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Introduction to the Buildings Sector Module of SEDS

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Disclaimer

Introduction to SEDS

The intention of this document is to present new users and developers with a general description of the purpose, functionality and structure of the buildings module within the Stochastic Energy Deployment System (SEDS). The Buildings module, which is capable of running as a standalone model, is also called the Stochastic Buildings Energy and Adoption Model (SBEAM). This document will focus exclusively on SBEAM and its interaction with other major sector modules present within SEDS. The methodologies and major assumptions employed in SBEAM will also be discussed.

The organization of this report will parallel the organization of the model itself, being divided into major submodules. As the description progresses, the nature of modules will change from broad, easily understood concepts to lower-level data manipulation. Because SBEAM contains dozens of submodules and hundreds of variables, it would not be relevant or useful to describe each and every one. Rather, the investigation will focus more generally on the operations performed throughout the model.

This manual is by no means a complete description of SBEAM; however it should provide the foundation for an introductory understanding of the model. The manual assumes a basic level of understating of Analytica®, the platform on which SEDS and SBEAM have been developed.

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Project Background

SEDS is a stochastic engineering-economics model that forecasts economy-wide energy consumption in the U.S. to 2050. It is the product of multi-laboratory collaboration among the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory (ANL), Lawrence Berkeley National Laboratory (LBNL), and Lumina Decision Systems. Among national energy models, SEDS is unique, as it is the only model written to explicitly incorporate uncertainty in its inputs and outputs. The primary purpose of SEDS is to estimate the impact of various US Department of Energy (DOE)R&D and policy programs on the performance and subsequent adoption rates of technologies relating to every energy consuming sector of the economy (shown below). It has previously been used to assist DOE in complying with the Government Performance and Results Act of 1993 (GPRA). The focus of LBNL research has been exclusively on develop the buildings model (SBEAM), which is capable of running as a stand-alone forecasting model, or as a part of SEDS as a whole. The full version of SEDS, containing all sectors and interaction is also called the "integrated" version and is managed by NREL. Forecasts from SEDS are often compared to those coming from National Energy Modeling System (NEMS).

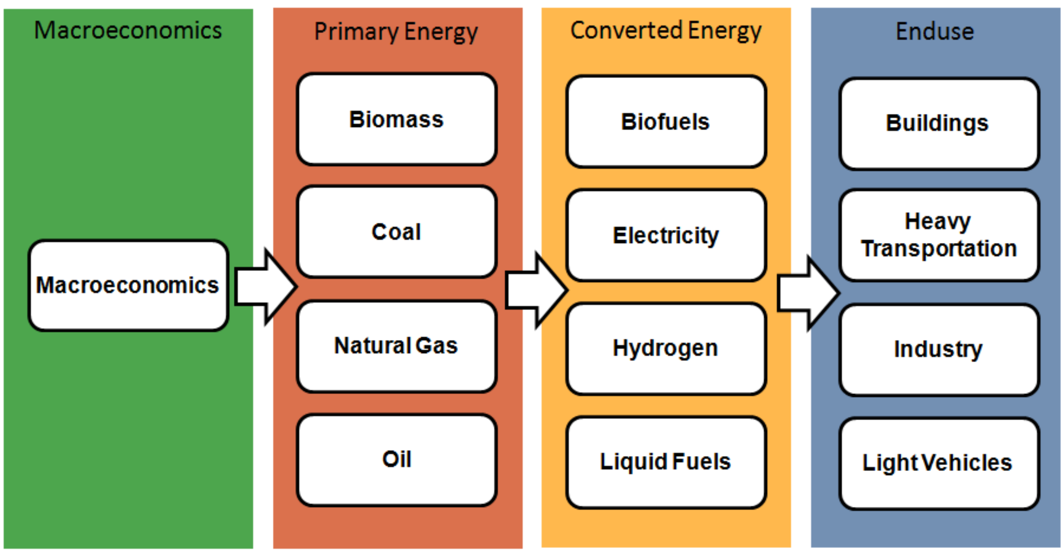

Figure 1: Overview of major sectors in SEDS

SEDS Platform: Analytica®

SEDS has been developed using Analytica (Lumina Decision Systems), which for a number of reasons is well suited for this type of project. First, Analytica is visually based, allowing for easier organization of SEDS's often complex and interrelated variables and algorithms. Variables and collection of variables (called "modules") are represented as nodes, which arrows indicating influence between nodes. The model can be navigated quickly and intuitively by clicking into and out of modules and submodules. This also allows for quick access to intermediate results. For instance, if one were interested in the evolution of lighting stock in commercial buildings, it is only a matter of locating the variable within the hierarchy of modules and pressing the evaluate button. This feature is invaluable for debugging changes made to the model .More importantly, Analytica is capable of incorporating uncertainty in inputs throughout the forecast process. The value of this in forecasting out to 2050--a rather uncertain task--should be obvious. The implementation of stochastic inputs (those including uncertainty) will be discussed later. Finally, Analytica allows indices to be easily attached to data and tracked through all subsequent calculations. For instance, commercial fuel use might be indexed by fuel type, census region year and funding scenario. Creating such multi-dimensional arrays on other platforms might prove problematic.

Each variable can be explored in detail by double-clicking, which brings up the object details window. An example of this is shown below. While the details of this particular variable, energy prices, are not important, there are several key observations to note. First, each variable has two names, a title, which is the superficial name shown in the module diagram and an identifier, in this case `B_in_enrgy_pric`, that is used in the definitions of other variables. Understanding this distinction is important whenever creating or editing a model.

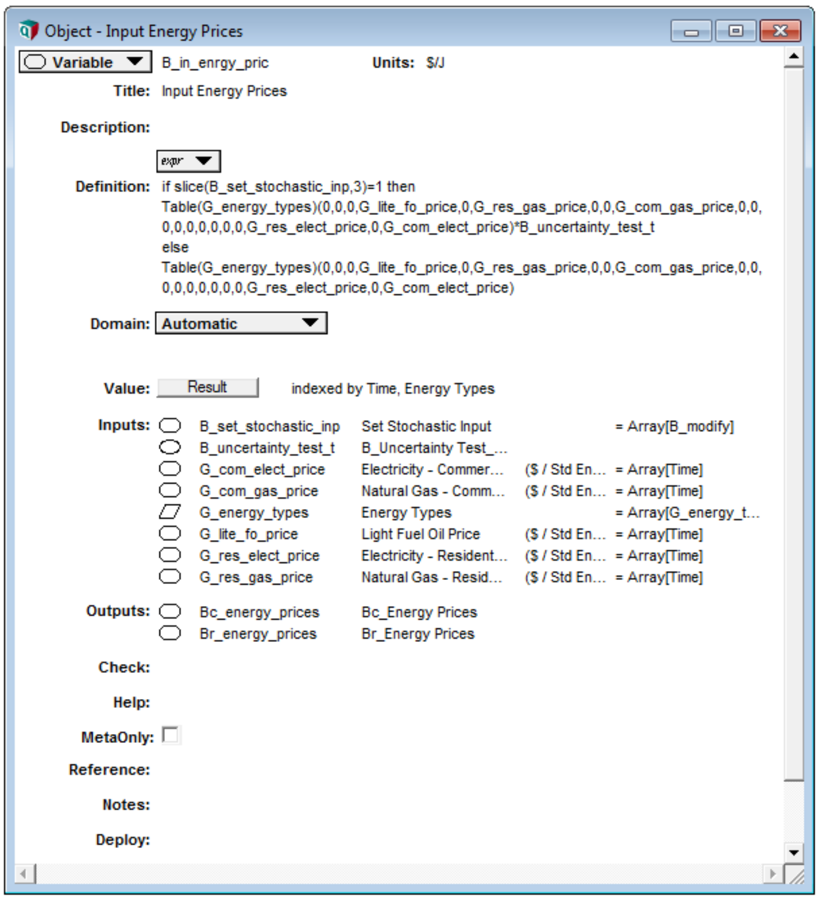

Figure 2: Example of variable object detail window in Analytica®

The object window also contains the mathematical definition of the variable as well as a list of all the inputs and outputs to and from the variable. Double-clicking on any of these will take the user to their individual object detail windows. This is another feature which helps to expedite navigation of the model. As a rule, variables in the buildings module are given and identifier with the prefix “B_”. Those that pertain specifically to the commercial or residential sectors begin with “Bc_” and “Br_”, respectively.

SEDS and SBEAM are written so they can be run either stochastically or deterministically. Stochastic results provide a more detailed perspective of the forecast, but generally at the cost of longer run-times. Similarly, the integrated version of SEDS may produce more detailed results than the standalone SBEAM, but its run-time is significantly longer.

For more information about Analytica, tutorials, a 30 day trial version and comprehensive user guide please, visit the website http://www.lumina.com/why-analytica/

Stochasticity within SEDS

One of the major features of SEDS is its ability to quantify uncertainty. In many instances, variables are defined as distribution of possible values. Utilizing Monte Carlo draws, Analytica is able to assemble stochastic distributions of the resulting forecasts. Uncertainty in SBEAM originates from a number of variables, including energy prices and macroeconomic data (population, GDP). Stochasticity also arises from the representation of important buildings technologies and their projected performance improvements over time. To create these projections, SEDS developers use the process of expert elicitation (Morgan, Henrion 1990). Industry experts are surveyed and asked to create 3 point distributions of technology parameters (price, efficiency, etc) at various years and under specified scenarios (Livingston 2009). The survey results are then collected and assembled into distributions which govern the technology's evolutions. Currently, expert elicitations have been conducted for such important buildings technologies as LED lighting, PV, and advanced windows. An example of this is shown below for dynamic electrochromic windows. The cumulative probability distribution shows the expected likelihood of improving capital cost at two forecast years and under two distinct DOE funding scenarios.

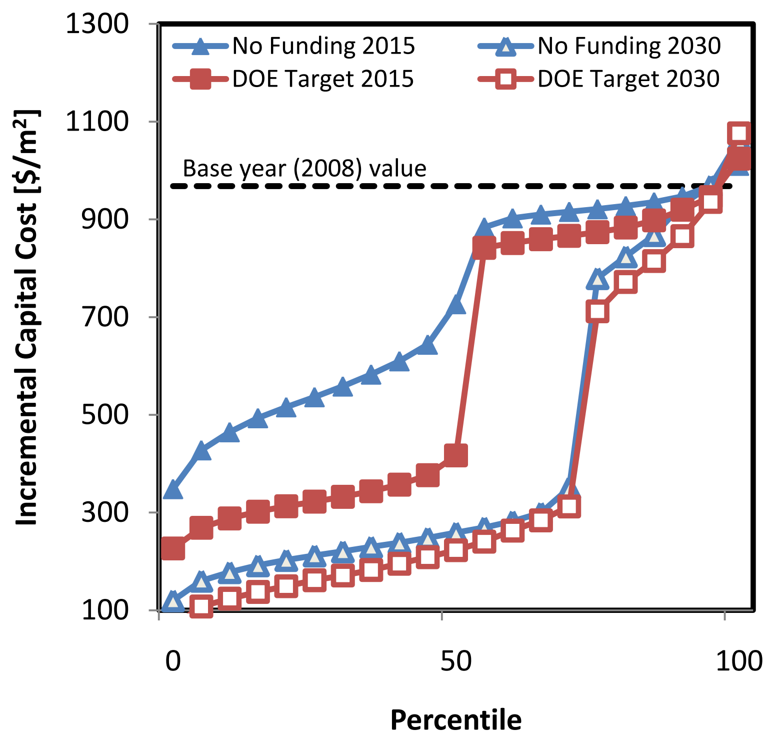

Figure 3: Probability distributions govern stochastic technology representation in SBEAM

SBEAM General Structure

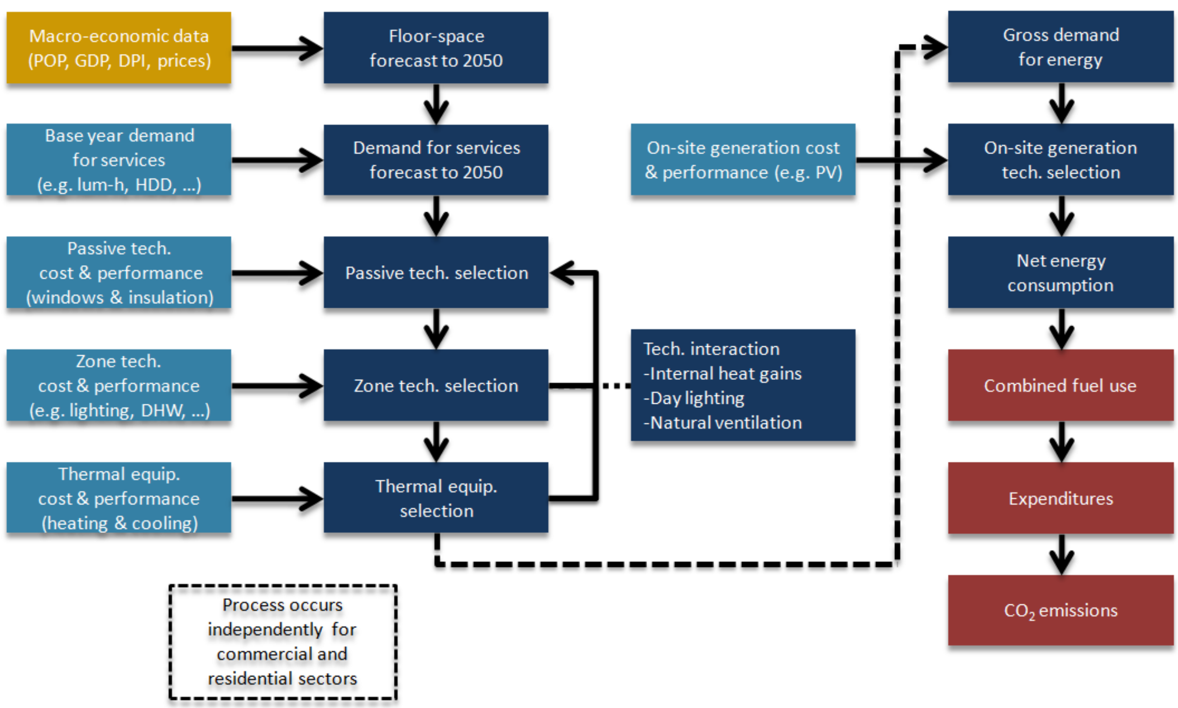

Figure 4: Schematic representation of SEDS data flow

The above figure shows a schematic representation of the general data flow within SBEAM, from major input to major outputs. This figure will serve as a helpful reference in understanding how specific submodules and algorithms fit into the big picture of SBEAM operations. Major inputs originating from outside the buildings module, namely macroeconomic data, are shown in gold. Inputs that are only applicable to the buildings module, such as building service technology performance data, are shown in light blue. The various operations and algorithms of the buildings module are shown in dark blue. Finally, the key outputs are shown in red. Note that while this simplified description may neglect some minor interactions present within the module, it should nonetheless prove helpful in establishing a general understanding.

The model disaggregates buildings energy consumption into major end-uses, listed below. Throughout this document, the term "end-use" is used generally to describe one or all of the following items. The demand units for each end-use are also included.

- Lighting – lumen-hours
- Refrigeration – ft^3
- Domestic hot water (DHW) – kWh
- Ventilation – kWh
- Other – kWh
- Heating – heating degree day (HDD)
- Cooling – cooling degree day (CDD)

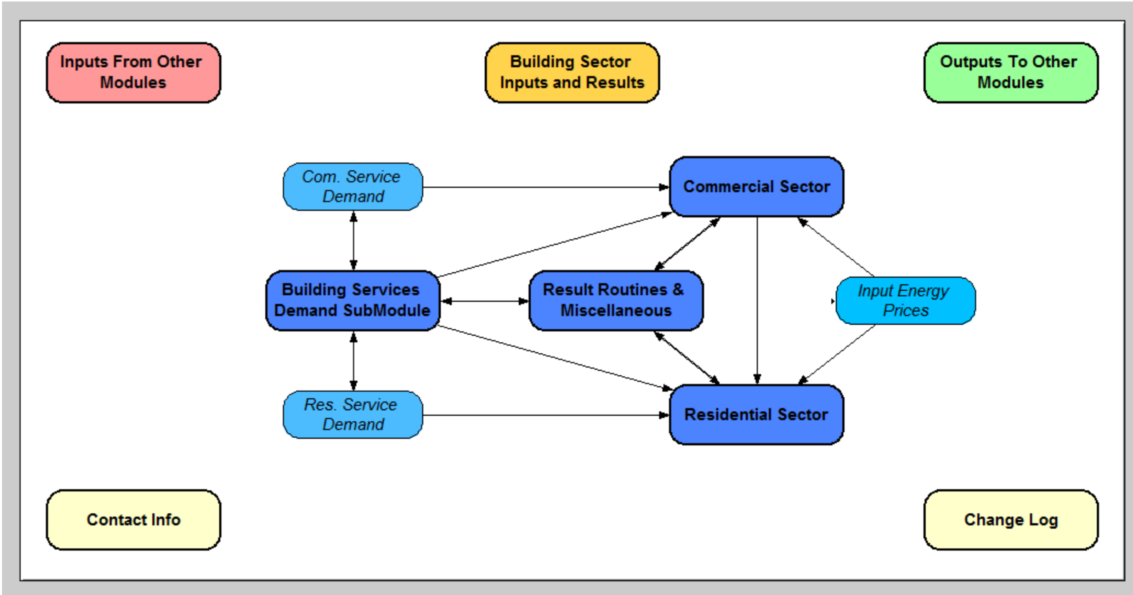

Figure 5: SBEAM building sector details module

The top level of SBEAM is simply the framework required for it to run independently of SEDS. It contains global variables and functions, which while used in the Buildings Module of SEDS, are contained in external modules. Most new users of SEDS will not need to access any of these support modules, beyond the **`Public Variables and Indices`** module, which allows users to select between stochastic and deterministic run modes.

The core of the buildings-related calculations exists within the **`Building Sector Details`** module. At this level, SBEAM consists of 3 major submodules: **`Buildings Services Demand`**, **`Commercial Sector`** and **`Residential Sector`**, as well as the less significant **`Results Routines & Miscellaneous`** submodule. The functionality of each submodule will be explored in detail in the following sections. As the above figure shows, this level also contains **`Inputs From Other Modules`**, **`Outputs to Other Modules`**, (both of which serve obvious purposes) and **`Building Sector Inputs and Results`**, which contains an interface for quick access to major SBEAM settings and results.

Buildings Services Demand Submodule

The purpose of this module is to calculate a forecast of demand for both total floorspace and building services. The model utilizes a linear multivariate econometric regression of population and GDP projections to generate forecasts of floorspace demand for both the commercial and residential sectors (Marnay 2008). The coefficients of these regressions have been determined externally using historical data. Demand for services is derived from CBECS on a demand unit per floorspace basis. Note that demand is given in units of service, for instance lumen-hours per m^2, rather than simply units of energy. This approach is different from most other energy forecast models and decouples service demand from the technology that meets it. It is assumed that the specified level of demand will stay constant per unit floorspace through time, which is to say consumers will not choose to adopt a higher or lower level of service per unit floorspace. In some cases, this assumption can be faulty. Changing trends in consumption levels have been known to occur. As such, this module includes the functionality to manually alter (as a percent of the existing level) any of these service demand levels. This can be seen under "Policy Levers

(Advanced Feature)" of the demand submodule shown in Figure 6. This interface also includes access to important initial conditions and forecast settings. The submodules that comprise the demand forecast are shown on the right.

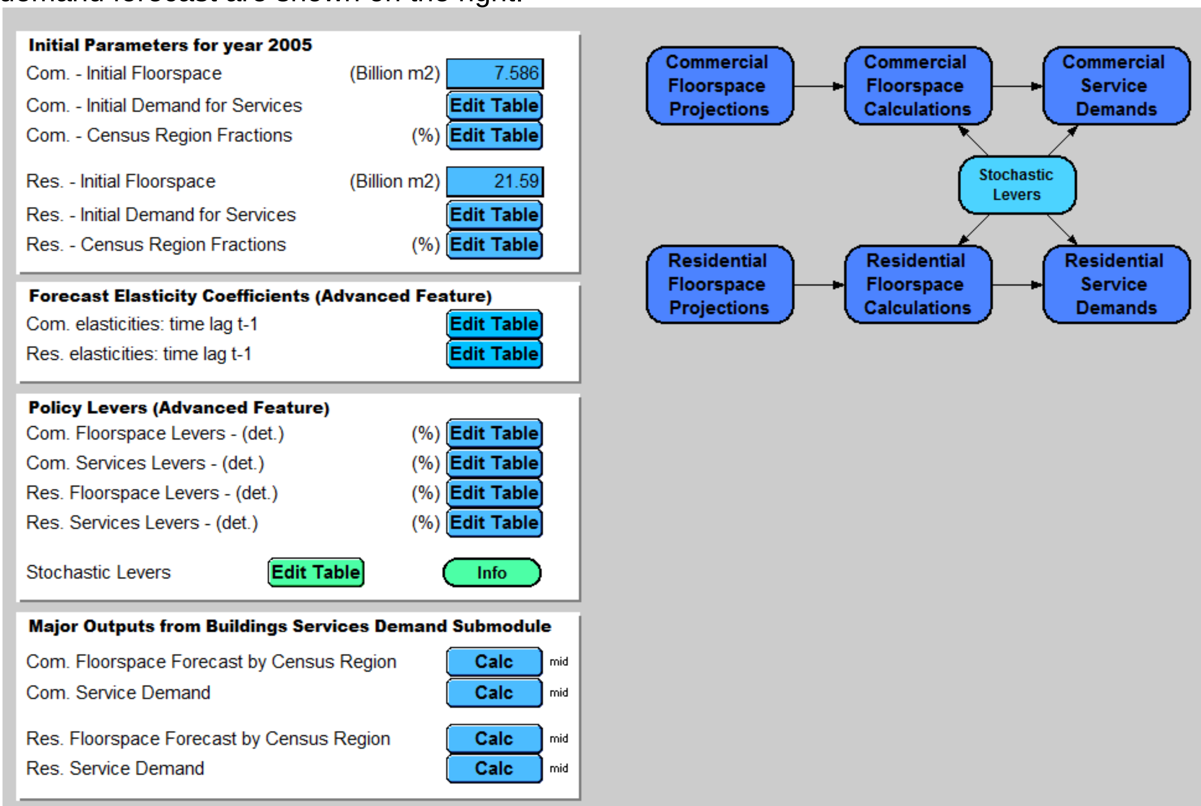

Figure 6: SBEAM building services demand submodule

Results Routines & Miscellaneous

This submodule contains operations that reduce data to a form required for output. It is home to several supplementary analysis modules, which help to explore and visualize intermediate forecast results of interest.

Commercial/Residential Sectors

SBEAM differentiates the residential and the commercial sectors, which share an identical structure. In fact, these two modules run in parallel to track their own characteristics and market shares. In a few instances, such as the PV submodules, there are minor interactions between these two sectors. These will be described as they occur throughout this document. In most cases, however, commercial and residential calculations occur independently of one another. Because of their similarity, the two modules will both be explored generically in the following sections.

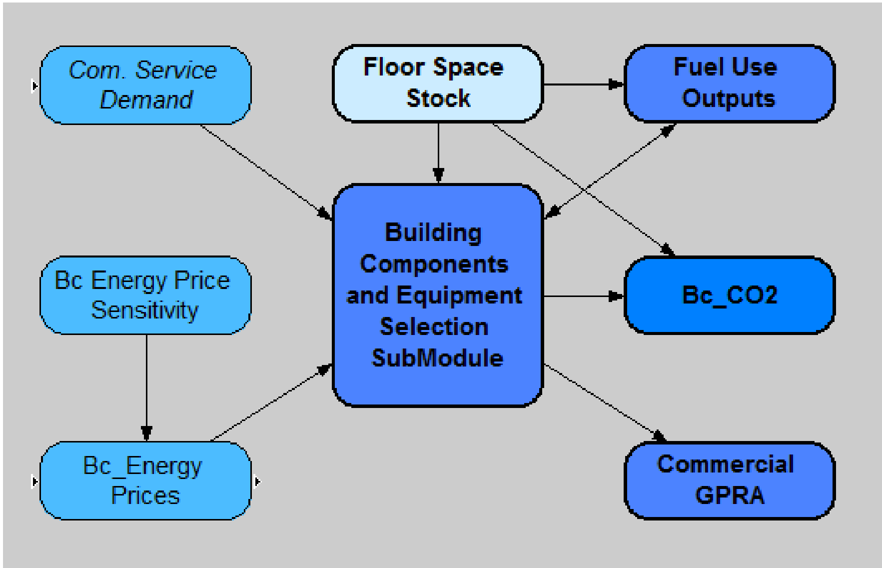

Figure 7: Commercial/Residential sector module

Within the sector module, there are a number of submodules and variables, most of which are minor or self explanatory. The two of greatest interest are **`Floor Space Stock`** and **`Buildings Components and Equipment Selection Submodule`**. In the former, the composition of the floorspace is allocated between "existing" (that which existed prior to the start of the simulation), "remodeled" (that which undergoes significant structural alteration during the course of the simulation) and "new" (that which is constructed during the simulation). The necessity of this will become more apparent once the building shell selection process has been covered. Existing and remodeled floorspace are determined based on parameters specified within the module (or in submodules thereof). New floorspace is specified such that the demand for floorspace (as calculated in the **`Buildings Services Demand`**) is met each year. These floorspace arrays are then passed to the **`Buildings Components and Equipment Selection Submodule`**.

Buildings Components and Equipment Selection

As the name suggests, it is within this module where equipment selection occurs. This is a major part of SBEAM because it is the efficiencies of the service equipment that will determine both energy use and emissions. Equipment is broken down into smaller related categories: passive, zone, thermal and PV, each of these categories may contain multiple end-uses, (e.g. lighting, DHW, heating). To determine which technology is employed to meet the demand for a particular end-use (i.e. marketshare), a selection process template is used. The details of this algorithm, which is largely identical for each end-use, will be explored in the methodology section. For the time being it will only be described generically. Notes will be made wherever meaningful differences in the template occur. Equipment selection follows a particular sequence (Figure 4) each year, so as to best capture interactions between end-uses and the effect on consumer behavior. Note that no iteration is used to determine equipment selection. This has been done to maintain a low run-time, one of the key benefits of the SEDS model.

Technology Selection Methodology

For every end-use, the same basic process is employed to determine important values including the initial state and turnover of the stock, the marketshare of each technology and the evolution of technology performance through time.

The first step of the process is to initialize the stock equipment. In other words, the marketshare of the first year equipment is specified (usually from CBECS data). The stock is then automatically placed into vintage categories. This is used to manage the turnover of the equipment as it reaches the end of its lifetime. Vintage settings will vary by end-use, providing additional detail for those that requiring, and allowing for quicker run-time for those that do not. SBEAM is capable of considering economic retirement of equipment; however the model currently only considers lifetime-based retirements. At each year, retirement of equipment is determined. This, along with the demand stemming from newly constructed floorspace comprises the unmet demand each year. This is fed into the template, which chooses the technology to meet it.

The marketshare of a given technology is determined by several factors. The most important is annualized cost, which incorporates the upfront capital cost, operations cost, fuel cost and lifetime to determine a cost per year over the lifetime of each technology. Novel technologies may also have their marketshare vary based on familiarity, which defines how well established a technology is in the mind of the consumer. In most instances, familiarity is complete. Another major parameter that affects marketshare is alpha (α). Alpha is a factor used to characterize consumer sensitivity to price. It is implemented via a logit function. A rigorous mathematical description of the logit is not included in this manual, as many resources on this topic already exist (Stadler 2009, Anderson 1992, Ben-Akiva 1985). Suffice it to say that the logit will allocate the majority of the marketshare to the most (annualized) cost effective technology, and progressively smaller portions to those less cost effective. The distribution of the marketshare portions will depend heavily on the specified alpha. If alpha were set to zero, equal shares would be given to each technology. In other words, consumers would be entirely insensitive to price. In case of high alphas, the logit will allocate a larger marketshare to cheaper technologies. This represents a high sensitivity to price. Wherever possible, alphas are generated from historical adoption data. However, in the case of many technologies, such data does not yet exist. As such, constant alphas are currently employed (except for PV). As the technologies mature and more data become available, this aspect of the model will likely be updated.

Utility (v_i) is determined by the a factor and the levelized (or annualized, LC_I) cost of each technology.

$$v_i = e^{(-\alpha \cdot LC_i)} \tag{1}$$

Marketshare (MS_i) is subsequently determined by the relative utilities of each technology.

$$MS_i = \frac{v_i}{\sum_i v_i} \tag{2}$$

SBEAM considers many novel or emerging technologies which are expected to improve significantly within the window of the simulation. As mentioned previously, the annualized cost is determined from cost, fuel use (which itself is calculated from efficiency) and lifetime. To capture how these factors are likely to change, SBEAM considers two distinct mechanisms for improvement. The first and primary is Research and Development (R&D), which specifies distributions of likely performance at various point in time. It only provides the opportunity to create R&D funding scenarios to assess the impact of funding technologies at different levels (called “base”, “target” and “overtarget”). The robustness of this improvement mechanism is dependent on the data that drives it. At the moment, it is only used for those technologies which have been included in expert elicitations.

The second mechanism for technology improvement is learning by doing or LBD. LBD is the expected improvement that comes from widespread manufacturing, installation and utilization of a given technology. It is based on distributions of expected improvements every time the cumulative installed capacity doubles. Similar to R&D, LBD is only used for technologies which have previously been stochastically characterized. Note that real-world LBD would be driven my worldwide manufacturing levels, however SBEAM is only capable of considering the cumulative installed capacity for the U.S. As a result, the LBD effect, particularly in the case of PV, modeled with in SEDS may be an underestimate.

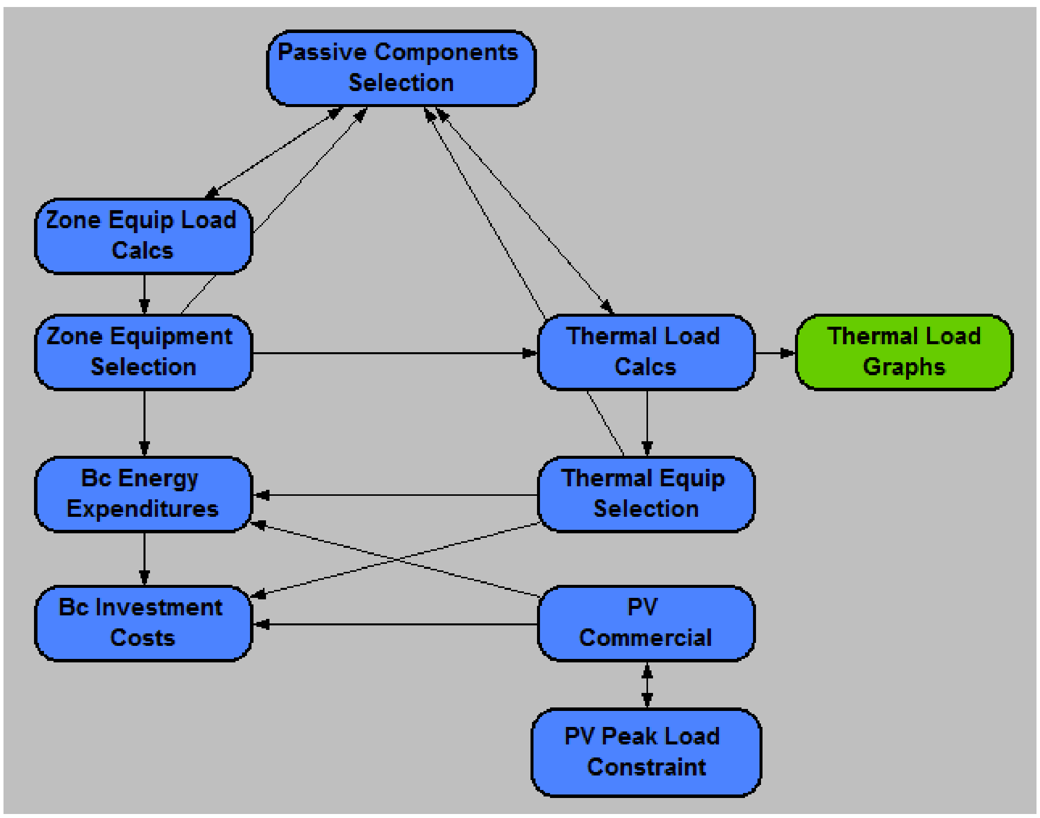

Figure 8: Building components and equipment selection submodule

Passive Components

The first category of equipment to be evaluated is passive. Passive technologies refer to building wall and windows and can be applied to two pools of floorspace, new and existing. In the case, new floorspace includes both “new” and “remodeled” floorspace as calculated in a previous module. The reason for this separation comes from the significant difference in prices when applying shell changes to buildings during the process of construction/renovation versus those that already exist and must be retrofitted.

The selection of passive components is made based on a comparison of a multi-attribute annualized cost that considers savings in heating, cooling and lighting that arise from improved building shell. The annualized cost and savings calculation utilizes the previous year value for lighting, heating and cooling consumption because the current year stock has not yet been determined. Because building shell components generally last a long time, the costs are not annualized over the component's lifetime, but rather a project payback period which is specified by the user. This is done to more accurately capture how these decisions are made by consumers.

The shell selection process for existing buildings acts as a proxy representation for retrofitting. Initially, all buildings are set to the least advanced shell type, which is given a lifetime of 25 years[1]. At each year, one twenty-fifth (or 4%) of the stock is given the choice to adopt a new building shell. Depending on the cost at the time, a portion of that stock will select advanced shells. Once this occurs, the stock is assumed to retain its advanced shell for the remainder of the simulation.

Zone Equipment

Zone equipment includes the following end-uses: lighting, refrigeration, domestic hot water (DHW), ventilation and other. Of these, the first three employ the technology selection template. In the case of lighting, the initial demand is adjusted to consider the availability of natural daylight (which is a characteristic of the building shell previously selected). Demand is then passed to the template, which compares each technology on an annualized cost basis and determines the marketshare. Note that within lighting are LEDs, one of the stochastically characterized technologies.

Ventilation and other are considered more simply. Ventilation is calibrated to CBECS data and is scaled up with floorspace. Other, which considers among other things, miscellaneous electrical loads, is somewhat more problematic. To determine the consumption within Other, two assumptions are employed. First, other consumption will scale with floorspace, GDP and PDI (personal disposable income). The elasticities of these relationships have been determined from historical data. Secondly, it is assumed that Other equipment that consumes electricity will become slightly more efficient over the years. As SBEAM can demonstrate, Other load represents a significant portion of overall energy consumption, upwards of 30% in some regions. However, given its vagueness, it is difficult to characterize this end-use with much additional detail.

Thermal Equipment

Thermal equipment at the moment refers only to heating and cooling, considered separately. Eventually, it may be expanded to consider equipment with provides combined heat and power (CHP) or heat pumps, which are capable of providing both heating and cooling[2]. To begin the

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[1]This turnover rate may easily be altered by the user to model more aggressive retrofitting scenarios.

[2]Note that the model does currently consider heat pumps, but not as a single technology capable of serving multiple end-used. In order to do this, significant modifications would need to be made to the decision template.

process of thermal equipment selection, thermal loads must first be determined. Demand for heating and cooling is initially given in heating/cooling degree days (HDD, CDD) annually. These specify the difference in degrees between the actual temperature outside and the desired temperature inside each day, summed over the year. From this point, two interactions must be considered to convert thermal demands from degree days to kWh of heating or cooling. Once this has been completed, equipment selection can occur. The first is interaction with the building shell, which governs heat losses/gains to and from the outside environment. The second is internal heat gains which result from the service equipment and people present inside the building. Both of these calculations occur within the **`Thermal Load Calcs`** submodule. Once completed, the selection process occurs as previously described.

PV Selection

At this point in the model, selection of equipment has been made such that all demands for building services have been met. SBEAM is now capable of determining the demand for fuel (natural gas, light fuel oil and electricity) necessary to provide these services. In the case of electricity, a selection process is employed to determine whether the source be from the grid or from an on-site photovoltaic installation. This is done based on a comparison between the annualized cost of PV versus the current electricity price (commercial or residential price, depending on the sector). The adoption level of PV throughout the forecast is heavily dependent upon the stochastic values for performance and price coming from the R&D and LBD sections.

There exist a few distinctions which make the PV selection process different from those previously outline. Several constraints are imposed to prevent PV from capturing an unrealistically large portion of the market (even when price and performance favor the adoption of PV). First, it is assumed that the total installed capacity of PV cannot exceed the available rooftop space of the building stock. Secondly, electricity demand is broken down into base load and peak load. Given its highly time dependent nature, it is assumed that PV can only be used to meet peak load. Finally, a constraint is imposed to limit the year to year growth. This is meant to capture manufacturing limitations which would prevent PV installation from growing explosively. This constraint is highly dynamic and will depend on the amount of PV installed in the previous year.

PV also utilizes a forecast for its alpha parameter that changes in time. The alpha forecast was generated from historical PV price and adoption data. In the cases of many technologies, there does not exist sufficient historical data to do this, and so constant alpha values are currently employed.

Regionality

In its earlier forms, SBEAM considered only a single generic building type in a generic region, utilizing national average data. This presents an accuracy problem, given the vastness of the U.S. and all the variation of conditions that occur within it. To address this, the latest development of SBEAM has been incorporate regionality into the modeling process. This first occurs within the **`Building Services Demand Submodule`**, which breaks floorspace and service demands down by region. Currently the model uses the nine census regions; however this could easily be modified to represent other geographical divisions, for instance climate zones. The breakdown enhances accuracy because it allows the model to utilize the vastly different demand values for heating and cooling degree days. The difference in demand levels will then drive the technology adoption templates in a separate, yet parallel process. Finally, national investment, consumption and emission values will be summed over the census regions to provide output to external modules in the same format as previous version of SBEAM.

The regional functionality provides additional benefits as well. It allows for analysis of policy which target only select portions of the country (for instance policies to promote insulation in cooler regions). It also allows modelers to input fuel and electricity prices that vary geographically. Climate, price and policy represent three major driving factors for energy consumption in buildings, and each can more accurately be modeled with the development of regionality in SBEAM.

The process of adding regionality was not altogether easy. Analytica in general provides for quick and easy management of indices, however, the regional index had to be applied to the appropriate variables. Adding it to additional variable would undoubtedly alter forecast results. Tracking down such errors proved surprisingly difficult. Additionally, the regional index create concerns for the following model processes: stock initialization, tracking through vintages, capacity constraints (i.e. limits on marketshare), and cumulative installed capacity for LBD. Each of these had to be addressed to ensure that the regionality had been employed properly. While still utilizing national average data, the regionality enable model was compared to the previous version to confirm this.

Fuel Use & CO_2 Outputs

Once the PV marketshare has been established, SBEAM can determine the total demand for fuel by type and the corresponding emissions. These results can be accessed in the **`Outputs to Other Modules`** module as well as in the right side of the **`Building Sector Inputs and Results`** module. Beyond fuel use and emissions, there are several other major building module results output to the rest of SEDS. They are as follows:

- Light fuel oil demand
- Electricity demand
- Natural gas demand
- PV generation
- Installed PV capacity
- CO_2 emissions
- CO_2 intensity (by floorspace)
- Energy use intensity
- Investment costs
- Investment expenditures
- Energy expenditures

Each output is given for the commercial and residential sector separately.

SBEAM future development

SEDS and SBEAM are both in a state of ongoing development. As such, there still exist areas for change and improvement. The following represent areas of SBEAM with potential for improvement

Adding multi-service technology selection

Several important building technologies, included heat pumps and fuel-cell CHP have the capacity to serve multiple enduses (i.e., heating, cooling and DHW). As it currently exists, the SEDS technology selection template is incapable of considering such technologies across those multiple enduses. Major structural changes to the template would be necessary to incorporate this functionality.

Data accuracy

Acquiring accurate and up-to-date data represents a major challenge in the development of SEDS and SBEAM. Continuing to add technologies of interest stochastically, via the expert elicitation process is a priority. At the moment, SBEAM is capable of disaggregating its forecasts to region level (currently by census region), allowing users to define with great accuracy regional variations in policies, prices and climates. However, much of the data being fed into the model does not yet take advantage of this feature. Locating and implementing this regional data presents another important task.

Building Types

Currently, the model considers only one generic building type for commercial and residential sectors. This prevents analysis that targets specific building types. Implementing a building type index to the model would present both technical and data-related challenges, however it would likely increase the value of the model immensely.

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