SF-11 SupplyFan
```

There are fourteen assets are enabled to be involved in the simulation. For example, if users want to select the following five assets {'AHU-1A SF', 'AHU-1C SF', 'AHU-1D SF', 'AHU-2 SF', 'Chiller1'}, he needs to select the assets in the following order: 'Chiller1' → 'AHU-1A SF' → 'AHU-1C SF' → 'AHU-1D SF' → 'AHU-2 SF' (see below).



<u>Limitation Three:</u>
Beam Executable, which using Matlab compiler runtime and BCVTB simulation framework, requires that Java JRE 6.0 has to be installed and the installation path has to be added into the system environment PATH.

Appendix H: Whitepaper - Integration of Tools for Building Energy Asset

White Paper

Integration of Tools for Building Energy Asset Management (BEAM) with DoD BUILDER

Yan Lu and Zhen Song
Siemens Corporation, Corporate Technology
Mohsen Jafari and Peter Winslow
Rutgers University

July 2013

1. INTRODUCTION

The challenges of managing the complex systems that run the buildings within the military's real estate portfolio require innovative software tools. Poorly informed planning, policy, and operating decisions waste money and misallocate personnel, consume excessive amounts of energy and increase greenhouse gas emissions, shorten asset life, and impede mission accomplishment. Commanders and their subordinates at all levels of management need timely, practical, insightful, accurate, actionable information with which to maintain buildings efficiently and economically while accomplishing assigned missions.

DoD BUILDER ("BUILDER") is one such software tool developed by ERDC-CERL of the US Army Corps of Engineers and widely adopted across the Department of Defense. BUILDER, which is not specifically focused on "energy assets," is designed to inform decision-making by planners and operators of buildings at military installations. The approach taken by BUILDER is to extend the residual life of an asset and to increase the reliability of that asset.

BEAM (Building Energy Asset Management) is an innovative software technology developed collaboratively by Siemens Corporation, Corporate Technology and Rutgers University that applies modeling and simulation to the process of asset management to inform decisions about how best to maintain and invest in critical "energy assets" in a building so as to assure that the building meets its missions (or business objectives) while minimizing its overall lifecycle cost. BEAM was identified by ESTCP as a potential technology for DoD building asset management and is being demonstrated under ESTCP Project EW-201262.

Both DoD BUILDER and BEAM provide software tools for assessing the condition of building assets and for managing their maintenance. BEAM, furthermore, introduces innovations including:
[1] integrating asset management with runtime automated condition monitoring; [2] introducing asset business value into the asset operation and maintenance policy decision-making process that enhances accomplishment of critical missions; and [3] embedding modeling and simulation in the asset management process to provide integrated quantitative assessments of energy usage, energy costs, maintenance costs, and opportunity costs resulting from asset degradation or failure. ESTCP has assigned Project EW-201262 the task of analyzing these two technologies to determine whether they are inherently compatible or conflicting and if their simultaneous use would be duplicative or redundant. ESTCP has further assigned EW-201262 the task of investigating whether and how the two technologies may be beneficially integrated.

Through the experience of demonstrating BEAM for Project EW-201262 and the study of DoD BUILDER in consultation with ERDC-CERL, the project team has developed an in-depth understanding of both software systems. While BEAM and BUILDER embrace the same conceptual principles and share engineering mechanisms, the software tools they provide are quite different. Because each technology has different strengths and weaknesses that are mutually complimentary, the project team believes that integration of BEAM and BUILDER to combine their separate and conjoined capabilities could best improve DoD asset management practices. An integrated tool set will help management to maintain existing critical assets and to plan investment in new critical assets more effectively, while identifying significant potential opportunities for energy consumption and cost reduction.

This whitepaper summarizes the results from our assessment of both software systems and describes our proposed solution for integrating them.

2. TECHNOLOGY Comparison - BEAM vs. BUILDER

2.1 DoD BUILDER

DoD BUILDER is the state-of-the-art asset management system for DoD properties. The result of decades of research and development based on various patented technologies - including [1] Building Exterior Condition Index, [2] Knowledge-based Condition Survey Inspection methodology, [3] Functionality Index for asset management, and [4] Condition Lifecycle mathematical model – BUILDER uses quantitative measurement to provide software tools for systematic, efficient, and thorough asset management.

2.1.1 BUILDER Approach and Work Flow

The workflow of typical DoD use cases are described in the report "Engineered Management Systems in War, An In-Theater Application for Builder" [See Reference 7], where army field engineers inspected living facilities in Kuwait. The BUILDER system includes two components, the server side and the client side. In this document, we refer to the service side software as "BUILDER" and the client software as "BuilderRED," following the Army terminology.

Under standard cases, field engineers downloaded asset information from BUILDER to BuilderRED in their office. To accomplish the download, they connected a tablet computer that was hosting BuilderRED to the network, logged into the BUILDER web portal [See Reference 8], and downloaded asset information. Once the download was completed, the BuilderRED file contained action items for field inspections. The engineers then took the tablet computer to the field and inspected assets in accordance with BuilderRED suggestions. The asset conditions in BuilderRED are classified by category with text instructions on how to rate asset conditions based on visual inspection observations. The building level inventory screen is shown in Figure 1. For example, if cracks are found on a wall, in accordance with text descriptions provided by BuilderRED, engineers assign an appropriate Condition Scale number for the wall. Missing assets are also recorded using the software. All of this information is uploaded to BUILDER once the engineer returns to the office and connects the tablet to the office network. The BUILDER server software system updates the Site Condition Index (CI) values recursively, i.e., the Site CI is calculated based on the asset Condition Scale. The site CI displays the average CI of the buildings in the site, weighted by replacement cost. This metric provides an overall sense of the condition of the site as viewed in its entirety [See Reference 7]. Based on the manually updated CI scores, facility managers then use BUILDER to plan for asset maintenance using a Triage Score that factors in the importance of the missions for those assets. The details will be given next.

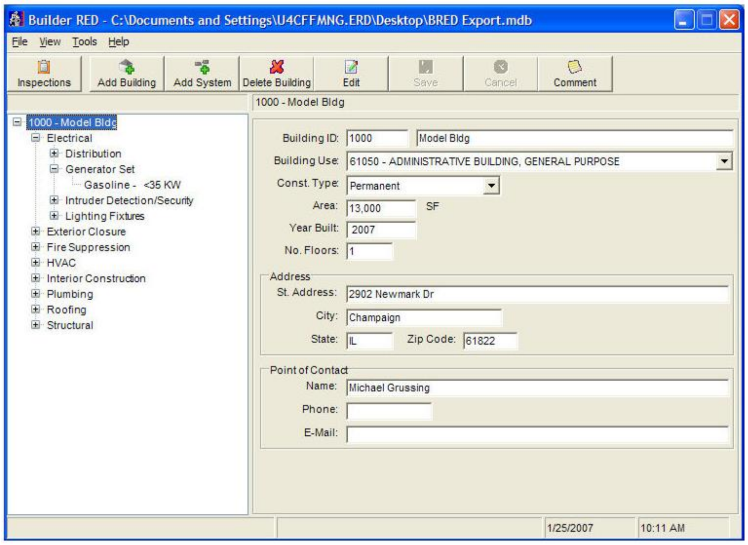


Figure 1 BUILDER RED building level inventory.

2.1.2 BUILDER Asset Condition Metric System

BUILDER introduced a metric system to quantitatively measure many asset management factors, including the aforementioned Condition Index (CI) and also other concepts, including Functionality Index (FI), Performance Index (PI), and Site Facility Condition Index (FCI). Most of these concepts are described in patents with numerous embodiments. To illustrate the concept, we briefly review this system of metrics and give basic examples for presentation purposes. Detailed design considerations and advanced use cases of these metrics are beyond the scope of this report.

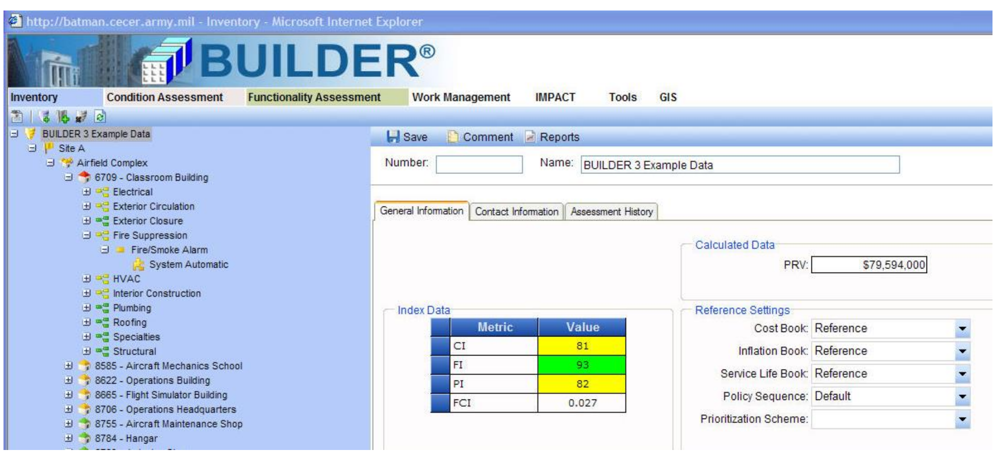


Figure 2 BUILDER organization data [9].

Table 1 shows the definition of CI in BUILDER from reference [See Reference 7], where the “Condition Scale” is the aforementioned CI. The condition descriptions are tailored especially for building system maintenance. More detailed assessment methodology is described in a standalone 161-page manual [See Reference 10], which contains a 100-page description of how to rate asset conditions for 22 different types of distresses based on visual inspections.

The exact input is based on experience and personal judgment. The system features an hierarchical CI system, starting from Building Component CI (BCCI), to System CI (SCI), to Building CI (BCI), to Complex CI, to Site CI, ending in the Group CI. From each lower level to the next higher level, CI values are weighted averages. Part of the hierarchical CI system is shown in Figure 3.

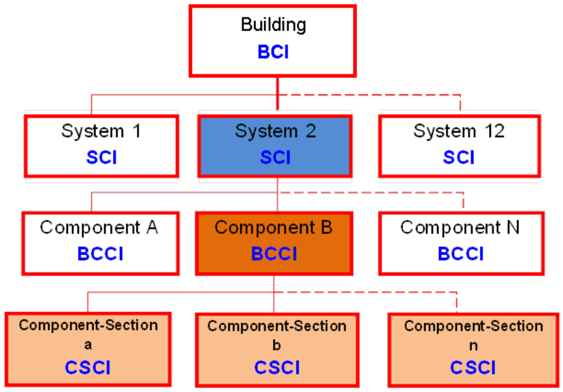


Figure 3 Hierarchical condition index system for BUILDER [10].

Table 1 BUILDER CI Scale Table

Condition Category	Condition Scale	Condition Description		
		Amount of Distress	Functionality	Type of M&R
Excellent	86 - 100	Minimal deterioration	Not impaired	Preventative or minor maintenance, or minor repair
Very Good	71 - 85	Minor deterioration	Slightly impaired	Preventative or minor maintenance, or minor repair
Good	56 - 70	Moderate deterioration	Somewhat impaired	Moderate maintenance or minor repair
Fair	41 - 55	Significant deterioration	Seriously impaired	Significant maintenance or moderate repair
Poor	26 - 40	Severe deterioration over small portion	Critically impaired	Major repair
Very Poor	11 - 25	Severe deterioration over moderate portion	Barely Exists	Major repair but less than total restoration
Failed	0 - 10	Severe deterioration over large amount	Lost	Total restoration

Similarly, Functionality Index (FI) can be quantified using Table 2. The organization FI is defined as the average FIs of the buildings in the organization, weighted by replacement costs. This metric provides an overall sense of the functionality of the organization as a whole.

Table 2 BUILDER FI Rating Table

FI	DESCRIPTION
100	No functionality problems exist in building.
86–99	Building, as a whole, is only slightly functionally impaired.
71–85	Building, as a whole, is functionally impaired but only to a minor degree.
56–70	Building, as a whole, is functionally impaired to a moderate degree.
41–55	Building, as a whole, is functionally impaired to a significant degree.
26–40	Building, as a whole, is functionally impaired to an extensive degree.
11–25	Building, as a whole, is barely able to serve its intended or proposed use.
0–10	Building is totally unable to serve its intended or proposed use.

Organization Performance Index (PI) displays the average PI of the buildings in the organization, weighted by replacement costs. This metric provides an overall sense of the performance of the organization as a whole [See Reference 9]. Building Performance Index (BPI) is a building-level metric, which measures the overall performance of buildings. It is a weighted combination of the Building Condition Index and the Building level Functional Index. The Site Facility Condition Index (FCI) represents the total maintenance and repair costs for the site, normalized by the total site present replacement values [See Reference 9]. This index represents the overall deferred repair work.

2.1.3 BUILDER Asset Management

With building inventory, condition assessment, and functionality data in place, a facility manager can begin to manage work in the building using BUILDER's powerful tools. Figure 4 is a dialog window in BUILDER to show all historical indices of a classroom building. Work item history is tracked in the format shown in Figure 5. For each expected repair, data for the fiscal year, budget, status, and return of investment (ROI) are stored in a database.

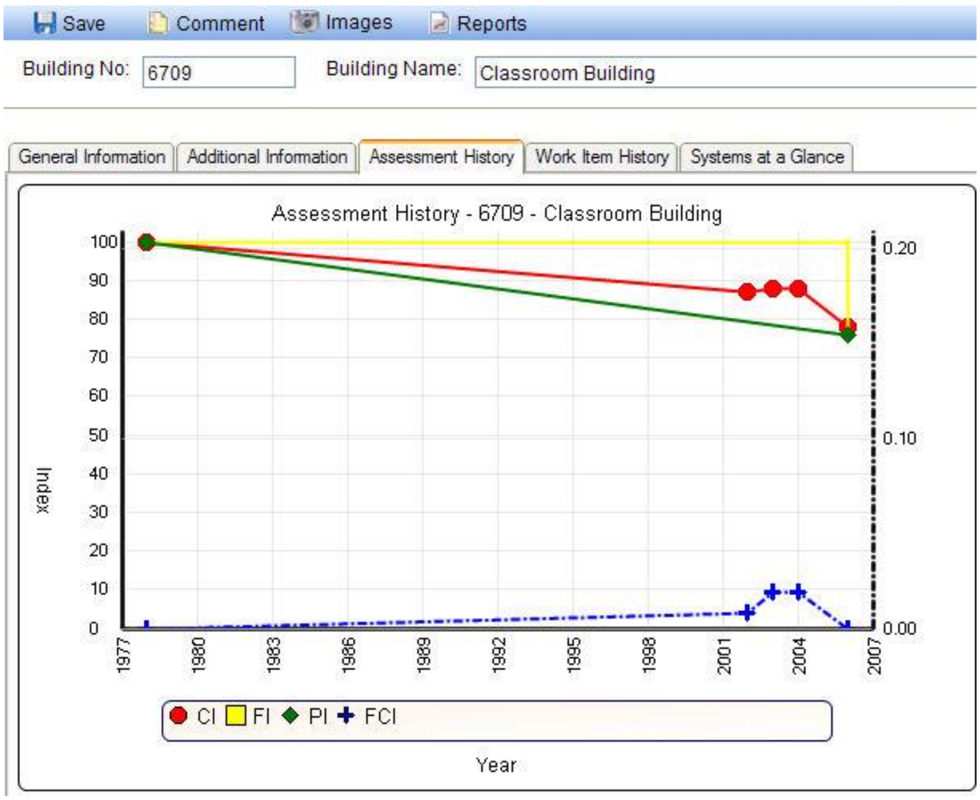
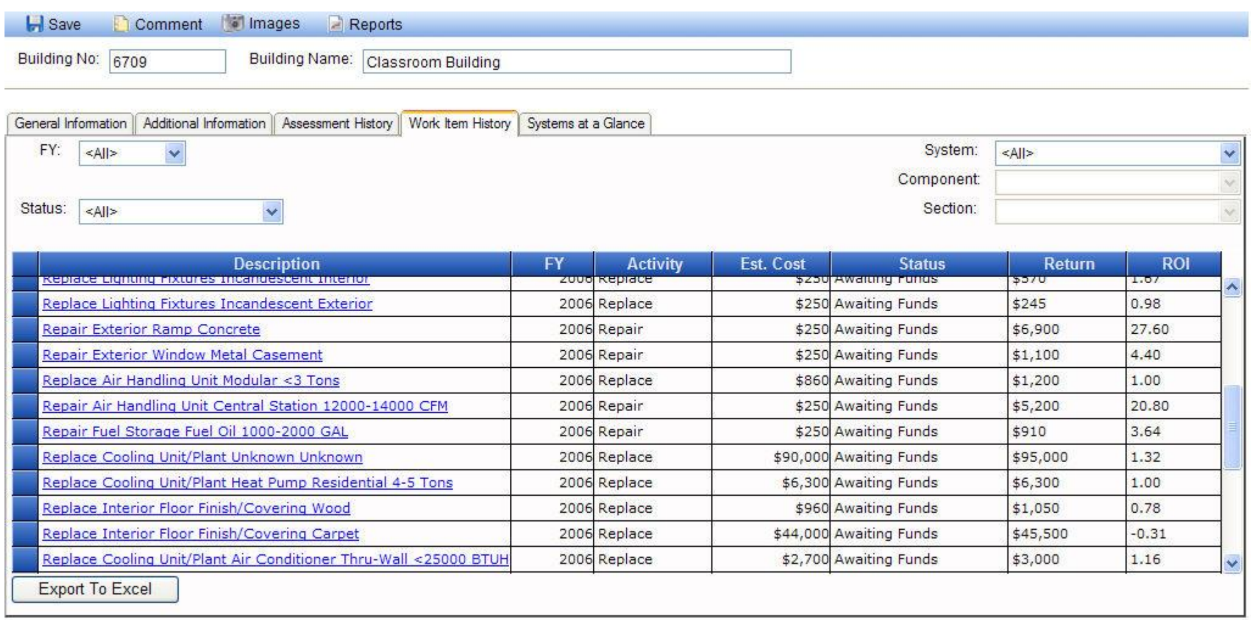


Figure 4 BUILDER assessment history.



Description	FY	Activity	Est. Cost	Status	Return	ROI
Replace Lighting Fixtures Incandescent Exterior	2006	Replace	$250	Awaiting Funds	$245	0.98
Repair Exterior Ramp Concrete	2006	Repair	$250	Awaiting Funds	$6,900	27.60
Repair Exterior Window Metal Casement	2006	Repair	$250	Awaiting Funds	$1,100	4.40
Replace Air Handling Unit Modular <3 Tons	2006	Replace	$860	Awaiting Funds	$1,200	1.00
Repair Air Handling Unit Central Station 12000-14000 CFM	2006	Repair	$250	Awaiting Funds	$5,200	20.80
Repair Fuel Storage Fuel Oil 1000-2000 GAL	2006	Repair	$250	Awaiting Funds	$910	3.64
Replace Cooling Unit/Plant Unknown Unknown	2006	Replace	$90,000	Awaiting Funds	$95,000	1.32
Replace Cooling Unit/Plant Heat Pump Residential 4-5 Tons	2006	Replace	$6,300	Awaiting Funds	$6,300	1.00
Replace Interior Floor Finish/Covering Wood	2006	Replace	$960	Awaiting Funds	$1,050	0.78
Replace Interior Floor Finish/Covering Carpet	2006	Replace	$44,000	Awaiting Funds	$45,500	-0.31
Replace Cooling Unit/Plant Air Conditioner Thru-Wall <25000 BTUH	2006	Replace	$2,700	Awaiting Funds	$3,000	1.16

Figure 5 BUILDER work item history dialog.

The IMPACT simulation tool embedded in BUILDER is designed to simulate performance and condition degradation. One simulation scenario is configured in Figure 6, where different maintenance strategies are assumed according to different CI zones. In Zone 1, where the CI value is the highest, preventative maintenance is adopted. The exact inspection interval and maximum number of inspections are specified in a dialog as shown Figure 6. In Zone 2, where

CI is less than in Zone 1, a corrective maintenance strategy is assumed. Based on the simulation configuration from the users, IMPACT simulates the asset's long term degradation conditions and budget usage for reference by the facility manager. For example, a facility manager can specify the knowledge-based maintenance strategies under different scenarios. The IMPACT software can simulate time periods of from 1 to 10 years and generate reports on expected degradation or on work plans, as shown in

Figure **8**. The report covers expected future CI, FCI, FI, PI performances, maintenance work plan, location budgets organized in different time frames, etc. This message gives a holistic overview on the impacts of a specific maintenance strategy.

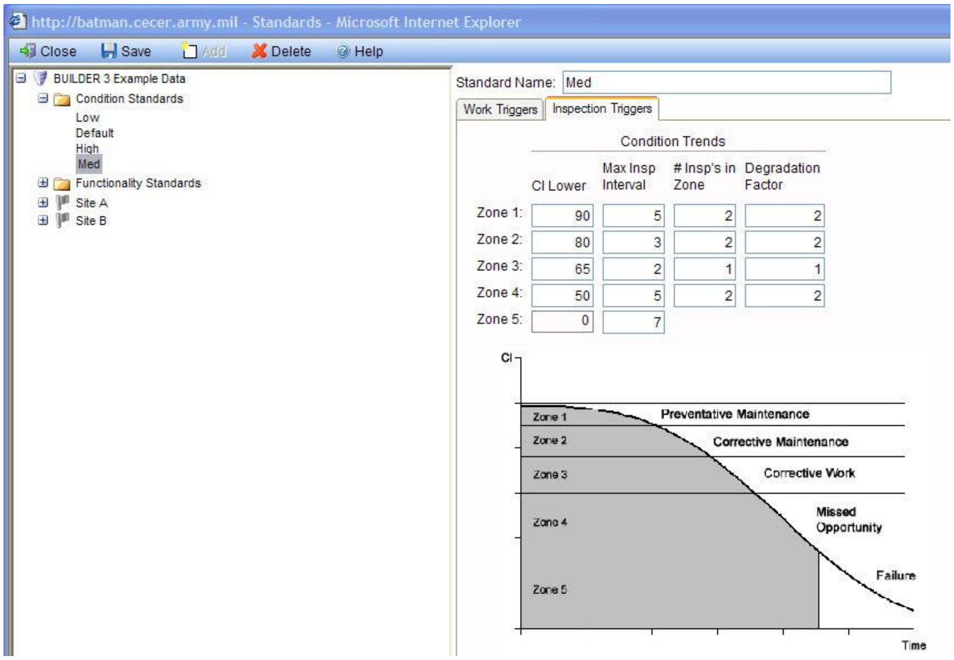


Figure 6 Knowledge based inspection schedule tool.

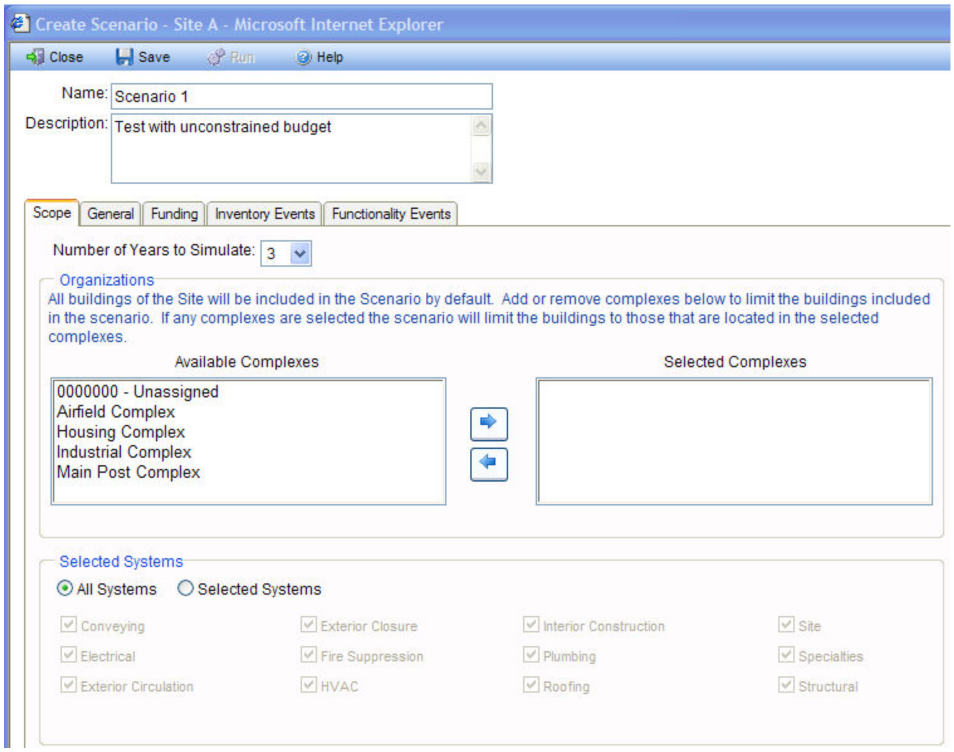


Figure 7 IMPACT scenario inputs.

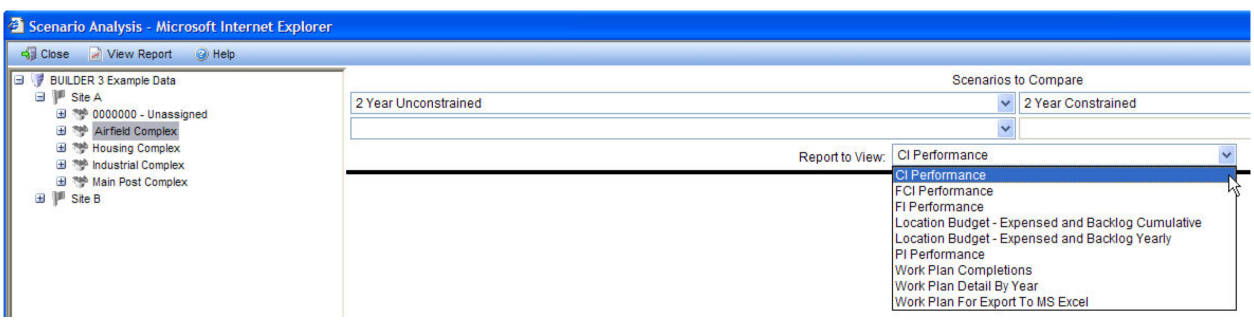


Figure 8 IMPACT scenario analysis outputs.

2.2 BEAM

BEAM is a suite of computer software tools which integrate innovative condition monitoring and asset management technologies and focus on how best to maintain and invest in "critical energy assets" in a building so as to assure that the building meets its missions (which in nonmilitary contexts are often referred to as "business objectives") while minimizing lifecycle costs. Figure 9 shows the schematic of BEAM framework.

In the BEAM framework, each building is conceived as being assigned "business objectives/missions" that its occupants are tasked to accomplish, for example, fire protection, air operations, admin support, morale welfare, recreation, education & training etc.. The "energy assets" - assets that produce, transfer, and/or use energy to support the activities associated with mission accomplishment at that building – possess what are considered "business values" that can be measured in relationship to their significance for mission accomplishment. Within the BEAM framework, the **business value** of each building energy asset plays key roles in the asset management process for prioritizing asset management investment and maintenance workflow. Meanwhile, the conditions of building energy assets are continuously monitored in BEAM - thereby enabling asset management decisions, whether preventive or predictive, to always be made based on the evaluation of current equipment and device conditions including fault and energy performance. For example, the BEAM tools can be connected to building automation systems and thereby incorporate run-time asset condition monitoring into asset planning. Moreover, BEAM asset planning optimization considers not only asset investment and maintenance cost, but also the building **operation cost and the potential penalty cost** projected to result from a loss of asset function. These unique features of BEAM support facility managers at building, military base, and regional command levels to make better decisions for optimizing energy asset operations and investments.

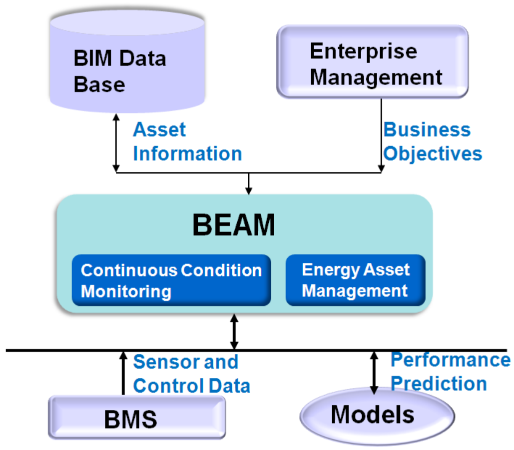


Figure 9 BEAM system architecture.

2.2.1 BEAM Approach:

BEAM technology uses a 5-step model as shown in Figure 10. The concept originates from Enterprise Asset Management (EAM) (Holland et al, 2005; Icon Group International, Inc. Staff, 2009), which has been used successfully by different sectors of the economy (e.g., Power grid, transit systems, and aerospace). The 5-step model applied to building energy asset management can be outlined as a 3-phase workflow, including Configuration, Planning and Execution phases. During the Configuration phase, the business values of energy assets are defined based on the mapping of building mission to energy assets through functional zones. The typical cycle for BEAM Configuration is in months, years, or whenever building mission/space purpose is changed. During Planning phase, the business values of building assets are used in simulations to evaluate building operation cost and failure risks from alternative O&M policies and to generate optimal strategies. The processes and the algorithms supporting BEAM configuration and BEAM planning phases are well developed by scholars and practitioners from both academia and industry. During Execution phase, BEAM runtime software is applied for continuous asset condition monitoring. Faults are detected and alarms on asset condition changes are generated and displayed for facility team to take actions. The continuous condition monitoring technology was developed by Siemens Corporate Technology.

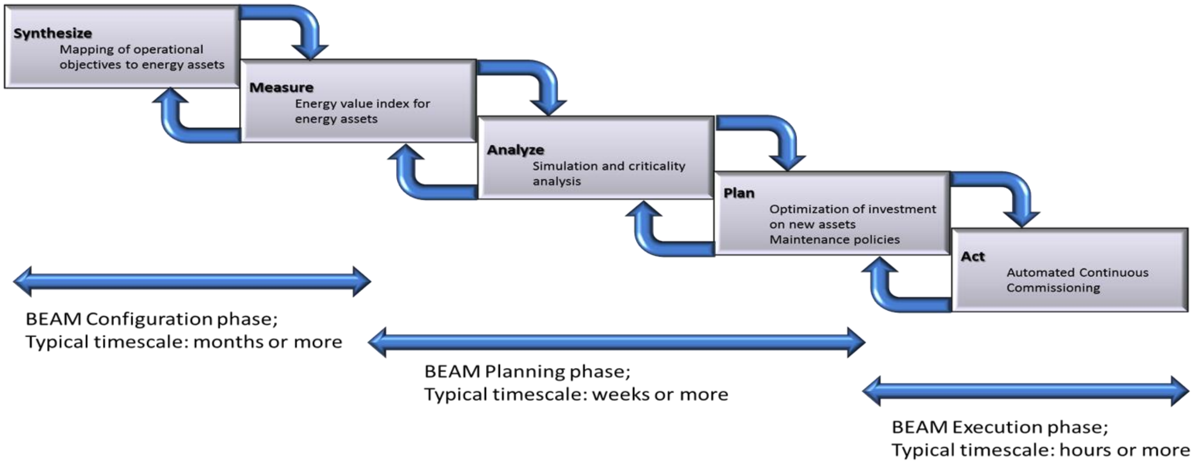


Figure 10. BEAM workflow

2.2.2 BVM Models:

The Building Energy Value Models (BVM) defined during the BEAM configuration phase map the "Missions" or "Business Objectives" identified for a building to the building energy assets available and critical for the fulfillment of those objectives. Using a combination of quantitative and qualitative techniques, "Business Value Models" identify the *Ordinal (criticality)* or *Monetary business value scores* of energy assets (*BVM-I*, *BVM-II* and *BVM-III*).

BVM-I measures criticality in ordinal terms [using a 0,1 matrix]; BVM-II measures criticality in dollar ($) terms; BVM-III measures criticality within a seasonal context in dollar ($) terms. More specifically,

- BVM-I derives ordinal criticality scores ($\in [0,1]$) for assets by mapping a building's Missions/Business Objectives to its Assets using a combination of *Analytic Hierarchy Process (AHP)* and *Failure Mode and Effects Analysis (FMEA).* Building "Missions" are mapped to systems of assets in the building, and their criticality is evaluated through AHP. FMEA is used to derive risks or criticality of assets to their corresponding asset systems. The two models are linked to derive criticality scores for building energy assets.
- BVM-II yields monetary business value scores for assets, which is applicable to most office buildings and commercial facilities. Such business values are defined by economic loss due to failure or degradation of building assets. In BVM-II, this economic loss is estimated using the aggregated value of the building employee's productivity loss due to unavailability of an asset. (Pay structure within the military - enlisted and officer - is comparable to civilian pay scales - labor and management; so the same principles for using compensation as a proxy for productivity apply.) Common indices such as *Predicted Mean Vote (PMV)* and it's relation with employee's productivity through regression analysis is utilized in BVM-II. The concept of PMV and its relation to productivity has been extensively used in practice.

- BVM-III extends BVM-II by introducing a function for seasonality, also measured in monetary terms. This model also extends BVM-II to be compatible for buildings with a wider range of “Business Objectives” and to include calculations for nontangible and difficult-to-quantify consequences of asset failure, thereby providing more sophisticated consideration of their contribution to the business value of building assets.

Note that BVM-I can be used for any building. It is Ordinal in nature and, therefore, independent of monetary considerations. In contrast, BVM-II&III use a monetary metric. However, dollar values are primarily a means for measurement; although related to monetary considerations in the real world – and usable for financial purposes – they are fundamentally measurement tools for purposes of comparative ranking and analysis. The monetary business models provide a better way to optimize asset maintenance policy considering both operation/repair cost and the penalty cost from asset failures.

BVM can be applied whether or not a building is “commercially oriented” or if it is occupied or unoccupied by people. Valuation can be derived in a variety of ways. For example, the value of dormitory space can be compared to market rents for comparable housing; the value of dining facilities can be valued based on meals served (in comparison to a comparable restaurant); fitness centers can be compared to membership fees in a commercial gym. Maintenance of environmental conditions for equipment or critical processes can be subject to similar valuation methodologies.

2.2.3 Continuous Condition Monitoring:

The Continuous Condition Monitoring (CM) module of BEAM is a function to check the status of systems and assets required for the building’s operation continuously. The status of each asset and system is quantified in terms of an index called “Condition Index.” Condition Index has a value between 0 and 100, with 0 corresponding to the worst condition and 100 indicating perfect condition. To calculate an asset’s Condition Index continuously, our CM module includes three major functions:

- Automated fault detection and diagnosis (AFDD): We use runtime data from building automation systems to determine faulty HVAC parts and equipment based on a Heat Flow Model (HFM). During the fault detection phase, measured sensor and control values are used to perform estimations based on the physical properties of the system. Discrepancies of estimated and measured values are collected as a detection failure vector. Diagnosis seeks to find the most probable cause for the observed failures. In HVAC systems, the failures and faults form an “m-to-n” (matrix) relation. Our diagnosis is performed with an associative network to map the relations among failures and faults using the inherent fault simulation capabilities of the HFM nodes at runtime. The automatic fault detection generates Function Index of building asset.
- Automatic energy asset performance estimation: We use runtime data from the building automation systems to determine the energy performance of those energy conversion devices in a building, including its chiller, fans, boiler, and other significant system components that are monitored. The condition index of these equipment is calculated as the ratio between the Expected Power Consumption and Actual Power Consumption:

$$CI = \frac{Expected\ Power\ Consumption}{Actual\ Power\ Consumption}$$

Their performance degradation can be captured by assessment of a drop in efficiency or an increase in power consumption for a particular working condition.

- Condition from manual inspection: Manual condition monitoring is designed to address conditions of those components for which sensor data is not available. Manual condition monitoring may be accomplished through simple inspection or through detailed inspection and distress analysis. The frequency and procedures for inspections are matters for policy decision, presumably determined through reference to manufacturer recommendations and established industry best practices. Similar to automatic condition monitoring, the output from manual condition monitoring is an asset level Condition Index which is consistent to BUILDER's definition.

2.2.4 BEAM Engine

The BEAM Engine is an optimization software program, designed to explore the implications of a variety of asset maintenance policies and to identify a policy that yields minimal Total Building Cost. Such cost minimization combines three main cost elements: (i) asset energy cost, (ii) building value loss due to asset failures (Asset Penalty Cost), and (iii) maintenance cost. Each maintenance action has a fixed cost term (based on such factors as materials cost) and a variable cost term (dependent on time duration and hourly labor cost required to perform the maintenance action). Asset Penalty Cost is defined as economic loss due to failure of an asset. This cost can be calculated using BVM. Finally, asset energy cost includes the fixed and variable costs of consuming or generating energy (e.g., electric energy and natural gas). The BEAM engine is integrated with a customized building energy simulation model, which takes into account such important factors as climate, occupancy, system reliability, degradation and maintenance to identify the maintenance policies that are optimal over a planning horizon and within budget and financial constraints.

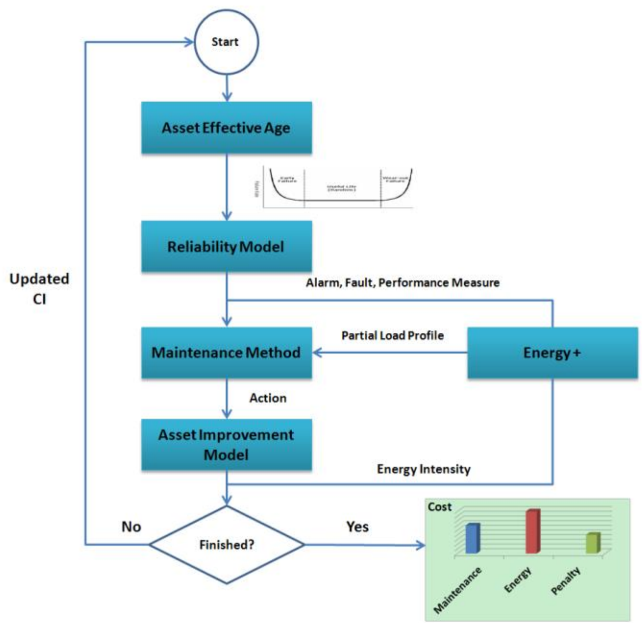


Figure 11 BEAM Engine

The probability of failure and degraded energy performance of an asset depends not only on the time elapsed since the asset's installation (actual age) but also on changes resulting from the cumulative load on the asset as well as the maintenance policies employed (Effective Age). Asset effective age is a function of asset condition index generated by BEAM-CCM. The Effective Age of assets is input to the BEAM Engine at the beginning of an optimization period. Using its Asset Reliability Model, the BEAM Engine then calculates the failure probability and energy performance efficiency of the assets as a function of Effective Age. After that both values are plugged into a building energy simulation to calculate building energy consumption. The BEAM Engine and Building Energy Simulation Model run in parallel, and communicate using a co-simulation platform. The Asset's Partial Load Profile is computed by the Building Energy Simulation Model and is input to the BEAM Engine's "Asset Efficiency Degradation" function, "Asset Reliability Model", and "Maintenance Optimization" model. The energy transfer or conversion efficiencies of assets are calculated based on their Partial Load Profile. Random failure events, characterized by asset availabilities, are also generated based on probability distributions. Asset performance and efficiency measures and availability indicators are then "injected" back to the Building Energy Simulation Model. Using the aforementioned inputs, the BEAM Engine identifies a maintenance policy that yields minimal asset energy cost, asset penalty, and maintenance cost. The BEAM Engine then updates the asset's Effective Age and CI according to the Improvement factor ($(IF \in [0,1])$) of the type of maintenance policy identified.

2.2.5 BEAM Tools

Tools for BEAM include software that can enable the 5-step workflow for BEAM configuration, planning, and execution with a focus on the energy asset systems within a building, including HVAC systems, lighting, building envelopes, etc. There are two main modules: BEAM Configuration and BEAM Runtime, as shown in Figure 12.

BEAM Configuration maps the "Missions" assigned to a building to the building's assets based on Business Value Models: *BVM-I*, *BVM-II* or *BVM-III*. The configuration tools are also used to generate models for automatic HVAC FDD, energy performance monitoring, and building energy simulation (Energy Plus). In addition, the building information and asset information gathered through the BEAM Configuration tool will generate a comprehensive xml-based database for BEAM Runtime to use, called Asset Information Model.

After configuration, building management personnel can use the BEAM Runtime software to browse building asset conditions in real time or for planning purposes. Building asset condition can be updated continuously if control and sensor data is imported to the software frequently (Figure 13). Device faults or energy performance degradations exceeding user-defined thresholds will trigger alarms. BEAM Runtime also provides asset-planning tools for projecting "what-if" scenarios to evaluate O&M policies or for synthesizing the best O&M policy for energy conversion devices such as chillers, fans, pumps, and boilers (Figure 14).

BEAM Runtime software can run in either *"Stand Alone"* or "*Integrated*" mode, differentiated by the connection types between BAS and BEAM Runtime software. For operation in the "Stand Alone" mode, the software doesn't need to be installed on the industry control network and communicate with BAS through BACNet. Instead, a user can upload BAS trend data daily, weekly or bi-weekly to assess asset condition at his own convenience. In this Way, BEAM technology presents lower security concerns to the control network. Running in an *"Integrated"* mode, BEAM will be integrated with the BAS system through the BACNet protocol; hence the continuous condition monitoring is fully automatic and there is no need for a user to upload data during operation. In addition, BEAM can detect and respond to faults more promptly in the "Integrated" mode.

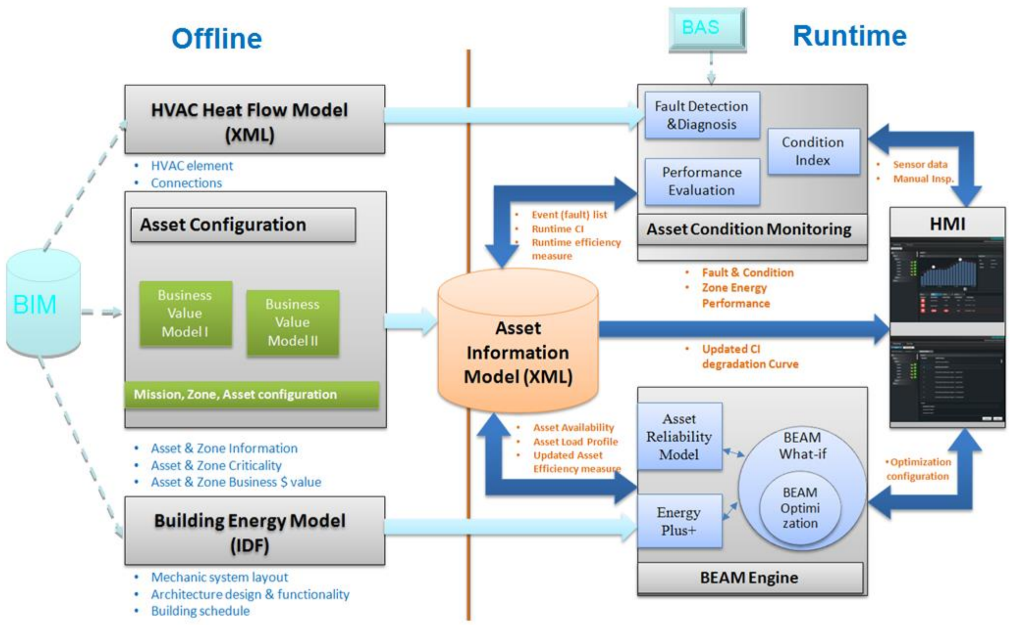


Figure 12 BEAM software overall architecture

Figure 13 Asset condition monitoring.

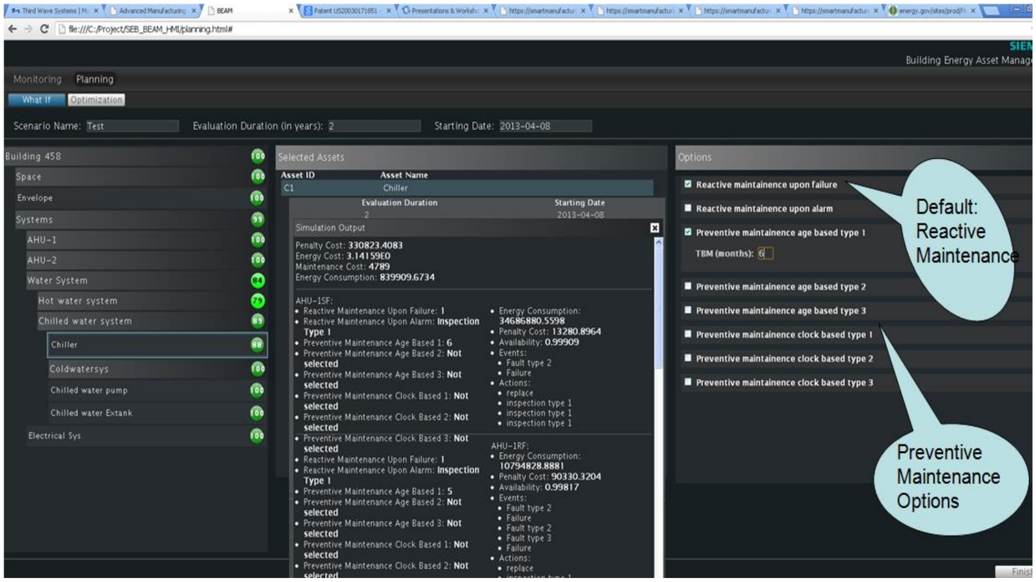


Figure 14 User interfaces of BEAM Runtime Software

2.3 Comparison-advantage and limitations of both technology

BUILDER and BEAM conceive the problems of managing the assets of a building in similar ways, and they embrace the same principles:

- Lifecycle tools for Management of Assets
- Weibull distribution for modeling risk of component failure
- Decisions for capital budgeting and operations budgeting

Both technologies are specifically concerned with Operations and Maintenance ("O&M") strategies, planning, policy, and activities.

2.3.1 BUILDER Pros and Cons

Matured methodology: BUILDER has been adopted in DoD facilities for years. It is used to manage hundreds of buildings and to assist in maintenance budget planning.

Simplicity: BUILDER is a fully manual, low engineering cost, knowledge-based methodology for asset management. This methodology requires relatively simple numerical calculations, which make the technology easy to implement in different buildings.

Low effort: Rooted in simplicity, BUILDER does not require field engineers to collect much information for a building; therefore the engineering effort is low. According to Lance Marrano, the developer of BUILDER, the costs of inspection for BUILDER is around \$0.1~\$0.3 per square foot.

Less advanced features**:** Without advanced calculations, BUILDER is not designed to address long-term cost factors when energy consumption is within its scope.

2.3.2 BEAM pros and Cons

Performance Advantages: The BEAM technology is innovative and has not been demonstrated previously. The integration of continuous condition monitoring with asset management based on asset reliability and building energy modeling is a new idea which can provide facility planners and managers with tools to optimize both asset maintenance and energy cost over short-term and long-term time horizons and to perform "what-if" analysis in response to significant unexpected events. In addition, asset planning that is driven by business value can optimize organizational performance and secure critical missions.

Cost Advantages: BEAM is a software-based solution. The acquisition cost, including licensing and software installation as well as user training is expected to be low. Major costs are currently required for implementation, because the technology requires significant engineering effort during the configuration phase, including generation of the building asset information model, reliability model, and building energy model. However, after commissioning, no maintenance is needed for BEAM. Since the software is designed with an interface to the existing building automation system and supports continuous commissioning, there is no need for manual data collection for purposes of asset condition assessment. The return of investment is expected to be within 5 years, if the building already has a BAS system.

Performance Limitations: The BEAM tool requires supporting data on asset reliability, performance, and operating schedules. The problem of data availability is non-existent for new buildings. For older buildings that keep no asset information archiving and maintenance logs, the lack of data for asset reliability modeling may significantly hinder the applicability of BEAM, unless data on similar assets is obtained from the literature. A scaled down version of BEAM for older buildings may be possible for purposes of generic planning for buildings of standardized construction types, such as Quonset huts or barracks.

BEAM technology performs planning and optimization on the basis of building simulations. The existing simulation technology (e.g., EnergyPlus) requires extensive computational time, especially when the building modeling includes sufficient details, and runs are made for several years (i.e., 4 or 5 years). A typical BEAM optimization may then take several hours of computer time to complete. While running offline, the BEAM execution time may pose limitations, if decisions are expected immediately or within a short time interval. Although the BEAM system is complex, its HMI is being designed such that a casual user can quickly and intuitively obtain actionable information, while a power user can access more sophisticated capabilities.

Cost Limitations: A potential barrier to acceptance of BEAM technology is the time and expense required to generate all the models required by BEAM Runtime software. For example, the project team estimates that between one to three months would be required to build an EnergyPlus model for most buildings, depending on the building type, the size and complexity of the building, and the experience of the engineers who create the model. However, considering the potential for integrating BEAM and BUILDER, interoperability between BEAM and BUILDER could reduce BEAM engineering cost substantially. Furthermore, generation of building information models and EnergyPlus models as a routine aspect of building design by the

US Army Corps of Engineers and other architectural planners within the near future is a distinct possibility.

Social Acceptance: Our military partners have been enthusiastic about the concept of BEAM, and they have been receptive to the prospective opportunity to become early adopters of the BEAM technology. However, they also advised the project team that the advanced concept in BEAM could be overwhelming to some civil engineering teams. We envision that well designed training is necessary for final technology transfer. And, parallel dissemination activities are planned to educate military and civilian users and to promote the acceptance of BEAM technology.

2.3.3 Comparison results

BUILDER determines its CI through a process of periodic expert inspections, procedures that are inherently subjective. BEAM regards periodic inspections as part of a maintenance strategy. ACC determines CI for BEAM through computerized monitoring and analysis of sensor and control data as well as values projected by BEAM algorithms, a methodology that is objective in application.

A comparison of BEAM and BUILDER features is provided below:

Features	BEAM	BUILDER
Considers Mission	BVM (I, II, & III) Assesses business penalty cost	Considered in a non-quantitative way
Uses Building Automation Sensors/Controls	Automatic Condition Monitoring Condition reporting in real time	N/A
Simulation	Quantified analysis based on models and simulations	Functional Assessments
Condition Index	CI based on both manual inspection and automatic detection, depends on assets.	CI based on manual inspection
Planning Objectives	Multi-Objectives: Setting maintenance policies; minimizing energy consumption; optimizing lifecycle cost-effective performance; computing penalty cost of impact on mission from loss of asset function	Prioritizing maintenance work; allocating maintenance budgets
Engineering Effort	Significant upfront investment in EnergyPlus and other modeling	Moderate investment in developing Inventory
Acceptance	Unknown	In use by DoD

3. Integration of BEAM with Builder

An integration of the BEAM and BUILDER technologies should be designed to have the following features:

- a means of communications between BUILDER and BEAM
  - For a tight integration, BUILDER shall offer an Application Programming Interface ("API") for BEAM to access its data and operations.
  - For the loose coupling scenario, BEAM will read the data exported from BUILDER and write back updated messages.
- a consistent Condition Index definition between BEAM and BUILDER.
- a unified workflow and template to establish default values for similar buildings of the same type.

There are two potential solutions to integrate BEAM tools with BUILDER through either loose coupling or tight integration.

3.1 Tight Coupling

The goal of tight coupling is to seamlessly merge the two software system into one, so that users do not feel they are actually using two separate applications together. This solution will offer the best user experiences but requires higher development efforts than the loose coupling scenario.

A tightly coupled BUILDER/BEAM system will follow the workflow of the BUILDER system, for the most part, whereby BEAM becomes a natural extension of the BUILDER system. The integrated system offers the following new features: 1) Automatic data collection from building automation systems (BASs); 2) Automatic condition monitoring, including fault detection and diagnostics (FDD), CI updates, etc.; 3) HVAC equipment energy performance monitoring; 4) Building envelop energy intensity monitoring; 5) Advanced data visualization and 6) value driven asset planning/maintenance policy analysis and optimizations.

The workflow of the integrated system is as follows: Field engineers collect information using BUILDER RED and mobile devices. The data is then uploaded into the BUILDER server and accessible by BEAM system. The field engineers also establish connections between BEAM and the BAS so that BEAM can monitor the building conditions on real-time. The BEAM user interface provides a complete visualization solution on sensor data and processed metrics, including the CI, EP, and EI values calculated by BEAM, also CI and Triage, calculated by BUILDER. Facility managers will be able to manage both systems from the BEAM web-based user interface. When a fault is detected, FM will be notified for in-depth analysis, such as maintenance policy optimization or what-if simulations using BEAM. The metrics from BUILDER is also accessible. After analysis, the results can be printed from BEAM.

The system architecture is shown in Figure 15, where we highlight the internal structure of the BEAM system. BEAM will be able to access both the data and calculation functions within BUILDER. During the engineering phase, BEAM acquires building information from the BUILDER database, in order to minimize the effort and maximize the utilization of existing data.

After fault detected, BEAM will update CI values in BUILDER database and trigger related analysis functions.

Without disturbing the existing BUILDER workflow, engineers can continue to use BUILDER RED to upload building information collected from the field. Meanwhile, BEAM establishes an extra communication chancel, i.e., automatic sensor data collection from BAS to the BEAM runtime engine via BACnet protocol. This is a significant enhancement to BUILDER, which uses a manual system. The sensor data are processed by the Condition Monitoring component in BEAM for run time fault diagnostic and detection for CI updates, which will be feed into the BUILDER database via the BUIDLER API. The Optimizer component inside BEAM can conduct "what-if" simulations and Optimizations based on user inputs. The simulation and optimization results can be shared with BUILDER via the API.

The communication between BUILDER and BEAM can be implemented in HTTP-based web services, such as RESTful services or SOAP services. BUILDER would need to expose an API for BEAM, which can access the engineering information of existing buildings. Based on information from the BAS, BEAM runtime detects component faults and calculates the CI degradation for each applicable item of HVAC equipment, based on FDD algorithms already developed by Siemens during the DoD ESTCP BEAM project (EW-201262). Please notice that Siemens's algorithm was designed to match the manual inspection guideline provided by BUILDER for those assets not instrumented and continuously monitored. Therefore, CIs obtained from BEAM can be used interchangeably with the CIs obtained from manual inspection using Builder RED.

To embrace the age of mobile computation, BEAM UI is built on the latest web technologies. The BEAM UI is an interactive functional dashboard and configuration tool based on HTML5 and Javascript technologies. Via the UI, facility managers can monitor the condition of individual assets within a building and optimize their maintenance policies using different solution methodologies provided in the optimizer. For example, if a fault is detected, a facility manager can simulate the impacts of that fault in terms of energy or business value. The result is displayed visually on the dashboard.

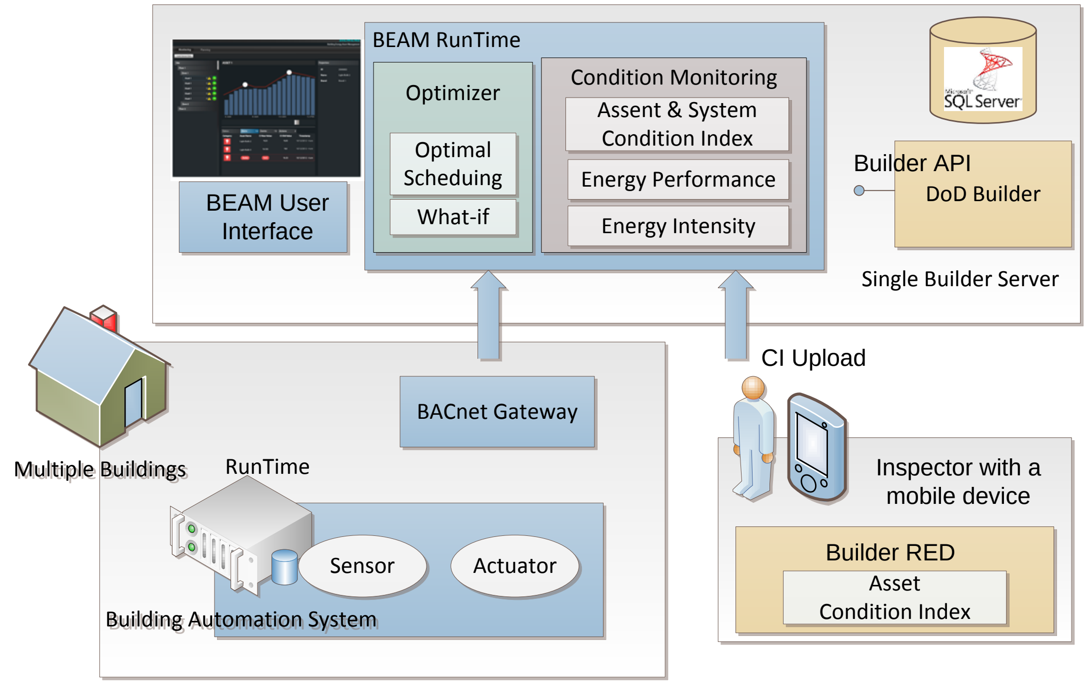


Figure 15 System architecture of tightly coupled Builder-BEAM system.

3.2 Loose Coupling

In the loose coupling scenario, facility managers need to operate BUILDER and BEAM as individual software and must manually transfer the data between the two applications. One advantage of this solution is that it requires less development efforts, at moderate sacrifice for the user experience.

The system diagram is shown in **Figure** 16, where BUILDER and BEAM interchange information via files on the same hard drive. In this scenario, users first collect building and asset information via the traditional BUILDER and Builder RED tool chain. The data are stored inside a Microsoft SQL server database and can be exported following the Microsoft Access format. Users than start the BEAM application and import the Access file into the BEAM system, more specifically an XML-based Asset Information Model database. This version of the BEAM engine is still featured with run time FDD, optimization and simulation, etc. The outputs of the BEAM engine are not automatically merged back to the BUILDER database. Instead, BEAM exports output into files and import into BUILDER. Notice that this import feature does not exist in BUILDER today. The BEAM and BUILDER teams can specify a common format for the data exchange purpose. Candidate formats include Excel, CSV, Access, XML, but not limited to these options.

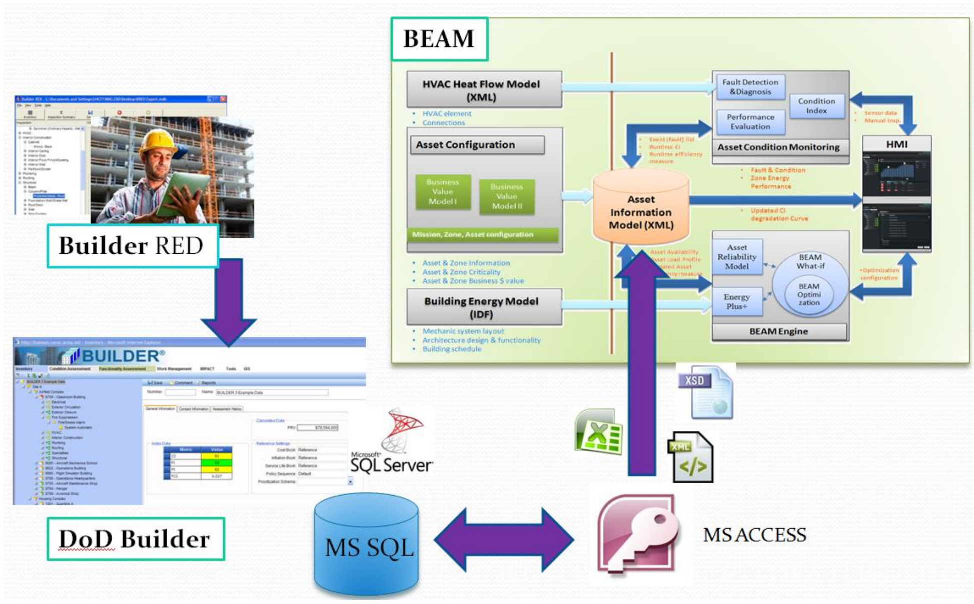


Figure 16 System architecture of loosely coupled BUILDER-BEAM system.

3.3 Additional Efforts needed for BEAM and Builder integration

1) API: An Application Programming Interface ("API") has not yet been developed for BUILDER. Development of an API would facilitate the integration of BUILDER with other software programs such as BEAM. In the absence of or preliminary to the availability of a BUILDER API, data sets in compatible format can be passed between the software programs, but an API is a superior solution.

2) Database: BEAM and BUILDER both use a unified database that describes the specifications for the (energy) assets of the building (its "Inventory") as well as data pertaining to the condition and function of those assets over time and in simulations. Protocols for sharing such information can avoid duplication of effort. Furthermore, automation of some data accumulation is possible.

3) CI: Both BEAM and BUILDER are driven by reference to a "Condition Index" metric that assesses the current and predicted future state of an Energy Asset. These two Condition Indexes are derived by using different methodologies, but they refer to the same assets and the status of those assets. A goal of the project is to coordinate these two Indexes so that they can be used interchangeably, or can exchange information, or can be synthesized so that only a single Index is required for all purposes.
    - The Siemens CI used for BEAM is calculated by an algorithm based on asset Energy Performance and Fault as detected by ACC.
    - The CERL CI used for BUILDER is based on a rating of components derived from inspection for the "Type" of negative condition, its "Severity," and its "Density."

4) In addition, standard works flows and templates are required for the integration of both technologies. A common template for BUILDER and BEAM for different types of

buildings can establish default values for initial configuration. As a result, the technologies can be extended more rapidly to multiple buildings and analysis of building cluster configurations.

4. Conclusion

The proposed integrated suite of tools will empower DoD strategic planners, capital budgeters, facilities managers, logistical tacticians, and base commanders with the combined strength from BEAM and BUILDER tools. The DoD will benefit generally from better decisions and better operations. Specifically, the DoD is expected to benefit from reduced energy expenditures, more efficient use of energy resources, more resilient building infrastructure relative to its energy assets, and better management of its built environment. Although the total dollar value of these benefits cannot be quantified at this time, when the models are run for scenarios provided by the DoD for testing purposes, the demonstration project will itself deliver analyses of typical savings to be derived.

Key Performance Indicators ("KPI") vary for different kinds of Energy Assets. Although their cumulative impacts cannot yet be determined, the range of annual benefit for specific contributions of the BEAM technology is known. For example, the savings per rooftop cooling unit ("RTU") from the fault detection and diagnostics ("FDD") functionality of BEAM can be between $700 and $2,000.

BUILDER is already in deployment at DoD facilities. Integration of BUILDER with BEAM will enhance its value to DoD users. Conversely, integration will assist adoption of BEAM tools as a valuable extension of BUILDER. When BEAM is commercialized, the BUILDER installed base will provide a distribution channel for the BEAM software products and supporting services.

BEAM software and associated tools will be manufactured and packaged by Siemens Building Technology ("SBT") in Buffalo Grove, IL. Training, engineering support, customer help, and other associated services will also be provided by the SBT division.

Since the identical human/machine interface ("HMI") and software tools can be used by all levels of management, BEAM will be marketed to base commanders, Directorates of Public Works ("DPW"), facilities managers, and others concerned with the efficient management of buildings. The deployment strategy will be to train one BEAM facilitator within the DPW and, initially, one "power user" who is the facility manager of the first building on the installation to be configured with a BEAM model. The base commander can then use that cadre, with SBT support, to extend the technology implementation to other buildings at the installation.

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