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# Design and Testing of an Illuminance Management System

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*Students, the professor, and eight systems engineering advisors for a class project in the fall of 2009 designed a light management system for an operations room for astronomers on Mauna Kea on top of Hawaii. For these astronomers who need constant illumination, BIMS is a light and energy management system that will make them more comfortable and productive, and will save money. Unlike conventional lights and blinds, BIMS will automatically control the illuminance in the room when the sun's or the moon's light rays change. The documentation for this design is lengthy; it has been condensed for this article: Parts that do not concern test and evaluation have been eliminated.*

**Key words:** Requirements, systems engineering process, SysML, UML, validation, verification.

This article shows how systems engineering principles (Sage and Rouse 2009) can be applied to test and evaluation. It is based on a set of documents written in the fall of 2009 with weekly iterations to help the systems engineering students at the University of Arizona model and design systems. This set of documents was not intended to be a *complete* design; instead, it shows a few good examples of each type of item that might be in a typical design document. It has only one use case and only one trade-off study. The full set of documents is located at http://www.sie.arizona.edu/sysengr/sie554/BIMS/. This site has more examples in each section, but before discussing this case study, we must explain our set of documents (http://www.sie.arizona.edu/sysengr/sie554/8docs.doc; Chapman, Bahill, and Wymore 1992; Pinewood 1992; Wymore 1993).

## The eight systems engineering documents

*Document 1: The Problem Situation Document* is the executive summary. It specifies the system's mission, explains the customers' needs and expectations, states the goals of the project, defines the business needs, prescribes the system's capabilities, delineates the scope of the system, expresses the concept of operations, describes the stakeholders, presents the key decisions that must be made, shows the incipient architecture, and (in the final version) highlights the preferred alternatives. It is written in natural language and is intended for management and the public.

*Document 2: The Customer Requirements Document* is a description of the problem in plain language. It is based on the use cases of document 6. It is intended for management, the customer, and engineering.

*Document 3: The Derived Requirements Document* is a technical description (or model) of the problem statement and the requirements of documents 1 and 2. Each requirement in this document must trace to document 1 or 2. Alternative names for this document are Technical Requirements and Design Requirements. The audience for document 3 is engineering.

*Document 4: The Verification and Validation Document* has four parts. **Validating the system** means building the *right system*: making sure that the system does what it is supposed to do. **Verifying the system** means building the *system right*: ensuring that the system complies with its requirements and conforms to its design. **Verifying requirements** means proving that each requirement has been satisfied. **Validating requirements** means ensuring that the *set* of requirements is correct, complete, and consistent; that a model can be created that satisfies the requirements; that a real-world solution can be built that satisfies the requirements; and that this real-world solution can be tested to prove that it satisfies the requirements. The intended audience for document 4 is systems engineering, test and evaluation engineering, and the customer.

*Document 5: The Concept Exploration Document* is used to study alternative system designs through brainstorming, modeling, simulation, prototypes, and finally the complete system (Daniels, Werner, and Bahill 2001; Smith et al. 2007). In early iterations of document 5, this exploration helps produce the incipient system architecture (Rechtin 2000). This document is rewritten continually as more information becomes available. Evaluation criteria are derived from a subset of the trade-off requirements. They are used in the heart of later iterations, which is a trade-off study where the preferred alternatives are suggested by the data. A sensitivity analysis identifies the most important parameters in a trade-off study; often these are the cost drivers that are worthy of further investment (Smith et al. 2008). This is one of the most popular documents. It should be readable by the public.

*Document 6: The Use Case Model* contains many use case reports that in the aggregate describe the required behavior of the proposed system (Daniels and Bahill 2004). The system design and the testing procedure should be based on these use cases. The early use cases should be independent of potential solutions. The intended audience for document 6 is management, engineering, the customer, and the public.

*Document 7: The Design Model* shows the objects that implement the required functionality of the system. System interfaces and test equipment are designed in this document. Its intended audience is engineering.

*Document 8: The Mappings and Management Document* shows the mappings between the documents. It also includes activity diagrams, the risk analysis, schedule information (Gantt charts, program evaluation review technique charts, etc.), the project work breakdown structure, the business plan, and a log of meetings with the customer.

These eight documents are often called a systems engineering management plan. They are living documents: They grow and are continually updated throughout the entire system life cycle. They are not written sequentially, but they are structured so they can be read sequentially. The order in which a scientific article is written is usually not Introduction, Methods, Results, Discussion, and Conclusion, but it *is* the order in which a scientific article is usually read.

> *"Begin at the beginning," the King said gravely, "and go on 'til you come to the end; then stop." (From Lewis Carroll,* Alice's Adventures in Wonderland.*)*

Bahill's system design process is a use-case-based iterative process. It starts with a problem statement in a preliminary document 1 (Problem Situation). Next we make a rough schedule of who does what and when, and we put that in document 8 (Mappings and Management). Those were brief activities. Now we write the use cases that describe the behavior of the system. While we are writing the use cases, we develop functional and nonfunctional requirements. These go into a fairly large document 6 (Use Case Model). The customer requirements (just discovered) go into document 2 (Customer Requirements) and also into the requirements verification section of document 4 (Verification and Validation). Design of tests can start as soon as the use cases are written. The systems engineers then derive the technical requirements, and the test engineers create the test requirements that go into document 3 (Derived Requirements). Now that we have some requirements, we can form evaluation criteria that will be used in the trade-off studies of document 5 (Concept Exploration). Document 7 (Design Model) contains Unified Modeling Language (UML) and Systems Modeling Language (SysML) diagrams that show the behavior and structure of the proposed system. This system design process is very iterative. Creating these eight documents is not a serial process. There must be many iterations, and there are many opportunities for parallel processing.

This article is based on one of the later iterations of the full set of design documents for the BIMS. It can be read from beginning to end, but it might be easier to read this article in this order: document 1, 6, 2, 3, 4, 5, 7, and 8.

## Bahill Intelligent Computer Systems (BICS) Illuminance Management System

### *Document 1: Problem Situation*

*Product position statement.* For astronomers who need constant illuminance, the BICS Illuminance Management System (BIMS) is a light and energy management system that will make them more comfortable and productive, and will save money. Unlike conventional lights and blinds, BIMS will automatically control the illuminance in the room when the light rays of the sun or moon change.

*Concept of operations (ConOps).* Our customer (the National Optical Astronomy Observatory [NOAO]) needs a total light-management system for the operations rooms of telescope enclosures to be built on Mauna Kea in Hawaii and on Cerro Pachón near Vicuña in Chile. However, the system must be designed so that it can be adapted for other structures. It should be the basis of a BICS company standard that will be sold in all commercial and residential venues. This system will be named the BICS Illuminance Management System.

The system must conserve energy and provide a natural daylight color spectrum. An efficient way of doing this is to have the system use daylight instead of artificial lighting as much as possible. BIMS will be politically correct (environmentally green) because it will use renewable-energy electric generators, such as solar panels or wind turbines, but other electric generation alternatives such as geothermal systems using the Kilauea volcano should be considered.

Astronomers will use the operations room day and night while observing both the sun and nighttime targets such as stars and galaxies. In the daytime, the astronomers want a constant illuminance of 500 lux. The operations room will have a large east-facing window. As the sun rises, the lights can be turned on. By midmorning, the lights can be dimmed and the window screens or curtains can be gradually opened. After noon, the window screens or curtains can be opened wide. As the sun sets, the lighting level will gradually decrease following a predetermined program.

During the night, the astronomers will be continually going in and out of the operations room. There will be no lights outside because that would interfere with the telescopes. So we want the light inside the operations room to be dim and constant so that (1) the astronomers do not have to wait minutes for their eyes to dark adapt and (2) the light inside does not leak out and interfere with the telescopes. Therefore, we want the inside illuminance at night to be 0.4 lux. This is roughly the illuminance of a full moon. So your system will have to accommodate phases of the moon, its rising and setting, and clouds that might obscure it. *Figure 1* shows the scope of this project.

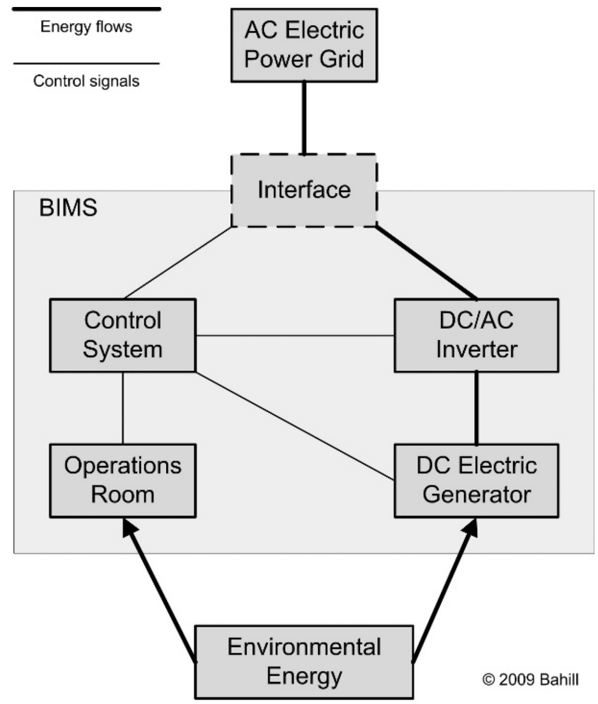


*Figure 1. Block diagram showing the scope of a BIMS.*

*BICS company policy*

All systems shall have built-in self test (BiST) with a continuous visual indicator of status. At startup all systems shall do self tests. In addition, whenever the system is not serving the customer, it should be performing BiSTs.

All systems shall have the BICS touch, feel, and look. The BICS look includes options that portray elegance.

All systems shall use the International System of Units (SI). Input and output can be in familiar units, but all specifications and calculations shall be in SI units.

Our design process uses sequential incremental iterations (simulate a little, build a little, test a little, repeat).

It is company policy that nondevelopmental products be considered the primary solution to addressing customer needs with customized implementations being secondary solutions. While the primary nondevelopmental products addressed in this policy are Commercial off the Shelf (COTS), the phrase *primary nondevelopmental products* also includes Government off the Shelf (GOTS), Open Source software, and previously developed in-house products.

System designs shall be satisficing designs, never optimal designs (Simon 1957, 1962).

All system designs shall follow the principles of good design presented in Bahill and Botta (2008) and http://www.sie.arizona.edu/sysengr/publishedPapers/goodDesignPrinciples.pdf.

The on-line BIMS document has more examples of company policy.

*Applicable standards.* Connection to the alternating current (AC) power grid must comply with the UL1741/IEEE1547 standard. The system must comply with Underwriters Laboratories, ISO 15288, EAI-632, OSHA, EPA environmental regulations, National Electrical Code (NEC), and Federal Communications Commission (FCC) regulations concerning our product's emissions and FCC regulations concerning the 434-MHz electromagnetic spectrum bandwidth allocation. The online BIMS document has other examples of applicable standards.

*Stakeholders.* BIMS stakeholders include architects, contractors, dealers, salespeople, end users, astronomers, NOAO, university students, a surrogate customer (an in-house person designated to have knowledge of end user needs and expectations), and potential victims (such as other astronomers on the mountain, construction workers, Hawaii Electric Light Company Inc., the environment, and Poliahu the snow goddess of Mauna Kea).

*Ubiquitous language glossary*

**brightness**: The amount of light coming from a unit area of a flat surface that is seen by the human eye. Brightness is perceived, not measured, so it has no units.

**capacity factor:** Electric generators do not generate electricity at their maximum rate 24 hours a day, 7 days a week. The system must be shut down for maintenance and repairs, and output will be reduced when the loads are small. In addition, renewable-energy systems will have reduced output when, for example, clouds cover the sun or there is no wind. The capacity factor is defined for specified period: It is the actual electricity generated divided by the energy that theoretically could have been generated if the system ran at maximum capacity for the whole period.

$$\mathrm{CapacityFactor} = \frac{\mathrm{ActualAverageDailyElectricityGenerated(kWh/d)}}{\mathrm{RatedPower(kW)} \times \frac{24\mathrm{h}}{\mathrm{d}}}$$

The capacity factor of renewable-energy electric generators is typically 5% to 40%. For photovoltaic solar power, the capacity factor is around 17%.

**dark adaptation:** When a person goes from sunlight to darkness, the retina can adjust its gain over nine orders of magnitude. But this adaptation takes around 10 minutes. This may be why pirates wore black eye patches. When a pirate (probably just the captain or the first mate) was above deck, he put a black patch over one eye: That eye then became dark adapted. When he went below deck, where it was dark, he would take the patch off and the dark-adapted eye would immediately be able to see. When the pirate returned topside, he would replace the black patch on his eye.

**electric generators:** Electric generators transform environmental energy into electric energy. Here are some common examples: photovoltaic solar panels; wind turbines; ocean currents, waves, and tides; hydroelectric dams; tapping static electricity stored in the atmosphere; and geothermal systems based on the Kilauea volcano. An electric generator generates electricity. It transforms another form of energy into electric energy. It does not create energy or electricity. (So, in this context, generate does not mean create.) Power is the time rate of change of electric energy.

**energy storage units:** Energy storage units smooth the electric grid voltage when the generating environment varies. However, energy need not be stored as electricity. The energy storage units could be electric (like super capacitors), chemical (like batteries), thermal (like a big rock, a pond, molten salt, or ice), potential (like pumping water between two altitudes or compressed air tanks), or kinetic (like a big flywheel).

**expected average daily electricity generation:** This term estimates the amount of electricity that a particular system would be expected to generate per day in a particular location (kWh/d).

**illuminance:** The amount of visible light coming from a source (such as the sun, the moon or a light bulb) that falls on a unit area of a surface. Its units are lux. One lux is one lumen per square meter. One lumen per square foot is one footcandle.

**insolation:** The amount of solar radiation that strikes a single location over a given period (usually 1 day) is called insolation. It has units of kilowatt-hours per square meter per day (kWh/[$m^2$·d]).

**inverter:** Renewable-energy electric generators produce direct current (DC) or some other form of voltage. The AC electric power grid has very well controlled 60-Hz sinusoidal AC. Generally an inverter changes DC into AC.

**luminance:** The amount of light coming in a particular direction from a unit area of a flat surface (such as a wall, a table, or a computer monitor). Luminance depends on the light source, the surface, and the viewing angle. Its units are candelas per square meter.

**light blockers:** Light blockers alter the amount of light coming into or out of a room. Examples are blinds, shades, screens, curtains, drapes, shutters, polarized windows, skylights, window films that change transparency with electricity, and opaque screens that unroll from the roof in front of the windows.

**rated power:** Rated power is the power that the system was designed to generate in steady-state at the normal operating point. This is usually near the maximum power. It is also called generating capacity and nameplate capacity.

**use case:** A *use case* is an abstraction of required functions of a system. A use case produces an observable result of value to a user. A typical system will have many use cases, each of which satisfies a goal of a particular user. Each use case describes a sequence of interactions between one or more actors and the system. This sequence of interactions is described in a use case narrative, and the relationships between the system and its actors are portrayed in use case diagrams. Names of the use cases are set in the Verdana font.

## Document 2: Customer Requirements

The system requirements are discovered in the use cases of document 6 (Daniels and Bahill 2004). They are formalized in document 2. Test engineers can use these requirements immediately to start writing test cases and test procedures. Finally new requirements are derived based on the customer requirements, the mission statement, and the concept of operation (Bahill and Dean 2009), and they are put into document 3 (Derived Requirements).

CuR1-1 The system shall use an ephemeris, tables, models, firmware, or similar methods to anticipate sunrise, sunset, moonrise, moonset, and the phase of the moon. Note: A ROM-based ephemeris is available commercially. DeriveReqt: Req 1-1 of Control Illuminance During the Day use case. Notes: DeriveReqt means that this requirement is derived from the indicated requirement in the use cases.

CuR1-2 The system shall control the illuminance of the lights. DeriveReqt: Req 1-2 of Control Illuminance During the Day use case.

CuR1-3 The system shall control the opening and closing of window screens or curtains. DeriveReqt: Req 1-3 of Control Illuminance During the Day use case.

CuR1-4 The system shall sense the illuminance in the operations room. DeriveReqt: Req 1-4 of Control Illuminance During the Day use case.

CuR1-5 The system shall buy electricity from and sell electricity to the AC electric power grid. DeriveReqt: Req 1-5 of Control Illuminance During the Day use case.

CuR1-6 The system shall exchange electricity between the DC electric generator and the energy storage device. DeriveReqt: Req 1-6 of Control Illuminance During the Day use case. This requirement was removed by A. T. Bahill October 17, 2009.

CuR1-7 The system shall execute Built-in Self Tests (BiST). DeriveReqt: Req 1-6 of Control Illuminance During the Day use case. Mandated by BICS company policy.

CuR1-8 The system shall maintain the daytime illuminance in the operations room at 500 ± 50 lux (≈50 ± 5 fc). Trace to CuR1-2, CuR1-3, and CuR1-4. DeriveReqt: Req 1-8 of Control Illuminance During the Day use case.

CuR1-9 The system shall maintain the nighttime illuminance in the operations room at 0.4 ± 0.2 lux (≈0.04 ± 0.02 fc). Trace to CuR1-2, CuR1-3, and CuR1-4. DeriveReqt: Req 1-9 of Control Illuminance During the Day use case.

CuR1-10 The system shall generate electricity at a cost that is competitive with commercial electricity costs at that location, after federal subsidies, etc. Trace to CuR1-5 and CuR1-6. DeriveReqt: Req 1-10 of Control Illuminance During the Day use case.

*Mandatory requirements.* This mandatory requirements section contains the key decisions of document 1 as well as some additional requirements. Mandatory requirements specify necessary and sufficient capabilities, use the verb *shall*, are passed or failed with no in between and should not be included in *trade-off* studies. An example is "The system shall not violate federal, state, or local laws."

The system shall have renewable-energy electric generators. Rationale: This is a political decision, not an economic or scientific decision. It is justified in document 8.

The system shall include all equipment needed for connecting to the local AC electric power grid.

The system shall satisfy all rules, regulations, and standards necessary for connecting to the local AC electric power grid.

The system shall *not* have local energy storage units. Rationale: Grid-connected electric generators do not need energy storage units such as batteries. In October 2009, Bill Henry of TEP said that very few of TEP's customers have batteries. Subsequently, Terry Bahill, president of BICS, decided that the BIMS will not have energy storage units.

The renewable-energy electric generators shall have the capability of supplying the operations room with an average daily electricity generation of 40 kWh/d. This result is derived in the analysis at NFPR1-4.

The system shall be designed with the following site constraints. The average ground wind speed at the telescope site on Mauna Kea is 10 miles/h (4.5 m/s). Yearly average insolation is 6 kWh/($m^2$ d). Average air density for July is 0.76 kg/$m^3$ (Bahill, Baldwin, and Ramberg 2009). *This means that if the astronomers were to play a baseball game in the caldera, a hit that would travel 365 feet in San Francisco would travel 430 feet on Mauna Kea.*

Renewable-energy electric generators shall not interfere with any of the telescopes on the summit.

Mandatory requirements are not tested only once at total system test. They are monitored continually. They are discussed at every design review. Because they are so important, some mandatory requirements will become technical performance measures (TPMs) (Bahill and Dean 2009). The requirement for an average daily electricity generation of 40 kWh/d is a prime candidate for a TPM.

*Model mapping rules.* Throughout the design of a system many models will be made. Usually each

*Table 1. The derived requirements for BIMS.*

| | |
|---|---|
| **Functional requirements** | |
| Identification tag (Id) | FR1-1 |
| Name | Predict Sunrise and Sunset |
| Text | The system shall predict sunrise, sunset, moonrise, moonset, and the phase of the moon. |
| Comment | Possible solutions include an ephemeris, tables, models, and firmware. A ROM-based ephemeris is available commercially. |
| DeriveReqt: | CuR1-1 |
| Verify method | Initially modeling, thereafter demonstration: Tester will observe the time of sunrise and sunset. The predicted times and the observed times must be within TBD minutes on average. All aconyms are expanded at the beginning of document 8. The TBD shall be resolved before PDR. |
| Priority | Low |
| Date of last change | December 3, 2009 |
| Identification tag (Id) | FR1-2 |
| Name | Control Lights |
| Text | The system shall control the illuminance of the lights. |
| Comment | Another requirement should be added that requires the illuminance to be uniform throughout the operations room. |
| DeriveReqt: | CuR1-2 |
| Refined by | NFPR1-1 and NFRP1-2 |
| Verify method | Initially inspection, later demonstration |
| Priority | High |
| Date of last change | December 3, 2009 |
| Identification tag (Id) | FR1-3 |
| Name | Control Light Blockers |
| Text | The system shall control the opening and closing of light blockers. |
| Comment | Light blockers are devices that alter the amount of light coming into or out of a room, such as blinds, shades and drapes. At night they will be closed to prevent light from leaking out to the telescopes. |
| DeriveReqt: | CuR1-3 |
| Refined by | NFPR1-1 and NFRP1-2 |
| Verify method | Initially inspection, later demonstration |
| Priority | Medium |
| Date of last change | December 3, 2009 |
| Identification tag (Id) | FR1-4 |
| Name | Sense Illuminance |
| Text | The system shall sense the illuminance in the room. |
| Comment | This requirement should be expanded to require that the sensors be distributed throughout the operations room. A nonfunctional performance requirement could specify the required accuracy of the light sensors. |
| DeriveReqt: | CuR1-4 |
| Verify method | Test during design and construction, thereafter demonstration: The illuminance sensor readings will be compared with calibrated illuminance meters on a monthly basis. |
| Refined by | NFPR1-1 and NFRP1-2 |
| Priority | High |
| Date of last change | December 3, 2009 |
| Identification tag (Id) | FR1-5 |
| Name | Buy and Sell AC Electricity |
| Text | The system shall be capable of buying electricity from and selling electricity to the AC electric power grid. |
| Comment | The Hawaii Electric Light Company Inc. is the electric company for the Big Island of Hawaii. This requirement has a measure of effectiveness, the amount of energy sold to this electric company per month. |
| DeriveReqt: | CuR1-5 |
| Verify method | Initially inspection, when operational weekly analysis |
| Priority | Low |
| Date of last change | December 3, 2009 |
| Identification tag (Id) | FR1-6 |
| Name | Generate Electricity |
| Text | The system shall be capable of generating electricity. |
| Comment | Electric generators transform environmental energy into electricity. Here are some common examples: PV panels, wind turbines, ocean waves, ocean tides, and geothermal systems. The energy storage part of this requirement was deleted by Bahill October 17, 2009. |
| DeriveReqt: | CuR1-6 |
| Verify method | Inspection |
| Priority | Medium |
| Date of last change | December 3, 2009 |
| Identification tag (Id) | FR1-7 |
| Name | Execute BiST |
| Text | The system shall execute BiSTs. |
| Comment | This comes from BICS company policy. |
| DeriveReqt: | CuR1-7 |
| Verify method | Test during design and construction, and thereafter in weekly demonstration. |
| Priority | High |

**Table 1.—Continued.**

| | |
|---|---|
| Date of last change | December 3, 2009 |
| Identification tag (Id) | FRz-1 |
| Name | Gather V&V Data |
| Text | The system shall facilitate gathering evidence that can be used to prove verification and validation (V&V) of the system and the requirements. |
| DeriveReqt: | BICS company policy |
| Verify method | Inspection |
| Priority | High |
| Date of last change | December 3, 2009 |
| **Nonfunctional performance requirements** | |
| Identification tag (Id) | NFPR1-1 |
| Name | Maintain Daytime Illuminance |
| Text | The system shall maintain the daytime illuminance in the operations room at 500 ± 50 lux (≈50 ± 5 fc). Trace to FR1-2, FR1-3, and FR1-4. |
| DeriveReqt: | CuR1-8 |
| Verify method | The system will record the illuminance every minute. This file will be examined weekly. The average value, the number of excursions from the limits and the total duration of the excursions will be computed. These measures shall be within TBD. This TBD shall be resolved before PDR. |
| Priority | Medium |
| Date of last change | December 3, 2009 |
| Identification tag (Id) | NFPR1-2 |
| Name | Maintain Nighttime Illuminance |
| Text | The system shall maintain the nighttime illuminance in the operations room at 0.4 ± 0.2 lux (≈0.04 ± 0.02 fc). Trace to FR1-2, FR1-3, and FR1-4. |
| DeriveReqt: | CuR1-9 |
| Verify method | The system will record the illuminance every minute. This file will be examined weekly. The average value, the number of excursions from the limits, and the total duration of the excursions will be computed. These measures shall be within TBD. This TBD shall be resolved before PDR. |
| Priority | Medium |
| Date of last change | December 3, 2009 |
| Identification tag (Id) | NFPR1-4 |
| Name | Rated Power |
| Text | The electric generating system shall have a minimum rated power of 10 kW. |
| Rationale | Expected average daily electricity generation in this location with this type of plant must be at least 40 kWh/d. To account for environmental variability, the capacity factor of renewable-energy electric-generators is typically 5% to 40%. For photovoltaic solar power, we estimate a capacity factor of 17%. Therefore the minimum rated power must be 10 kW. $\mathrm{RatedPower} = \frac{\mathrm{AverageDailyElectricityGeneration}}{\mathrm{CapacityFactor} \times \frac{24\mathrm{h}}{\mathrm{d}}} = \frac{40\mathrm{kWh/d}}{\frac{1}{6} \times \frac{24\mathrm{h}}{\mathrm{d}}} = 10\mathrm{kW}$ |
| DeriveReqt: | FR1-6 |
| Verify method | Inspection |
| Priority | High |
| Date of last change | December 3, 2009 |
| **Test requirements*** | |
| Identification tag (Id) | FRz2 |
| Name | Acceptance Testing of COTS Equipment |
| Text | There shall be an office and yard in Hilo that will be used for receiving, testing, and initial assembly of purchased equipment. |
| Rationale | Each major piece of equipment shall be tested to ensure that it satisfies the manufacture's specifications. Equipment will be preassembled in Hilo. Once equipment gets up to 13,800 feet, testing and assembly will be more difficult and more expensive, and it will interfere with operation of the telescopes. |
| DeriveReqt: | Test and Evaluation |
| Verify method | Inspection |
| Priority | High |
| Date of last change | December 3, 2009 |
| **Cost requirements** | |
| Identification tag (Id) | CoR3 |
| Name | Cost of Generated Electricity |
| Text | The system shall generate electricity at a cost that is competitive with commercial electricity costs at that location, after federal, state, local, and electric utility company credits. |
| Comment | Trace to CoR2 and NFPR1-4. To evaluate the cost of producing electricity, the streams of costs are converted to a net present value using the time value of money. The cost includes design, purchase, installation, operation, maintenance, retirement, and replacement. It depends on the interest rate and the amortization period. |
| DeriveReqt: | CuR1-10 |
| Verify method | Analysis |
| Priority | High |
| Date of last change | December 3, 2009 |

*Test and evaluation engineers will create requirements for test and evaluation and put them in this section.

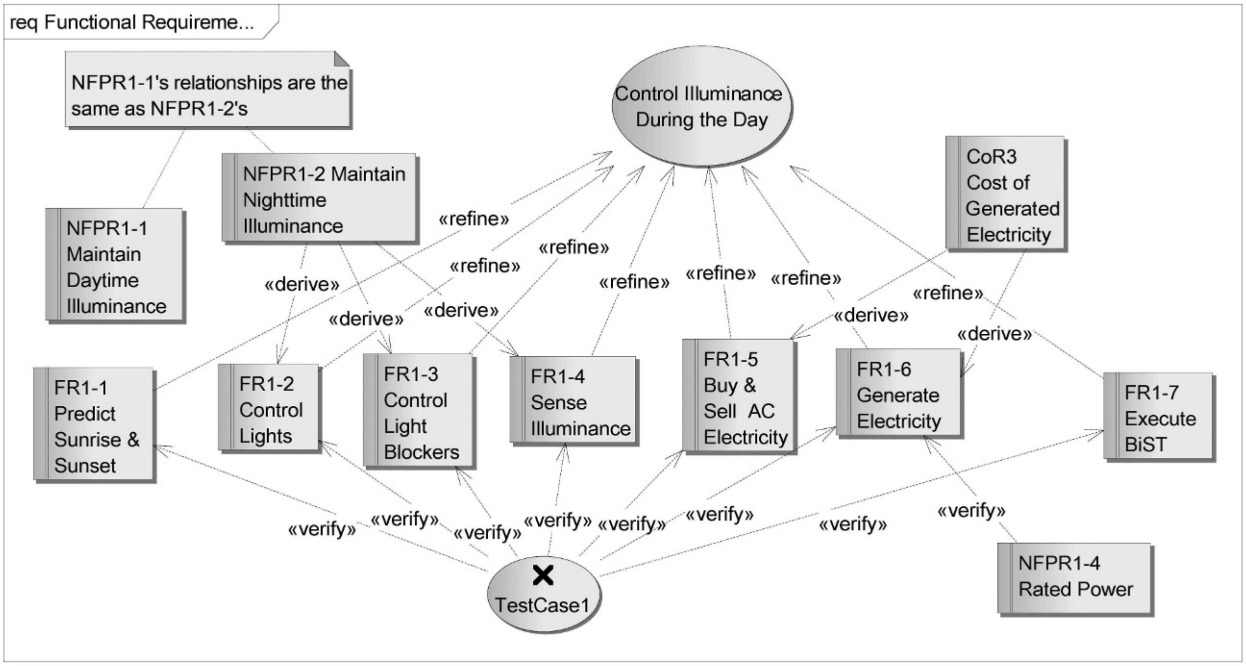


*Figure 2. Requirements diagram (**req**) for one use case of a BIMS.*

iteration produces more complex and more detailed models (Bahill et al. 2008). It is imperative that rules be written to show this progression between models (Mellor et al. 2004). For example, documents 6 and 2 use phrases like "window screens or curtains." In documents 3, 4, and 7, this phrase will be replaced with the class name Light Blocker. The ConOps and documents 6 and 2 use phrases like "solar panels or wind turbines." In documents 3, 4, and 7 this phrase will be replaced with the class name DC Electric Generator.

In the use cases, the requirements are labeled as, for example, Req 1-2, where the 1 indicates the first use case and the 2 indicates the second requirement in this use case. In document 2, the requirements are labeled as customer requirements, for example, CuR1-2. In document 3, the requirements are labeled as functional requirements, for example, FR1-2, and nonfunctional performance requirements, for example, NFPR1-2.

### Document 3: Derived Requirements

Each requirement is verifiable by (ordered by increasing cost) logical argument, inspection, modeling, simulation, analysis, test, or demonstration (Bahill and Dean 2009). Here are dictionary definitions for these terms.

**logical argument:** a series of logical deductions.
**inspection:** to examine carefully and critically, especially for flaws.
**modeling:** a simplified representation of some aspect of a system.
**simulation:** execution of a model, usually with a computer program.
**analysis:** a series of logical deductions using mathematics and models.
**test:** applying inputs and measuring outputs under controlled conditions (a laboratory environment).
**demonstration:** to show by experiment or practical application (flight or road test). However, some sources say demonstration is less quantitative than test. Demonstrations can be performed on electronic breadboards, plastic models, sterolithography models, prototypes made in the laboratory by technicians, preproduction hardware made in the plant using developmental tooling and processes, and production hardware using full plant tooling and production processes.

The attributes of the requirements of *Table 1* are listed row by row, because this is a Word document. If this were a spreadsheet, they would be listed column by column. *Figure 2* shows the relationships between the use cases, the requirements, and the test cases. The online BIMS set of documents has more requirement examples.

### Document 4: Verification and Validation

Verification and validation has four parts (Bahill and Dean 2009; Bahill and Henderson 2005). **Validating the system:** Building the *right system*: ensuring that the system does what it is supposed to do. **Verifying the system:** Building the *system right*: ensuring that the system complies with its requirements and conforms to its design. **Verifying requirements:** Proving that each requirement has been satisfied. **Validating requirements:** Ensuring that the *set* of requirements is correct, comprehensive, complete, and consistent.

*Validating the system.* Validating the system means building the *right system*: making sure that the system does what it is supposed to do in its intended environment. Validation determines the correctness and completeness of the product, and ensures that the system will satisfy the actual needs of the customer.

It is very important to note that validation is not done once and that it is not a serial process. Like all systems engineering processes, it is iterative and highly parallel. System validation artifacts can be collected at the following *discrete* events: trade-off study reviews, phase reviews, life cycle reviews, red team reviews, system requirements review, preliminary design review (PDR), Critical Design Review (CDR), and field test. Validation defects can be detected at inspections: The role of tester should be given an additional responsibility, validation; tester should read the vision statement and the concept of operation, and specifically look for such system validation problems. System validation artifacts that can be collected *continuously* throughout the life cycle include white papers, results of modeling and simulation, and a count of the number of operational scenarios (use cases) modeled. Detectable system validation defects include mismatches between the model and simulation, and the real system. For BIMS, validation evidence will be collected throughout design and construction.

A sensitivity analysis can reveal validation errors (Smith et al. 2008). If a system is very sensitive to parameters over which the customer has no control, then it may be the wrong system for that customer. If the sensitivity analysis reveals the most important parameter and that result is a surprise, then it may be the wrong system. If a system is more sensitive to its parameters than to its inputs, then it may be the wrong system or the wrong operating point. If the sensitivities of the model are different from the sensitivities of the physical system, then it may be the wrong model. The sensitivity analysis in document 5 shows that our trade-off study is valid.

*Verifying the system.* Verifying the system means building the *system right*: ensuring that the system complies with its requirements and conforms to its design. Components are verified during component testing. Systems are primarily verified at Total System Test. Sensitivity analyses can also be used to help verify systems. In a manmade system or a simulation, unexpected excessive sensitivity to any parameter is a verification mistake. Sensitivity to interactions should definitely be flagged and studied: Such interactions may be unexpected and undesirable.

*Verifying requirements.* Verifying requirements means proving that each requirement has been satisfied. Verification can be done by logical argument, inspection, modeling, simulation, analysis, test, or demonstration. The verification matrix must show a one-to-one mapping between the requirements and the test plan. Its audience is systems engineering and the customer.

The way documents 2 and 3 were written, we do not have to verify any of the document 2 requirements because they all have derived requirements in document 3. In the test section, we will verify each of the system functional requirements. We will not verify the business model requirements, process requirements, the cost requirements, the schedule requirements, or the verification and validation requirements.

It is important to note that verification is not a serial process: It is iterative and highly parallel. Verification and validation are not done sequentially. They are done in parallel with many iterations.

### System test

*Requirements verification.* The system will have built-in self-tests. In addition, it will be subjected to the following logical tests.

TestCase1 for BIMS Functional Requirements

{Test using the main success scenario of the `Control Illuminance During the Day` use case}

1. Before sunrise, tester starts BIMS and records that it has executed all of its built-in self tests. This verifies FR1-7.
2. The sun rises in the morning. The system turns up the lights and closes the light blockers.
3. Tester records the result including actual and predicted time of sunrise. This verifies FR1-1, FR1-2, FR1-3, FR1-4, and NFPR1-1.
4. The system senses the illuminance in the operations room and adjusts the illuminance with light dimmers and light blockers.
5. Tester measures the illuminance in the operations room, observes that the system is following the sunrise sequence diagram fragment *(Figure 7)* and records the result. This verifies FR1-2, FR1-3, FR1-4, and NFPR1-1.
6. The sun moves across the sky and the illuminance from the sun increases.
7. The system decreases illuminance from the lights and partially opens the light blockers.
8. At half-hour intervals, tester measures the illuminance in the operations room and records

the result. This verifies FR1-2, FR1-3, FR1-4, and NFPR1-1.

9. The sun rises to its zenith.
10. The system reduces the illuminance of the lights and opens the light blockers as far as possible, while maintaining the illuminance within its daytime limits.
11. Tester measures the illuminance in the operations room and records the result. This verifies FR1-2, FR1-3, FR1-4, and NFPR1-1.
12. The system senses the illuminance in the operations room with light sensors and adjusts the illuminance with light dimmers and light blockers.
13. At half-hour intervals, tester measures the illuminance in the operations room and records the result. This verifies FR1-2, FR1-3, FR1-4, and NFPR1-1.
14. The sun starts to set.
15. The system slowly adjusts the illuminance to its nighttime level.
16. Tester measures the illuminance in the operations room, observes that the system is following the sunset sequence diagram fragment *(Figure 7)*, and records the result. This verifies FR1-2, FR1-3, FR1-4, and NFPR1-1.
17. The sun sets.
18. Tester observes that the system has shifted to the Control Illuminance During the Night use case and records the result.

{Test using the Clouds Cover the Sun unanchored alternate flow of the Control Illuminance During the Day use case}

1. While the BIMS is operating properly during the daytime, tester blocks sunlight from the operations room. This could be done by waiting for natural clouds to come by or by unrolling an opaque screen from the roof in front of the operations room window. If wind turbines or other electric generating devices are used, then this statement will have to be changed accordingly.
2. The system opens the light blockers.
3. Tester measures the illuminance in the operations room, observes that the system is following the Clouds Cover the Sun unanchored alternate flow and records the result. This verifies FR1-2, FR1-3, FR1-4, and NFPR1-1.
4. The system draws energy from the AC electric power grid.
5. Tester measures the illuminance in the operations room and the flow of energy from the AC electric power grid and records the result. This verifies FR1-2, FR1-3, FR1-4, NFPR1-1, and FR1-5.
6. Tester turns off unnecessary electric loads and removes the opaque screen from the operations room window.
7. The system delivers energy to the AC electric power grid.
8. Tester measures the illuminance in the operations room and the flow of energy to the AC electric power grid and records the result. This verifies FR1-2, FR1-3, FR1-4, NFPR1-1, FR1-5, and FR1-6.
9. Tester observes that the system returns to the main success scenario and records the result.

{End of testCase1 for the Control Illuminance During the Day use case}

This test case procedure has verified FR1-1, FR1-2, FR1-3, FR1-4, FR1-5, FR1-6, FR1-7, and NFPR1-1. Nonfunctional performance requirement NFPR1-2 will be verified in tests based on the Control Illuminance During the Night use case. CR3 will be verified by analysis.

{Start of Verification and Validation (V&V) Test}

1. Tester uses the system as in the test for the main success scenario for the Control Illuminance During the Day use case.
2. Tester observes and records the result.
3. Tester examines the data and writes a V&V report. This verifies FRz-1 Gather V&V data.

{End of V&V Test}

### System verification

{Test by system experiment}

The system experiment in *Table 2* will test the high-level system functioning. It is based on the BIMS Illuminance controller state machine diagram in document 7 *(Figure 8)*.

Preconditions:

Wait for weather conditions that will generate above average electricity, such as a sunny afternoon for photovoltaic panels or winds above 15 mph for wind turbines.

Disconnect the system from the AC electric power grid and turn off all possible loads.

The system experiment shown in *Table 2* is a state-based test. If the problem statement requires a state-based solution, then state-based tests *must* be used. It is not possible to test a state-based system using only input–output behavior (Botta, Bahill, and Bahill 2006; Wymore and Bahill 2000).

*Validating requirements.* Validating requirements means ensuring that the *set* of requirements is correct, complete, and consistent, that a model can be created that satisfies the requirements, that a real-world

*Table 2. Test of the BIMS Illuminance Controller using a system experiment (Wymore 1993).*

| Time | Input | Present state | Output | Next state | BiST indicator | Related requirement |
|---|---|---|---|---|---|---|
| 0 | Connect to AC Electric Power Grid and turn on the loads | Initial | | Running BiST | Fail | |
| 1 | statusBiST = finished | Running BiST | statusBiST = running; statusBiST =finished; resultBiST = pass | Maintaining Daytime Illuminance | Fail | FR1-7 |
| 2 | illuminance > 550 | Maintaining Daytime Illuminance | set (lightLevel, blockingPercent) | Decreasing Daytime Illuminance | Pass | FR1-2<br>FR1-3<br>FR1-4<br>NFPR1-1 |
| 3 | illuminance ≤ 550 | Decreasing Daytime Illuminance | set (lightLevel, blockingPercent) | Maintaining Daytime Illuminance | Pass | FR1-2<br>FR1-3<br>FR1-4<br>NFPR1-1 |
| 4 | sunset | Maintaining Daytime Illuminance | set (lightLevel, blockingPercent); requestProgram (sunset); | Running Sunset Program | Pass | FR1-1<br>FR1-2<br>FR1-3<br>FR1-4<br>NFPR1-1 |
| 5 | programDone | Running Sunset Program | set (lightLevel, blockingPercent); signal(programDone) | Maintaining Nighttime Illuminance | Pass | FR1-2<br>FR1-3<br>FR1-4<br>NFPR1-2 |
| 6 | sunrise | Maintaining Nighttime Illuminance | requestProgram (sunrise); set (lightLevel, blockingPercent); | Running Sunrise Program | Pass | FR1-1<br>FR1-2<br>FR1-3<br>FR1-4<br>NFPR1-2 |
| 7 | programDone | Running Sunrise Program | runProgram(sunrise); set (lightLevel, blockingPercent); signal(programDone) | Maintaining Daytime Illuminance | Pass | FR1-2<br>FR1-3<br>FR1-4<br>NFPR1-1 |
| End of test | | Maintaining Daytime Illuminance | set (lightLevel, blockingPercent) | | Pass | FR1-2<br>FR1-3<br>FR1-4<br>NFPR1-1 |

There are many more transition arrows of the state machine diagram that need to be tested.

solution can be built that satisfies the requirements, and that this real-world solution can be tested to prove that it satisfies the requirements. If the client has requested a perpetual motion machine, this is the place to stop the project and save the money. Requirements validation often uses comparisons to existing systems that do most of the desired tasks. Lutron Electronics has two products that satisfy most of our light management requirements: the Daylighting system and the Hyperion–Solar Clock. The features of BIMS that are not included in either of those two systems are using renewable-energy electric generators, remote locations, and consideration of moonlight. We are sure that we can design and build a system that satisfies these requirements because most of them can be fulfilled with presently available COTS systems. There are lots of renewable-energy electric-generating systems, including many that are already connected to AC electric power grids. The validation process should start at the beginning of the project.

### Document 5: Concept Exploration

*Alternative architectures.* The BIMS project will do trade-off studies for many decisions such as choosing the type of light blockers, selecting a system to control the entire light management system, and suggesting an energy storage unit to smooth the electric generation when the environment varies. This article only shows the trade-off study for the type of electric generator that will be recommended.

Electric generators transform environmental energy into electric energy. Here are some common examples:

*Figure 3. Brainstroming illustration of alternative electric generators fit in the Mauna Kea environment. A trade-off study to help determine the system architecture must consider multiple alternatives situated in the environment in which the system will operate. Photo montage credit: Alex and Zach Bahill.*

photovoltaic (PV) solar panels; thermal solar panels; wind turbines; ocean currents, waves, and tides; hydroelectric dams; balloons for tapping static electricity stored in the atmosphere; and geothermal systems based on the Kilauea volcano. For this project the electric generators will be connected to the AC electric grid. *Table 3* shows the alternative systems that were analyzed in this project.

The question posed to this trade-off study was, "In terms of using renewable energy to generate electricity for the telescope operations room on top of Hawaii, what is the preferred electric generating system?" *Figure 3* suggests a part of the analysis that went into fitting the alternatives into the environment.

*Evaluation criteria.* Evaluation criteria will be needed for each trade-off study. Some of the criteria may be reusable in several trade-off studies. Here are some of the criteria for choosing the preferred renewable-energy electric-generating systems.

*Performance*

Name of criterion: *Perceived Ease of Test and Evaluation*

Name of criterion: *Vendor Evaluation*

Name of criterion: *Possible Interference with Telescope Views*

Each criterion will have a full description such as the following.

Name of criterion: *Rated Power*

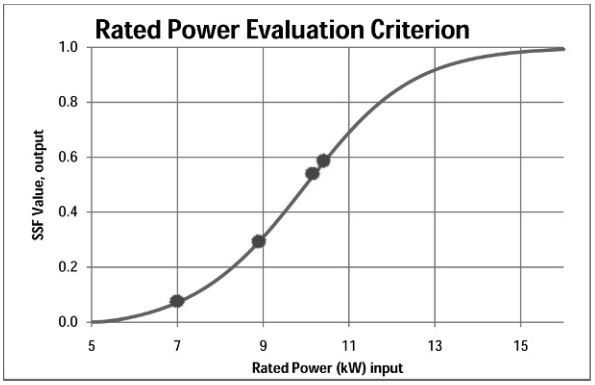


*Figure 4. Scoring function for the* Rated Power *evaluation criterion.*

Description: Rated Power (kW) is the power that the system was designed to generate in steady state at the normal operating point, which is usually near the maximum power point. It is also called generating capacity and nameplate capacity. The normal operating point for the telescope site on top of Hawaii has an average wind speed of 10 mph and an average insolation of 6 kWh/(m$^2$ d).

Weight of importance (priority): 4 (Botta and Bahill 2007)

Basic measure: The power that the system was designed to generate

Units: kW

Measurement method: Initially we will believe the manufacturers' specifications. During operations we will compute the value of the average power that is actually produced in steady state at the normal operating point.

Input: Rated power (kW), with a domain of 0 to 1 MW, and expected values between 5 and 25 kW.

Scoring function: Monotonic increasing, LL = 5, BL = 10, S = 0.2, UL = 25 plotting range 5 to 16 (Daniels, Werner, and Bahill 2001; *Figure 4*).

Output: 0 to 1

Traces to NFPR1-4

The input to the function of *Figure 4* is Rated Power, which has legal values between 0 and 1 MW. Feasible alternatives will have expected values between 5 and 25 kW. The preferred alternatives shown in *Table 4* had rated powers between 7 and 11 kW, which is where the curve has its maximum slope and therefore the greatest differentiating power. Four of the alternatives are shown in the figure. The output is normalized to the 0 to 1 range, and more output is better.

*Cost*

Name of criterion: *Total Life Cycle Cost* (thousands of U.S. dollars)

Name of criterion: *Price to Power Ratio* ($/W)

Name of criterion: *Cost of Generated Electricity* ($/kWh)

*Company policy*

Name of criterion: *Built-in Self Test*:

Name of criterion: *Reusability*:

The online BIMS set of documents has more evaluation criteria examples.

The trade-off study matrix for this project is shown in *Table 4*. It shows that the PV solar panels have the highest alternative ratings. The complete trade-off study and sensitivity analysis is located at http://www.sie.arizona.edu/sysengr/sie554/BIMS/BIMS11.xls.

The values for the cells were derived by a panel of domain experts using the Delphi method. The values came from manufacturers' data, peer reviewed journal articles, and (only for the weather data) Internet Web sites. A value was derived for each alternative and for each criterion. This value was put into the scoring function for that criterion and the resulting score (Sc) was put into *Table 4*. Each score was then multiplied by its corresponding normalized weight (Wt), and these products were summed in each column to produce the alternative ratings.

This trade-off study answered the question "In terms of using renewable energy to generate electricity for the telescope operations room on top of Hawaii, what is the preferred electric generating system?" by stating that the preferred alternatives are the PV solar panels without battery storage.

Each number in a trade-off study matrix should have an explanation. For example, the score for total life cycle cost for the "do nothing" alternative is 0.2. Its purchase price is zero, which would give it a high score. But it would sell no energy to the electric company so it would not generate revenue. This lowers its score to 0.2. The original estimation was made by Bahill, December 3, 2009.

When filling in a trade-off study matrix, like *Table 4*, it is important to pay attention to common mental mistakes (Smith et al. 2007). For example, the criteria total lifecycle cost, price to power ratio, and cost of generated electricity are dependent; evaluation criteria should be independent. Second, there is an uneven level of detail in the description of the PV solar panels and the LIMPET system. This often occurs for straw men but should not exist for serious alternatives.

The sensitivity analysis (Smith et al. 2008) performed on this trade-off study showed that the most important category weight was that for company policy, the most important subcategory weight was that for BiST, and the most important scores were for BiST for alternatives 1, 2, 3, 4, and 7. Therefore, we spent extra time discussing among ourselves and with top management whether performance, cost, or

*Table 3. Trade-off study matrix for BIMS using a sum combining function with the number of alternatives,* $m = 10$.

| Criteria | Wt. | Norm. criteria weights | Norm sub criteria weights | Alt 1 do nothing | | Alt 2 Sun Electronics PV | | Alt 3 DMSolar PV | | Alt 4 Solar Calculator Generic PV | | Alt 5 Jacobs Wind Turbine | | Alt 6 Bergey WindPower | | Alt 7 ARE 442 | | Alt 8 Skystream 3.7 | | Alt 9 LIMPET | | Alt 10 Nordtank 65 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Sc | Wt × Sc | Sc | Wt × Sc | Sc | Wt × Sc | Sc | Wt × Sc | Sc | Wt × Sc | Sc | Wt × Sc | Sc | Wt × Sc | Sc | Wt × Sc | Sc | Wt × Sc | Sc | Wt × Sc |
| Performance | 8 | 0.38 | | | | | | | | | | | | | | | | | | | | | |
| Vendor evaluation | 8 | | 0.36 | 0.9 | **0.33** | 0.5 | **0.18** | 0.6 | **0.21** | 0.8 | **0.29** | 0.5 | **0.18** | 0.5 | **0.18** | 0.5 | **0.18** | 0.4 | **0.15** | 0.8 | **0.29** | 0.8 | **0.29** |
| Interference with telescopes | 10 | | 0.45 | 1.0 | **0.45** | 1.0 | **0.45** | 1.0 | **0.45** | 1.0 | **0.45** | 0.2 | **0.09** | 0.2 | **0.09** | 0.2 | **0.09** | 0.4 | **0.18** | 1.0 | **0.45** | 0.1 | **0.05** |
| Rated power | 4 | | 0.18 | 0.0 | **0.00** | 0.5 | **0.10** | 0.6 | **0.11** | 0.3 | **0.05** | 0.1 | **0.01** | 0.0 | **0.00** | 0.0 | **0.00** | 0.0 | **0.00** | 1.0 | **0.18** | 0.5 | **0.09** |
| Cost | 4 | 0.19 | | | | | | | | | | | | | | | | | | | | | |
| Total lifecycle cost | 6 | | 0.24 | 0.2 | **0.05** | 0.5 | **0.12** | 0.5 | **0.12** | 0.8 | **0.19** | 0.5 | **0.12** | 0.5 | **0.12** | 0.5 | **0.12** | 0.5 | **0.12** | 0.4 | **0.10** | 0.5 | **0.12** |
| Price to power ratio | 9 | | 0.36 | 0.5 | **0.18** | 1.0 | **0.36** | 1.0 | **0.36** | 0.8 | **0.29** | 0.5 | **0.16** | 0.0 | **0.00** | 0.0 | **0.00** | 0.2 | **0.07** | 0.0 | **0.00** | 0.8 | **0.30** |
| Cost of generated electricity | 10 | | 0.40 | 0.2 | **0.08** | 0.5 | **0.20** | 0.5 | **0.20** | 0.8 | **0.32** | 0.5 | **0.20** | 0.5 | **0.20** | 0.5 | **0.20** | 0.5 | **0.20** | 0.6 | **0.24** | 0.6 | **0.24** |
| Company policy | 9 | 0.43 | | | | | | | | | | | | | | | | | | | | | |
| BiST | 10 | | 0.63 | 0.8 | **0.50** | 0.9 | **0.56** | 0.9 | **0.56** | 0.7 | **0.44** | 0.1 | **0.06** | 0.1 | **0.06** | 0.9 | **0.56** | 0.1 | **0.06** | 0.5 | **0.31** | 0.3 | **0.19** |
| Reusability | 6 | | 0.38 | 0.3 | **0.11** | 0.5 | **0.19** | 0.5 | **0.19** | 0.8 | **0.30** | 0.5 | **0.19** | 0.5 | **0.19** | 0.5 | **0.19** | 0.5 | **0.19** | 0.1 | **0.04** | 0.9 | **0.34** |
| Alternative rating | | | | | **0.62** | | **0.73** | | **0.74** | | **0.77** | | **0.31** | | **0.27** | | **0.49** | | **0.31** | | **0.57** | | **0.51** |

*Table 4. Renewable-energy electric-generating systems that were analyzed in a trade-off study.*

| Manufacturer | Rated power (kW) | Purchase price without installation (U.S. dollars) |
|---|---|---|
| Grid-connected PV systems | | |
| Sun Electronics | 10.2 | $34,000. |
| DMSolar | 10.4 | $34,000. |
| The Solar Calculator | 8.9 | $55,000. |
| Grid-connected wind turbines | | |
| Jacobs Wind Systems | 7 | $55,000. |
| Bergey WindPower | 2 | $30,000. |
| Abundant Renewable Energy | 3.5 | $50,000. |
| Southwest Wind Power | 2.4 | $14,000. |
| Nordtank 65 | 10.2 | $62,000. |
| Other | | |
| LIMPET, wave power | 100 | $260,000 |
| Helium balloons | $6 \times 10^{-12}$ | $100 |
| The do-nothing alternative | 0 | 0 |

company policy should have the highest weight. We expended extra resources consulting with management and the customer about the relative weights of the subcriteria. We did extra research, analysis, and modeling to get more reliable scores for BiST for alternatives 1, 2, 3, 4, and 7.

### Document 6: Use Case Model

A *use case* is an abstraction of required functions of a system. A use case produces an observable result of value to the user. Each use case describes a sequence of interactions between one or more actors and the system.

**Name:** Control Illuminance During the Day
**Iteration:** 3.4
**Derived from:** ConOps
**Brief description:** The sun rises and sets, but the BIMS will keep the illuminance in the operations room constant.
**Level:** High
**Priority:** This is of the highest priority.
**Scope:** The operations room of a telescope facility on a remote mountaintop and a renewable-energy electric generator ~~and an energy storage device~~. Note: the original ConOps specified the use of energy storage devices. This requirement was subsequently removed. In this use case, we show the removal by using a ~~strikethrough effect~~.
**Added value:** Astronomers are more comfortable and more productive.
**Goal:** Maintain specified illuminance in the daytime.
**Primary actors:** Astronomer, engineer, tester
**Supporting actors:** Sun, clouds (and during the night the moon).
**Frequency**: It will be used every day.
**Precondition:** The system has passed all of its BiSTs, and tester or the engineer has started the system.
**Trigger:** The sun rises.

*Main success scenario*

1. The sun rises in the morning.
2. The system turns up the lights and closes the window screens or curtains.
3. The system senses the illuminance in the room with light sensors and adjusts the illuminance with light dimmers and window screens or curtains.
4. The sun moves across the sky, and the illuminance from the sun starts to increase. (Actually, the earth rotates, but it more intuitive to say that the sun moves.)
5. The system decreases illuminance from the lights and partially opens the window screens or curtains. The trade-off between these two would be determined by sunlight shining on computer monitors, heating and cooling considerations, as well as electricity usage.
6. The sun rises to its zenith.
7. If it will not waste heating or cooling energy, the system opens the window screens or curtains.
8. The system senses the illuminance in the room with light sensors and adjusts the illuminance with light dimmers and window screens or curtains.
9. The sun starts to set.
10. The system slowly adjusts the illuminance to its nighttime level. (Because of its complexity, this step will probably become a separate use case in future models.)
11. The sun sets.
12. Include the Control Illuminance During the Night use case.

*Clouds Cover the Sun unanchored alternate flow*

1. Electric generation falls because of the wind dropping, waves disappearing, or clouds covering the sun.
2. The system opens the window screens or curtains.
3. The system draws energy from the ~~energy storage device~~ AC electric grid.
4. Electric generation resumes because of the wind increasing, waves coming back, or clouds blowing away.

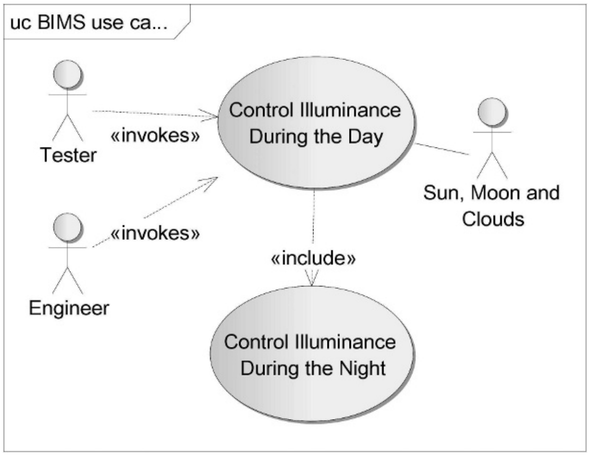


*Figure 5. Use case diagram (**uc**) for a BIMS.*

5. The system delivers energy to the ~~energy storage device~~. AC electric grid.
6. The system readjusts the light dimmers and window screens or curtains. [return to the main success scenario.]

**Postcondition:** The system is in the Control Illuminance During the Night use case.

*Specific requirements (Daniels and Bahill 2004)*

*Functional requirements:*

Req1-1 The system shall use an ephemeris, tables, models, firmware, or similar methods to anticipate sunrise, sunset, moonrise, moonset, and the phase of the moon.

Req1-2 The system shall control the illuminance of the lights.

Req1-3 The system shall control the opening and closing of window screens or curtains.

Req1-4 The system shall sense the illuminance in the operations room.

Req1-5 The system shall buy electricity from and sell electricity to the AC electric power grid.

Req1-6 The system shall generate electricity and use energy. Here are some common examples of sources of renewable energy: PV panels, wind turbines, ocean waves, ocean tides, and geothermal systems. The energy storage requirement was removed by Bahill October 17, 2009.

Req1-7 The system shall execute built-in self tests (BiST). (Derived from BICS company policy.)

*Nonfunctional requirements:*

Req1-8 The system shall maintain the daytime illuminance in the operations room at 500 ± 50 lux (≈50 ± 5 fc). Trace to Req1-2, Req1-3, and Req1-4.

Req1-9 The system shall maintain the nighttime illuminance in the operations room at 0.4 ± 0.2 lux (≈0.04 ± 0.02 fc). Trace to Req1-2, Req1-3, and Req1-4.

Req1-10 The system shall generate electricity at a cost competitive with commercial electricity costs at that location, after federal subsidies, etc. Trace to Req1-5 and Req1-6.

**Author/owner:** Walt Zaharchuk

**Last changed:** December 3, 2009

A use case diagram is the table of contents of a use case model. It shows all of the use cases that have been described so far. *Figure 5* is our first use case diagram.

*Other use cases.* So far, we have written one use case. A complete design will probably have dozens of use cases. Here are some other proposed use cases:

Control Illuminance During the Night
Buy Electricity from and Sell Electricity to the AC Electric Power Grid
Generate Electricity Using Renewable-energy Electric-generators
Follow Sunrise and Sunset Programs. For the telescopes, these programs will be different from residential venues because during this critical time of day naked-eye observations by astronomers, meteorologists, naval personnel, etc., are important. The algorithms here may be the most complex because the change of illuminance will have the largest dynamic range and the fastest time constant.
Run Built-in Self Tests
Run Tests and Evaluate the System
Control Temperature in the Operations Room. The lighting control system must interact intimately with the HVAC system. This will produce requirements of temperature goals and tolerances.

### *Document 7: Design Model*

Document 7 contains UML and SysML diagrams (Bahill and Szidarovszky 2009; Friedenthal, Moore, and Steiner 2008; OMG UML 2010; OMG SysML 2010). First, we will work on the class diagrams. The following classes were obtained by (a) thinking about concepts in the problem domain, (b) underlining nouns in the use cases and ConOps, and (c) considering the stereotypes of interfaces (boundary classes), data storage needs (entity classes), and state machines (controller classes). *Figure 6* shows the high level classes of BIMS.

*Figure 7* shows a sequence diagram for BIMS. A complete model might have dozens (maybe hundreds) of sequence diagrams. The sequence diagrams and class diagrams are produced concurrently: use sequence diagrams to find the operations (functions) of the

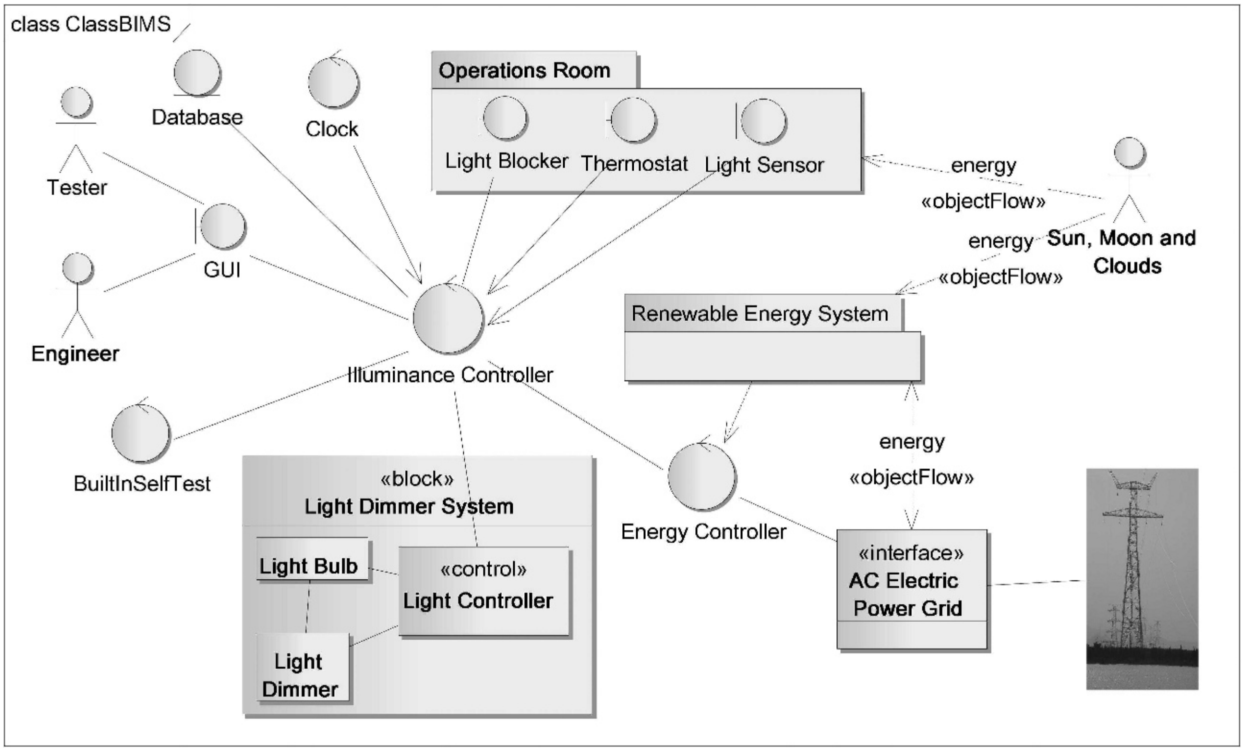


*Figure 6. High-level class diagram for a BIMS.*

classes. There should be a sequence diagram for every flow of every use case. After the CDR, test and evaluation should ensure that the commands and messages of the sequence diagrams are related to the functions (operations) of the classes.

*Analysis classes*

Engineer <<actor>>
name: String
programBIMS
troubleshootBIMS

An engineer programs and troubleshoots the BIMS. Lifetime: An engineer exists from the moment a person has been classified as an engineer with BICS until the moment the engineer ceases his or her relationship with BICS.

Tester <<actor>>
name: String
troubleshootBIMS
testBIMS

The role of tester will be filled by a member of the test and evaluation team. It could be filled by the same person(s) who fills the role of engineer.

Sun, moon, clouds <<supporting actors>>
name: String
varyIlluminaceOfEarth()

Later this class will be decomposed into three classes. Lifetime: The sun is about 5 billion years old: It will last another 5 billion years. The earth is about 4.5 billion years old, and the moon is a bit younger. Each cloud lasts a few hours.

Operations Room <<package>>
depth: Real = 7 {m}
height: Real = 4 {m}
width: Real =30 {m}

The operations room contains the thermostat, the light sensor, and the light blocker. It is 7 m deep, 30 m wide, and 4 m high. Its east wall is all glass and faces directly east. All other walls have minimal glass and maximum insulation.

Thermostat <<boundary class>>
temperature: Integer = 65 {0–100, degrees Fahrenheit}
measureTemperature()
sendTemperature()

The thermostat measures the average temperature in the operations room and sends that value to the BIMS illuminance controller.

Light Sensor <<boundary class>>
illuminance: Real {0.01–3000, lux}
measureIlluminance()
sendIlluminance()

The light sensor measures the average illuminance in the operations room and sends that value to the BIMS illuminance controller.

Light Blocker <<boundary class>>

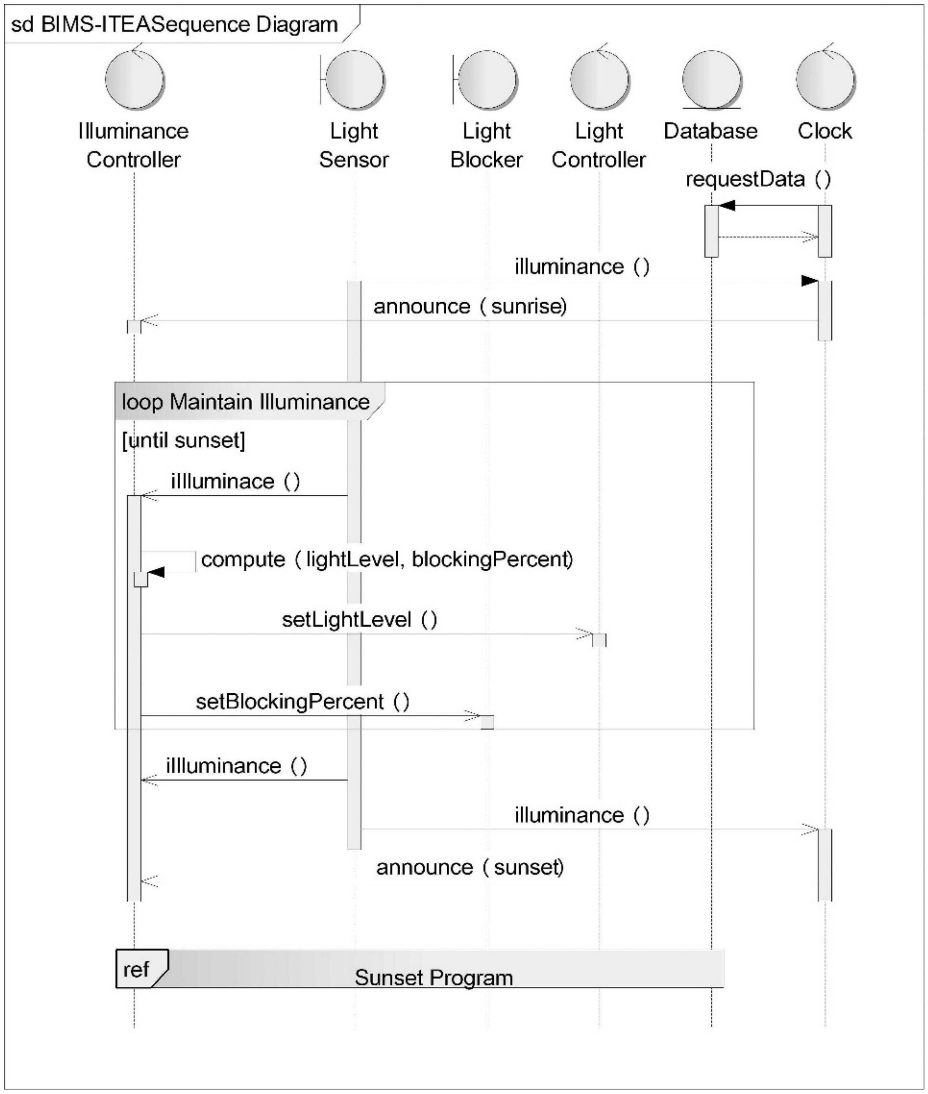


*Figure 7. Time runs from top to bottom in this sequence diagram (**sd**) for one instance of the main success scenario of the Control Illuminance During the Day use case.*

blockingPercent: Integer = 100 {0–100}
blockingPercent()

The light blocker blocks some percentage of the incoming light.

Light Dimming System <<block or package>>

The light dimming system is composed of the light controller, the light dimmer, and the light bulb. There will be many light bulbs in this system, but in UML and SysML we name the classes with a singular noun.

Light Controller <<control class>>
lightLevel: Integer = 100 {0–100, percent}
lightLevel()

The light controller is the brains of the Light Dimming System. The bars on the sides of this box indicate that the BIMS Light Controller is an active class. That means it has one or more state machine diagrams.

Light Dimmer
powerLevel: Real {watts}
increasePower()
decreasePower()

The light dimmer varies the power being sent to the light bulb.

Light Bulb
illuminance: Integer = 0 {0–12,000 lumens}
colorTemperature: Integer = 3,500 {Kelvins}
emitLight()

Beverage Store <<subsystem>>
address1: String = "Hawai'i Nui Brewing, 275 E. Kawili St, Hilo, HI 96720"

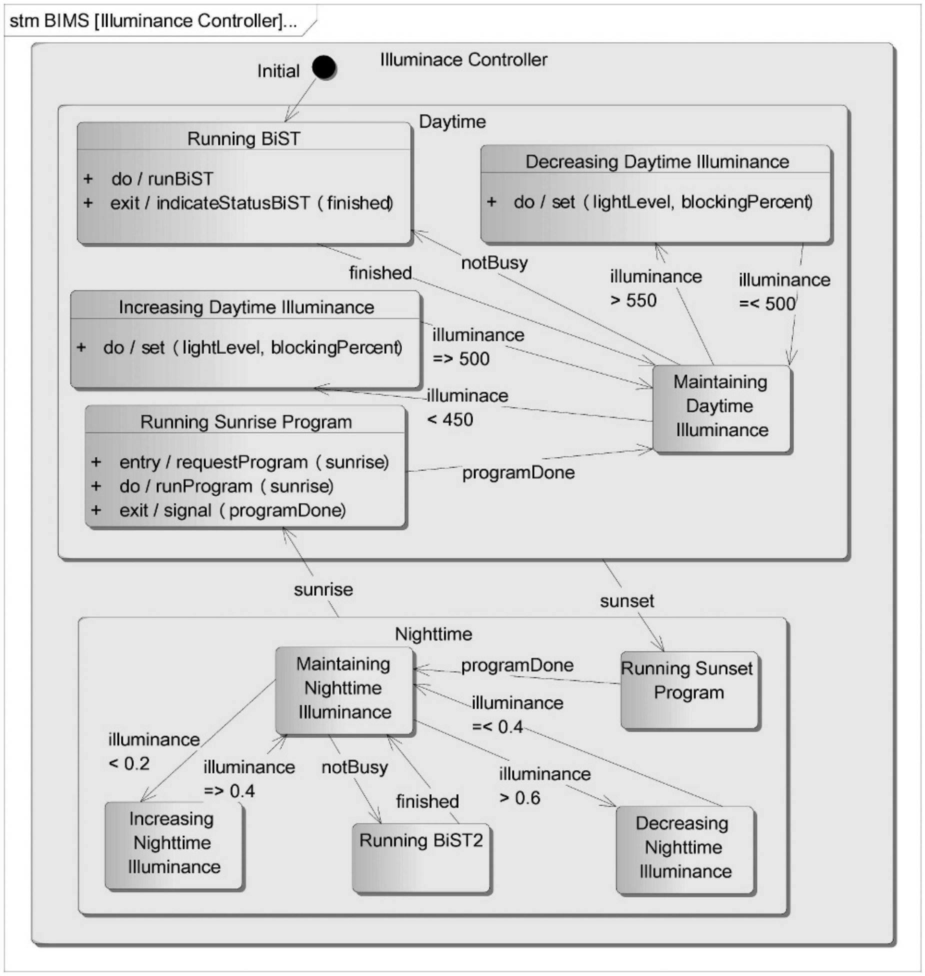


*Figure 8. State machine diagram (**stm**) for a BIMS Illuminance Controller (IC). The illuminance limits could be parameters instead of fixed values. The IC increases or decreases the illuminance by commanding a different lightLevel and blockingPercent. Running the sunrise program is accomplished by commanding a sequence of preprogrammed lightLevel and blockingPercent.*

address2: String = "Stores in the town of Vicuña, a one-hour drive from the top of Cerro Pachón"
sellBeer(MehanaMaunaKeaPaleAle)
sellBeer(RogueChipotleAle)

Graphical User Interface (GUI) <<boundary class>>
statusGUI: Boolean = off {on, off}
Use the company standard GUI.

AC Electric Power Grid Interface <<boundary class>>
statusAC: Boolean = buying {buying, selling}
energySold: Real {kWh or J}
sellACelectricity()
buyACelectricity()

Our system must be able to buy and sell electricity through the AC electric power grid interface. The WattHourMeter indicates the direction of and amount of energy flow. The measure of effectiveness attribute energySold indicates the amount of energy that has been bought or sold to the electric power grid. Physically, this could be 1 WattHourMeter or 2.

Renewable-Energy System <<subsystem>>
The Renewable-Energy System is a subsystem of BIMS composed of a DC electric generator and a DC to AC inverter.

DC Electric Generator
ratedPower: Real {kW}
generateElectricity()

DC/AC Inverter
ratedPower: Real {kW}
convert DC to AC()

Database <<entity class>>
read/writeData()

*Table 5. Standard ports that show the movement of signals, commands, or messages.*

| Control class | Inputs and outputs | Source and destination class | Explanation |
|---|---|---|---|
| Illuminance Controller (IC) | Inputs | Source Class | |
| | announce {sunrise, sunset, moonrise, moonset, phaseOfMoon} | Clock | This algorithm uses predicted sunrise and sunset, and the illuminance to announce when the sun is rising or setting. |
| | illuminance() | Light Sensor | Average illuminance in the operations room. |
| | programs {sunrise, sunset, etc.} | Database | Preprogrammed sequences of light and light blocker parameters. |
| | statusBiST {running, finished} | BiST | |
| | statusIC {busy, notBusy} | IC | |
| | Outputs | Destination Class | |
| | setLightLevel() | Light Controller | |
| | setBlockingPercent() | Light Blocker | |
| | requestProgram() | Database | |
| | programDone() | IC | |
| | statusIC {busy, notBusy} | IC | |
| Light Controller | Inputs | | |
| | setLightLevel() | IC | |
| | Outputs | | |
| | lightLevel() | Light Dimmer | |
| BiST | Inputs | Source Class | |
| | runBiST | IC | |
| | Outputs | Destination Class | |
| | statusBiST() | IC | |
| | resultBiST() | IC, et al. | |
| Clock | Inputs | Source Class | |
| | data() | Database | |
| | illuminance() | Light Sensor | |
| | Outputs | Destination Class | |
| | announce {sunrise, sunset, moonrise, moonset, phaseOfMoon} | IC | |
| | requestData | Database | |

provideData()

The clock and the database work together so that they always know the correct time and date. They use this in conjunction with tables or models so that they always know where the sun and the moon are. The database also stores light programs. For example, the sunrise program might look like this:

1. The sun starts to rise.
2. The light blockers close as necessary to eliminate direct sun rays on computer screens.
3. The light dimming system turns up the lights to provide the desired daytime illuminance.
4. As the sun rises, the light blockers are opened and the lights are dimmed.

Clock <<control class>>
time(hh:mm): String {hh [0–24], mm [0–60]}
date(mm/dd/yy): String {mm [1–12], dd [1–31], yy [0–99]}
daytime(): Boolean {AM, PM}
compute() {sunrise, sunset, moonrise, moonset, phaseOfMoon}
announce() {sunrise, sunset, moonrise, moonset, phaseOfMoon}
requestData()

Built-in Self Test (BiST) <<control class>>
resultBiST: Boolean = fail {pass, fail}
statusBiST: Boolean = finished {running, finished}
sendResultBiST()
indicateStatusBiST()

Whenever the system is not serving the customer, it should be doing BiST. In addition, at startup it will do self tests. And finally it will run large diagnostic tests once a day.

Illuminance Controller (IC) <<control class>>
statusIC: Boolean = notBusy {busy, notBusy}
compute(lightLevel, blockingPercent)
setLightLevel()
setBlockingPercent()
runBiST()
requestProgram()
runProgram()
programDone()

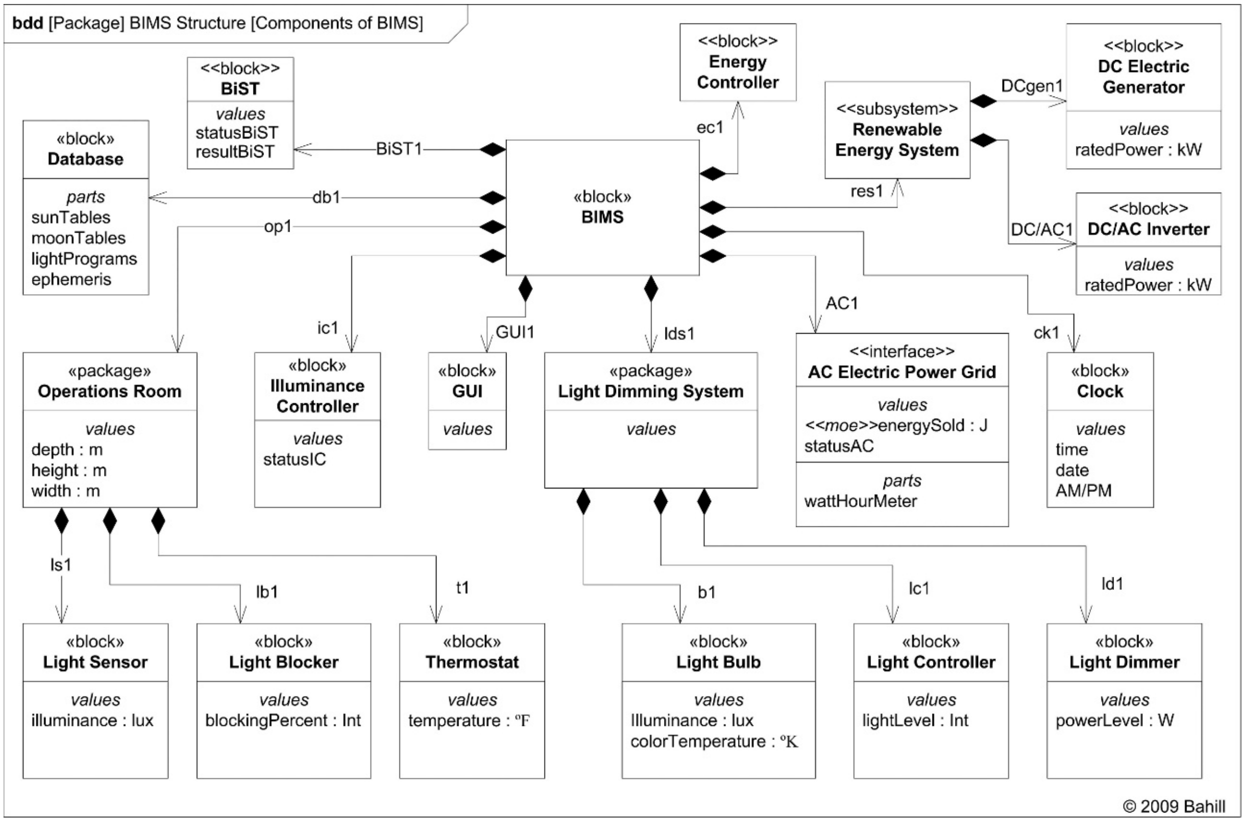


*Figure 9. SysML block definition diagram (**bdd**) showing the structure of a BIMS. Most of the values in the component blocks were described with the classes. The new one is the Measure of Effectiveness (MoE) for the amount of energy sold to the commercial electric power grid.*

The illuminance controller is an active class. That means it has one or more state machine diagrams. It sends commands to the light controller and the light blocker to make the illuminance follow certain programs, such as for sunrise and sunset. The light sensor sends illuminance levels to the illuminance controller.

The major required functionality of the system (shown in the last two dozen class boxes) will be captured in the use cases and put into the customer requirements document. These functions will be tested in the use case derived test procedures. Detailed design will produce additional lower level functions that must be tested. Test and evaluation must test each of the functions (the bottom compartment, the operations) of every one of these classes.

*Other diagrams.* *Figure 8* shows a state machine diagram (stm) for a BIMS illuminance controller (IC). *Table 5* shows standard ports that describe the movement of signals, commands, and messages. *Table 1* showed a system experiment that would test the behavior described in the state diagram of *Figure 8*. After CDR, test and evaluation should ensure that the inputs (events) and outputs (functions) of the state machine diagrams are related to the commands and messages of the sequence diagrams and the functions (operations) of the classes.

*Figure 9* shows a SysML block definition diagram (**bdd**) illustrating the structure of a BIMS. The values in these blocks must be tested. These values should be the same as the attributes in the center box of the classes of the previous section.

*Figure 10* shows a SysML block definition diagram (**bdd**) illustrating the constraints of a BIMS. *Figure 11* shows a SysML parametric diagram (**par**) that illustrates the bindings for a BIMS: It shows the location of the values that will be used in the equations of *Figure 10*. There is a constraint, shown in *Figure 10*, that the illuminance rate of change shall not be greater than 10 lux/s. To test compliance with this constraint, the tester must know where to get values for this equation. A SysML parametric diagram (*Figure 11*) shows where these values can be found.

## Document 8: Mappings and Management

*Acronyms*

BICS-Bahill Intelligent Computer Systems
BIMS-BICS Illuminance Management System
BiST-Built-in Self Test

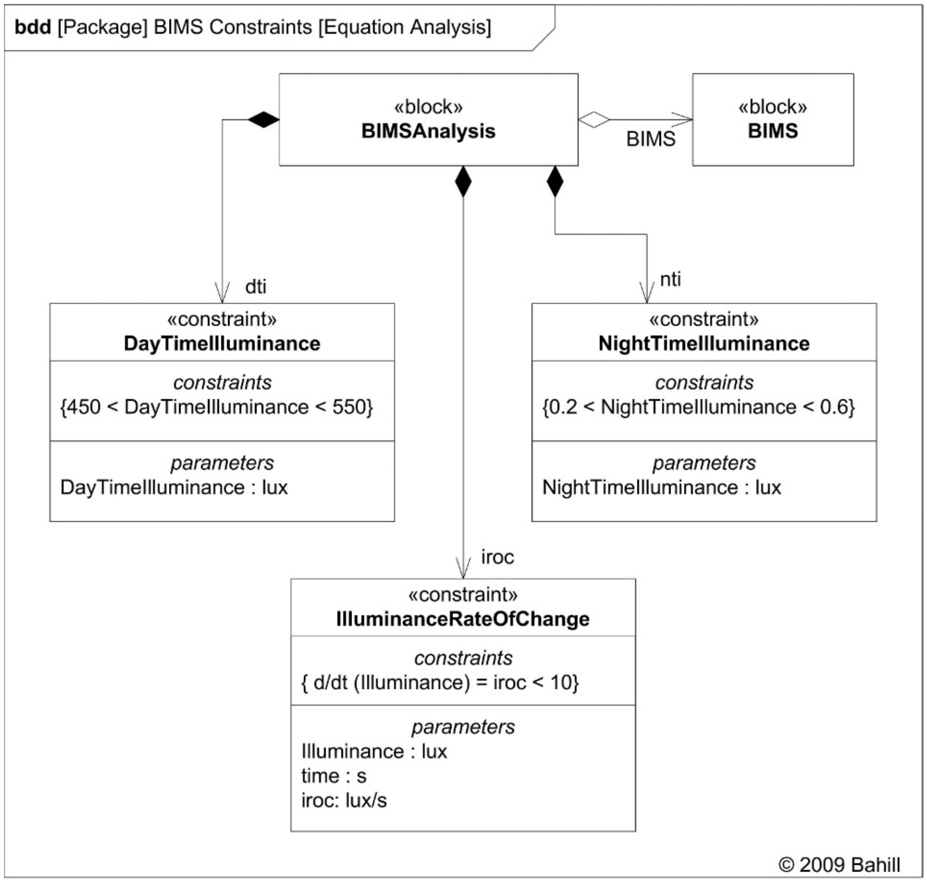


*Figure 10. SysML block definition diagram (**bdd**) showing the constraints of a BIMS. The block named BIMSAnalysis would describe the engineers doing the analysis, the computer operating system (LINUX, Windows, Macintosh), the software (MATLAB, Maple, Mathematica), and the algorithms (Runge-Kutta, Adams-Moulton, Cooley-Tukey FFT) that would be used to analyze the equations of BIMS.*

CDR-Critical Design Review
CDRL-Contract Deliverable Requirements List
ConOps-Concept of Operations
CoR-Cost Requirement
CuR-Customer Requirement
FR-Functional Requirement
HVAC-Heating, Ventilation and Air Conditioning
IC-Illuminance Controller
LED-Light Emitting Diode
NFPR-Nonfunctional Performance Requirement
OCD-Operational Concept Description
PDR-Preliminary Design Review
PV-Photovoltaic
RR-Risk Requirement
SI-Systeme International d'Unites
SR-Schedule Requirement
SRR-System Requirements Review
TBD-To Be Determined
TEP-Tucson Electric Power Company

*Risk analysis.* Risk is an expression of the potential harm or loss associated with an activity executed in an uncertain environment (Bahill and Smith 2009). Astronomical observatories face heightened scrutiny from environmentalists because of their prominent siting. To ameliorate this potential opposition, BIMS will use renewable-energy electric generators. This is a political decision, not an economic or scientific decision. In the risk analysis of *Table 6*, the greatest risk is that environmental activists will try to prevent funding and construction of the facility. *Tables 6* and *7* present two risk analyses: One is specific for the telescope project, and the other is for home owners in general connecting PV-solar electric generators to an AC power grid.

The greatest risk is that environmental activists will try to prevent funding and construction of the facility. We must alert our public relations people about this risk now. The second biggest risk is that a similar system has already been patented. Therefore, we should start

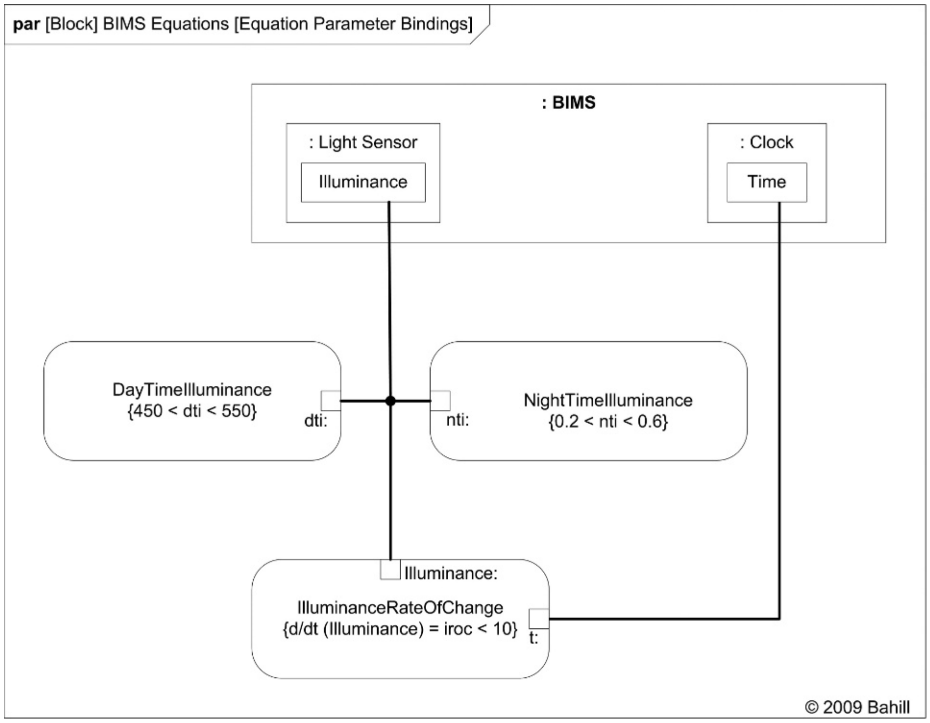


*Figure 11. SysML parametric diagram (**par**) showing the bindings for a BIMS. This diagram shows where tester would go to get values to plug into these equations.*

working on this risk immediately. We should contact BICS's lawyer and then start a patent search.

*Table 7* contains a failure modes and effects analysis (FMEA) for Tucson Electric Power's (TEP) AC electric power distribution grid. The input data were given to us by Tom Hansen, vice president of TEP, October 2008. We derived the rest of the numbers. First, we changed frequency of occurrence into a percentage. Then we calculated the range of these frequencies: about six orders of magnitude. The range for frequency and severity *must* be the same (Bahill and Smith 2009) so we assigned numerical values to the severities as follows:

| | |
|---|---|
| extreme | 1,000,000 |
| very high | 100,000 |
| high | 10,000 |
| medium | 1,000 |
| low | 100 |
| very low | 10 |
| miniscule | 1 |

The biggest risk in *Table 7* is the short to ground on the distribution grid. This is indeed a big risk because it cannot be fixed by merely throwing a switch on the computer control panel. The next biggest risks are injury or death to humans. This shows that TEP cares about its employees. The next risks are weather related: intermittent loss of the energy source (such as sunlight or wind) and interruption of power produced due to thunderstorms. Although we cannot do anything about the weather, we can affect how it affects our system.

*Environmental risks.* Raptors with large wing spans can get electrocuted when their wings touch two power wires at the same time. All birds can be killed if they fly into the blades of a wind turbine. Many people are worried about possible noise from wind turbines.

Solar panels could destroy habitats and modify bird migration patterns. Large fields of solar panels mounted flat to the earth's surface could look like a lake to migratory birds and throw them off course. Panels mounted on roofs could reflect light into the eyes of car drivers or airline pilots.

*Economic risks.* The following are some factors that could affect the economic risks of attaching solar electric generating equipment to the AC power grid: interest rates; continuation of federal, state, and utility company rebates; amortization period; federal stimulus funds; and federal regulations.

*Risks that have already been addressed.* The electric utilities have been doing risk analyses for years. When they identified a risk, they did something to minimize its effects. Here are a few examples.

There could be strong opposition from environmentalists, neighbors, or businesses around the areas where installation of solar panels is proposed. They might claim that solar panels are unsafe or ugly. Home owners

*Table 6. Failure modes and effects analysis for a BIMS.*

| Failure mode | Potential effects | Relative likelihood* | Severity of failure | Estimated risk |
|---|---|---|---|---|
| **Performance** | | | | |
| The volcano might erupt. | Acts of God are not normally included in a risk analysis. But in this case we should ensure that our system is connected to the USGS Volcano Hazards Program, at the Hawaiian Volcano Observatory in case we have to evacuate the mountaintop. | 0.001 | 0.9 | 0.0009 |
| The electric generators might not supply enough electricity in cold temperatures, at high altitudes. | We would not be able to sell power to the AC electric power grid. | 0.01 | 0.02 | 0.0002 |
| Telescopes operate below the temperature of the outside air so telescope enclosures are typically kept cold inside. | HVAC demands will be different than for a typical office building (reuse). | 0.9 | 0.001 | 0.0009 |
| Commercial AC electric power grid may fail for hours at a time. | We may have to incorporate backup diesel electric generators. | 0.01 | 0.1 | 0.001 |
| **Cost** | | | | |
| It is expensive to build in such a remote location. Skilled labor may be more expensive than expected. | We could overrun our budget. | 0.9 | 0.001 | 0.0009 |
| Construction workers working at 13,800 feet (4,200 m) will have trouble breathing. | This will make the workers less efficient, and they will need medical observation. | 1 | 0.001 | 0.001 |
| Something could interrupt the supply lines across the ocean and up the mountain. | We could overrun our budget and schedule. | 0.5 | 0.001 | 0.0005 |
| Electric power is expensive on Hawaii because it has no natural sources of fossil fuels. The average electricity rate is \$0.2/kWh to \$0.3/kWh compared with the national average of \$0.1/kWh. | This could increase construction and operations costs. It will also affect the balance between electric lighting cost and HVAC costs. This is also an advantage because it will help us compete with commercial electricity rates. | 1 | 0.001 | 0.001 |
| Cost of generating electricity in this location is more than the cost of buying it. | We would abandon this part of the project. | 0.05 | 0.5 | 0.025 |
| **Business** | | | | |
| The project might lose political support, and Congress or the NSF could stop funding. | The project would be terminated. | 0.01 | 1 | 0.01 |
| Observatories face heightened community scrutiny because of their prominent siting. | Proactively seeking accommodation with environmental concerns is one ingredient to a successful project. | 0.5 | 0.5 | 0.25 |
| A similar system has already been patented | We would have to license patent rights. Although it would cost at least \$5,000, we should initiate a patent search. If no similar patent is found, then we should initiate a patent application. We should immediately contact BICS's lawyer and ask if putting this document on my Web site constitutes disclosure. | 0.8 | 0.1 | 0.08 |
| One of your teammates might refuse to do any work. | You will have to fire that teammate, and everyone else will have to work harder (process). | 0.15 | 0.2 | 0.03 |

*Likelihood that the event would happen within the next year. Estimated risk is the product relative likelihood and severity of failure. These values were estimated by Terry Bahill September 13, 2009.

associations could prohibit or strongly discourage PV systems. This was considered a long time ago, and the state of Arizona passed laws making it illegal for home owners associations to impose rules against PV systems.

If a home owner tried to install a photoelectric system, he (or she) could get electrocuted. Installation looks like a simple task, but high voltages are involved. TEP has considered this, and they created the green

*Table 7. Failures modes and effects analysis for TEP's electric AC power distribution grid.*

| Failure mode | Effect | Frequency of occurrence, raw data, % of time | Severity | Risk |
|---|---|---|---|---|
| Short to ground on the distribution grid. | This could damage TEP's equipment, particularly transformers and capacitor banks. The system should be back up within 2 hours. This is unlikely to damage our customers' equipment. | Twice a month, 0.6% | Medium, 1,000 | 6 |
| Loss of ability to supply full load. | This would trip breakers and leave customers without electric power. | One hour in 10 years, 0.001% | Low, 100 | 0.001 |
| Accidents. | Injury to humans requiring medical attention. | 0.02% | High, 10,000 | 2 |
| Human mistakes. | Death of humans, with 100 employees, TEP has had no fatalities in 25 years of operation. | 0.0005% | Extreme, 1,000,000 | 5 |
| Intermittent local loss of energy source such as wind or sunlight due to, for example, clouds. | Voltage on the grid changes and frequency of coal-fired generators may change. Big electric generators do like transients. The average annual sunshine in Tucson is 85%. | 15% | Very low, 10 | 1.5 |
| Massive interruption of power generation due to monsoon thunderstorms. | This would cause the voltage on the grid to change, and this might cause the frequency of coal-fired generators to change. | 1% during July and August | Low, 100 | 1 |
| TEP must have the capacity to supply peak power even if clouds cover all of the solar panels. | This not a problem when solar power comprises only 1% or 2% of the load. But if solar power were to approach one-fourth to one-half of the peak power, then TEP would have to have an expensive, seldom used, backup system. | Presently, 0.01% | Medium, 1,000 | 0.1 |
| Grid frequency goes out of ±0.5-Hz limits | This will trip generators, perhaps overloading transmission lines and may result in fines. Duration is usually less than 5 minutes. This failure has a low severity with existing equipment. However, it will increase with distributed generation. | Twice a week, 0.7% | Low, 100 | 0.7 |
| Feeder circuit disconnects from substation | Feeder circuit voltage gets out of phase with the grid. This failure has a medium severity for existing equipment, but it will get worse with PV solar panels. It may require synchronized reclosers. Interruption may last 10 minutes. | Twice a month, 0.05% | Medium, 1,000 | 0.05 |

incentives program. If a business or a home is retrofitted with electricity-saving or electricity-producing devices, TEP will pay about one-third of the purchase price. But to qualify for the program, the system needs to be installed by a *certified* professional; this discourages people from installing the system themselves because they would forego the rebate.

Electric companies might refuse to buy electricity from homeowners. Federal law requires electric companies to buy electricity from their customers (http://irecusa.org/wp-content/uploads/2009/10/IREC_NM_Model_October_2009-1.pdf).

Photovoltaic panels contain no toxic chemicals or heavy metals. Smashing a panel would not release toxic gases, produce short circuits on the power grid, or create unusual flying debris.

## Summary

The system design process is a use-case-based iterative process. Use cases describe the required functionality of the system; the functional and nonfunctional requirements are developed while writing the use cases. These customer requirements are used to derive technical requirements and create test procedures. Some of the highest priority requirements will be made into evaluation criteria for use in trade-off studies. The system functions (described in the use cases) are mapped to classes and blocks, and these are interconnected to reveal the system architecture. Testing is more effective if it is planned right along with the system. Basing the tests on the use cases allows development of the testing procedures to begin right at the beginning of the system design. This should help produce more complete test plans and develop customer support for the test plans. The test plans should also include system experiments that will test the logic of the state machine diagrams. The system design process is not serial; it is very iterative, and there are many opportunities for parallel processing. ❑

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