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Refrigeration Modeling Components in OpenStudio

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ABSTRACT

OpenStudio, developed at the National Renewable Energy Laboratory (NREL), is a cross-platform collection of simulation tools for whole building energy modeling. EnergyPlus and Radiance are the primary simulation engines in OpenStudio and the latest addition is a collection of refrigeration objects developed at the Oak Ridge National Laboratory (ORNL) which makes the refrigeration system components of EnergyPlus available for use through OpenStudio. This paper highlights the benefits of including refrigeration modeling functionality in OpenStudio, the object model, the exposed Application Programming Interface, the user interface, and discusses some of the design challenges faced. It is expected that the addition of these refrigeration components fills a gap and will enhance the successful adoption of OpenStudio as a modeling tool of choice in the buildings simulation community. Furthermore, it is hoped that these refrigeration capabilities will allow retailers to assess the energy impact of a variety of supermarket and distribution facility refrigeration system design options and aid in the selection and implementation of energy efficient systems.

1. INTRODUCTION

Whole building energy models are computer-based tools which simulate the annual energy consumption of a building, including electricity and gas usage. Typically, these tools calculate, on an hourly or sub-hourly basis, the thermal loads on a building, including radiant and convective loads as well as conduction through building elements and moisture adsorption or desorption. Miscellaneous loads due to people and lighting, as well as electric and gas appliances can also be included in the analysis. The thermal and moisture loads are then used in conjunction with equipment models to determine the total energy consumption of the building, including its heating and cooling equipment. Building energy modeling tools may even predict various emissions, such as CO_2, SO_x, and NO_x, which occur during on-site energy conversion processes.

Several commercial and public domain building energy modeling tools are available. These energy modeling tools contain equipment models that are suitable for determining the energy consumption of heating and cooling equipment typically found in commercial and residential buildings. Such systems include vapor compression based air conditioning and heat pump systems, chillers, gas or electric furnaces, boilers, water heaters, desiccant

dehumidification units, and humidifiers. Furthermore, some tools also include the capability to model refrigeration systems such as those found in supermarkets, grocery stores, refrigerated warehouses and distribution centers.

To facilitate refrigeration modeling in OpenStudio, several new objects have been added which makes the refrigeration system components of EnergyPlus available for use through OpenStudio. The following sections provide a background of available refrigeration modeling tools, the various refrigeration components added to OpenStudio, various aspects of implementation, the user interface provided, and a concluding summary of the software contributions to OpenStudio.

2. BACKGROUND

2.1 Existing Refrigeration Modeling Tools
Computer models for determining the annual energy consumption of refrigeration systems used in commercial and industrial applications fall into two basic categories. One category of model makes use of very detailed component models to determine the energy consumption of the whole system, while the other category of model involves the use of whole building energy simulation programs that are capable of modeling refrigeration systems in conjunction with internal and external building loads, the building envelope, heating and cooling systems, etc.

Refrigeration system modeling tools based on detailed models of the individual components of a refrigeration system generally lack information regarding the heat transfer to the evaporator and from the condenser. Typically, these modeling tools assume a constant evaporator load and they assume that the energy is rejected from the condenser at a single specified temperature. Thus, these refrigeration system modeling tools make it difficult to account for the effects of variations in ambient dry-bulb and wet-bulb temperatures as well as variations in internal and external loads. Several such refrigeration system modeling tools include the following (Becker *et al*. 2012):

- CoolPack (IPU 2014a)
- Pack Calculation II (IPU 2014b)
- Heat Pump Design Model (HPDM), Mark VII (ORNL 2014)

Since whole building energy simulation tools are capable of modeling the building envelope, heating and cooling loads and HVAC performance based on detailed weather data and building construction data, variations in ambient dry-bulb and wet-bulb temperatures as well as variations in internal and external loads can be taken into account. Thus, for refrigeration system modeling, these tools can determine the interaction between supermarket display cases and the store environment. Two commonly used public domain whole building energy models that can be used for refrigeration system modeling include:

- EnergyPlus (DOE 2014a)
- eQUEST (JJH 2014)

2.2 Refrigeration Modeling in OpenStudio
OpenStudio provides a powerful and flexible platform for modelers to easily design simulation models using the primary simulation engines of EnergyPlus and Radiance. Availability of a consistent and intuitive user-interface saves time and affords greater productivity. The addition of the refrigeration modeling capabilities in OpenStudio exposes EnergyPlus's refrigeration modeling capabilities through the OpenStudio user interface.

The Oak Ridge National Laboratory's Building Technologies Research and Integration Center (BTRIC) is recognized for its expertise in refrigeration research. The software effort described here is the result of a combined effort by ORNL and NREL with ORNL being the developers of the refrigeration objects and NREL developing the user-interface components.

3. REFRIGERATION COMPONENTS

3.1 EnergyPlus Refrigeration Modeling Capabilities
EnergyPlus is capable of modeling a variety of refrigeration systems and components found in commercial and industrial applications. System types which can be modeled include:

- Multiplex direct expansion (DX) systems
- Cascade systems
- Secondary loop systems using either single-phase or two-phase heat transfer fluids
- Transcritical CO_2 booster systems

Models are included for the following refrigeration components:

- Refrigerated display cases
- Walk-in coolers and freezers
- Air cooling coils
- Air-cooled, evaporatively-cooled, or water-cooled condensers
- Air-cooled gas coolers
- Compressors
- Mechanical and liquid-suction line heat exchangers

In addition, any refrigerant can be modeled by providing tabular thermodynamic data for the refrigerant. A typical refrigeration cycle in EnergyPlus can consist of several loads (i.e., several refrigerated display cases and/or walk-in coolers and freezers), several compressors connected in parallel, and a condenser. Furthermore, multiple refrigeration systems can be incorporated within a single building to satisfy the various refrigeration loads which may exist in the building.

The component performance models in EnergyPlus make use of readily-available manufacturers' performance data, performance maps and specifications. For example, the performance of a compressor is specified by the 10 coefficients of the AHRI compressor performance polynomial (AHRI 2004). This data is readily obtained from compressor manufacturers. As another example, display case specifications and performance at the rated conditions of 24°C, 55% relative humidity are required, including rated cooling capacity, lighting power, fan power, defrost type and defrost heater power, among others. Again, this data is readily obtained from display case manufacturers. As an aid to the user, a library of component performance data and specifications is provided with EnergyPlus, and the user may include additional components as required.

3.2 Refrigeration Components added to OpenStudio

The objects within OpenStudio follow the EnergyPlus objects quite closely. Users can pull together several refrigeration components in a meaningful way to create a refrigeration system. The resulting model can then be simulated using EnergyPlus as the simulation kernel but through the OpenStudio interface.

Several refrigeration objects were identified as critical components to support in the modeling of refrigeration components in OpenStudio. Figure 1 and Figure 2 illustrates the overall architecture of the refrigeration system and transcritical refrigeration system, respectively, and how different refrigeration components relate to one another in the refrigeration system object model. Translators for each of the classes were developed that allow for the automatic conversion from EnergyPlus objects to OpenStudio objects and vice-versa. A listing of the objects added to OpenStudio with descriptions from the EnergyPlus Input Output Reference (DOE 2014b) is as follows:

a. RefrigerationSystem – Simulates the performance of a supermarket refrigeration system when used along with other objects to define the refrigeration load(s), the compressor(s), and the condenser.
b. RefrigerationTranscriticalSystem – Models detailed transcritical carbon dioxide booster refrigeration systems used in supermarkets and allows for modeling of both medium- and low-temperature loads.
c. RefrigerationCompressor –Models a compressor using manufacturer's data for curves that provide the efficiency, cooling capacity, and power consumption. The rated values for cycle superheat and subcooling are also required.
d. Condensers:
    i. RefrigerationCondenserAirCooled – Rejects refrigeration system heat characterized by a linear relationship between the difference between the inlet air and condensing temperatures.

ii. RefrigerationCondenserEvaporativeCooled – Rejects refrigeration system heat characterized by a four-factor relationship between the condensing temperature and the difference between the outside wet bulb and condensing temperatures.

iii. RefrigerationCondenserWaterCooled – Rejects refrigeration system heat to a water plant loop.

iv. RefrigerationCondenserCascade – Rejects refrigeration system heat to another, higher-temperature, refrigeration system, thus acting as a heat rejection object for one system and a refrigeration load for another system.

e. Subcoolers:

i. RefrigerationSubcoolerLiquidSuction – Uses cool suction gas to subcool the hot condensate after it leaves the condenser and before it reaches the thermal expansion valve within the same refrigeration system.

ii. RefrigerationSubcoolerMechanical – Used to transfer cooling capacity from one refrigeration system to another.

f. RefrigerationGasCoolerAirCooled – Rejects transcritical refrigeration system heat characterized by a linear relationship between the difference between the outside dry-bulb and gas cooler outlet temperatures.

g. RefrigerationSecondarySystem – This object works in conjunction with refrigerated display cases and walk-ins to simulate the performance of a secondary loop supermarket refrigeration system. The heat from the refrigeration loads served by the secondary loop is absorbed by a primary refrigeration system.

h. RefrigerationCase – This object works in conjunction with a refrigeration system or a secondary loop to simulate the performance of a refrigerated display case system.
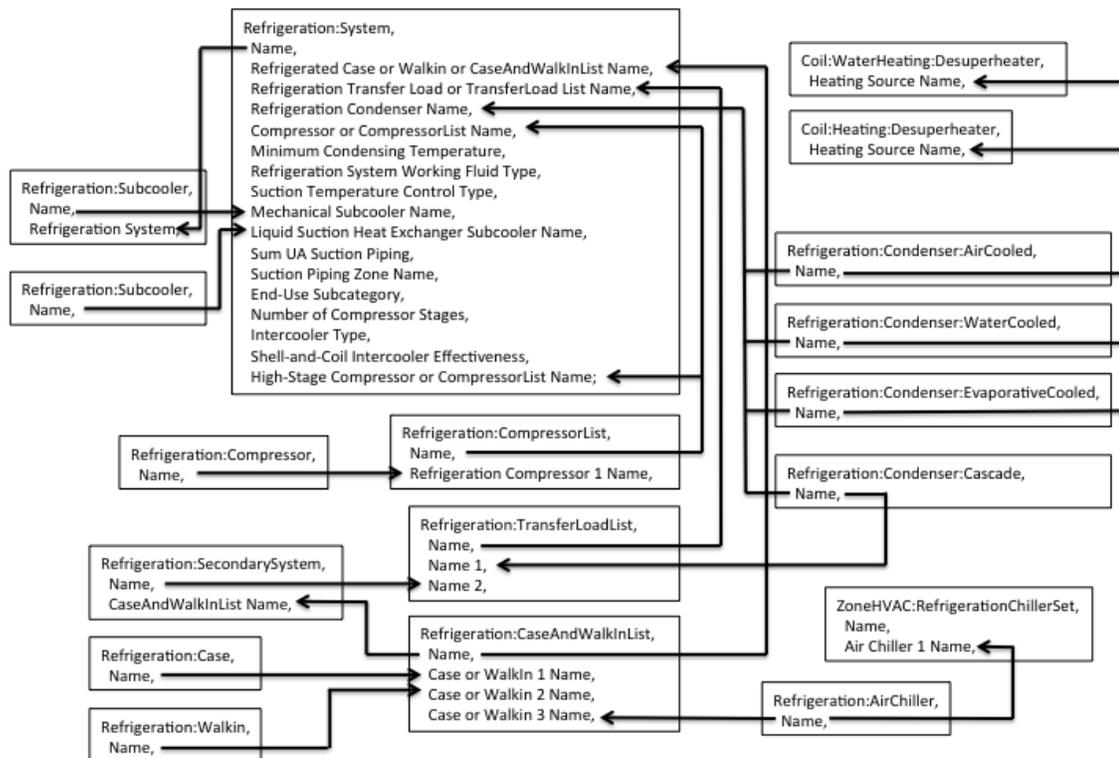

Figure 1: Illustration of the overall refrigeration system components added to OpenStudio.
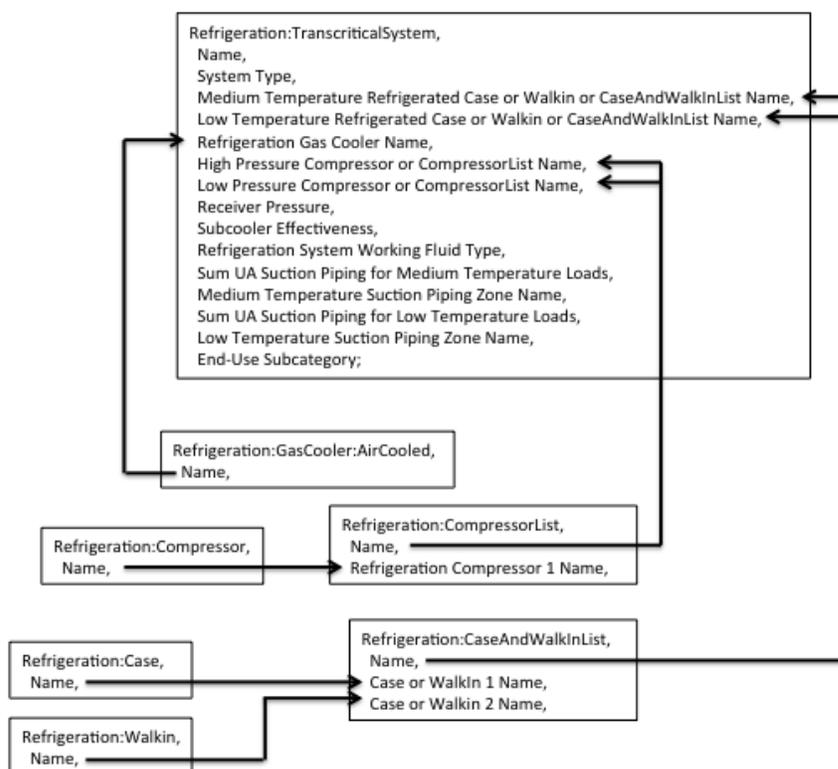
Figure 2: Illustration of the transcritical refrigeration system components added to OpenStudio.

    i.   RefrigerationWalkin – This object works in conjunction with a refrigeration system or a secondary loop to simulate the performance of a walk-in cooler.
        i.   RefrigerationWalkinZoneBoundary – Contains the 12 fields normally found as extensible fields in a RefrigerationWalkIn object, which defines the properties of the walls, ceiling and doors of the walk-in.
    j.   RefrigerationAirChiller – This object works in conjunction with a refrigeration system or a secondary loop to simulate the performance of an air chiller, similar to those found in a refrigerated warehouse which chill the refrigerated storage space.

Additionally, functionality was added to handle the thermodynamic properties of the various fluid types. The resource data for standard fluid types were added to OpenStudio or contained within the EnergyPlus engine. There are 11 refrigerants/fluids in total, each contained in a separate resource file. Figure 3 illustrates the object design for the fluid properties.

3.3 Additions to the Building Component Library
A library of components helps make refrigeration systems more accessible and quicker to model in the OpenStudio application. A primitive HVAC library used to be packaged with OpenStudio in the form of a single model file which was populated with various HVAC components. However, this did not scale well and did not support user contributions. From a developer's perspective, the single HVAC model was very difficult to manage because it required hand editing the model file's text.

Thus, the U.S. Department of Energy maintains the Building Component Library (BCL), which is a comprehensive online digital library of various building blocks of an energy model. A system built around the Building Component Library (BCL) infrastructure was desired for the refrigeration components in OpenStudio that addressed the above limitations.

This led to the creation of classes that created and managed a library of refrigeration components. EnergyPlus comes with metadata information for hundreds of refrigerated display cases and refrigeration compressors. The classes

helped create BCL components from the metadata and were then contributed to the library thereby allowing the refrigeration components to be easily downloadable from the BCL by any user.
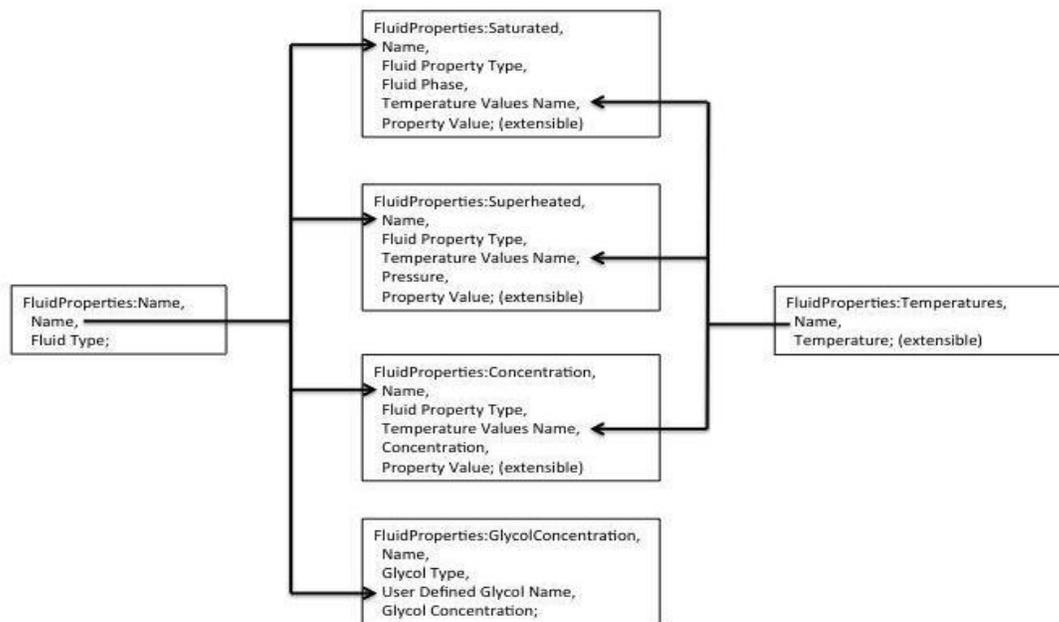

Figure 3: Fluid properties in OpenStudio.

4. IMPLEMENTATION

4.1 Agile software development
A modern 'Agile-scrum' software development method was used by the project team. Agile is an iterative method of software development where the software requirements and solutions are developed in close collaboration with the team members with a focus on delivering a useful product. This software development methodology alleviates some of the traditional approaches where a significant amount of time was spent in defining the requirements which were often poorly captured. While Agile does not completely do away with requirements gathering, it focuses on delivering incremental functioning components thereby recognizing that requirements evolve and change over time and allows software development to adapt to the change.

4. 2 Phases of development
The project was implemented in four phases with each phase focusing on one aspect of the software. An initial set of EnergyPlus refrigeration components were selected and implemented, following which, additional components in decreasing order of priority were implemented. This was the product backlog in the Agile software development philosophy while using GitHub for source control.

During the initial design, six main refrigeration components were determined to be critically important. These were Refrigeration System, Compressor, Display Case, Walk-In, Air-Cooled Condenser and Secondary System. Scripts were used to automatically convert various objects from the EnergyPlus Input Data Dictionary (IDD) file into C++ code. These prototypical source code files for the refrigeration objects were then modified to allow full instantiation of the objects. The objects, complete with their unit tests, were then submitted for integration into OpenStudio's main development branch.

During the second phase, the following components were implemented: Mechanical Subcooler, Liquid-Suction Subcooler, Cascade Condenser, Evaporative-Cooled Condenser, and Water-Cooled Condenser. During the third

phase, the remaining refrigeration components from EnergyPlus were added: Air Chillers, Transcritical Refrigeration System, Transcritical Compressors, Air-Cooled Gas Cooler and waste heat recovery using the Air Heating Desuperheater Coil or the Water Heating Desuperheater Coil. In addition, metadata from the hundreds of refrigerated display cases and refrigeration compressors that are provided with EnergyPlus were added to the BCL.

Since OpenStudio follows EnergyPlus objects closely, EnergyPlus documentation provided the basis for the design of many of the developed components. However, in some cases, classes were redesigned to better reflect the functionality desired from the components.

During the fourth and final phase, documentation of the developed Application Programming Interface (API) was created. In all phases, close collaboration with multi-lab partners was maintained, who provided extensive support and developmental feedback to the ORNL team.

4.3 Application Programming Interface
The addition of these refrigeration classes makes them immediately available for scripting through OpenStudio's object model. Ruby, Python, and C# language bindings are available for the advanced user to implement custom scripts using the OpenStudio API.

5. USER INTERFACE

To address long-term design of HVAC&R components in OpenStudio, a system view and a table view, were determined to be essential. Figure 4 shows a screenshot of the OpenStudio interface with a blank refrigeration system template. Components such as display cases, compressors and condensers from the "Library" tab on the right of screen can be dragged and dropped onto the appropriate locations on refrigeration system template to build up a complete system, an example of which is shown in Figure 5. The parameters of individual components may be edited by selecting the "Edit" tab on the right of the screen and clicking on the component to reveal the parameters. For example, Figure 5 shows the compressor power coefficients on the right side of the screen, and these values may be edited as necessary.
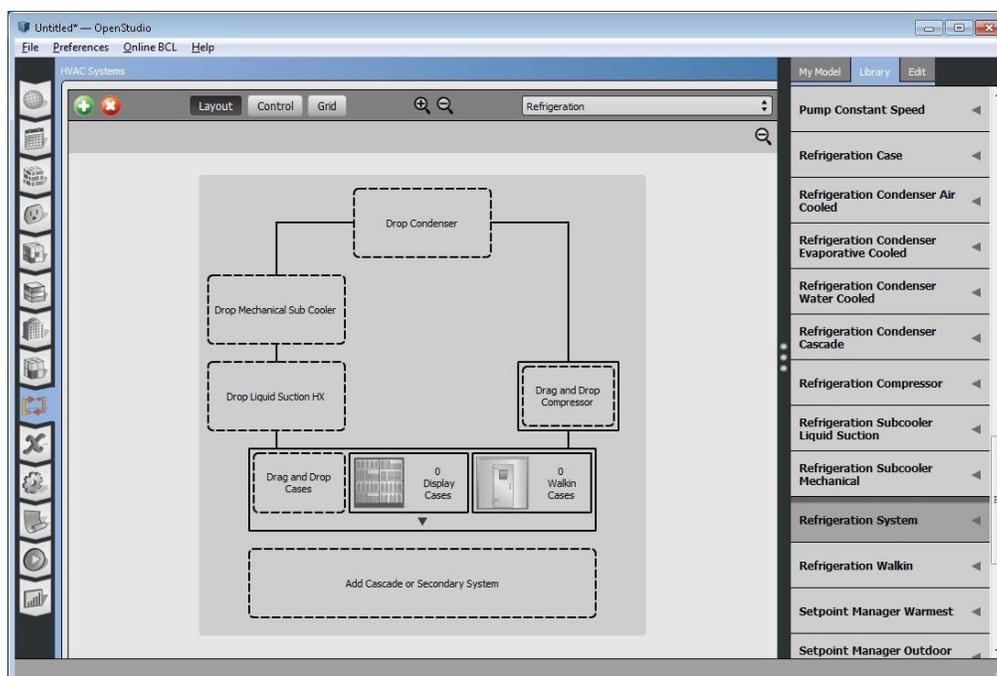

Figure 4: OpenStudio user interface showing blank refrigeration system template.
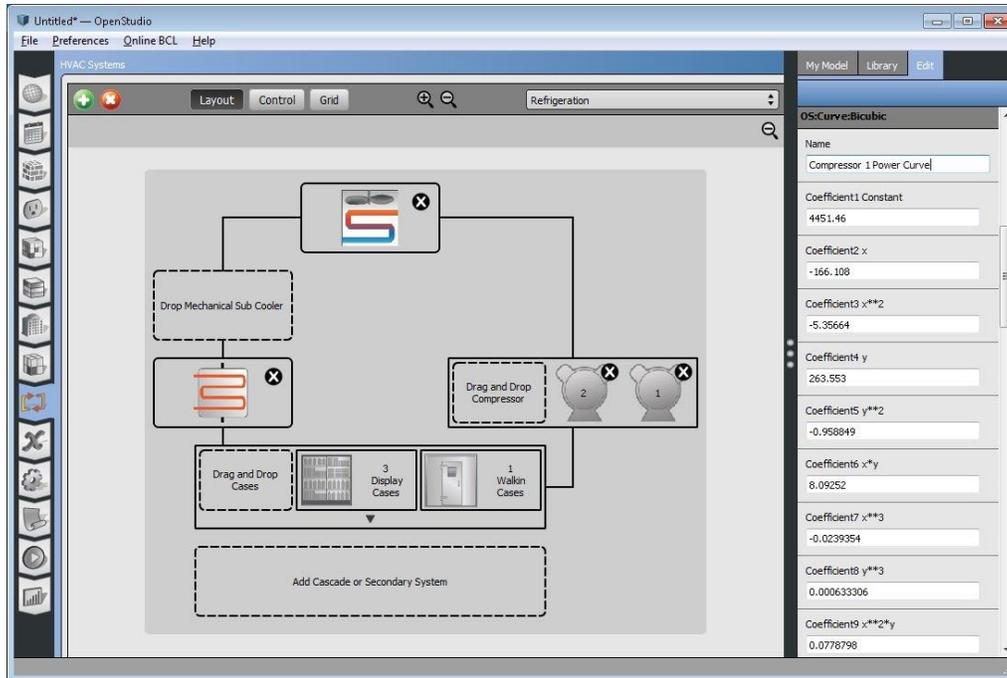
Figure 5: OpenStudio user interface showing a refrigeration system complete with components.

Typically, a user selects a system type they want to model from a drop-down list. Depending on the selection, relevant options are made available to the user. The new refrigeration system is then made available in a drop-zone in the user interface. This is illustrated in Figure 6. The user can also select drop zones in the individual systems and then the available options will appear on the right. The components are editable in this mode as well.

As the user drags in systems, they can select them by clicking on the colored title area and editing the fields in the edit window.
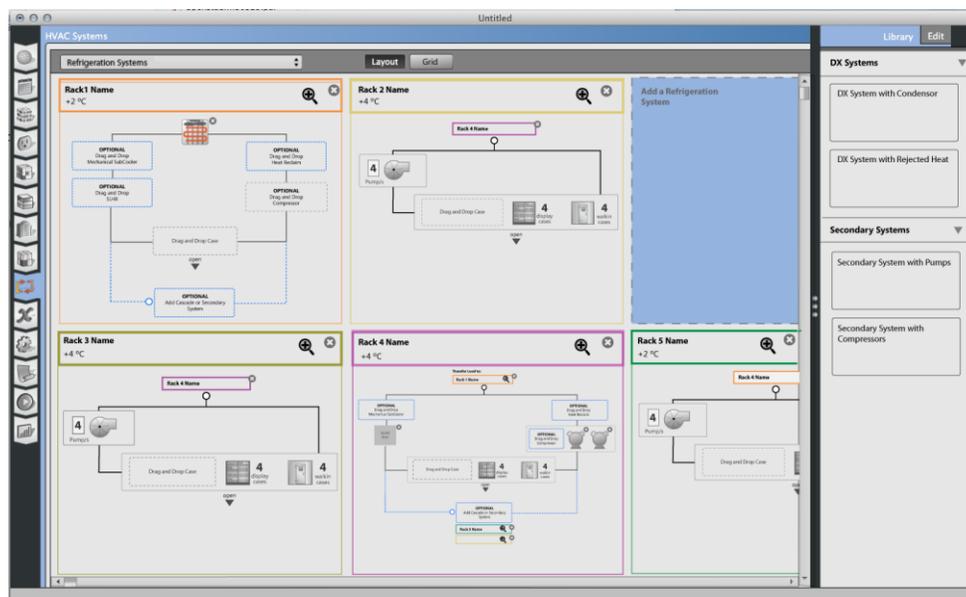
Figure 6: Configuring multiple racks of a refrigeration system.

A grid view of the refrigeration system, illustrated in Figure 7, shows the attached loads and can be viewed by clicking on the "Grid" button near the top center of the screen. The grid view allows for an easy way to view and edit the parameters of all of the display cases and walk-ins attached to the selected refrigeration system.
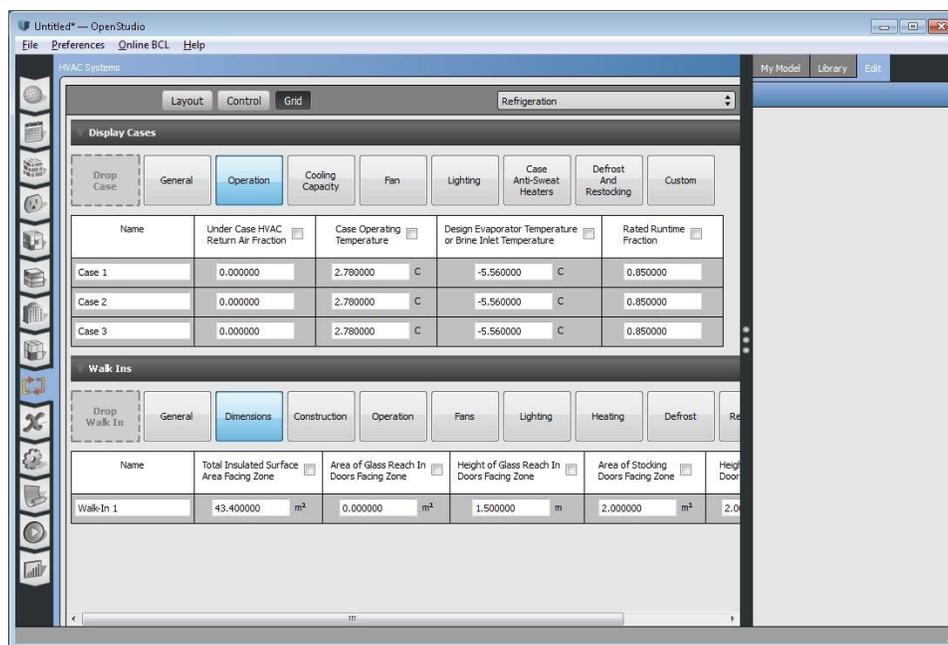

Figure 7: Grid view showing details of the attached display cases and walk-ins.

6. CONCLUSION

This paper described the development of drag-and-drop refrigeration modeling capabilities in OpenStudio using the underlying EnergyPlus simulation engine. The object hierarchy and design, which enables the refrigeration application programming interface, were presented. Elaborations of the graphical user interface elements were illustrated. In addition, the contribution of hundreds of refrigeration objects to the Building Components Library was highlighted.

It is expected that the addition of these refrigeration components fills a gap and will enhance the successful adoption of OpenStudio as a modeling tool of choice in the buildings simulation community. Furthermore, it is hoped that these refrigeration capabilities will allow food retailers to assess the energy impact of a variety of supermarket and distribution facility refrigeration system design options and aid in the selection and implementation of energy efficient systems.

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