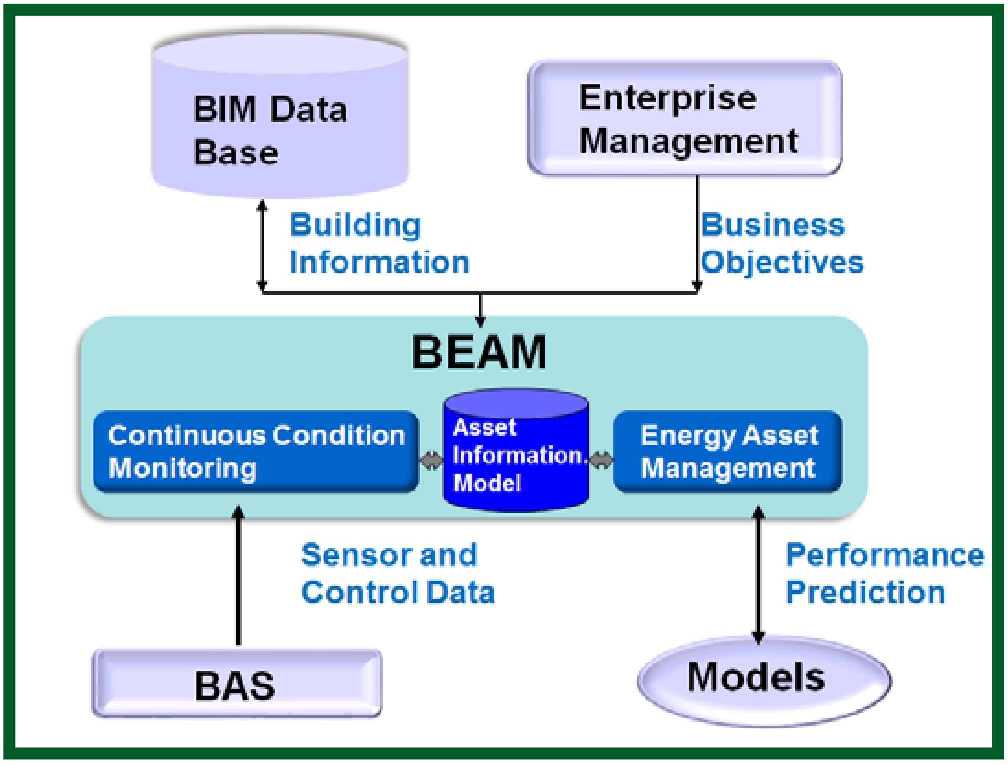
ESTCP
Cost and Performance Report

(EW-201262)



Tools for Building Energy Asset Management (BEAM)

July 2014

This document has been cleared for public release; Distribution Statement A

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
Project: EW-201262

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AFDD	automatic fault detection and diagnosis
AFI	Air Force Instruction
AFPD	Air Force Policy Directive
AHU	air handling unit
APAR	air handling unit performance assessment rules
BAS	building automation system
BEAM	building energy asset management
BIM	building information model
BTU	British thermal unit
BVM	building energy value model
CCM	continuous condition monitoring
CERL	Construction Engineering Research Laboratory
CI	condition index
COP	coefficient of performance
DoD	U.S. Department of Defense
DoD BUILDER	the “BUILDER” software (developed by USACE CERL)
DOE	U.S. Department of Energy
EAM	energy asset management
EEB-HUB	Energy Efficient Building Hub of the DOE (formerly GPIC)
EO	Executive Order
ESTCP	Environmental Security Technology Certification Program
EUI	energy use intensity
EW	energy and water
FDD	fault detection and diagnosis
GHG	greenhouse gas
GPIC	Greater Philadelphia Innovation Cluster for Energy Efficient Buildings (Currently the EEB-HUB)
HGL	HydroGeoLogic, Inc.
HMI	human-machine interface
HVAC	heating, ventilation, and air conditioning
kW	kilowatt
kWh	kilowatt hour
MAT	mixed air temperature
MOU	memorandum of understanding

NIST	National Institute of Standards and Technology
O&M	operations and maintenance
PM	preventive maintenance
PMV	predicted mean vote
PO	performance objective
ROI	return on investment
RU	Rutgers University
SCT	Siemens Corporation, Corporate Technology
SEB	Smart Energy Box
USACE	U.S. Army Corps of Engineers
USAF	U.S. Air Force
USAFA	U.S. Air Force Academy
VAV	variable air volume
VPACC	VAV Box Performance Assessment Control Charts

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) under Project EW-201262. The team thanks Dr. James Galvin for his leadership during the project execution. We are also very thankful for the technical support provided by Mr. Scott Clark and Mr. Glen DeWillie from HydroGeoLogic, Inc. (HGL). The team gratefully acknowledges the support from the staff of the U.S. Air Force Academy (USAFA) who not only provided information and coordination assistance for the project, but also actively participated in the project by evaluating our software.

This page left blank intentionally.

EXECUTIVE SUMMARY

Military installations maintain a portfolio of buildings plus their supporting infrastructure. "Building energy assets" are the devices, equipment, and systems that produce, transfer, and/or use energy to support occupant activities for mission accomplishment. Proper management of complex energy assets is essential. Otherwise, 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 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 management workflow process: Synthesize, Measure, Analyze, Plan, and Act. This process is performed using two main modules of the BEAM software suites: the BEAM Configuration Tool and the BEAM Runtime Tool.

BEAM technology combines continuous condition monitoring with analytic tools for asset management. Integration of such software with existing building automation systems generates real-time data for building energy asset conditions, thereby enabling predictive maintenance and repair actions prior to complaint occurrence. In addition, embedded modeling and simulation engines empower building operators to evaluate and improve existing asset maintenance policies and decision making, specifically promoting maintenance and investment in critical "energy assets" to assure accomplishment of missions while minimizing overall lifecycle costs.

The fundamental goal of Environmental Security Technology Certification Program (ESTCP) EW-201262 Demonstration Project was application of BEAM software to manage the performance of building energy assets to optimize their availability, reliability, and energy consumption while fulfilling the building's functional objectives that support 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 waste due to operation of faulty assets?
2) Can BEAM-derived optimal maintenance policies show significant savings of lifecycle cost compared to current practices at the demonstration site?
3) Can BEAM's calculation of potential business penalties 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 U.S. Air Force Academy (USAFA) in Colorado Springs, Colorado from May 2012 to December 2013, to answer the questions posed above, as well as to assess the costs and implementation issues related to deployment of BEAM by the Department of Defense (DoD). During the 18-month project, we customized the BEAM tools for military installations to support a "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 collected periodically by the operator of the BAS. We then applied BEAM to one of the campus buildings, Arnold Hall, for performance validation and cost analysis.

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 a CI serves to alert 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 operations and maintenance (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. BEAM maintenance planning demonstrated reasonable levels of improvement in energy savings over the baseline and significant improvements in asset failure prevention, maintenance cost reduction, availability of assets, and avoidance of penalties due to business loss. The facility mangers also showed reasonable levels of satisfaction with BEAM ease of use and user interface Overall, the BEAM-derived optimal maintenance policy showed significant improvement in lifecycle cost saving over current practices at the demonstration site. The cost and benefit of using BEAM have been quantified, indicating a payback of investment in 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 cost and performance report has been prepared for Environmental Security Technology Certification Program (ESTCP) for Energy & Water (EW), 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 named Building Energy Asset Management (BEAM), a technology designed to empower the commanders of military installations and their facilities management subordinates to manage the operations and maintenance (O&M) activities of their buildings better so as 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 U.S. Air Force Academy (USAFA) in Colorado Springs, Colorado. This demonstration performed asset maintenance planning optimization 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).

1.1 BACKGROUND

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” of a building so as to ensure that the building meets its missions (or business objectives) while minimizing lifecycle costs. BEAM uniquely combines business values of assets (computed based on the building’s missions and functions) with asset failure models and building energy simulations to plan for maintenance or replacement of assets in ways that are optimal over a time horizon. The BEAM optimization model takes a holistic approach to costs that combines the direct costs of energy and maintenance with indirect costs of business loss and occupant discomfort. The configuration and criticality of these cost factors are left to the discretion of the building owner or operator.

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, over time, 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 heating, ventilation, and air conditioning (HVAC) and lighting systems and the building envelope. Allocating limited resources of finances and personnel, the commander of an installation is responsible for managing the 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, other considerations 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 efficiency at its installations through adoption of advanced O&M tools to be provided by BEAM:

- The BEAM technology provides military decision makers with robust analytical tools for managing maintenance policies for the energy assets within their buildings;
- 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; and
- 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.

1.3 REGULATORY DRIVERS

The primary drivers for this project are 1) Executive Orders (EO): EO 13423 of 24 January 2007 and EO 13514; 2) Legislative Mandates: Energy Policy Act of 2005 and Energy Independence and Security Act of 2007; 3) Federal Policy: Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding (MOU) 2006; 4) DoD Policy: Strategic Sustainability Performance Plan, Energy Security MOU with Department of Energy (DOE); and 5) U.S. Air Force (USAF) Policy: Air Force Energy Plan 2010.

Executive Orders: EO 13423, EO 13514

EO 13514, Federal Leadership in Environmental, Energy, and Economic Performance, dated 5 October 2009, expands EO 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.

Energy Policy:

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, states 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.

This page left blank intentionally.

2.0 TECHNOLOGY DESCRIPTION

BEAM is a software platform. It provides the means to assign a business value for an energy asset that quantifies its impact on accomplishment of the missions or business objectives of the building. 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. Moreover, BEAM asset planning optimization considers not only asset investment and maintenance cost, but also the building operation cost and the potential penalty cost from a loss of asset functions. 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 shows the schematic of the BEAM framework.

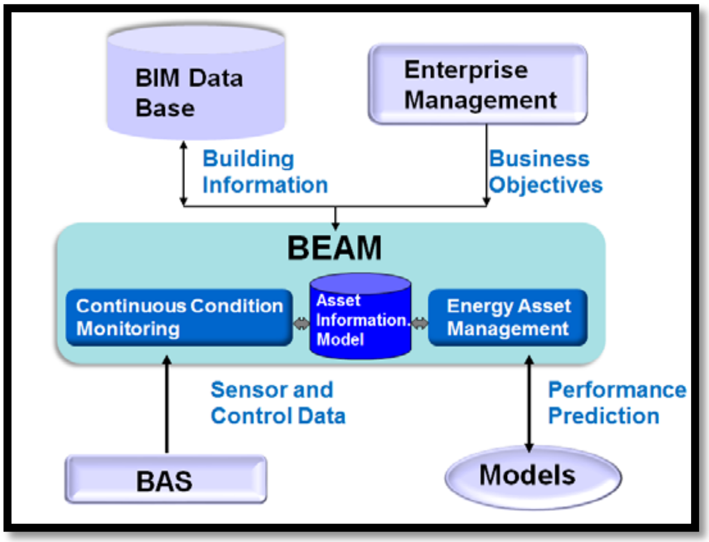


Figure 1. BEAM framework.

2.1 TECHNOLOGY OVERVIEW

BEAM Approach: The BEAM concept originates from EAM (Holland et al., 2005; McMullan I., 2004; Icon Group International, Inc. Staff, 2009), which applies a 5-step model to the asset management of different sectors of the economy (e.g., power grid, transit systems, and aerospace). The 5-step model involves processes to Synthesize, Measure, Analyze, Plan, and Act. With some simplification, BEAM can be outlined as a 3-phase workflow, 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. 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.

Building Energy Value Models (BVM): BEAM includes alternative BVMs, named BVM-I, BVM-II, and BVM-III. These models differ in the way they calculate the business value of building assets. In this project, we only employ BVM-III which monetizes the value of each asset by relating asset failure or degradation to loss of productivity and occupant discomfort. For simplicity of the presentation, we will use the term BVM throughout the report. The BEAM configuration phase maps 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 *monetary business value scores* of energy assets. Such business values are defined by economic loss due to failure or degradation of building assets. 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 computing Building Energy Value (BVM). The concept of PMV and its relation to productivity has been extensively used in practice (Kosonen et al, 2004; Lan et al, 2011; Roelofsen, 2002).

The 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.

Continuous Condition Monitoring: The 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 (CI). CI has a value between 0 and 100, with 0 corresponding to the worst condition and 100 indicating perfect condition. To calculate an asset's CI continuously, our CCM module includes three major functions:

- ***Automated fault detection and diagnosis (AFDD):*** 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. The automatic fault detection and diagnosis generates CI for the building asset detected with faults. This applies to general assets such as variable air volume (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 (BAS) 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 CI 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 kilowatt hours [kWh]/square foot per year) divided by 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. Similar to automatic condition monitoring, the output from manual condition monitoring is an asset level CI that is consistent with the definition used by DoD BUILDER (a software system developed by the U.S. Army Corps of Engineers [USACE] Construction Engineering Research Laboratory [CERL]).

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: (1) asset energy cost, (2) building value loss due to asset failures (Asset Penalty Cost), and (3) 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.

A flow chart of a BEAM Engine simulation cycle of 1 hour is displayed in Figure 2. 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 CI 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.

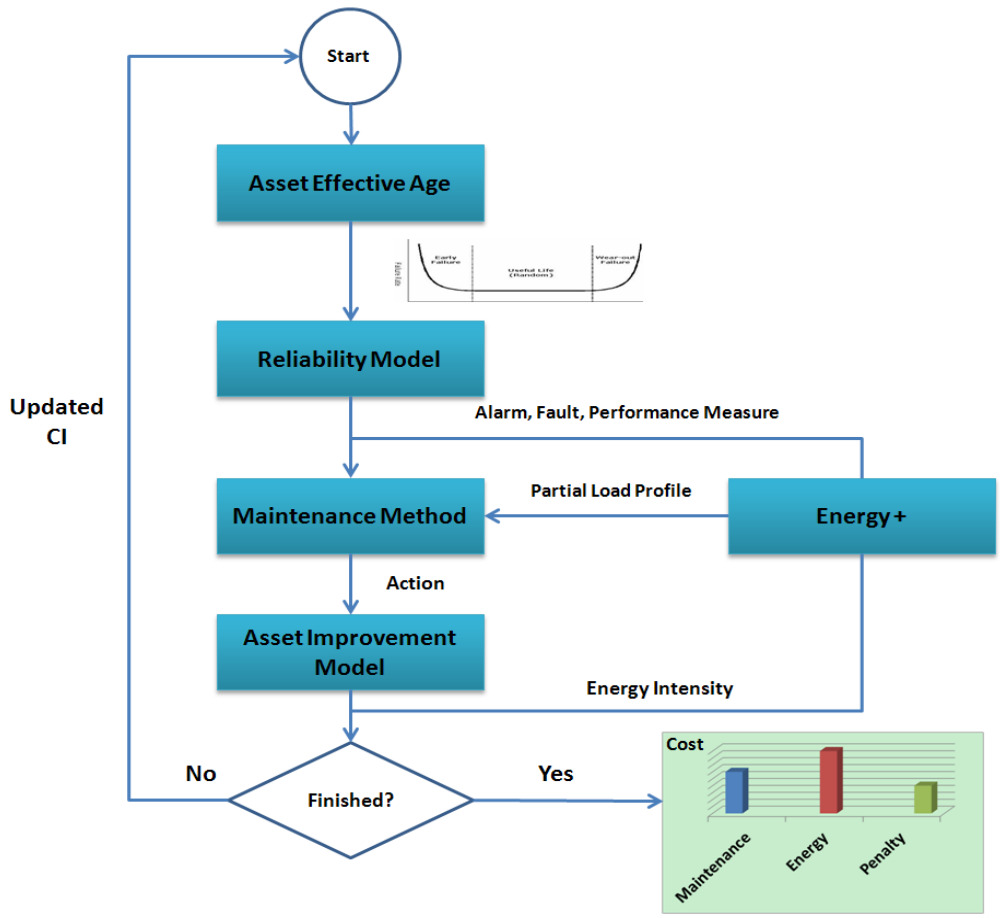
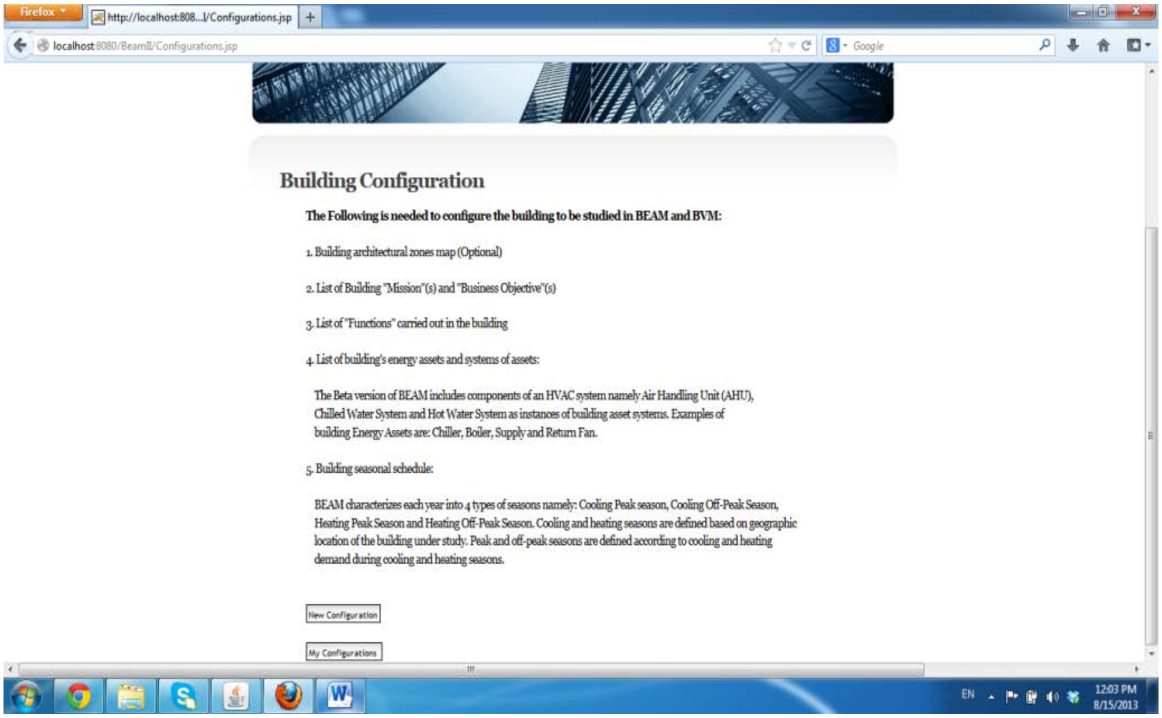


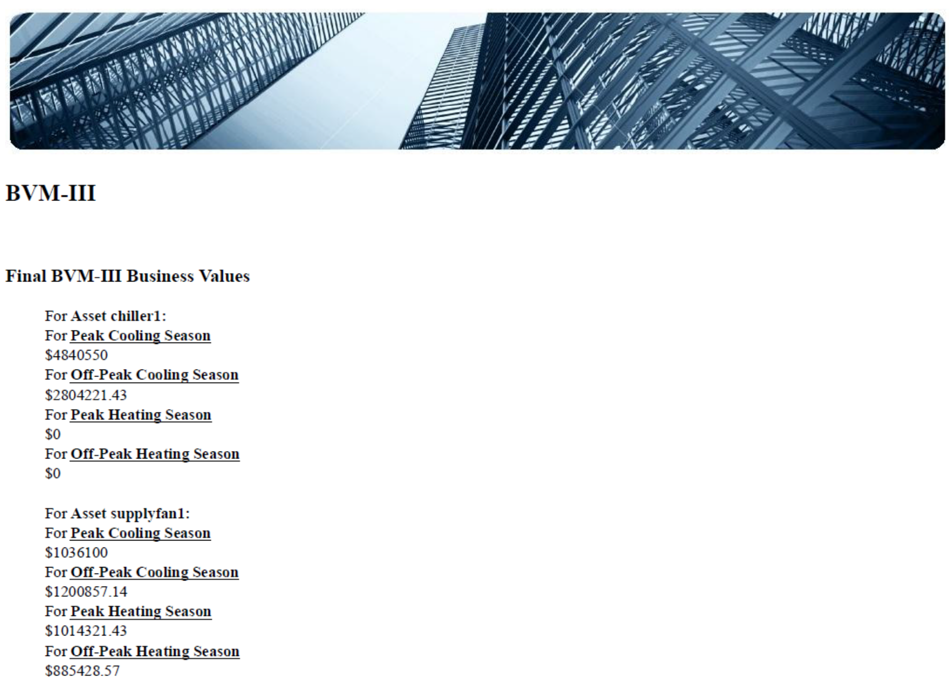
Figure 2. BEAM optimization flow chart for a 1-hour cycle.

Chronological Summary: The BEAM EAM and CCM technologies were developed independently of each other. The SCT efforts to develop HVAC CCM have been underway for the past decade. This technology is now well advanced; it has been tested in SCT settings previously. RU'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 DOE, formerly known as the Greater Philadelphia Innovation Cluster (GPIC) for Energy Efficient Buildings (EEB-HUB).

Technology Development: During the course of the project both the BEAM CCM module and the BEAM engine were further enhanced by Siemens and RU respectively. However, the major technology development efforts under the project were applied to the development of BEAM Tools. There are two main modules of the BEAM tools: BEAM Configuration and BEAM Runtime, as shown in Figure 3 and Figure 4.



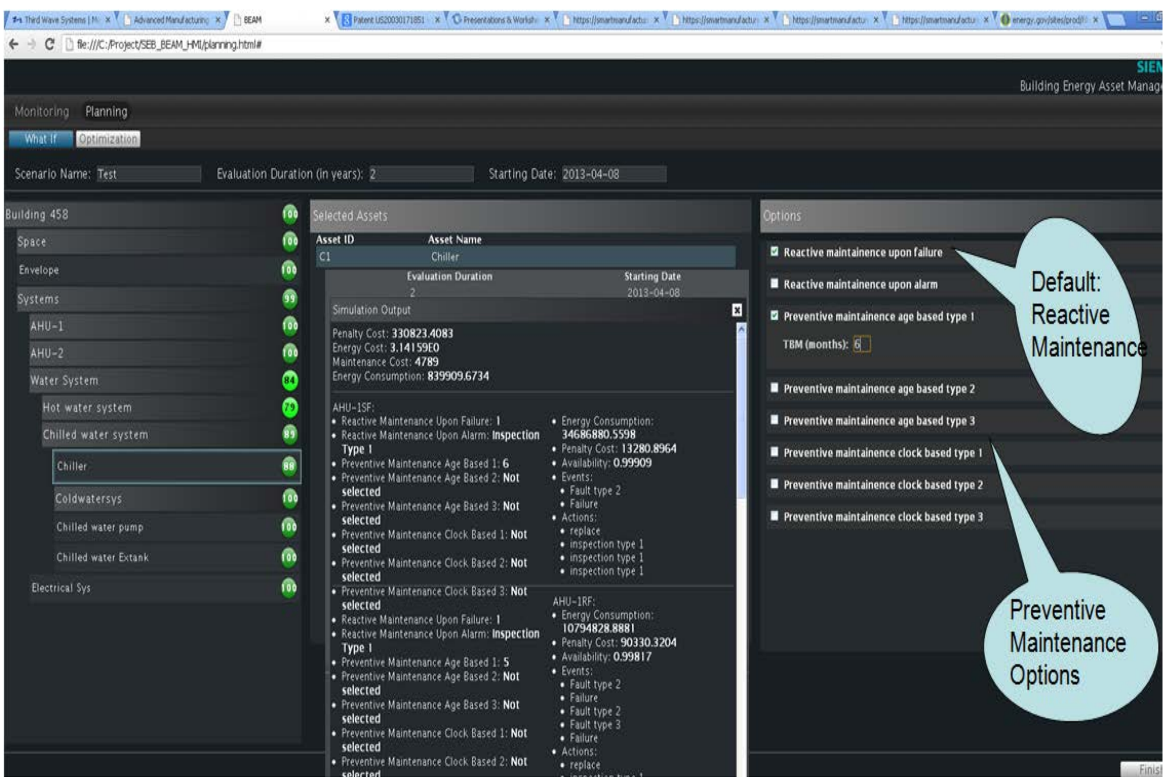
(a) User interface



(b) An example of BVM output

Figure 3. BEAM Configuration tool.

(a) Asset condition monitoring



(b) Asset management planning

Figure 4. BEAM Runtime software.

RU 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. The configuration tools are also used to generate models for automatic HVAC fault detection and diagnosis (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 3 (a) shows the web-based BEAM Configuration tool for energy asset BVM value generation. Figure 3 (b) shows the results of the configuration tools.

The SCT team implemented the BEAM Runtime tool. Both CCM and the BEAM Engine are implemented as plugins to an existing runtime energy management platform. In addition, the Siemens team developed a new web-based Human Machine Interface (HMI) using JavaScript and HTML5 technology. The HMI allows browsing of assets from the Asset Information Model using the Web Server Smart Energy Box (SEB).The user is also 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 4 a). 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 4b).

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, a user can upload BAS trend data daily, weekly, or bi-weekly to assess asset condition at his/her own convenience. Running in an "Integrated" mode, BEAM is integrated with the BAS system through the BACnet protocol; hence CCM 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.

<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 operate more energy efficient and cost effective systems of energy assets at the single building level 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.

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. And, as missions and/or their timeframes or other parameters change, decision makers can use BEAM to reevaluate O&M policies by projecting their associated direct and indirect costs.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages: The BEAM technology is innovative and has not been demonstrated previously. It provides innovative methods for CCM and asset management. The technology uses asset reliability assessment methods and building energy models. The technology gives facility planners and managers means to optimize both asset maintenance and energy cost. It also allows users 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 operations.

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 expense is 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 BAS 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 has an existing BAS system, especially when considering avoidance of the penalty cost that would be incurred due to the non-availability of assets.

Limitations: The BEAM tool requires supporting data on asset reliability, performance, and operating schedules. Recently constructed buildings typically have sufficient data to set up BEAM tools. For older facilities that have kept no archives of asset information and maintenance logs, the lack of asset data may significantly hinder the applicability of BEAM, unless data on similar assets can be obtained from the manufacturers or user groups. In addition, existing simulation technology (e.g., EnergyPlus) requires extensive computational time, especially when the building modeling includes sufficient details, and long simulation periods, i.e., 4 or 5 years.

A potential barrier to acceptance of BEAM technology is the time and expense required to generate all the models needed for 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 USACE and other architectural planners within the near future is a distinct possibility.

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) (POs 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 POs 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 O&M activities. The results of such technology impacts were reflected in measurements of annual energy usage (British thermal unit [BTU] and/or kWh – PO I), asset down time (Hours – PO IV), and lifecycle costs (cost – PO III). Therefore, the POs measure both directly and indirectly the ability of the technology to help O&M personnel reduce energy consumption (BTU and kWh) and allocate personnel, material, and financial resources.
- ***Cost Avoidance:*** The POs 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.

- ***GHG Reduction:*** The POs for EW-201262 do not attempt to measure the reduction of GHG emissions for installations.

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 POs through simulations that assess performance improvements in relation to the baseline.

Table 1. Performance objectives.

PO		Metric	Data Requirements	Success Criteria	15 Years Results
Quantitative Performance Objectives (based on E+ simulation results)					
I	Building total energy consumption	Energy intensity (MMBTU/ft^2 and/or kWh/ft^2)	Meter readings of energy used by installation and/or utility consumption recorded by 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.

4.0 FACILITY/SITE DESCRIPTION

The demonstration was conducted at the USAFA in Colorado Springs, Colorado using Arnold Hall (Figure 5) 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 USAFA. It houses a 3000-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, 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 kilowatts (kW). The USAFA contracts CH2M Hill for HVAC asset maintenance services. The policy requires the contractor to conduct monthly preventive maintenance (PM) for chillers in cooling season in addition to two annual PMs at the beginning and the end of cooling season. For air handler units, only semi-annual PMs are performed.

Figure 5. USAFA Arnold Hall selected for the demonstration.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The USAFA is a military school for officer candidates for the USAF. 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 (2000 Area).

- ***Demonstration Site Description:*** The Air Force Academy is a university campus within a military base. Arnold Hall is located in the 2000 Area of the base which contains the buildings used most intensely by the cadet wing. All 2000 Area buildings are held to strict architectural integrity requirements of 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. 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 building occupancy 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:*** BEAM was executed in a standalone mode with no need to access any other Air Force systems or networks.
- ***Other Concerns:*** The strong, existing relationship that Siemens Building Technology has with the Air Force Academy created an ideal demonstration site.

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. 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. For the purpose of this demonstration, we do not think such impact was significant.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

In reality, the facility hardware faults may happen once a year or couple of years. Due to the limited duration of this demonstration project, there was no physical alternations made to the building, so all the following results are simulated. For the purpose of conceptual test design, the BEAM 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. Table 2 summarizes the variables of the designed experiments.

Table 2. Test design summary.

Controlled Variables (constant between baseline cases and test cases)	**Independent Variables** (manipulated or changed by the user)	**Dependent Variables** (changing based upon the independent variables)
• Building characteristics (size, set points, etc.) • Weather pattern • Occupancy pattern • Building missions	Use of BEAM tools versus no use of BEAM tools	• Energy usage per asset and energy usage for whole building • Asset reliability and availability • Business penalty cost • Validation/rejection of baseline asset 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.

5.1.1 Hypothesis of the Test

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.

5.1.2 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 the final report. We also compared asset reliability and maintenance logs for these test cases.

5.2 BASELINE CHARACTERIZATION

Except for the baseline data, all inputs and results were calculated using simulations. The project period was too short to make real alterations to the way the building assets are run or maintained.

Reference Conditions: The following data was collected and used to establish reference conditions to assess each performance objective: building temperature *(source: Building Management System)*, building energy consumption data *(interval meter data bill provided by the utility Bill – facility manager)*, asset service contract and/or maintenance log, building event log and occupant complaint logs *(interview with the facility management team 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 additional hardware installed 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 to calibrate an EnergyPlus Model on a monthly basis. The model was further calibrated using the trended meter data collected during 2012/2013 on an hourly basis.

- ***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. Then we broke down the overall building asset maintenance cost into individual and service type-dependent itemized maintenance costs shown in Table 7.
- ***Business penalty cost:*** The business penalty cost baseline was established based on data collected during interviews with the Arnold Hall building operator concerning the building's business activities and their corresponding economic values. The business penalty cost due to failure or degradation of building assets was calculated according to the type of space they serve. For the office spaces, the penalty is occupants' productivity loss, which was translated to monetary impact based on their compensation. 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 the Arnold Hall building operator, who has been working there for more than 30 years.

BEAM model 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.
- ***Asset reliability model:*** We collected historical data on asset failures and conditions for Arnold Hall to establish the reliability model. Based on trend data collected on the site for the period of 2012-2013 we were able to compute the performance degradation and improvement of the Chiller (see Appendix B of the Final Report).

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 representative 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.

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, due to 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.

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. 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 3 and Figure 4). The system tested is a software tool that requires a Windows Operating System to run on a PC.

System Integration: Figure 6 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 both onsite and offsite, 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 BEAM runtime tool 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.

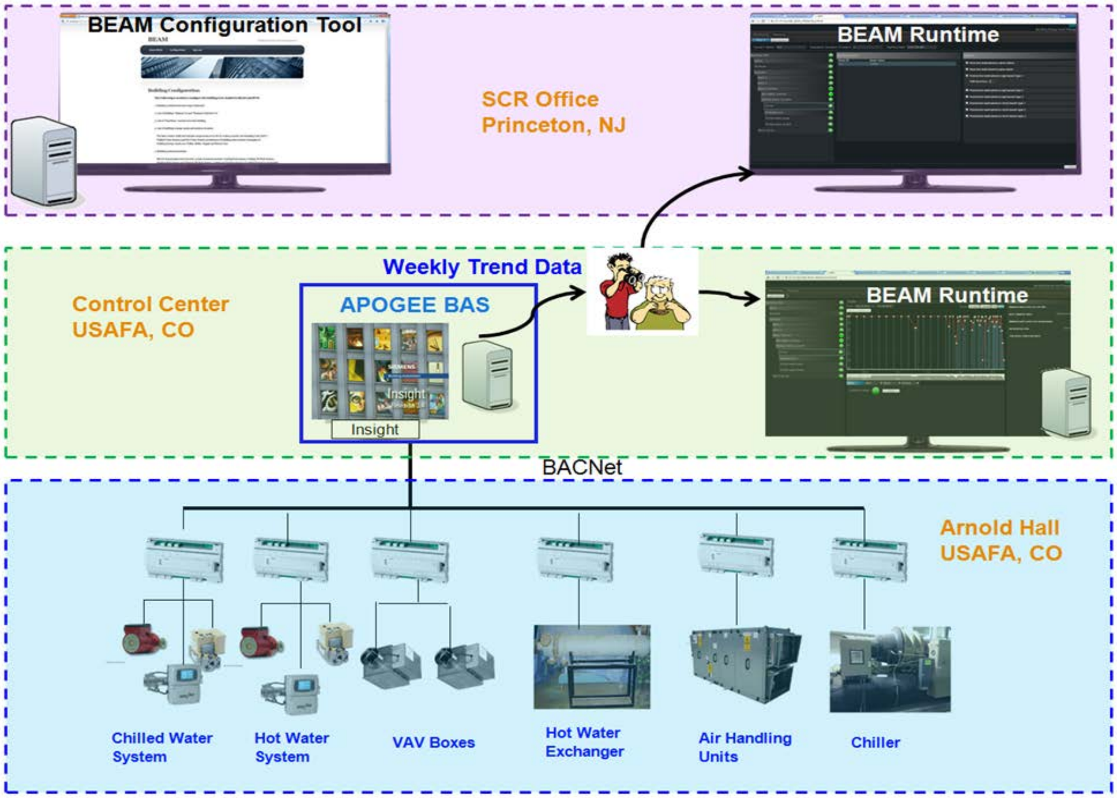


Figure 6. BEAM demonstration setup.

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.

5.4 OPERATIONAL TESTING

We conducted an integrated assessment of BEAM technology including the two main tasks: T1 - Modeling and simulation and T2 - hypothesis validation.

5.4.1 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. An interoperable meta-data model that was extended from an existing Building Information Model (BIM) captured all available energy use information. In addition to the attributes defined by BIM, we added time series data in our asset information model to capture performance and maintenance history for the assets.

5.4.2 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. The Model of Arnold Hall used for this experiment was calibrated on a monthly basis for year 2009, as shown in the picture below. Table 3 summarizes the validation criteria as applied.

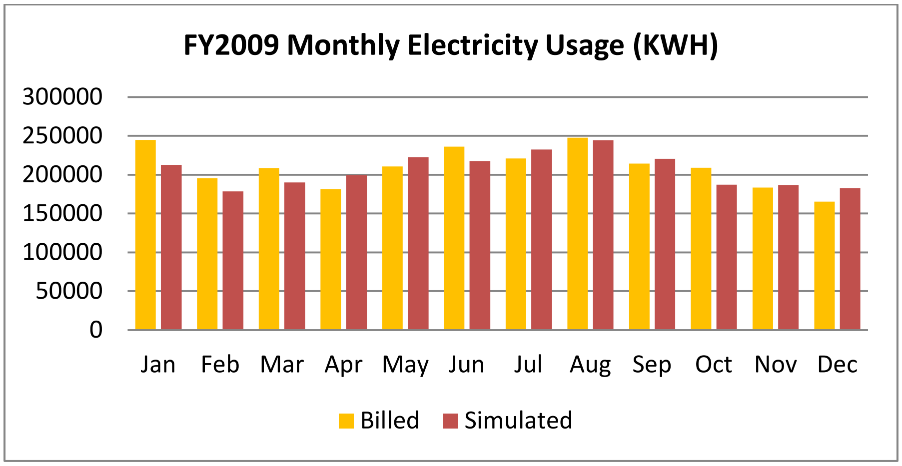


Figure 7. Monthly electricity usage calibration comparison for 2009.

Table 3. 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	Empirical data
6	Equipment failure and degradation are modeled correctly	Yes

For details on the EnergyPlus simulation model of Arnold Hall building see the Final Report.

5.4.3 T1.3: CCM Model Validation

The models for asset continuous condition monitoring include two parts: the equipment fault models which were represented by a set 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 (AHU) performance assessment rules (APAR) 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 of the Final Report for details).

5.4.4 T1.4: Building Value Model Validation

We applied the BVM model to Arnold Hall based on interviews with the building operator. The results can be found in the final report.

5.4.5 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. Some faults were detected. For example, the heating coil of AHU 1A (a dual deck AHU) 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 of the Final Report.

5.4.6 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 shown in Table 4) for periods of 2, 5, and 15 year durations.

Table 4. 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. Below is the result from 15-year simulation. 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 failures of equipment, we save penalty cost.

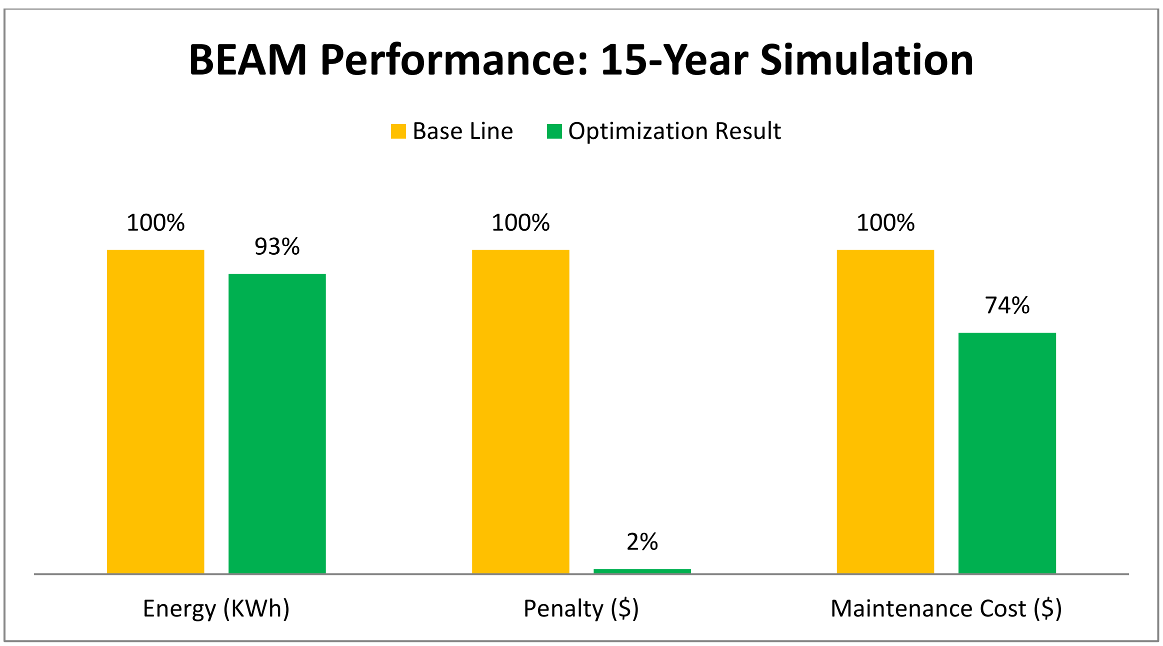


Figure 8. Comparison baseline versus optimization for 15-year simulation.

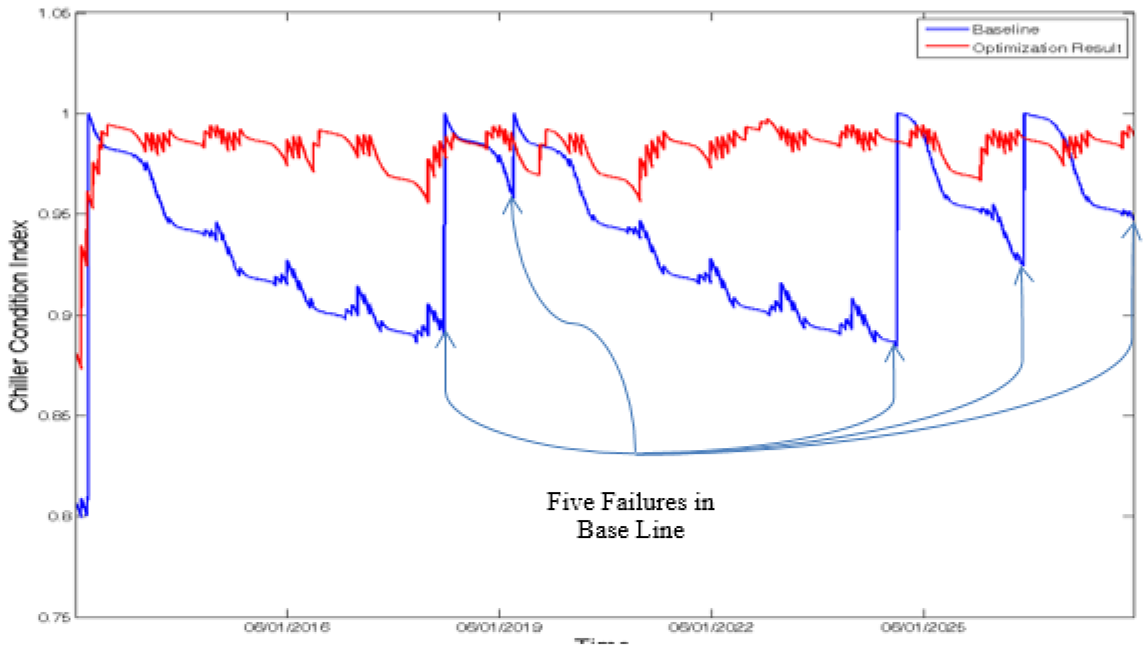


Figure 9. Chiller CI for 15-year simulation.

Technology Transfer or Decommissioning: Siemens Building Technology is already servicing USAFA and is conducting the technology transfer to the Academy. There is an ongoing discussion with SBT on the commercialization of BEAM technology as part of SBT services. With regard to decommissioning, BEAM software can be easily decommissioned through a de-installation function as part of the BEAM framework.

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 of the Final Report. 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. 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 5 below summarizes the types, the sampling rates used, data collectors, and storage.

Table 5. 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

GForge = Free web-based software for project-management and collaboration

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.

This page left blank intentionally.

6.0 PERFORMANCE ASSESSMENT

BEAM assessments were carried out mainly by using simulations provided by the BEAM. The following figure shows the performance validation approach applied to this demonstration. In practice, the EnergyPlus model may be adjusted to match the changes in the buildings. In current project, we adopted one EnergyPlus model for simulations of different durations, including the 15 years evaluations.

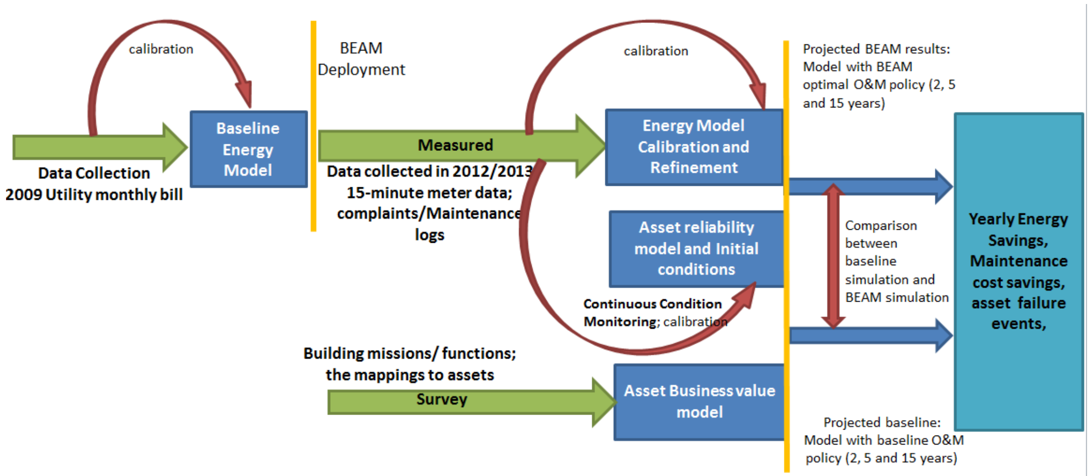


Figure 10. BEAM performance validation approach.

As indicated in Section 5, 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. Nevertheless, lifecycle cost and benefit approximation using BEAM can be achieved by extending the planning period so that the full life of a majority of a building's assets is included.

With respect to asset maintenance the BEAM platform is capable of providing a catalog of maintenance plans that can be configured by users. The BEAM framework can find the optimal policy in terms of total costs. The optimal policy obtained from BEAM can be compared to the baseline for each asset quantitatively, such as the number of times the asset fails, repaired or replaced. BEAM users could also compare the types of actual maintenance actions that are practiced with the actions that are proposed by the BEAM platform.

6.1 PO I: BUILDING TOTAL ENERGY CONSUMPTION

The results of the experiment on Table 6 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 6. PO I results summary.

Arnold Hall (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%

6.2 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 7. PO 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%

6.3 PO III: BUILDING SYSTEM ECONOMIC RESULTS

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 show 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.

Table 8. PO 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%

6.4 PO IV: BUILDING ASSET AVAILABILITY & RELIABILITY

Table 9. PO IV results summary (in %).

		2 Years		5 Years		15 Years	
	Assets	**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 10. PO 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 PO 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 10, 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 having no impact on availability.

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

6.5 PO V: EASE OF USE & USER SATISFACTION

We interviewed and surveyed the site facility manager, building operator, and control engineers; and all expressed their willingness to use the BEAM tools to monitor asset conditions and conduct energy asset management in performing their daily jobs. The figure below shows the survey result from the facility manager.

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 11. Survey result from the facility manager (EMCS-Chief).

6.6 SUMMARY OF RESULTS

The performances of the optimal asset maintenance policy and baseline maintenance policy are captured by Table 11 below.

Table 11. Demonstration results summary.

Arnold Hall (200,000 ft^2)	2 Year's BEAM	5 Year's BEAM	15 Year's BEAM	POs
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

This page left blank intentionally.

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 Return on Investment (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.*

7.1 COST MODEL

Listed in Table 12 are 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 12.
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 (estimated at 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 2 years no maintenance will be needed. But after 5 years some changes to the buildings should be anticipated that could require some adjustment to the different models.)

Table 12. 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	$2900	1	$2900	1	$2900	2	$5800
	Network cables	$10	3	$30	3	$30	3	$30
	Industrial hub (for the group)	$100	1	$100	1	$100	2	$200
	Monitoring station (dedicated laptop computer for the logical group)	$500	1	$500	1	$500	2	$1000
Software and Commissioning	Building asset audit (1 day)	$4800	1	$4800	1	$4800	3	$14,400
	Maintenance log collection and review (2 days)							
	Configuration of BACNet (2 days)							
	Total (1week@$4800)							
	Integration and system testing (1 week @$4800)	$4800	1	$4800	1	$4800	1	$4800
	First installation (1 week @$4800)	$4800	1	$4800	1	$4800	1	$4800
	System yearly maintenance/upgrade once every 5 years (1 day @$960)	$960	0	$0	1	$960	3	$2880
	License BEAM condition monitoring	$2500	1	$2500	1	$2500	1	$2500
	SEB License	$2500	1	$2500	1	$2500	1	$2500
	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.

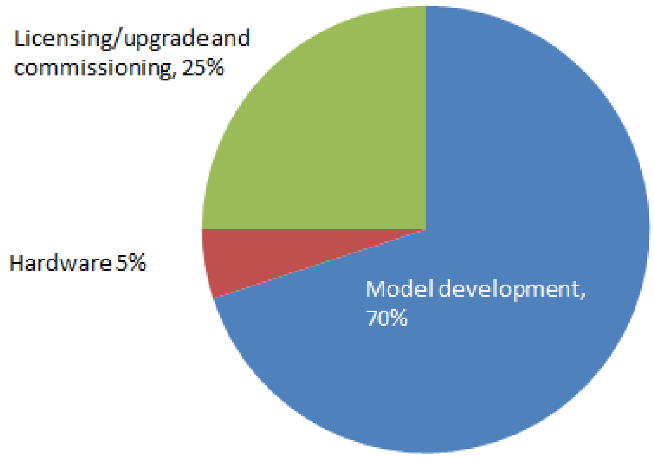


Figure 12. BEAM cost distribution.

Table 13. Cost of BEAM technology by category over lifetime.

Technology	Cost	Cost Proportions
Hardware	$7030	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 regular occurrences. Furthermore, most assets considered by BEAM have a lifetime 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 ROI from direct savings on energy and maintenance cost justifies the investment.

Table 14. 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 14 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 this 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 prevented from running the BEAM tool in integrated mode due to security consideration in a military environment 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.

This page left blank intentionally.

9.0 REFERENCES

[1] Holland C. P., D. R. Shaw, P. Kawalek, “BP's Multi-Enterprise Asset Management System,” Information and Software Technology, 2005.

[2] Icon Group International, Inc. Staff, “The 2009 Report on Enterprise Asset Management Systems (EAM): World Market Segmentation by City,” Icon Group International Inc., 2009.

[4] Salahi N., K. Mahani, J. Zhu, M.A. Jafari, Y. Lu, P.J. Winslow, “Business Value Driven Asset Management,” paper accepted, American Society for Heating, Refrigeration and Air-Conditioning Engineers Transaction, 2014.

[5] Mahani N., Salahi, J. Zhu, M. A. Jafari and Y. Lu, “Integrated Approach for Energy and Performance Optimization,” paper accepted, American Society for Heating, Refrigeration and Air-Conditioning Engineers Transaction, 2014.

[6] http://www.siemens.com/innovation/apps/pof_microsite/_pof-fall-2013/_pdf/PoF-2-2013-E-doppel.pdf.

[7] Schein J., “Results from Field Testing of Embedded Air Handling Unit and Variable Air Volume Box Fault Detection Tools,” http://fire.nist.gov/bfrlpubs/build06/PDF/b06033.pdf.

[8] Kosonen R., and F. Tan, “Assessment of productivity Loss in Air-Conditioned Buildings Using PMV Index,” *Energy and Buildings*, vol. 36, pp. 987-993, 2004.

[9] Roelofsen P., “The Impact of Office Environment on Employee Performance: The Design of the Workplace as a Strategy for Productivity Enhancement,” *Journal of Facilities Management*, vol. 1, no. 3, pp. 247-264, 2002.

This page left blank intentionally.

APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-Mail	Role In Project
Dmitriy Okunev	Siemens Corporation, Corporate Technology	Phone: 609-734-3540 E-Mail: yanlu@siemens.com	Principal Investigator
Sue DeMeo	Siemens Corporation, Corporate Technology	Phone: 609-734-4469 E-Mail: susan.demeo@siemens.com	Business Contact
Thomas Gruenewald	Siemens Corporation, Corporate Technology	Phone: 609-734-3546 E-Mail: thomas.gruenewald@siemens.com	Project Manager
Dr. Mohsen Jafari	Rutgers University	E-Mail: jafari@rci.rutgers.edu	Principal Investigator
Larry Lawrence	US Air Force Academy	Phone: 719-333-1447 E-Mail: Larry.lawrence@us.af.mil	Site Support

This page left blank intentionally.

ESTCP Office

4800 Mark Center Drive
Suite 17D08
Alexandria, VA 22350-3605

(571) 372-6565 (Phone)

E-mail: estcp@estcp.org
www.serdp-estcp.org