NIST Technical Note 1981

Users Guide to HVAC-Cx v2.2

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NIST

National Institute of
Standards and Technology
U.S. Department of Commerce

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December 2017

U.S. Department of Commerce
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National Institute of Standards and Technology
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Acknowledgements

Disclaimers

Table of Contents

1 HVAC-Cx Software Overview

1.1 Introduction

HVAC-Cx is a semi-automated commissioning software tool designed to facilitate performance analysis for heating, ventilating, and air conditioning (HVAC) mechanical equipment in buildings [1]. It can be used for functional performance testing (FPT) and ongoing monitoring. It provides the ability to detect faults related to improper operation, using expert rules to present results of the most likely fault causes and to assist in documenting results. The goal is to improve the system performance in terms of occupant comfort, energy management and equipment life. It was conceived exclusively for commercial buildings equipped with one or more air handling units (AHUs), terminal units, hot and chilled water loops, and chillers. The commissioning methods developed can be applied to several types of equipment and custom rules can be introduced. The structure includes future expansion capabilities for the analysis of boilers and other common mechanical equipment.

HVAC-Cx aids building operators in decision-making by importing batch data collected from the building energy management system (BEMS) in .csv format, and evaluating the data using a set of expert rules governing the proper operation of the mechanical equipment.

HVAC-Cx software has many useful features, in particular:
- It can analyze large amounts of data collected from BEMS;
- Fault detection is applied using expert rules for AHUs, chiller loops, and terminal units;
- Simplified results are presented in the forms of graphs and tables; and
- Diagnostic assistance is provided through a list of possible causes for each fault detected.

HVAC-Cx can be downloaded at:
https://www.nist.gov/services-resources/software/hvac-cx-building-hvac-systems-commissioning-tool

2 Installing HVAC-Cx

This section presents the step-by-step instructions for installing HVAC-Cx.

2.1 Minimum requirements

The HVAC-Cx software requires a computer running Windows XP or newer version of Windows. The computer must have at least 1GB RAM and 200 MB free hard drive space. This does not include additional hard drive space which will be required for data files.

2.2 Installation instructions

If installing the software from a CD or other media, simply insert the CD or media and the setup should start automatically. If you are installing from a downloaded file, you will have to browse to the location and run the executable file. It is recommended to install the software using a Windows profile/login with administrative privileges.

2.2.1 Welcome Screen

The installation wizard will start with a Welcome Message.
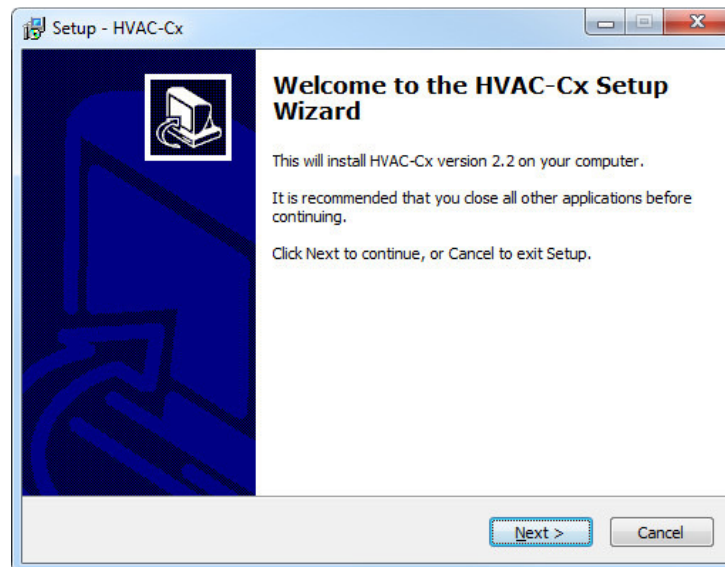
Click **Next** to continue.

2.2.2 Installation Destination folder

Next you will be prompted to specify the folder where all the program files will be copied on to your machine. The default location is under *C:\Program Files (x86)\HVAC-Cx*.
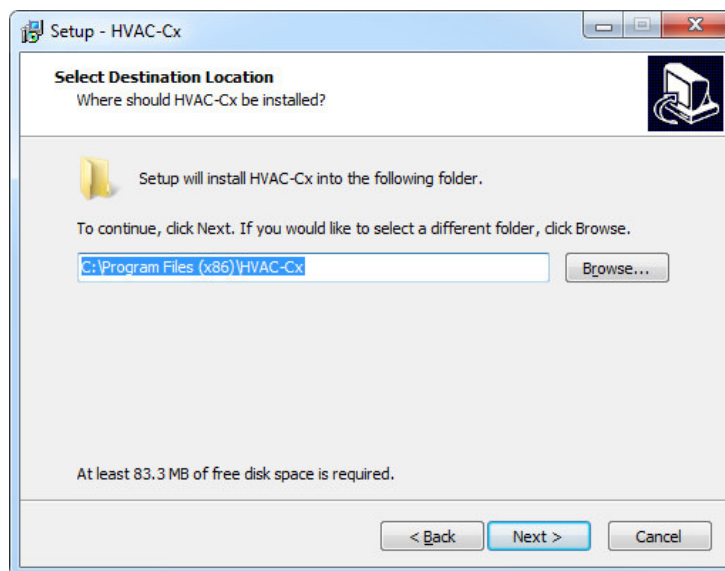
To change this location, click **Browse**. This will open "Browse for Folder" dialog. You can navigate to your preferred location and then select **OK**.

Click **Next** to continue.

2.2.3 Start Menu Folder
Next the installation wizard will prompt you to select the folder where the programs shortcuts will be placed. You may keep the default folder or change it to your preference.
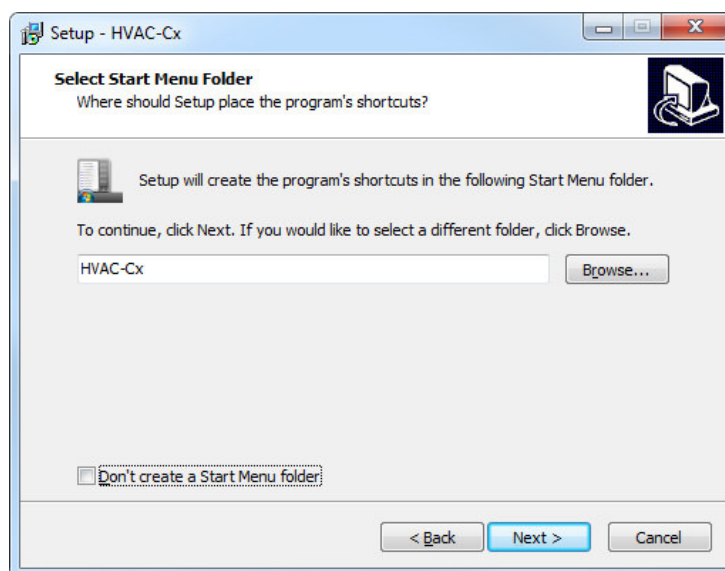
Click **Next** to continue.

2.2.4 Create a Desktop Icon
If you want to have a desktop icon for the software for easy access, please select the check box for "Create a desktop icon". By default it is NOT checked.

3
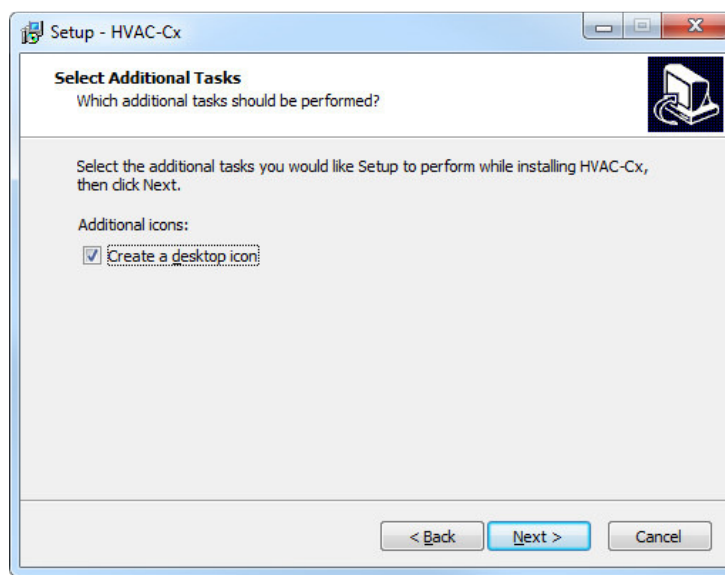
Click **Next** to continue.

2.2.5 Setup Configuration Confirmation

On this screen you will be shown your configuration selections for the software. If you need to make any changes, click **Back** to reach the appropriate portion of the Installation Wizard and then proceed.
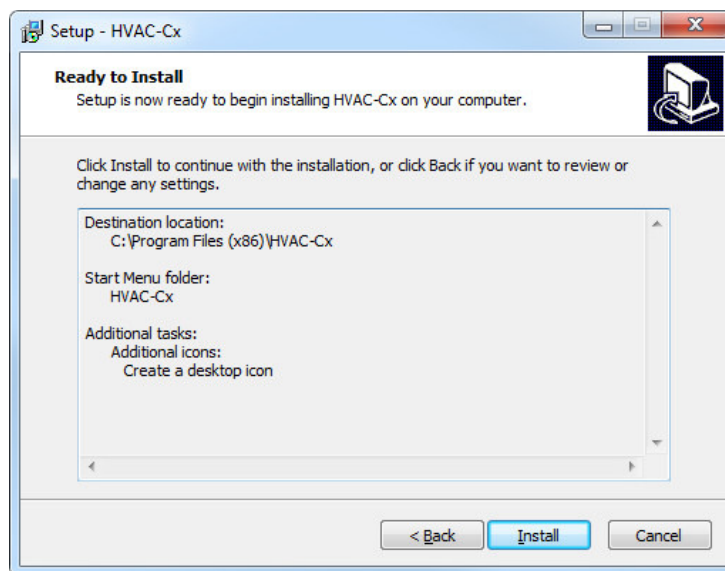
Click **Install** to continue.

2.2.6 Installation Progress

The installation will start copying the required files to the machine. Files which are modified by the software, such as configuration files and data, are stored in the users folder

AppData\Roaming\HVACCx and read-only files are stored in the folder C:\Program Files (x86)\HVAC-Cx. Note that the AppData folder is a subfolder in the user's home directory.

You may choose to cancel the installation by clicking the **Cancel** button.

2.2.7 Install Complete
Once the installation is successful, you will see the following screen.
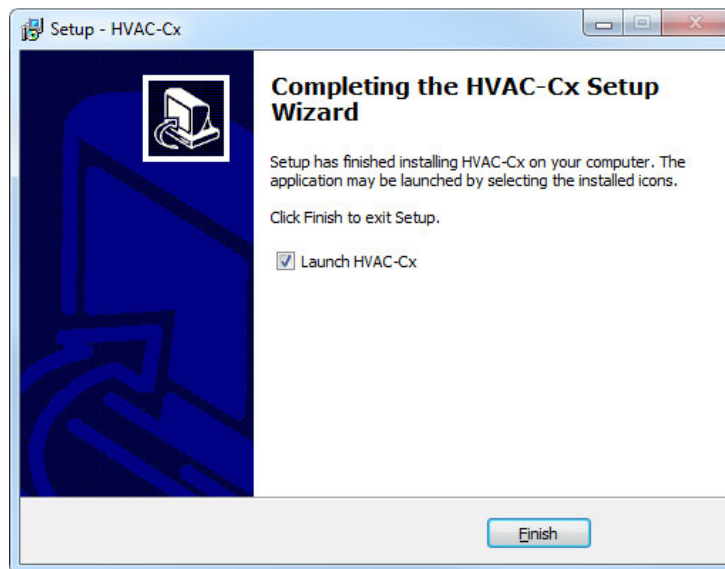
Click **Finish** to complete the setup and exit the installer.

3 Equipment Overview

HVAC-Cx can perform analysis on several different types of equipment, including AHUs, terminal units, chilled water loops, and chillers. The different types of equipment, and how they are represented in HVAC-Cx, are discussed below.

3.1 AHUs

Air handling units are mechanical systems designed to ensure the ventilation, heating and cooling of buildings or zones within a building. Their construction is often modular which facilitates customized layouts and configurations in a variety of systems for a specific application.

Air handling units are generally located in an unconditioned space in, on, or near the building. There are two types of AHU's analyzed in HVAC-Cx:

1. Constant Air Volume (CAV) systems, which are designed to provide a constant volumetric flow of supply air to the HVAC system; and
2. Variable Air Volume (VAV) systems, which are designed to provide supply air at a specified pressure while varying the flow to meet building loads.

The two types of systems typically include the following components:
- An air supply fan to provide air flow via a duct network to the various parts of the building (zones);
- A return fan to extract air from the zones;
- Outdoor air, return air, mixed air and exhaust air dampers to control the fraction of air returned from the building to be reconditioned as supply air. (The movement of the dampers may be interlinked);
- A heating coil to heat the supply air;
- A cooling coil to cool the supply air; and
- A filtration unit to trap particles in the air.

3.1.1 AHU Operating Modes

HVAC-Cx software automatically detects the operating modes of each AHU. There are nine operating modes:
1. **Heating**: The supply air is heated by the heating coil;
2. **Free cooling**: Fresh outdoor air is mixed with return air and is neither heated nor cooled mechanically;
3. **Mechanical cooling with 100% outdoor air**: The supply air is composed of 100% outdoor air, and is cooled further by the cooling coil;
4. **Mechanical cooling with a minimum of outdoor air**: The supply air is composed of a minimum amount of outdoor air required for ventilation, and is cooled further by the cooling coil;
5. **Night cooling**: Free cooling during unoccupied periods when temperatures permit;
6. **Frost-protection**: This operating mode of the air handling unit is switched on when outdoor air is cold enough to present a risk of freezing the coils or pipes in the AHU;
7. **Stop**: The air handling unit is stopped, possibly for maintenance or due to a fault;

8. **Unknown**: This operating mode is detected when none of other operating modes are activated and detected; and
9. **OFF Mode:** The AHU is off. OFF periods should be indicated in the schedule.

Each operating mode has its own rules of operation. When the operating data is evaluated, faults are detected by the software. Because in many cases there are multiple possible causes for a specific fault, a list of possible fault causes is presented to the user.

If certain faults keep recurring, the software allows the user to stop analysis of the rules indicating them. This would be used for faults that they no longer wish to observe (i.e., if a service call has been scheduled to address a specific problem).

3.2 Chilled Water Distribution Systems

A chilled water distribution loop (chiller loop) is the distribution network that delivers chilled water to the various mechanical systems in a building or set of buildings. This can be as simple as a closed-loop connecting a dedicated chiller to a building air handling unit, or it can be a complex network of pumps, valves, strainers and insulated piping that connects a central chiller or bank of chillers to meet the cooling needs of many buildings, as in a campus application. There are several reference guides that discuss chilled water plant design [2, 3].

The following section presents the operating modes for the chilled water distribution system in a particular field site that was evaluated using HVAC-Cx [4]. This site differs from typical sites by having both a chiller and a chilled water distribution loop. The diagram below contains details of the test system, with typical components of a chilled water distribution system in blue and the atypical components in red.
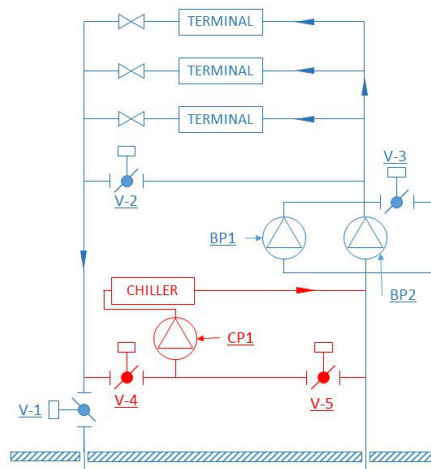
3.2.1 Operating Modes for Chilled Water Distribution

In the field site, there are four operating modes that may be manually selected by the building operator:
1. **Off (Mode 1).** The system is off and all valves and pumps are closed;
2. **Central plant cools the building (Mode 2)**. This mode is the normal operating mode to leverage the capabilities of the higher efficiency central plant chiller. This mode has

two options, Mode 2a without building pumps operating, and Mode 2b, with building pumps operating;

3. **Chiller cools the building and feeds the distribution (Mode 3).** This mode is intended for use when the central plant is making ice, and the building chiller can provide supplemental cooling to the campus loop. This mode has identical options to run with or without the building pumps as described in Mode 2**;** and

4. **Chiller cools the building (Mode 4).** This last mode is intended for use when there is no access to the plant loop, and there is a limited load in the building that can be met by the chiller.

Typical configurations would be limited to Modes 1 and 2. HVAC-Cx software has been configured with this information and can automatically detect the operating mode of the configured chiller loop. Each operating mode has its own rules of operation. When the operating data is evaluated, faults are detected by the software. Because in many cases, there are multiple possible causes for a specific fault, a list of possible fault causes is presented to the user.

3.3 Terminal Unit Overview
Terminal units are mechanical systems designed to fine tune the flow and temperature of the air coming from the air handling unit to meet the conditions needed for the zone they serve. The flow is typically adjusted by a mechanical damper. The temperature is typically adjusted by a hydronic heating coil or electric heating element.

The terminal units analyzed by HVAC-Cx are single duct, variable air volume terminal units with hydronic reheat.

Variable air volume terminal units usually include the following components:
- an insulated metal housing with a single duct air inlet supplied by the AHU to provide conditioned air to the building zone serviced by the terminal unit,
- a flow sensor to detect the air flow through the unit,
- an actuator to dynamically control the air flow going to the zone, and
- a hydronic heating coil or electric heating element to heat the supply air.

4 Fault Detection and Diagnostics

The fault detection and diagnostic analysis is performed by entering recorded device data including inputs from sensors such as a temperature or flow, output commands such as to a damper or valve, and state data such as alarms or mode status, from the BEMS and applying a set of logical expert rules to the data to identify operational faults. HVAC-Cx uses the control signals to detect the specific operating mode. For each operating mode of the air handling unit, terminal unit or chiller loop, expert rules have been developed to detect common operational faults. The logical rules are derived from determining expected values during modes of operation, from transcribing expectations outlined in the documented sequence of operations, and from recording fault reports and alarms from the devices themselves. Each rule is expressed as a logical statement that, if true, indicates the presence of a fault. As each mode of operation has different mass and energy balances, a different subset of the rules applies to the various modes of operation. Each time that the conditions of an expert rule are satisfied, faulty operation is identified, a fault detection alarm is generated and potential causes of the fault are presented to the user for further diagnostic assistance.

The detection and diagnostic methodology was originally developed for passive monitoring of single-duct, VAV and CAV AHUs [5, 6, 7]. These rules were expanded and modified in field tests applied to air handling units [7]. The rules are evaluated at a user-defined interval (e.g., 1 min, 5 min). The data is examined to determine the operational mode, and rules appropriate for the mode of operation are applied. A diagnostic report is prepared and shown via the graphical user interface (GUI). This report shows the faults that are detected in a minute, an hour, and over a day. To prevent excessive reporting of faults, the software allows the user to stop analysis of specific faults. Each fault corresponds to one or several fault causes. The software posts the cause most often indicated and thus the most probable. The graphical capabilities of HVAC-Cx provide the user the ability to look at data to provide further insight.

New expert rules, or sets of rules, can be added to address other types of equipment. In general, the extent of the performance assessment is limited by the availability of design data (e.g., control requirements and sequencing strategy), and operational data including setpoint values, sensor measurements, and control signals. Typical commercial grade sensors installed for control purposes have sufficient accuracy to conduct the performance assessment.

5 Using HVAC-Cx

There are four basic steps to using HVAC-Cx: entering data, configuring equipment, selecting rules, and analyzing data. The HVAC-Cx GUI has dedicated screens for each of these functions.

HVAC-Cx saves performance data and equipment configuration data using different types of *constructs* which are implemented as databases. The performance data is saved in *data constructs* and equipment configuration data is saved in *equipment constructs*. Each *data construct* corresponds to a set of imported data, and each *equipment construct* corresponds to actual equipment configured in HVAC-Cx. The information in these *constructs* is accessed through the HVAC-Cx GUI. The dedicated screens and the various types of *constructs* used by HVAC-Cx are discussed in the following sections.

5.1 The HVAC-Cx User Interface

There are five main screens that are accessed by the user, as shown in the table below. The screens are accessed by clicking on their respective button on the **Main Toolbar** that appears to the left of each screen. The **Main Toolbar** also has a button ( ), located at the bottom, to open the Functional Performance Test Module (FPTM). The FPTM will open in a separate window.

Screen Name	Description
Database	This screen is used to create and configure databases, and to import data into them.
Equipment Configuration	This screen is used to create the list of equipment that will be analyzed, and to configure the equipment.
Rules	This screen is used to configure the rules to be analyzed.
Analysis	This screen is used to perform the analysis, and to view the results. It contains an hourly view screen, a daily view screen, and a monthly view screen.
Manual Commissioning	This screen enables users to make a detailed system generated report on the field inspection of the Building under test.

5.2 The Database Screen

The Database screen is used to create and configure databases, and to import data into them. This screen is accessed by clicking the **Data** button in the Main Toolbar. The database (*Data*
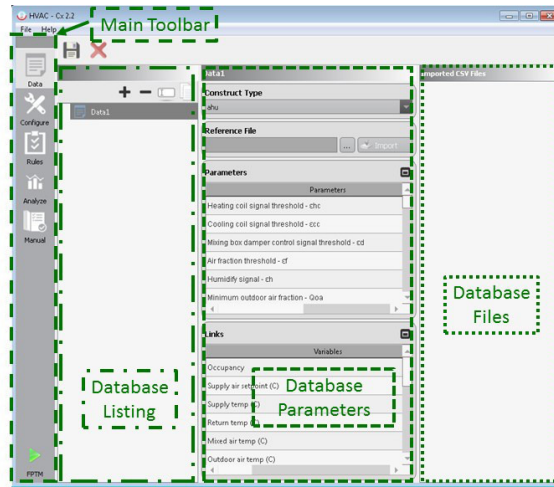
construct) will hold HVAC equipment performance data, importing from the building energy management system (BEMS) or other sources. In our work we use the BACnet Data Source (BDS), another tool developed by NIST, to collect equipment performance data which we then import into HVAC-Cx [7, 8]. Equipment performance data must be saved in comma separated value (CSV) format to be imported by HVAC-Cx, with a title row at the beginning of each file. HVAC-Cx uses different data construct templates for each type of equipment analyzed, and allows the creation of multiple data constructs for each type of equipment. The steps to create a data construct are described below in detail.

5.2.1 Adding a Data Construct

This section describes the steps necessary to add a new *data construct*. These steps are performed on the Database Screen in the Database Listing section.

1. Click **Add Data** (the + sign) in the construct bar, **OR** right click in the Database Listing section and click **Add Data** from the pop up menu, as shown in the figure below.
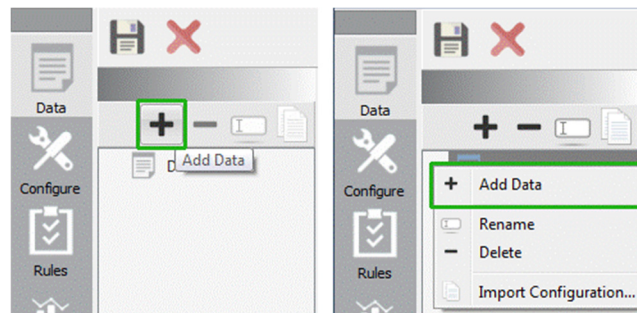
2. A new *data construct* appears in Construct view with the default name "DataX", where X = 1, 2, 3... etc.
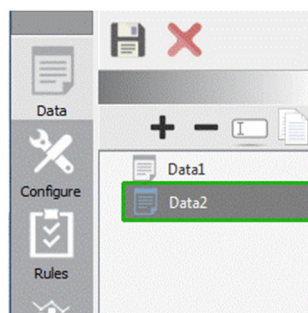
3. Click the floppy disk icon to save the changes.

5.2.2 Renaming a Data Construct

HVAC-Cx allows data constructs to be renamed. The steps to rename a data construct are:
1. Select the data construct to be renamed.
2. Click **Rename** in the construct bar, **OR** right click in the Database Listing section and select **Rename** from the pop-up menu, **OR** select the database and press the F2 key.
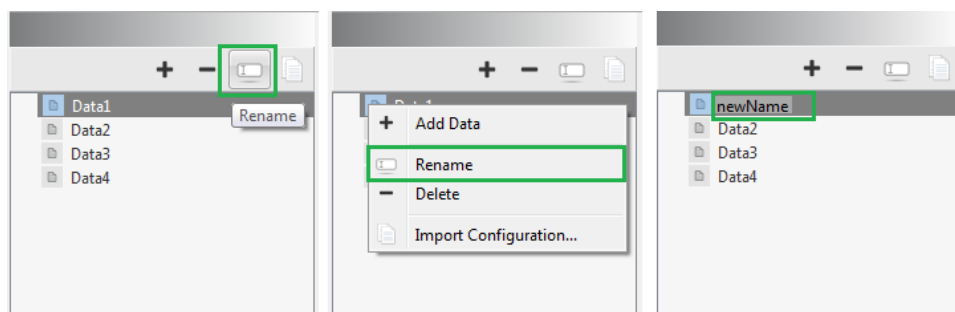
3. Enter the new name.
4. Click the floppy disk icon to save the changes.

5.2.3 Deleting a Data Construct

HVAC-Cx allows data constructs to be deleted. The steps to delete a data construct are:

1. Select the data construct to be deleted.
2. Click **Delete** in the construct bar (the – sign), **OR** right click in the Database Listing section and select **Delete** from the pop-up menu.
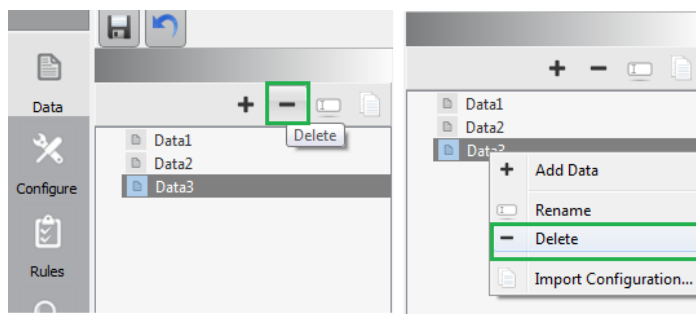
3. Click the floppy disk icon to save the changes.

If the data constructs was linked to any of the *equipment constructs* you will need to link that equipment construct with a different data construct.

5.2.4 Configuring a Data Construct

After creating a data construct you must configure it before importing data. The controls that enable this are in the area marked Database Parameters in the figure in Section 5.2. The controls are:

1. Construct Type;
2. Reference file;
3. Parameters; and
4. Links.

The purpose of each control is described in the following sections.

5.2.4.1 Selecting the Construct Type

After creating a new data construct, the associated equipment construct type must be selected. The default choice is AHU. The other choices are chiller, chiller loop, and terminal unit. The selection window is shown in the image below.
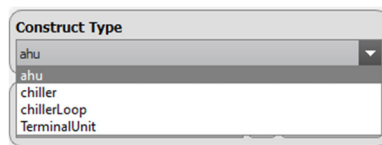
5.2.4.2 Configuring Rule Threshold Parameters

Next, the parameters required for thresholds used in the fault detection rules should be reviewed. The controls that enable this are immediately below the construct selection type controls. When a new database is created they are set to default values. Values that have been modified are displayed in bold. Click the **Set to Default** button ( ) to return to the default value.

The Parameter view can be maximized for better view and can be restored when done, by using the **Maximize/Restore** button as shown in the picture below.
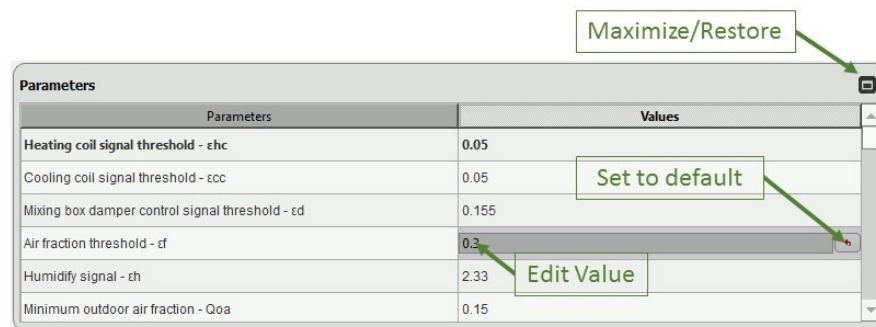
5.2.4.3 Mapping BEMS Data Values to HVAC-Cx Input Variables

Before importing the BEMS data to convert it to HVAC-Cx data we need to create a mapping between the data values and the HVAC-Cx analysis input variables. The **Variables** column of the Links section lists all the input variables. The user needs to map them to corresponding columns in the data input file.
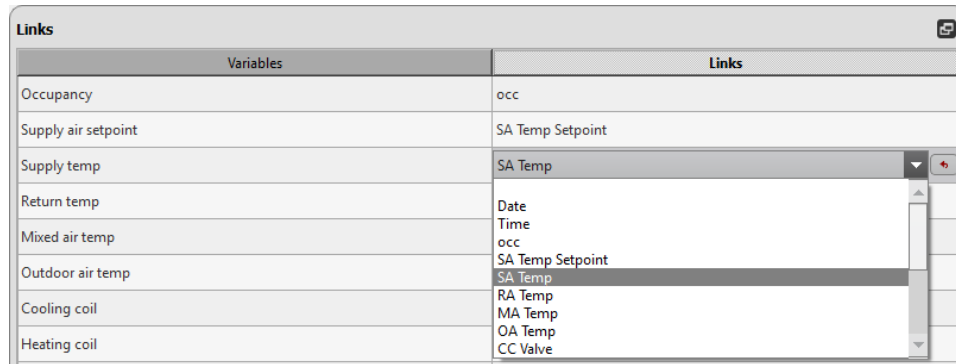
The first step is to select a BEMS data file as a reference file to retrieve the data header. The first line in this input file must have the names of each data column. These names will be used to link the input data to the input variables. To select the reference file, click on the **Browse Reference File** button (...) in the Reference File section, and use the dialog box that opens to select a reference file. The file will be read when the OK button is selected. After the reference file has been read, the Links column will be populated, with the column names appearing in a drop down box on each line. A mapping must be selected for each variable. An example of a populated drop down box is shown in the previous graphic.

The Links view can be maximized for better view and can be restored when done by using the **Maximize/Restore Link View** button.
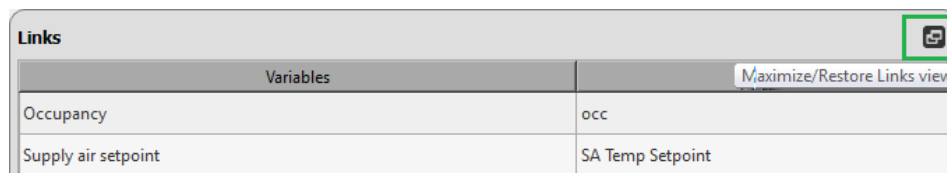
5.2.4.4 Save and Cancel

The configuration can be saved or changes can be reverted to a previously saved state using the **Save** (💾) or **Cancel all changes** (✖) buttons in the Action Bar. The Action Bar is located above the Database Screen.
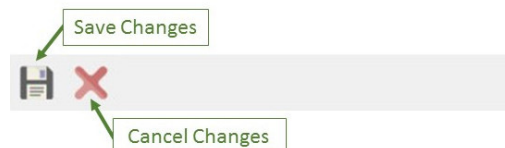
5.2.4.5 Copying Configuration From One Data Construct To Another

The configuration for a *data construct* can be imported/copied from another *data construct* using the **Import Configuration** button in the Configuration Toolbar.
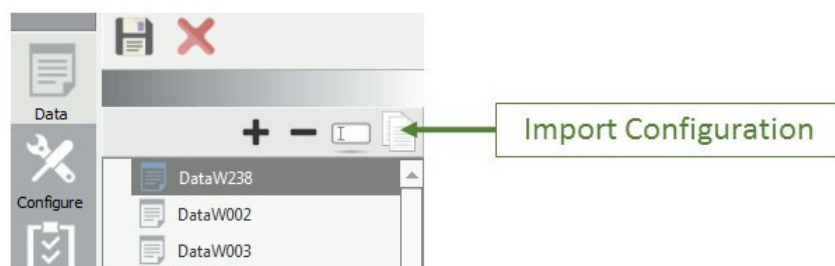
5.2.5 Importing the Contents from a BEMS Data File

Importing is the process in which the BEMS data is converted to HVAC-Cx data. To import data:

1. Select **Data** from the Main Toolbar to go to the data configuration window.
2. Select a database.
3. Click the **Import** button. A file selection dialog will open.
4. Select CSV files to import. You can select multiple files.

If the import was completed without any errors, then an "Importing completed" message is displayed. Note that additional data files may be imported at any time.

- If the selected file's header doesn't match the headers in the reference file, the import will fail.
- If all the links are not properly mapped, the import will fail.

Previously imported BEMS data files are displayed in the Imported CSV Files section. Hovering the mouse over a file name shows the time period of data in that file, as shown in the figure below.
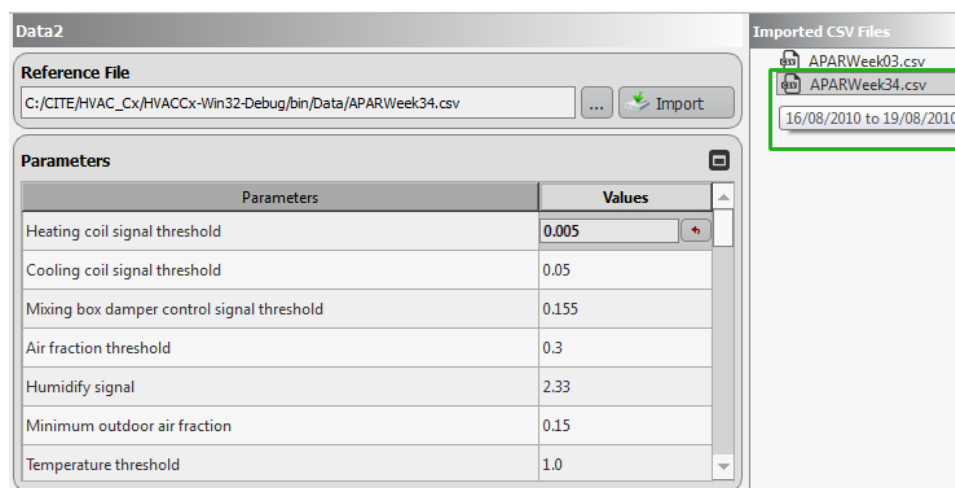
5.3 The Equipment Configuration Screen

The Equipment Configuration screen is used to create the list of equipment that will be analyzed, and to configure the equipment. This screen is accessed by clicking the **Configure**

button in the Main Toolbar. Once the *data construct*s have been added and mapped, the next step is to add the *building* and *equipment constructs*. Select the Configure screen from the Main Toolbar, as shown in the figure below.
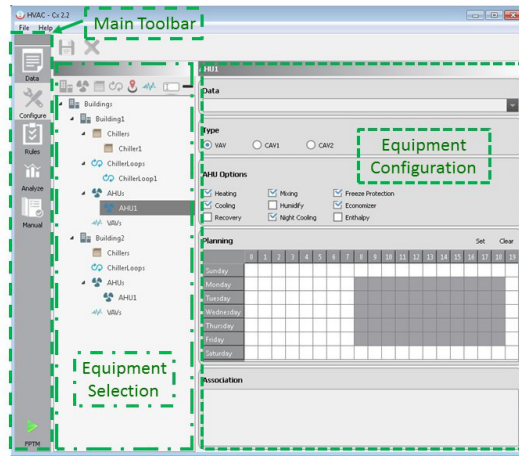
In the Equipment Selection section you can see previously created constructs. There are two types of constructs: *active constructs* and *inactive constructs*. *Active constructs* include physical equipment, such as AHUs, chillers, and chiller loops. *Inactive constructs* define logical groupings of constructs, and consists of items such the *buildings construct* and *grouping constructs* like AHU groups and chiller groups.

The hierarchy of constructs is:
BuildingsConstruct > Building# > *GroupingConstructs* > EquipmentConstruct# > Zones/Terminal Unit#.

The *buildings construct* is the top level inactive construct, "Building#" is one or more *building constructs* added by the user, *GroupingConstructs* is an *inactive construct* labelled AHUs, Chillers, or ChillerLoops. EquipmentConstruct# is an *equipment construct* added by the user, such as an AHU, Chiller, or Chiller Loop. Zone and terminal unit constructs may be added to an *AHU construct*. The *buildings construct* acts as the parent construct to all other *equipment constructs*. The *building construct* and *AHU construct* types can also have child constructs.

5.3.1 Adding A Building Construct
The *buildings construct* is an inactive construct which is designed to group the equipment that would be in one building, including AHUs, chillers, and chiller loops. This section describes the steps necessary to add a new active *building construct* to the *buildings construct*. These steps are performed on the Configure Screen in the Equipment Selection section:

1. Select the *buildings construct* in the construct view tree or any current *building construct*.
2. Click **Add Building** in the construct bar, **OR** right click on **Buildings** in the Equipment Selection section and select **Add Building** from the pop-up menu.
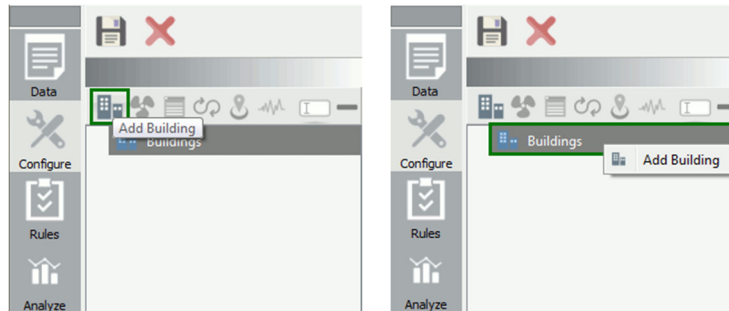
3. A new *building construct* appears in Construct view with a default name "BuildingX", where X = 1, 2, 3... etc. You can add multiple *building constructs* using these techniques. The *building construct* will contain inactive constructs for each equipment type, which will allow the later addition of active equipment constructs.
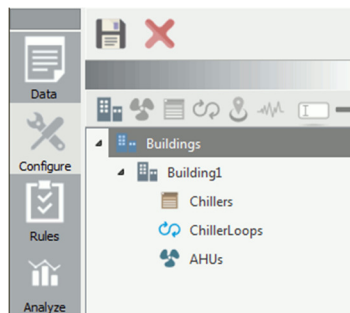
4. Click the floppy disk icon to save the changes. Click the Cancel button to undo all changes.

5.3.2 Renaming a Building Construct

HVAC-Cx allows *building constructs* to be renamed. The steps to rename a *building construct* are:

1. Select a *building construct* to be renamed.
2. Click **Rename** in the construct bar, right click on the *building construct* and select **Rename** from the pop-up menu, **OR** select the *building construct* and press the F2 key.
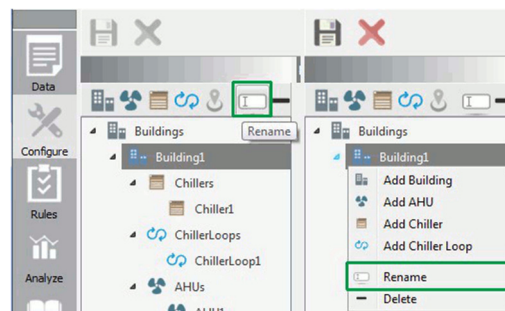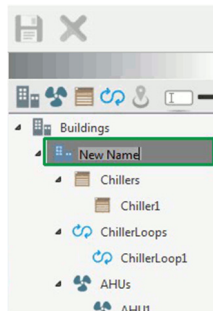
3. Enter the new name.

4. Click the floppy disk icon to save the changes. Click the Cancel button to undo all changes.

5.3.3 Deleting a Building Construct

HVAC-Cx allows *building constructs* to be deleted. The steps to delete a *building construct* are:

1. Select the *building construct* to be deleted.
2. Click **Delete** in the construct bar (the – sign), **OR** right click in the Equipment Listing section and select **Delete** from the pop-up menu. All child constructs under the deleted *building construct*, including all AHUs, chillers, and chiller loops, will be deleted automatically.
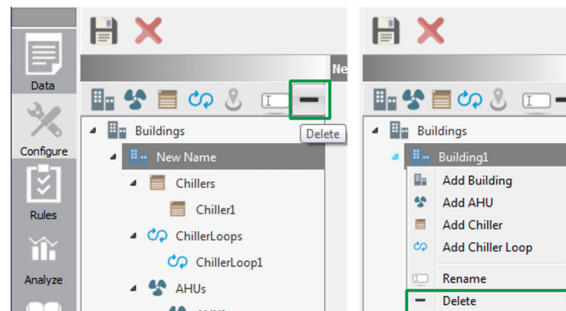
3. Click the floppy disk icon to save the changes. Click the Cancel button to undo all changes.

5.3.4 Adding Equipment Constructs

The method used to add, rename, delete, and configure *equipment constructs* is similar for AHUs, terminal units, chiller loops, and chillers. This section presents the general steps using AHUs as an example. The examples in this section are performed on the Configure Screen in the Equipment Selection section.

The steps to add an *AHU/equipment construct* are:

1. Select a *building construct* or the *AHUs construct* under which AHU is to be added.
2. Click **Add AHU** (   ) in the construct bar, **OR** right click on the AHUs construct and select **Add AHU** from the pop-up menu.
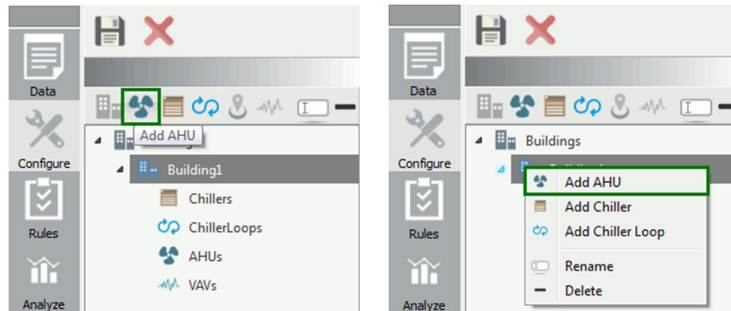
3. A new *AHU construct* will appear with a default name "AHUX", where X = 1, 2, 3... etc.
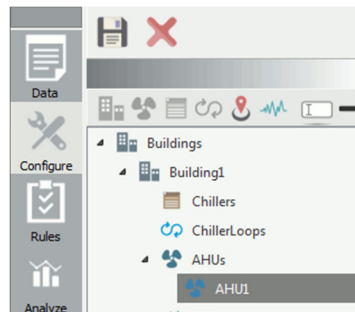
4. Click the floppy disk icon to save the changes. Click the Cancel button to undo all changes.

5.3.5 Renaming an Equipment Construct

HVAC-Cx allows *equipment constructs* to be renamed. The steps to rename an *equipment construct* are:
1. Select the AHU or other *equipment construct* to be renamed.
2. Click **Rename ([I])** in the construct bar, **OR** right click on the selected construct and select **Rename** from the pop-up menu, **OR** select the construct and press the F2 key.
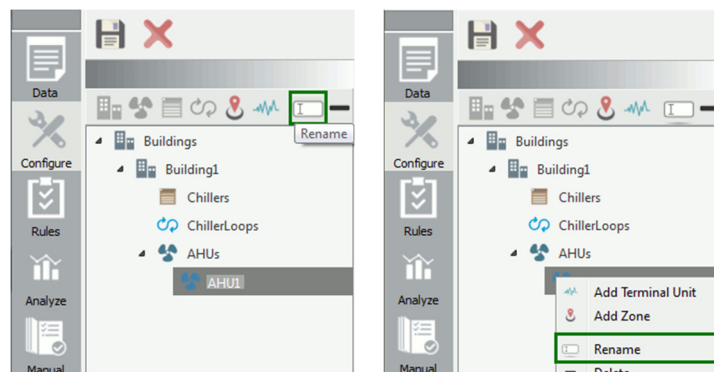
3. Enter the new name.
4. Click the floppy disk icon to save the changes. Click the Cancel button to undo all changes.

5.3.6 Deleting an Equipment Construct

HVAC-Cx allows *equipment constructs* to be deleted. The steps to delete an *equipment construct* are:

1. Select the *equipment construct* to be deleted.
2. Click **Delete** in the construct bar, **OR** right click on the selected construct and select **Delete** from the pop-up menu.
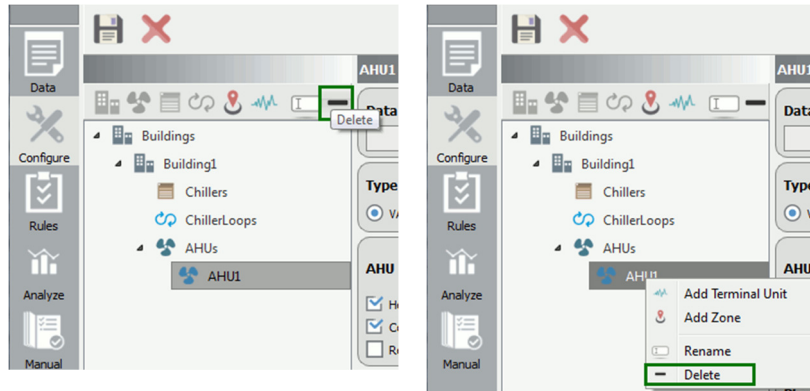
3. Click the floppy disk icon to save the changes.

5.3.7 Configuring Equipment Constructs

Each type of *equipment construct* is configured using a different set of options. The specific details of configuring the different types of *equipment constructs* are covered in this section.

5.3.7.1 Configuring an AHU Construct

This section describes the options available to configure an *AHU construct*. To view the configuration screen, navigate to the Configure Screen and select an AHU, as shown in the figure below. In the Equipment Parameters section there are different areas to allow configuration of different parameters. The areas are labeled Data, Type, AHU Options, Planning, and Association. Use of these areas is explained in the following sections.
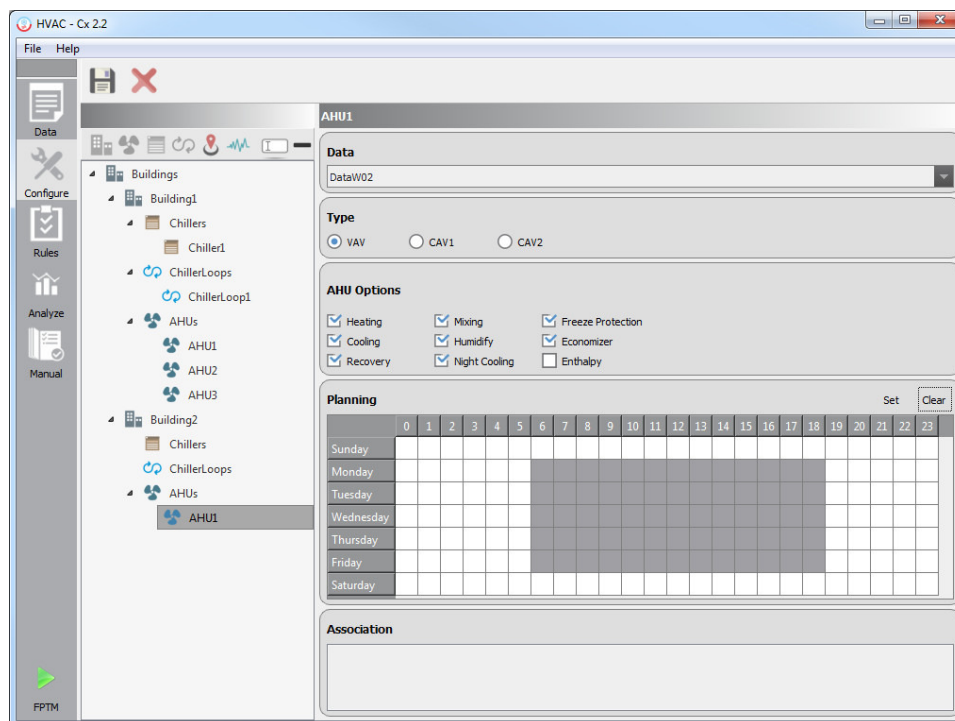
5.3.7.1.1 Linking an AHU with a data construct

The **Data** combo box is used to link a database to an *equipment construct*. Use the pull-down menu to select a database. Only databases with an equipment type matching the currently selected *equipment construct* will be displayed. Each *equipment construct* can only be linked to one *data construct* at a time, but the database link can be changed. This would be useful if databases are separated by time, i.e., different databases are used for each month.

Note: If a *data construct* connected to an AHU is deleted, the user must link a new *data construct* to the AHU.

5.3.7.1.2 Selecting the Type of AHU

There are three types of AHU's, VAV, CAV1 and CAV2. Select the type of AHU using the radio button. CAV2 includes a heat exchanger.

5.3.7.1.3 Setting AHU Options

The AHU options should be set to match the physical configuration of the AHU.

Option	Description
Heating	Does the AHU have heating capability?
Cooling	Does the AHU have cooling capability?
Recovery	Does the AHU have heat recovery capability?
Mixing	Does the AHU have a mixing box?
Humidify	Does the AHU have humidity control?
Night Cooling	Is the AHU configured for night cooling?
Freeze Protection	Is the AHU configured for frost protection?
Economizer	Does the AHU have an economizer?
Enthalpy	Does the AHU use enthalpy-based calculations?

The options can be set using the checkboxes in the AHU Options section.

5.3.7.1.4 Planning

The Planning section is used to set the occupancy schedule, which indicates the time the building is occupied or unoccupied. There is only one week-long schedule and changes to the schedule will persist in the current session until they are modified again. The schedule view consists of a grid with days of the week indicated in rows and hours of the day indicated in columns. Each cell of the grid indicates occupancy for one hour of one day, with white cells indicating unoccupied and grey cells indicating occupied. To modify the occupancy schedule:

1. Select the AHU to configure.
2. In the Planning section, select the cells to be modified by clicking in a cell or selecting a range of cells, either by clicking and dragging over several cells or by holding the Ctrl key while clicking on cells.
3. Click either the **Set** button to set the selected range as Occupied, or the **Clear** button to set the range as Unoccupied
4. Click the floppy disk icon to save the changes.

5.3.7.1.5 Association

The Association section for each AHU will display the chiller loops and zones that are associated with the current AHU. The Association list is read only in the AHU view. The user can add an association from the Chiller Loop or Zone Configuration screen. Only chiller loops and zones defined in the same *building construct* can be associated.
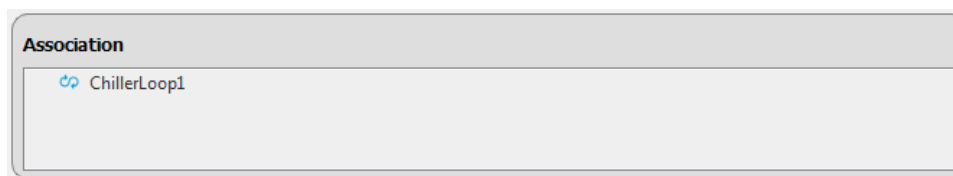
5.3.7.2 Configuring a Chiller Construct

This section describes the options available to configure a *Chiller construct*. To view the configuration screen, navigate to the Configure Screen and select a Chiller. In the Equipment Parameters section there are different areas to allow configuration of different parameters. The areas are labeled Data, Planning, and Association. The Data and Planning sections are identical to those described for AHUs in Section 5.3.7.1.1 and Section 5.3.7.1.4. Use of the Association area is explained below.

5.3.7.2.1 Association

The Association section for each Chiller will display the AHUs that are available for association, and chiller loops that have been associated. The Association list has a checkbox next to each AHU listed. Chiller loops can only be associated from the chiller loop configuration screen. The user can modify an association between the chiller and AHU by modifying the checkbox next to the AHU. Only chiller loops and AHUs defined in the same *building construct* can be associated. The image below shows the Association section for a chiller which has been associated with a chiller loop.

5.3.7.3 Configuring a Chiller Loop Construct

This section describes the options available to configure a Chiller Loop construct. To view the configuration screen, navigate to the Configure Screen and select a Chiller Loop. In the Equipment Parameters section there are different areas to allow configuration of different parameters. The areas are labeled Data, Planning, and Association. The Data and Planning sections are identical to those described for AHUs in Section 5.3.7.1.1 and Section 5.3.7.1.4. Use of the Association area is explained below.

5.3.7.3.1 Association

The Association section for each Chiller Loop will display the AHUs and Chillers that are available for association. The Association list has a checkbox next to each AHU and Chiller listed. The user can modify an association between the Chiller Loop and AHU or Chiller

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construct by modifying the checkbox next to the construct. Only Chillers and AHUs defined in the same *building construct* can be associated. The image below shows the Association section for a chiller loop which has been associated with four AHUs and two chillers.
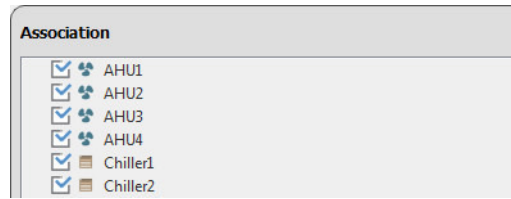
5.3.7.4 Configuring a Terminal Unit Construct

This section describes the options available to configure a *terminal unit construct*. To view the configuration screen, navigate to the Configure Screen and select a terminal unit. Note that *terminal unit constructs* must be added under an *AHU construct*. In the Equipment Parameters section there are different areas to allow configuration of different parameters. The areas are labeled Data, Options, Planning, and Association. The Data and Planning sections are identical to those described for AHUs in Section 5.3.7.1.1 and Section 5.3.7.1.4. Use of the Options and Association areas is explained below.

5.3.7.4.1 Options

The terminal unit options should be set to match the physical configuration of the terminal unit.

Option	Description
Cooling Coil	Does the terminal unit have cooling capability?
Reheat Coil	Does the terminal unit have reheat capability?
Window Sensor	Does the terminal unit have a window sensor?

5.3.7.4.2 Association

The Association view for each terminal unit will display the zone(s) to which it has been associated. The associations are configured in the screen for the zone.
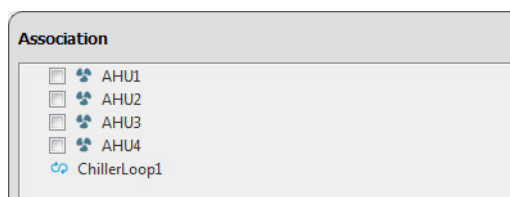
5.3.7.5 Configuring a Zone Construct

This section describes the options available to configure a *zone construct*. To view the configuration screen in the GUI, navigate to the Configure Screen and select a zone. Note that *zone constructs* must be added under an *AHU construct*. In the Equipment Parameters section there is an Association area to configure associations with AHUs and terminal units. Use of the Association area is explained below.

5.3.7.5.1 Association

The Association section for each zone will display the AHUs and terminal units which are available for association. The Association list has a checkbox next to each AHU and terminal unit listed. The user can modify an association between the *zone construct* and *AHU* or *terminal unit construct* by modifying the checkbox next to the construct. Only the AHU under which the zone is listed and terminal units listed under the same AHU can be associated to a zone.

5.3.8 Save and Cancel

Changes made to the configuration can be saved by clicking on the **Save** button (⊟) in the Action Bar. Changes can be reverted to a previously saved state using the **Cancel all changes** button (✖) in the Action Bar.

5.4 The Rules Screen

The Rules screen is used to select which rules will be used when evaluating an *equipment construct*, such as an AHU or chiller. This screen is accessed by clicking the **Rules** button in the Main Toolbar. The rules can be set differently for each *equipment construct*. The user may select all rules for use, or may select a subset of the rules. Custom rules, written by the user, will also appear here. Rules that report faults that are already known may be deselected in order to help focus on finding other faults. To configure rules, select the Rules screen from the Main Toolbar as shown in the figure below.
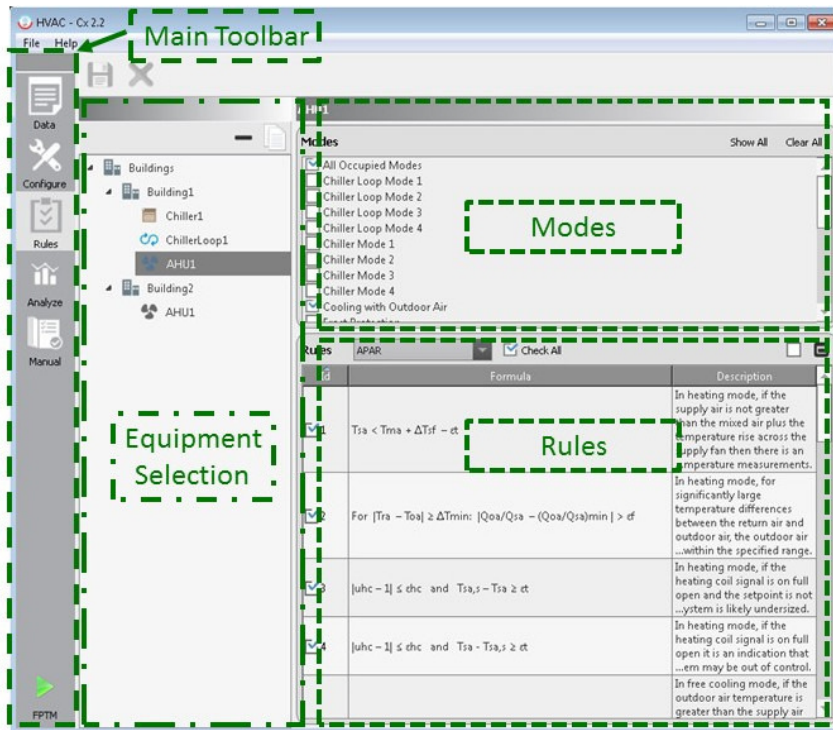
On the Rules Screen there are three sections- the Equipment Selection section, the Modes section, and the Rules section. The Equipment Selection section is used to select the equipment which will have its rules reviewed. The Modes section and the Rules section are described in detail below.

5.4.1 The Modes Section

Different types of equipment operate under their own sets of modes. Accordingly, there are different rules for each mode. In the Modes section the user can select which modes of operation will be active when the rules are evaluated. If a mode is not active, the associated rules will not be evaluated.

Some rules are applicable to all modes when the zone is occupied. Instead of repeating these rules for each mode, they are grouped in a mode called All Occupied Modes. This mode will be automatically selected whenever any other occupied modes are selected. For types of equipment that do not have relevant rules, this will still be selected but it will not add additional rules to the evaluation.

All modes can be selected using the **Show All** button. All modes can be cleared by using the **Clear All** button.
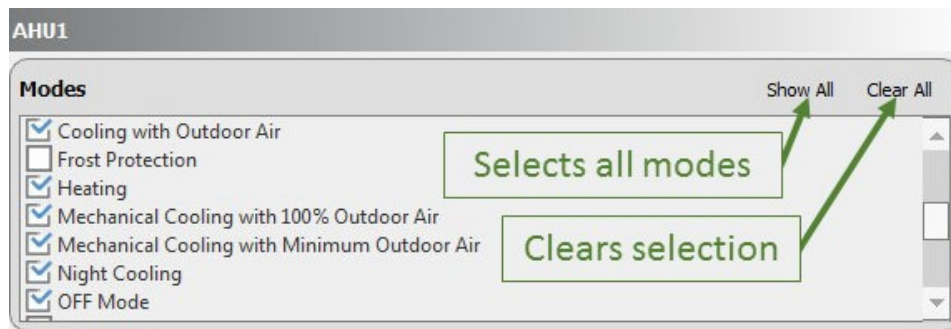
5.4.2 The Rules Section

In the Rules section the rules are displayed and can be selected or unselected. Each line in this section displays information for one rule and has a checkbox, a numerical identifier, an area displaying the formula for the rule, and a text description of the rule.

5.4.2.1 Rule Set Selection

There are two sets of rules for each type of equipment, a pre-installed set of rules and custom rules designed by the user. AHUs use the AHU Performance Assessment Rules (APAR) rule set developed by NIST [e].

The rule set combo box provides three options for viewing rules:
- **All -** View rules from all rule sets;
- **APAR -** View only rules from the APAR rule set; and
- **Custom -** View only rules from the custom rule set.

5.4.2.1.1 The Show All/Selected Button

The **Show All/Show Selected** button toggles the view between showing all rules and only selected rules.

5.4.2.1.2 The Maximize/Minimize (Restore) Button
The **Maximize** button changes the rules view to full screen, which allows the display of more rules. The **Minimize** button restores the display.

5.4.2.2 Writing a Custom Rule
Custom rules may be created in HVAC-Cx to allow for greater flexibility in analysis. The rules are specified in the file *<install location>\Settings\CustomRules.xml*. Typically *<install location>* would be "C:\Program Files (x86)". Rules are specified by selecting a rule template and the input values to match variables used in the template. Each custom rule has a separate node in the XML file, with the parameters as described in the following table:

Rule Parameters	Description
id	The index of this custom rule. Start at 1 for the first custom rule
formula	Text that represents the formula, i.e., "Tsa – Tra > 5". This does not affect the calculation of the formula.
mode	The operational mode for which this rule is valid.
type	For AHUs, set to "VAV1", "CAV1", or "CAV2".
causes	The list of causes indicated by this rule, separated by semicolons, i.e., "1;2;5;7".
description	Text that describes the purpose of the rule, i.e., "Check supply temperature."
ruleIndex	The index of the rule template, see the Rule Templates table.
valueIndex2	The database template index of V2 in the rule template.
valueIndex3	The database template index of V3 in the rule template.
valueIndex1	The database template index of V1 in the rule template.
paramIndex	The index of P1 in the rule template
paramValue	Allows user to specify a value to be used for P1. If this is used, the value of paramIndex will be ignored.
allowEqual	Allows equal values to trigger rule by changing comparison from > to >=, or < to <=.

To use a custom rule, first determine which input values and parameters will be used for the rule. The input values will be indicated by their input order in the database, i.e., the first input value would be input number 1. The order is listed on the Database screen. Parameters are indicated using the same method. Next, select a comparison from the table below which matches your requirements. The V1, V2 and P1 variables in the table represent the value indexes and parameter index selected in the first step. Note that an index may be entered as -1 or omitted to use a value of 0. For P1 a value may be indicated instead of an index, by use of the paramValue parameter. Parameters only affect the rule they are specified in.

Rule Templates	
1	V1 + P1 > V2
2	V1 + P1 < V2
3	V1 – P1 > V2
4	V1 – P1 < V2
5	V1 – V2 > P1

27

Rule Templates	
6	V1 – V2 < P1
7	V1 + V2 > V3
8	V1 + V2 < V3
9	abs(V1 – 1) > P1
10	abs(V1 – 1) < P1
11	abs(V1 – V2) > P1
12	abs(V1 – V2) < P1

A sample custom rule is provided in the box below, encoding the rule | Tsa – Tsa,s | > εt using rule index 11.

```
<rule id="1" formula="| Tsa – Tsa,s |  > εt" mode="All Occupied Modes" type="VAV1"
causes="1;5;6" description="Custom Rule 1." ruleIndex="11" valueIndex1="2"
valueIndex2="1" paramIndex="6" />
```

5.4.2.3 The Rule List
The rules are displayed in a table, which includes the following columns:
1. A check box, to select or unselect the rule.
2. A Rule ID which acts to identify the rule
3. The formula for the rule.
4. A description for the rule.

Custom rules are displayed with a yellow background for easy identification.
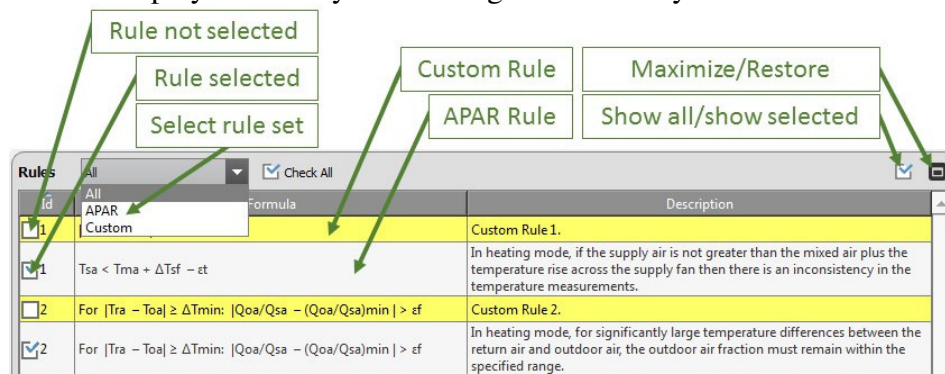
5.4.2.4 Construct Toolbar Options
The Construct Toolbar allows the user to import a rule configuration from another construct, or to deselect all rules.

28
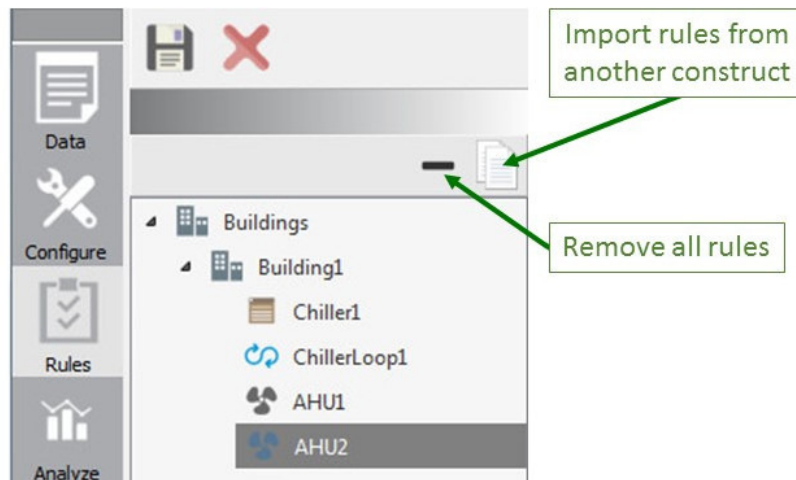
5.4.2.5 The Remove All Rules Button

This button will deselect all rules.

5.4.2.6 The Import Rule Configuration Button

This button allows you to copy the rule configuration from another construct of the same type. Clicking this button opens a wizard where you first select the Construct from which to copy, and then to select the modes from which to copy the rules. You can press the **Cancel** button to exit this wizard.

5.5 The Analyze Screen

After importing data, configuring the constructs and selecting rules, the user can proceed to analysis of the data. Analysis is the process by which the selected rules are applied on data collected from BEMS. Note that HVAC-Cx analyzes the data in batch format, not as a real-time data stream. The result of the analysis is presented in graphs, tables and detailed text descriptions. To open the Analyze Screen, select the **Analyze** button from the Main Toolbar.

The Analyze Screen has three sections- the Equipment Selection section, the Action Bar section, and the Analysis Results section, as shown in the figure below. The Equipment Section is used to select the equipment to be analyzed. The Equipment Selection, Action Bar and Analysis Results sections are described in detail below.
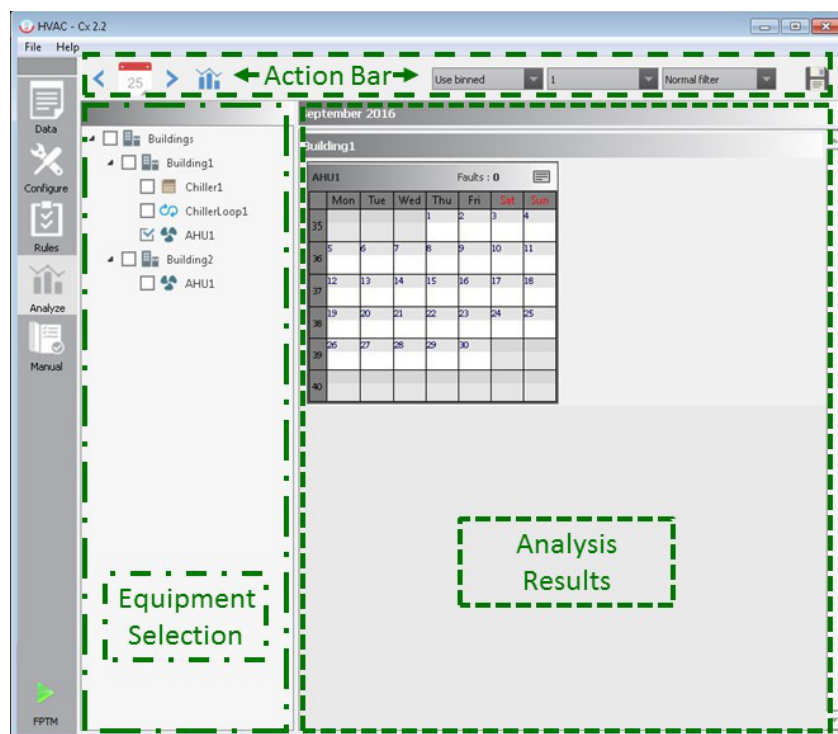
5.5.1 Equipment Selection

In this section you will select the *equipment constructs* to be analyzed. When a construct is selected, a calendar will be displayed in the Calendar section for that construct. Multiple constructs may be selected, and the selection may vary by type of construct and building. The calendar display will separate selected constructs by building and construct, as shown in the figure below.
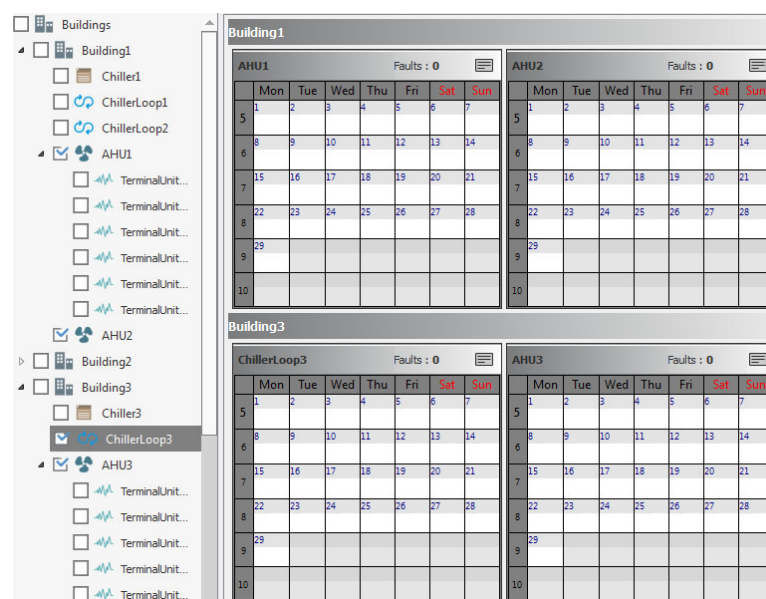
5.5.2 The Action Bar

The Action Bar is at the top of the Analyze Screen. It provides access to data analysis options, and to the **Start Analysis** button. The bar also provides controls to select the analysis date. The Action Bar is shown in the figure below.
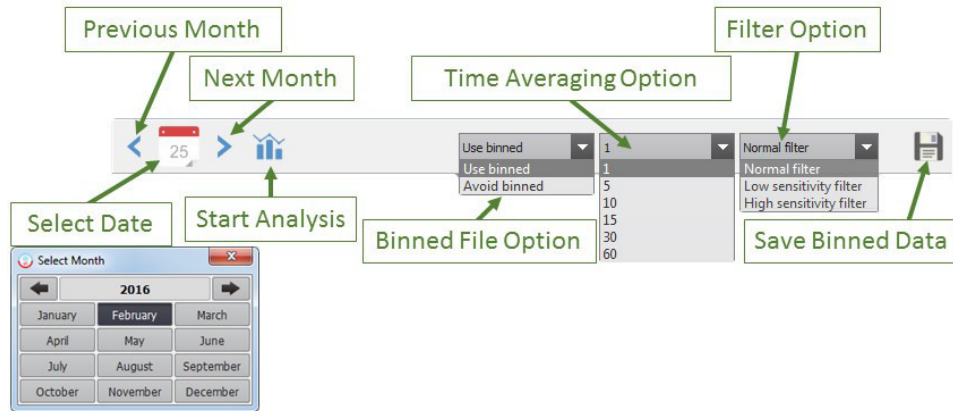
5.5.2.1 Date Selection

Analysis in HVAC-Cx is performed for one month at a time. The **Date Selection** controls allow you to select the desired month. If there are multiple *equipment constructs* selected, they will all use the same month. Clicking on the **Select Date** button will open a window which allows you to select the proper year and month for analysis. Buttons are also provided on the **Action Bar** to quickly navigate to the next or previous month.

5.5.2.2 Binned File Selection

Binned data is data which has been separated into 'bins' based on the time. This drop-down menu allows you to select if the source data uses binned data or the data as originally read in. The size of the bins, which is a time span, can be modified by the user by the selecting a value in the Time Averaging Option drop-down menu, as explained below.

Use binned – Selecting this option will use the data file saved from an earlier analysis (binned) which used the same settings. If a binned file is not available, the imported data will be read. Data is binned by averaging the raw data over the time span indicated.

Avoid binned – This option will always only use the raw imported data. Analysis will be performed on the exact data as imported.

5.5.2.3 Filter Selection

The detection filter allows the user to select a sensitivity level (normal, low or high) for the fault analysis, enabling the user to view only the most severe faults as a starting point and to increase sensitivity to detect less severe faults as desired. The filter modifies the threshold applied in the analysis. The larger the threshold setting, the lower the sensitivity level.

5.5.2.4 Start Analysis

Selecting the **Start Analysis** button ( ) will start analysis of the selected *equipment constructs* for the selected month. The results are shown in the Analysis Results section.

5.5.2.5 Save Binned Data

The **Save Binned Data** button allows you to save binned data.

5.5.3 Performing Analysis

There are several steps involved in performing an analysis. To begin a new analysis, perform the following steps:

1. Select Constructs: You can select one or more constructs to be analyzed from the Equipment Selection section, as shown in the figure below.
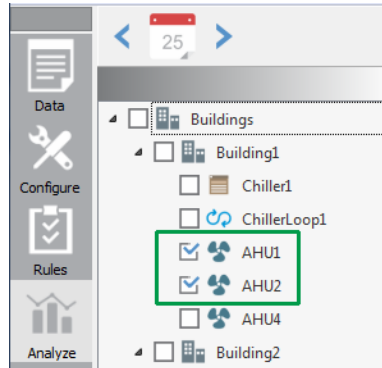
2. Select the desired month.
3. Modify binning and filter options for analysis as appropriate.
4. Click the **Start Analysis** button.

The results will be overlaid on the calendars for each construct.

Note: After any change in construct configuration, rules configuration or analysis options, the analysis must be performed again.

5.5.4 Viewing Analysis Results

After performing an analysis, an overview of the results will be displayed on the calendar view for each *equipment construct* analyzed. The result overview consists of a number added to each day that was analyzed, and a color code. The number indicates the maximum number of faults found in any one-hour period during that day, and the color indicates a range for the number of faults. Selecting a day from the calendar will open up a more detailed view. These views are discussed in more detail below.

5.5.4.1 The Month View Screen

Initial results are shown in the month view for each construct selected. This view allows the user to quickly get a general view of the results. Clicking a cell will open the Day View screen on that particular date. Clicking on the **Show Fault Report** button will open the Fault Report screen. The picture below shows the details of a month view.
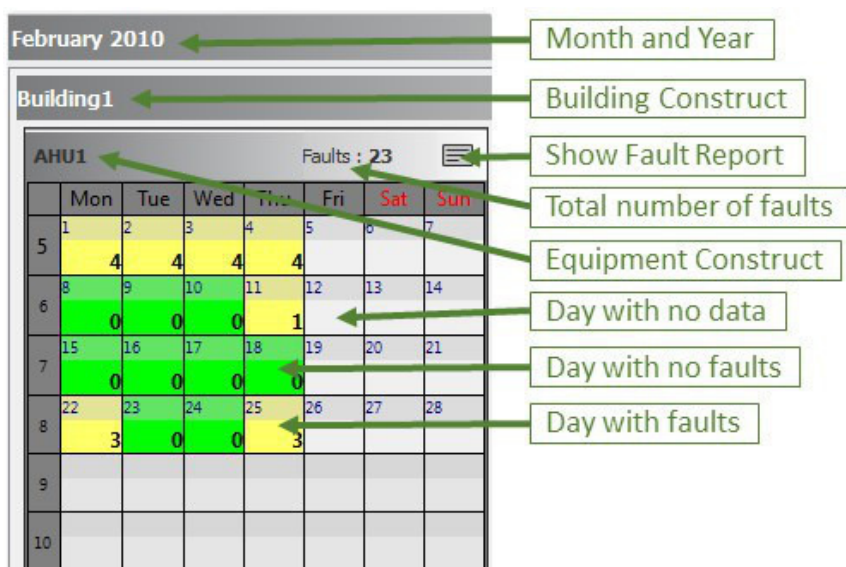
Each cell represents a day. The color of each cell is an indication of the range of number of faults

Color	Description
Grey	No data available
Green	No fault detected
Yellow	1-5 faults
Red	more than 5 faults

5.5.4.1.1 The Fault Report Screen
Clicking the **Show Fault report** button opens the Fault Report screen which displays the complete fault detection results and diagnostics in text format. The details can be saved to a text file by pressing the **Save** button.
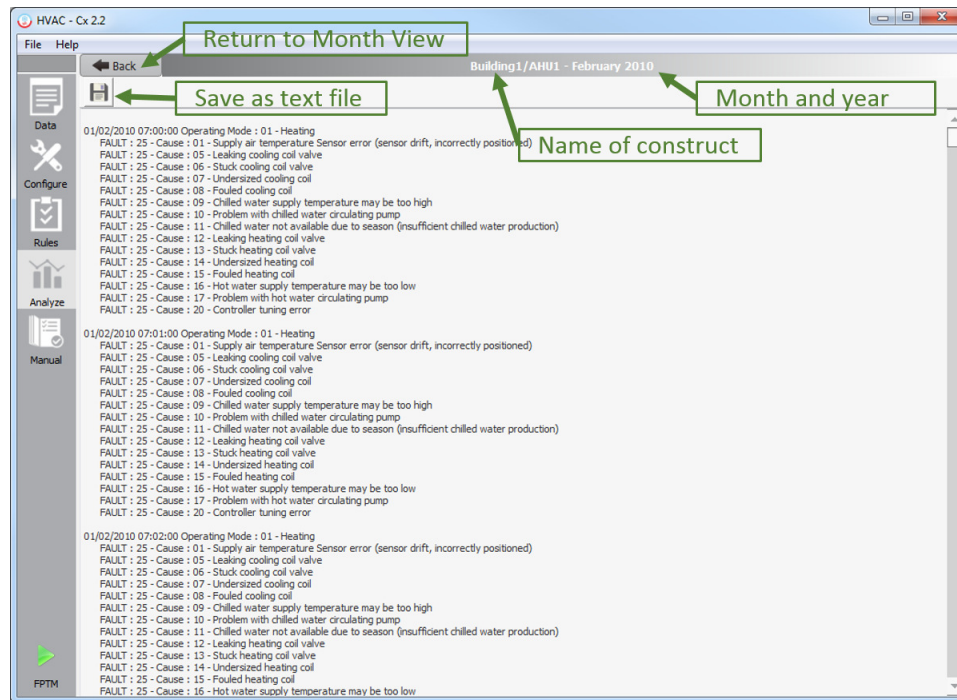
You can return to month view by pressing the **Back** button.

5.5.4.1.2 The Day View Screen

Selecting a cell in month view will open the Day View screen for that particular day. This screen gives more insight about the faults on that day, and contains three tabs: the Results tab, the Details tab, and the Graphs tab. These tabs are explained in detail below.

By clicking the **Back** button, you can go back to Month View.

5.5.4.1.3 The Results Tab

The Results tab displays the details of faults for the selected day as a bar graph. It also provides the details of occupancy schedule and operating modes.

Number of faults:

The bar graph displays the number of faults on the Y–axis and the time of day by hour on the X–axis, with each bar representing the number of faults for that hour.
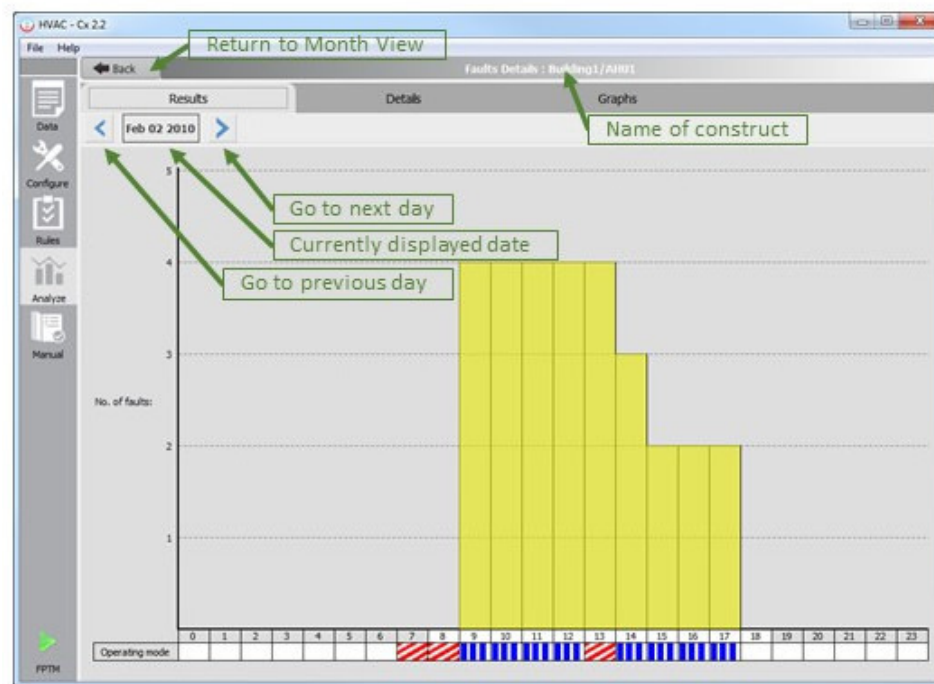
Occupancy schedule:

The background color of the x-axis label cell indicates whether the space was occupied (white) or unoccupied (grey) during the time interval.
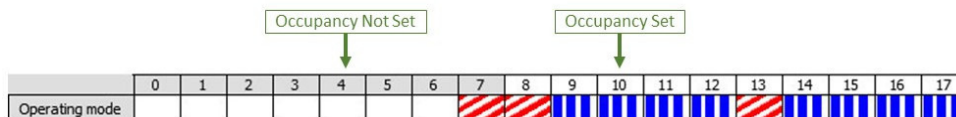
Operating Mode:

The operating mode is shown on the x-axis, with a legend for each time unit. Hovering the mouse over the legend will show the name of the mode as a tool tip pop-up.

Legend	Mode
	Heating
	Cooling with outdoor air
	Mechanical cooling with 100 % outdoor air
	Mechanical cooling with minimum outdoor air
?	Unknown occupied modes
✖	Stopped
☽	Night cooling
✳	Frost protection

Faults and Possible Causes:

Hovering the mouse over a bar will show a minimal description of faults and their possible causes as a tool tip pop-up to be displayed, as shown in the figure below. If the Time Averaging

35

option was set to less than one hour, clicking on a bar will open the Hourly View screen. This screen has a **Results** tab and **Graphs** tab that operate similarly to those on the Day View screen.
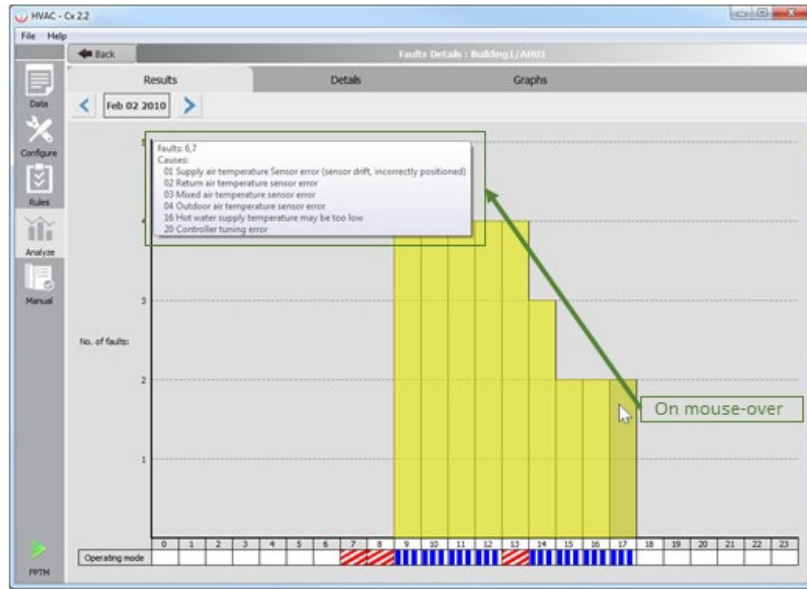
5.5.4.1.4 Adding a Note to the Graph

Users can add notes to the bar graph by right clicking on a bar and selecting **Add Note** from the context menu. If a note already exists for the selected bar, then **Edit Note** and **Delete Note** options are also available from context the menu.

When adding or editing the note, the user can save it by clicking the **OK** button. There is also an **Undo** button available. Images relating to the Note windows are shown in the figure below.

5.5.4.1.5 The Details Tab

The Details tab displays a detailed text report for every hour. The operating mode, faults and the possible causes are displayed in a hierarchical view. The report can be saved to a text file using the **Save** button.
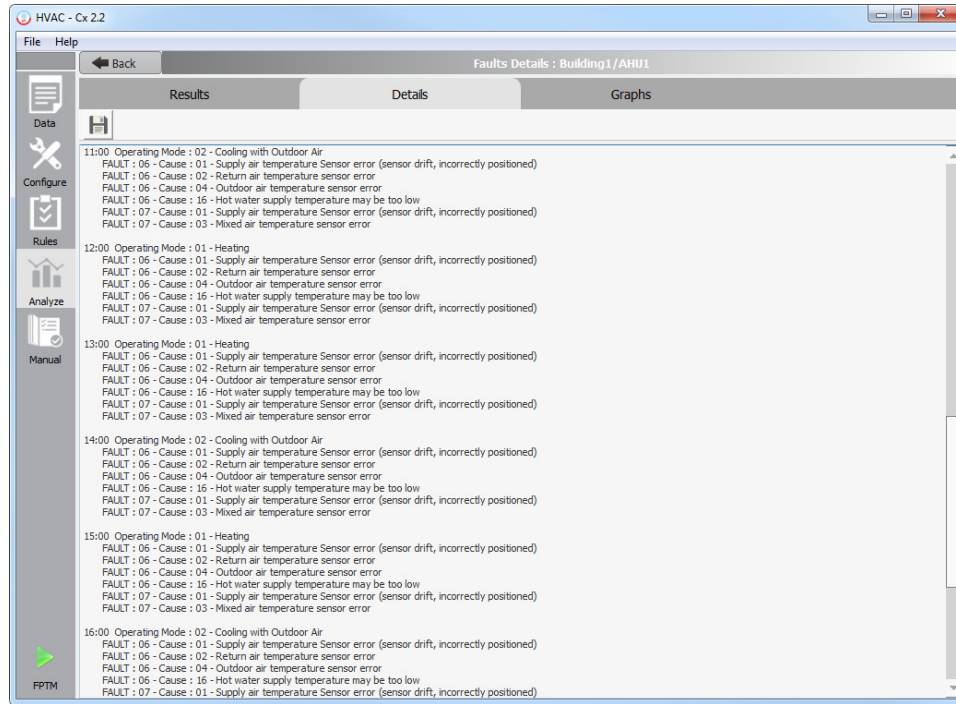
5.5.4.1.6 The Graphs Tab

The Graphs tab displays the values used for analysis as line graphs. If a time averaging option was selected for analysis, then the graphs will use the averaged data. When accessed from the Day View screen, the X -axis will show the hour of the day. When accessed from the Hourly View, the X-axis will show minutes. Individual inputs can be selected or deselected using the check boxes next to the labels on the right side of the tab. Sensor values, such as temperature or pressure readings, are shown as solid lines. The left Y-axis is associated with these values. Control actions and Occupancy are shown as dotted lines. The right Y-axis is associated with these values. Hovering the mouse over a data point will cause the value to be displayed in a pop-up window.
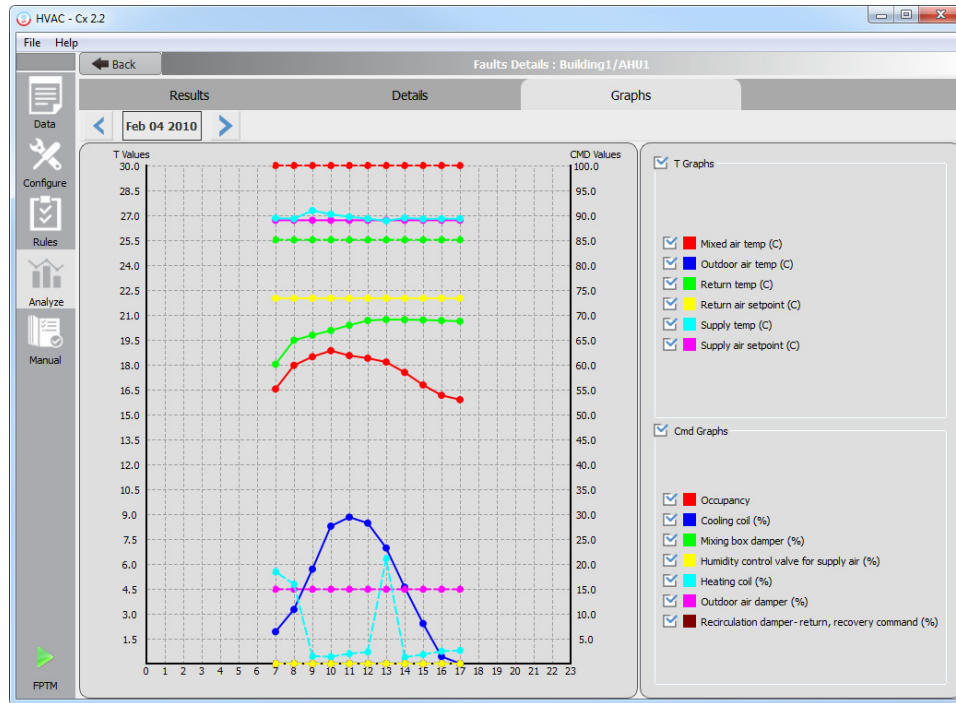
5.5.4.2 The Hourly View

Selecting a bar in the Day View screen will open the Hourly View screen. This screen displays more detailed information about the selected hour, and has a Results tab and Graphs tab that operate similarly to those on the Day View screen. Clicking the **Back** button will restore the Day View screen. The Hourly View Results tab (top) and Hourly View Graphs tab (bottom) are shown below.
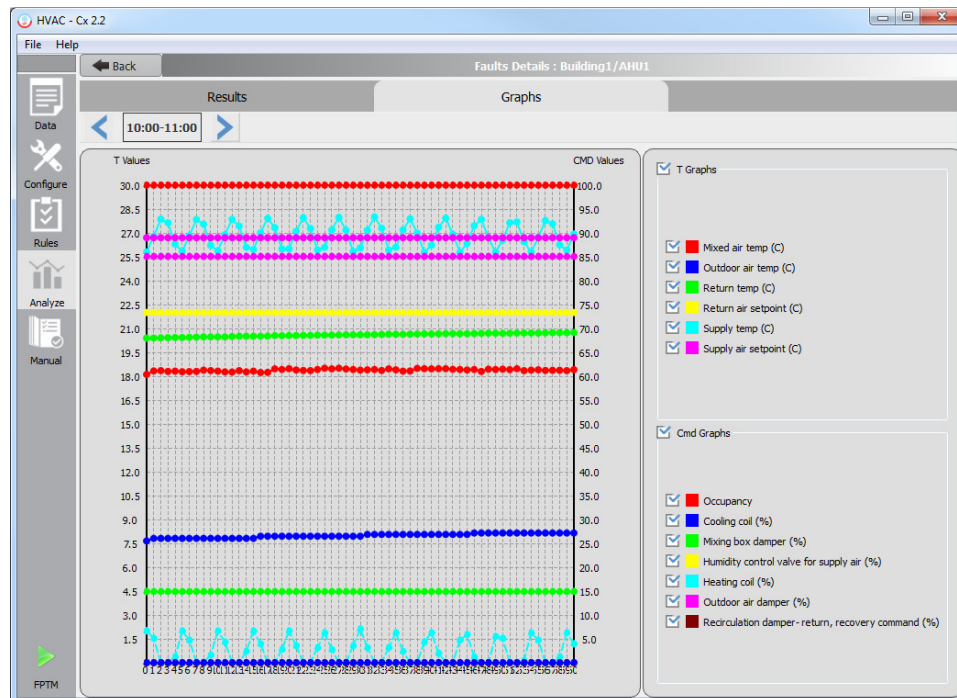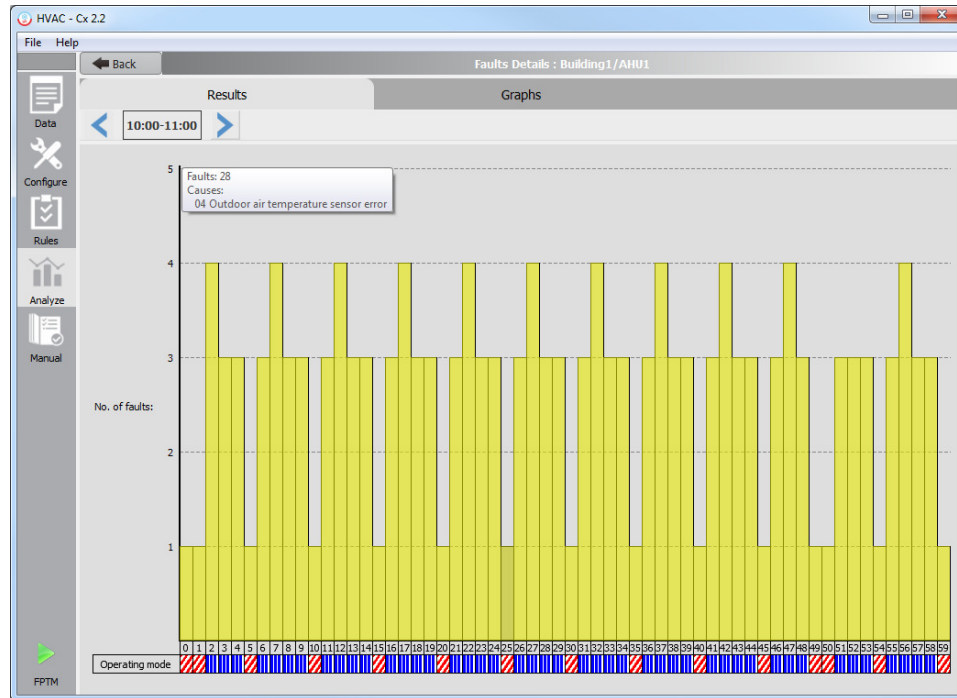
5.6 The Manual Commissioning Screen

The Manual Commissioning screen enables users to make a detailed system-generated report on the field test data collected from the building under test. The screen allows the user to enter/modify the status and feedback notes on every parameter of air handling units in the building. Currently this feature is only available for AHUs. A detailed view of the screen showing an air handling unit named AHU1 having three tabs, Sensors, Actuators and DDC, is shown below. Each of these tabs shows a list of components that is identified by its Name/title

and an image. Users can mark the status obtained against each parameter, for example Availability, Location, Wiring or Consistency and also can add a note through the comment box. In addition, the user can fill-in/modify the Verification Date, Update Date and Commissioning Provider fields as needed to appear in the final report.

Users should enter the name of the person performing the commissioning in the Commissioning Provider box. They should also set the Verification Date and Last Update boxes to the correct dates.

Users can switch to another AHU through the **Construct Ref** selection box. When selected, this box will present a list of all *AHU constructs*, sorted by *building construct*.
After entering all data, users can select tabs to be included in the report by checking the Add to report checkboxes, which are on the upper left side of each tab. By clicking the **Print** button, the report will be opened in the default browser enabling users to verify data and print a report.

This view is configurable using the settings file:
 <Application folder>\Settings\ManualAnalyze.xml.
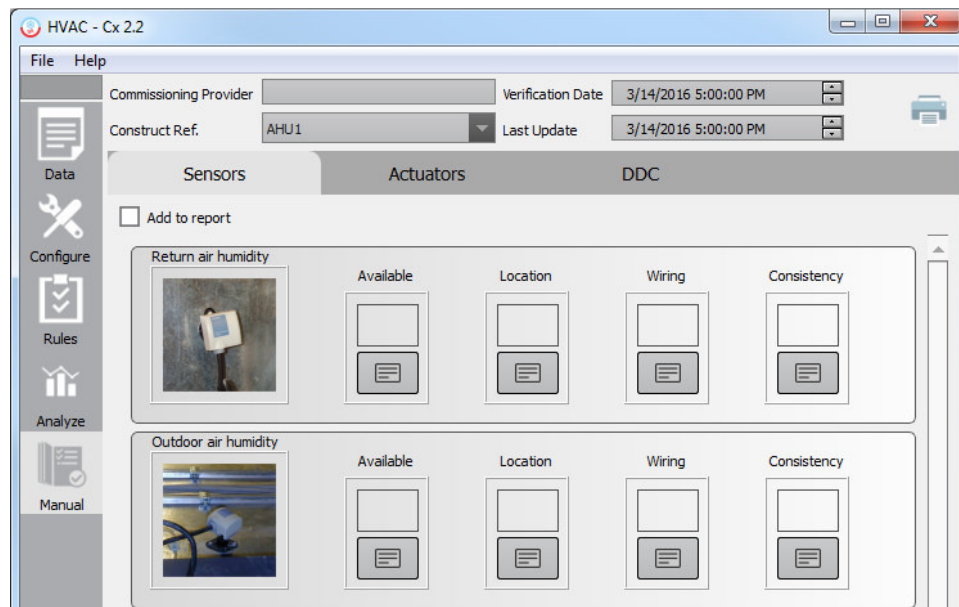
5.6.1 The Sensors Tab
Each component has the following status fields that can be updated:
- Available- The equipment is installed;
- Location- The equipment is accessible;
- Wiring- The wiring is properly installed; and
- Consistency- Values are consistently in range for inputs and outputs.

Users can mark each of these as OK or Fail, or leave blank, as shown in the figures below. The given suggestions for use of each field may be modified as appropriate.
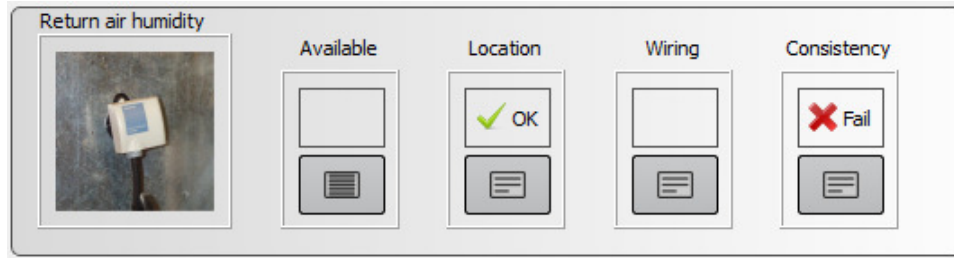
Additionally, notes can be added to each option by clicking in the area below the status field. These notes are shown on the printed report.
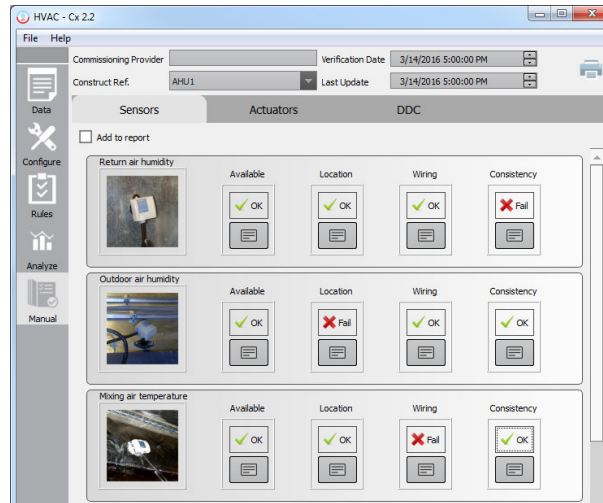
If the 'Add to report' check box is clicked the details in the page will be added to the final report.

5.6.1.1 Adding Notes
Multiline notes can be added to each of the items. If a note is already present it can be edited. These notes appear while printing reports. While editing, the **Clear** button ([↻]) can be used to clear the comment box.
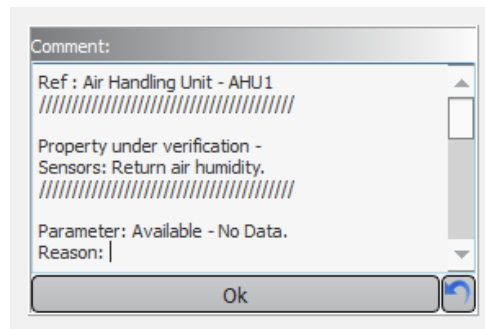
5.6.2 The Actuators Tab
The Actuators Tab functions similarly to the Sensors tab. Each component has the following status fields that can be updated:
- Available- The equipment is installed;
- Location- The equipment is accessible; and

- Operating- The equipment is operating as designed.

The status fields operate identically to those in the Sensors tab. The Actuators tab is shown in the figure below.
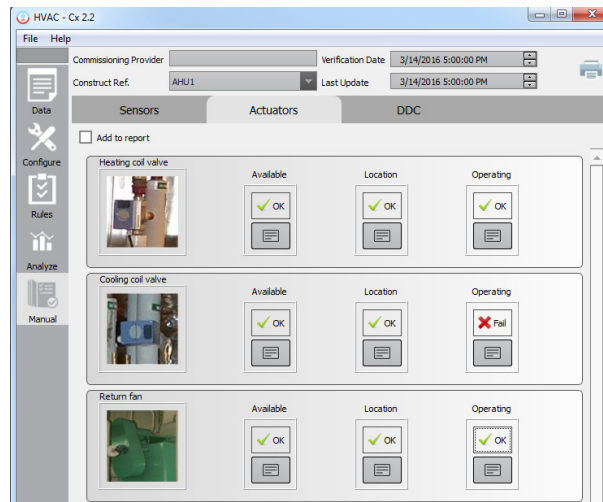
5.6.3 The DDC Tab

The **DDC** tab functions similarly to the **Sensors** tab and the **Actuators** tab. This tab focuses on tests concerning controller I/O. Each component has the following status fields that can be updated:
- Available- Is the point available on the controller?
- Type- Is the type of point appropriate?
- Addressing- Is the addressing of the point correct?
- Consistency I/O- Are the input and output ranges appropriate?

The status fields operate identically to those in the **Sensors** tab and **Actuators** tab. The **DDC** tab is shown in the figure below.
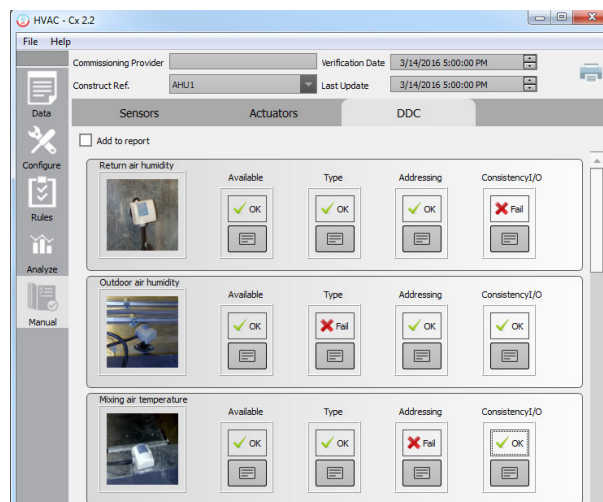
5.6.4 Printing Reports

The reports can be printed using the **Print** button. The user has to select the pages to be included in the final report by checking the Add to report checkboxes on each tab. Clicking the **Print** button creates a detailed report, of the data already entered, which is formatted into an HTML file which will be opened in the default browser. From there the user can print the report.

Reports are created using the templates from the folder **<Application Path>/Tables** folder. To change the design of the reports the user has to edit the files in this folder.
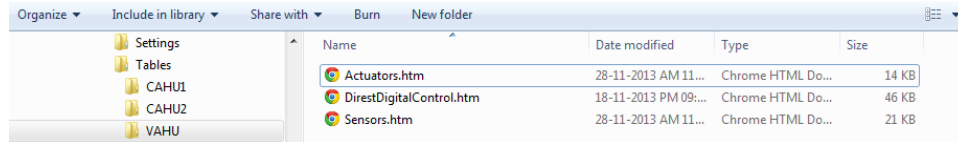
The final report file will be an HTML file saved locally into the folder **<Workspace Path>/Reports** under the name Report_<verification_time>.htm. This file will be opened in the default browser for preview and print the report.
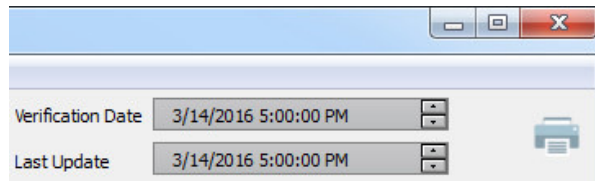
The printed report will appear as follows.

6 The Functional Performance Test Module (FPTM)

The FPTM is a feature of the HVAC-Cx tool used to perform passive or active testing and analysis of heating, ventilating, and air conditioning (HVAC) systems by interacting in real-time with BACnet systems. The FPTM uses a series of commands to drive the mechanical systems into its various normal modes of operation. The user may then apply established criteria to determine whether the system response was appropriate. The FPTM is accessed by clicking the **FPTM** button ( ) on the HVAC-Cx Main Toolbar.

The FPTM allows the user to configure a series of commands to be sent to BACnet controllers at specified times. The commands are entered either through a script file or manually. The commands are specific steps that would occur as part of a test of an HVAC system, such as for active commissioning. These commands can overwrite the value of BACnet object properties, or read the current value of a BACnet property. An event would consist of an action such as changing a setpoint or reading a sensor value as one step in the test. The sequences of commands can be saved in a script file for later use. Data is collected during and after the test sequence, allowing the user to check that the system response is appropriate (pass/fail). The FPTM can be useful to a commissioning agent carrying out a system assessment, or a building operator doing routine ongoing commissioning checks.

6.1 The FPTM User Interface
The FPTM user interface consists of four main sections, each with a separate purpose. The sections are enumerated in the figure below.
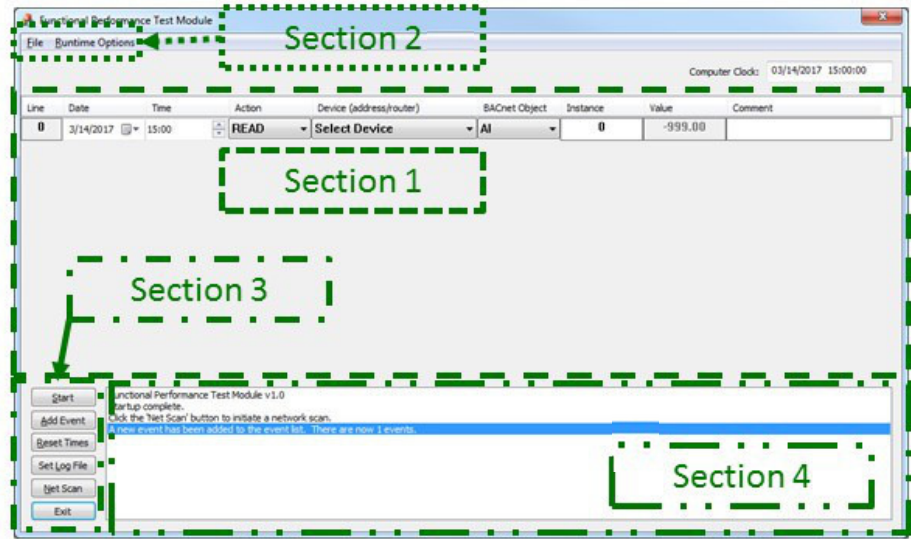
Section 1 of the FPTM GUI shows the list of events and the components that define them. They are executed sequentially and can span multiple devices, object types, and instances. In the picture above there is only one event in the list.

The following list describes the columns shown in the events section:

- Line: The number corresponding to each command and the order in which they execute. The user may click on the line number for an event to delete it or to reset the value of the indicated BACnet object if it has been overwritten.

- Date & Time: The date and time at which the command will execute. The use of a date field allows for longer term tests. Holding the Shift key while changing date or time will cause the changes to be propagated to lines below. Right-clicking on a date or time will fill in that value to lines below. Right clicking on a time again will fill the time with incrementing minutes. Subsequent right clicks on the time will cycle between the two modes.

- Action: Defines whether the event is for reading from or writing to the controller. Right-clicking on this field will fill in the selected value to lines below.

- Device (address/router): Defines the specific controller (through its network address) to which the command is being sent. This is populated from the list of devices entered through a script file and devices discovered on the network. The display will show the MAC or IP address of the device, and subnet and router if it is on a different subnet. If a text label is available that will also be displayed. Due to space limitations not all network parameters are displayed. Right-clicking on this field will fill in the selected value to lines below.

- BACnet object: The type of data point being read/written. This can be an Analog Input, Analog Output, Analog Value, Binary Input, Binary Output, Binary Value, Multi-State Input, Multi-State Output, or Multi-State Value. The present-value property will be read/written as indicated by the Action. Optionally, the out-of-service property will be changed. Right-clicking on this field will fill in the selected value to lines below.

- Instance: The instance of the BACnet object targeted. For Analog Input 1, the value of this field would be 1.

- Value: The value to be written on a write command or a default value that will be overwritten by the read value on a read command.

- Comment: A space for the user to annotate the operation or for any other comment they would like to make

Section 2 of the FPTM GUI includes the **File** menu and the **Runtime Options** menu. The File menu allows the user to save or open event script files. An event script file may also be opened by dragging it from Windows Explorer and dropping it on the FPTM window. The Runtime Options menu allows the user to specify if out-of-service messages are sent with write commands, to modify the priority level write commands are sent at, to automatically repeat the event list when it finishes running, and to manually reset all values that have been written to. The submenus for out-of-service commands (left) and setting write priority levels (right) are shown below.
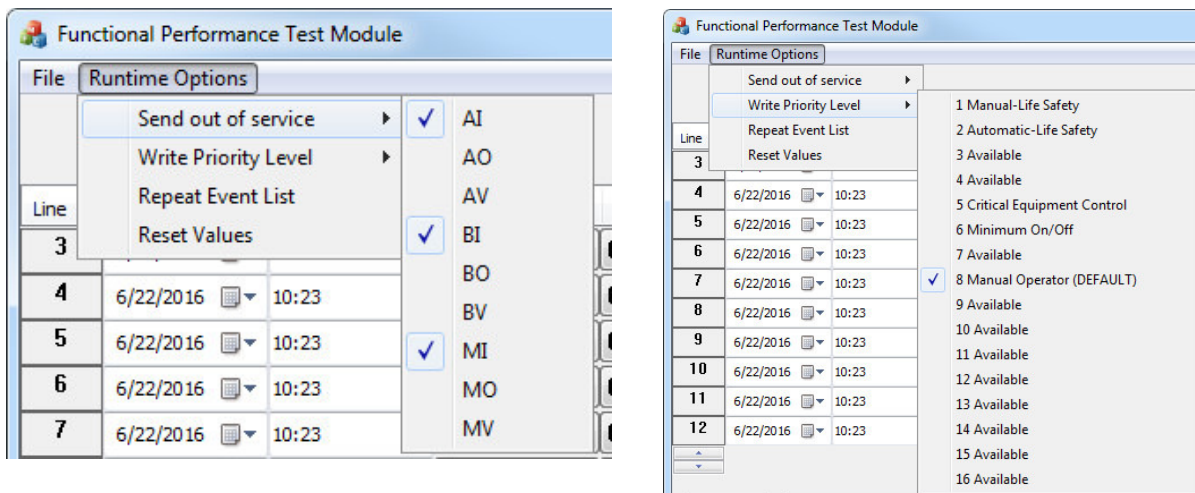
Some BACnet points require being set out of service to accept a value written to them. The **Send out of service** option allows the user to choose which types of BACnet objects should be set out of service when being written to. If this is set it applies to all instances of the object type indicated. This is included as an option to allow for variability in manufacturer implementation. Use cases demonstrating this feature will be discussed in a later section. The points affected will be reset to their original values automatically when the program exits. If running more than one test, be sure to reset the values after the first test concludes and before modifying any point settings, otherwise the FPTM will not be able to reset the points.

The user can also select the priority level at which written commands will be sent. Building automation systems send commands at a priority level in the range from 1 to 16, with 1 being the highest priority and 16 being the lowest. Control systems send normal operational commands at a priority level in the range 9 to16, and manual operator commands are sent at Priority Level 8. Because the FPTM is typically emulating a manual operator override to perform a functional test, Priority Level 8 is the default level at which commands are written. The full range of priority levels is available to allow for flexibility in testing.

Section 3 of the FPTM GUI shows user commands that control the operation of the FPTM. These are:

- Start: Begins the execution of the event list. The commands will execute when the computer time reaches the time listed for each event.
- Add Event: adds a new event to the end of the event list.
- Reset Times: Changes the date and times of the event list to start at the current date and time. The event(s) with the earliest time are set to the current time and any events with time stamps following the first event(s) maintain their time step away from the first event. Note that all times are rounded to the nearest minute, and the reset time will be the next minute.
- Set Log File: The user can specify a text file to which the FPTM will record all of its actions as well as the results from each event. This must be done before execution begins.
- Net Scan: May be performed when starting the FPTM, the user clicks this to have the FPTM find all of the BACnet devices that share the same internetwork. The

FPTM will send out a BACnet Who-Is command over the local Ethernet and UDP-IP connections.

- Exit: Closes the FPTM program.

Section 4 of the FPTM GUI is the status box, and is where the program displays information to the user. It informs the user of events such as when they have made a change to the runtime conditions, when the net scan is complete and the result, the results of each event while the test is running, and when a test is complete. Similar to the log file, the FPTM reports to the user the values sent and received for the respective events as they execute.

6.2 Writing a Script for the FPTM

To effectively reproduce the tests performed by a commissioning agent, one must understand these tests as well as the components that they test. Tests performed by commissioning agents target specific elements of a HVAC system. These elements are also accessible to the FPTM. It is possible to break down a test performed by a commissioning agent into individual commands (events) as well as to correlate each event to a specific element of the HVAC system. These commands will be saved in a script file.

Scripts files contain information needed to perform a test using the FPTM. This includes a list of network devices including information on how to contact them, a list of events for which the FPTM will read or write a value, the write priority level, the out-of-service settings, and the optional Log File. The FPTM script files use an XML format, and may be edited by any text or XML editor. A brief example of how to write an FPTM script is given below:

1. Define the commissioning test in terms of the components tested, the values that need to be accessed, and what the desired results are for the test.
   - For instance, a damper test will inspect the damper position and mixed air temperature. As a result one would want to see the mixed air temperature change and the damper change position.
2. Each action taken (read or write) during the test will correspond to one event in the FPTM. Break the Cx test into steps (events) that each correspond to an action.
   - Think about how many times something needs to be checked, if it needs to be turned off and on again, etc.
3. The address on the network of each device used in the test needs to be known. This includes Ethernet or IP address, BACnet Device object instance number, and BACnet network numbers and routers if configured. This information may come from as-built plans, a network scan, or a combination of sources.
4. Open the FPTM and add an event for each of the steps. Set each component of the events to the correct information. Annotate each step in the comment area.
5. When complete, use the option under the File menu to save the script from the FPTM as an XML file. If building a long script, you may wish to save it periodically. Once saved, the script file may also be edited with an XML editor. An example of the XML format is given below. For additional information on the XML format, see the FPTM Users Guide Supplement [9]. When saving the file, it is recommended to use a descriptive name, for example including "PF" in the name for pre-functional tests or "AT" for active tests.

47

An example of the device and events formats is given below.

```
- <FPTM>
-   <devices size="1" >
       <device id="0" mac="00E0C9218349" ip="10.101.9.62" ipport="47808" net="0" configID="3" label="Device 1" />
    </devices>
-   <events size="3" reset="1">
-    <event id="0" >
       <bacdevice>0</bacdevice>
       <eventTime>2017-03-14T15:00:00</eventTime>
       <object>5</object>
       <instance>42</instance>
       <readwrite>1</readwrite>
       <value>1</value>
       <comment>activate mode 1</comment>
     </event>
```

6.3 Library of Functional Performance Test Scripts

A library of prefunctional test (PF) scripts and functional performance test (FPT) scripts is available for commissioning chilled water loop and air-handling unit operation [9]. Table **6.1** lists the available test scripts for an AHU system or component being evaluated (PF or FPT), describes the purpose of the test, and lists the criteria for a passing the test. Table 6.2 provides the same information for PTs and FPTs available for evaluating Chilled Water Loops. The scripts are available as a reference to users who may use them as an example, configure them for use in their projects, or adapt them. The FPTs mostly address the overall performance of the systems, but also provide basic checks at the component-level and sensor level. Where available, industry reference functional performance tests were used or adapted.

Prefunctional checks of the ancillary equipment are to be carried out as a prerequisite to carrying out FPTs for these systems and components. Test scripts are employed to facilitate this step, when possible. Because the FPTM documents the tests scripts, along with the criteria for pass or failure, it also serves as a training tool for building operators, making operation more transparent.

Table 6.1: List of Prefunctional Test Scripts and Functional Performance Test Scripts for Air Handling Units

Test Name	Description	Criteria for passing
PF1 – check SA temp sensor	Determine whether the supply air temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF2 – check MA temp sensor	Determine whether the mixed air temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF3 – check RA temp sensor	Determine whether the return air temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF4 – check RA CO_2 sensor	Determine whether the return air carbon dioxide sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF5 – check filter dp sensor	Determine whether the filter differential pressure sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.

Test Name	Description	Criteria for passing
PF6 – Heating coil	Verify that the heating coil can open and close as well as heat the air moving across it.	Supply air temperature rises when valve opens, valve physically opens. Temperature returns to previous value when valve closes, valve physically closes.
PF7 – Cooling coil	Verify that the cooling coil can open and close as well as cool the air moving across it.	Supply air temperature drops when valve opens, valve physically opens. Temperature returns to previous value when valve closes, valve physically closes.
PF8 – OA/RA damper	Verify that the damper opens and closes fully, lets in outside air.	OA damper goes to 0 when RA is at 100 and vice versa. Mixed air temp rises when OA damper is open.
PF9 – fan operation	Verify that the fan can shut on and off fully.	Fan shuts off completely (verify in person) when commanded and opens fully.
FPT1 – Change OA damper sp	Check that the OA damper responds to a change in the minimum OA damper sp.	The OA damper position changes to the new setpoint (if not doing CO_2 control or economizing)
FPT2 – RA smoke safety	Trigger smoke alarm and see if system shuts down.	All valves close, fan stops, and dampers close
FPT3 – SA smoke safety	Trigger smoke alarm and see if system shuts down.	All valves close, fan stops, and dampers close
FPT4 – response to occupancy	System turns on when occupied and off when not.	Valves close, fan stops, and dampers close when unoccupied and turn back on when occupied
FPT5 – night setback and setup responses	Determines if system maintains its unoccupied setpoints.	Heating coil turns on when temp is below sp. Cooling coil turns on when temp is above sp.
FPT6 – MA safety test	System responds appropriately to mixed air that's too cold.	Heating coil opens and OA damper shuts when mixed air goes below sp.
FPT7– Enthalpy-activated economizing	Checks that system activates economizer mode in response to adequate outdoor air enthalpy.	Check that air-handlers open outdoor air dampers and have economizing enabled.

Table 6.2: List of Prefunctional Test Scripts and Functional Performance Test Scripts for Chilled Water Loops

Test Name	Description	Criteria for passing
PF1 – plant supply temp sensor	Determine whether the plant supply temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF2 – bldg supply temp sensor	Determine whether the building supply temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF3 – bldg return temp sensor	Determine whether the building return temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF4 – plant return temp sensor	Determine whether the plant return temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.

Test Name	Description	Criteria for passing
PF5 – entering chiller temp sensor	Determine whether the entering chiller temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF6 – leaving chiller temp sensor	Determine whether the leaving chiller temperature sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF7 – chw bldg dp sensor	Determine whether the building differential pressure sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF8 – chw plant dp sensor	Determine whether the plant differential pressure sensor is reading the correct value.	Check if the reported value matches a value physically taken from system.
PF9 – valve 1	Checks if valve opens and closes on command.	Opens and closes on command (physical inspection needed).
PF10 – valve 2	Checks if valve opens and closes on command.	Opens and closes on command (physical inspection needed).
PF11 – valve3	Checks if valve opens and closes on command.	Opens and closes on command (physical inspection needed).
PF12 – valve4	Checks if valve opens and closes on command.	Opens and closes on command (physical inspection needed).
PF13 – valve 5	Checks if valve opens and closes on command.	Opens and closes on command (physical inspection needed).
PF14 – chw bypass valve	Checks if valve opens and closes on command.	Opens and closes on command (physical inspection needed).
PF15 – chw pump 1	Checks if pump stops and starts on command.	Starts and stops on command (physical inspection needed).
PF16 – chw pump 2	Checks if pump stops and starts on command.	Starts and stops on command (physical inspection needed).
PF17 – chw pump 3	Checks if pump stops and starts on command.	Starts and stops on command (physical inspection needed).
FPT1 – Mode 1	Verifies the valve and pump sequences for Mode 1.	All valves close and pumps stop.
FPT2 – Mode 2a and chw available	Verifies the valve and pump sequences for Mode 2a and checks if chw is available from the plant.	Appropriate valves open for Mode 2a, pumps 1-3 do not turn on. Plant supply water should be around 5.6 °C (42 °F).
FPT3 – Mode 2b	Verifies the valve and pump sequences for Mode 2b.	Appropriate valves open for Mode 2b, building pump BP1 or BP2 should come on.
FPT4 – Mode 3a	Verifies the valve and pump sequences for Mode 3a.	Appropriate valves open for Mode 3a, chiller comes on (physically inspect), pump CP1 on.
FPT5 – Mode 3b	Verifies the valve and pump sequences for Mode 3b.	Appropriate valves open for Mode 3b, chiller comes on (physically inspect), pump CP1 on, either pump BP1 or BP2 on.
FPT6 – Mode 4	Verifies the valve and pump sequences for Mode 4.	Appropriate valves open for Mode 4, chiller comes on (physically inspect), pump CP1 on, either pump CP1 or CP2 on, V-1 shut.
FPT7 – Mode 2 V-1 modulation	Verifies that V-1 modulates to maintain temperature difference across building.	In Mode 2a with a call for cooling, V-1 should close as necessary to maintain a 8.3 °C (15 °F) max temperature difference across the building pipes. Change this setpoint to a 11 °C (20 °F)

Test Name	Description	Criteria for passing
		difference and observe the change in V-1.
FPT8 – VFD modulation for min flow	Verifies that the VFD bypass valve opens as necessary to prevent overpressurization.	In Mode 3b with no calls for cooling. The plant dp might increase to 172 kPa (25 psi) where the bypass valve would then open. See if this happens then change the setpoint and see how the bypass valve responds.

6.4 Using the FPTM- Use Cases

This section instructs the user in how to use the FPTM through various examples given by use cases, as suggested by ASHRAE Guideline 20-2010 [10]. Various interactions a user could initially or commonly have with the FPTM are described in the use cases presented here. This is not an exhaustive list, but a set chosen to be sufficient to allow a new user to become familiar with and use the FPTM. The use cases described are:
1. Opening the FPTM and starting a script file;
2. Adding new events manually;
3. Reviewing point configuration and runtime options; and
4. Resetting values.

6.4.1 Opening the FPTM and starting a script file

The FPTM may be started from the HVAC-Cx interface, as shown in the figure below. When started and while connected to a network that has access to communicate via BACnet with the building automation system (BAS), the user may load a script file by selecting **File→Open Event File**, or by
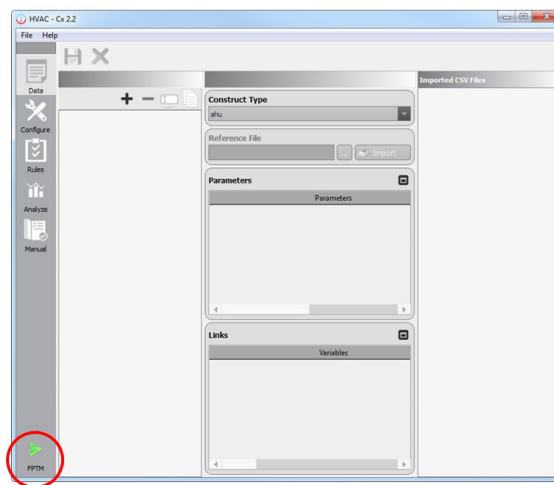
dragging it from Windows Explorer and dropping it on the FPTM window. The steps to perform this use case are:
1. Open the FPTM;
2. Open the script file by clicking on **File→Open Event File** and use the open file dialog, **OR** click and drag the script file from Windows Explorer;
3. Review the status box to check for any errors or other relevant information. Make any necessary changes to the events or settings, including updating the start time; and

4. When ready, click on the **Start** button to begin the test.

At this point, all of the events will be grayed out, lightening up as the tests are executed. Read events will have their values updated to the recorded value. The status box will report information from each event as it is executed. The user should evaluate the data as it comes in to determine if they are seeing what is expected for the test conducted. At the conclusion of the test, the success or failure of the test can be determined by the user in a conclusive manner.

6.4.2 Adding new events manually

New events may be added to the FPTM manually. This may be the preferred method when creating a new test. New events are added by clicking on the **Add Event** button in section 3. The elements of the configuration will have default values and will need to be reviewed individually. The steps to perform this use case are:

1. Open the FPTM.
2. There will be one event in the events section. Use the Add Event button to add more events as needed. Additional events can be added at any time, unless a script is executing.
3. Review the configuration:
   a. Date and Time: The first event will have the date and time from when the FPTM was started. Subsequent events will have the date of the previous event. Modify the date, if needed, by using the date picker. Modify the time by either clicking on the **Reset Times** button, or by selecting the hour or minute field and clicking on the up/down arrows. Hold the Shift key down while making changes to the date or time field to have the changes applied to date/time fields below the one being modified. For example, holding the shift key and incrementing the top event by one minute will cause all events below to also be incremented by one minute. Right-clicking on a date or time field will set that exact date or time in all events below.
   b. Action: This defaults to READ, which will read the value indicated. Change to WRITE to write a value to the controller. The value to be written must be entered in the Value column.
   c. Device: This drop-down menu provides a list of all known BACnet devices. Devices become known either from being described in a configuration file or from a net scan. Select the appropriate device from the list. Right-clicking on an entry in the list will set that device in all events below.
   d. BACnet Object: This drop-down allows the user to select the type of object which will be read from or written to. The choices are Analog Input (AI), Analog Output (AO), Analog Value (AV), Binary Input (BI), Binary Output (BO), Binary Value (BV), Multi-state Input (MI), Multi-state Output (MO) and Multi-state Value (MV). Right-clicking on an entry in the list will set that object selection in all events below.
   e. Instance: Enter the instance number of the BACnet object in this box.
   f. Value: If READ is selected in the Action column, the value read from the BACnet controller will be displayed here. If WRITE is selected in the Action column, a value must be entered here. The default value is -999.

g. Comment: Text describing the event may be entered here.
4. It is recommended to save the configuration to a script file. Select File->Save File to open a dialog box which allows you to save the configuration.
5. When ready to begin a test, click on the Start button.

Note that an event may be deleted by clicking on the line number box for that event and following the prompt.

6.4.3 Reviewing point configuration and runtime options

After the events have been created the point configuration and runtime options should be reviewed. This includes the configuration information on each line in the events section and the options in the Runtime Options menu. Each configurable element of the events should be reviewed:

a. Date and Time: If the events were read from a script file it is likely the date and time will need to be adjusted. Click the **Reset Times** button to change the date and time of the first event to the current date and time. Intervals between events will be maintained. The date may be changed manually be selecting an element (day, month, or year) and typing in a number. Right click on the changed date to propagate the change to subsequent events. The time may be changed manually by selecting an element (hour, minute) and typing in a number. The time may also be changed by selecting an element and clicking the up or down arrows in the time control. Holding down the Shift key while using the arrows will cause the change to be propagated to subsequent events, i.e., they will all be incremented or decremented by the same amount. Right clicking on the time field of an event once will cause subsequent event times to be set to the clicked time. Right clicking again will cause subsequent event times to each be incremented by one minute, i.e., if the clicked time is 3:00, subsequent event times will be 3:01, 3:02, etc. Further right clicks will alternate between the two modes. These features are provided to make it easier to implement lengthy event lists.

b. Action: Review that this is set for the desired action.

c. Device, Object, Instance: Confirm that there has not been a change to the device configuration that would affect these values. If a controller has been replaced the address may need to be updated. If the event list is to be reconfigured to evaluate a different device, it is possible that the instance numbers will change.

d. Value: Confirm that any values being written meet the requirements of the current test.

e. Comment: If any values have been changed, it may be appropriate to update the comment field to reflect this.

The options in the Runtime Options menu should also be reviewed. These include the choices for objects sent an out-of-service notification on writes, and the priority level that write requests are sent at. These should only be adjusted if write requests failed on a previous test. Note that any written values should be reset before changing any of these options.

6.4.4 Resetting values

When writing values to a controller, the FPTM writes values at a higher priority level than the value used for normal operations so that changes due to normal programmed operations will be ignored during the test. Resetting the values removes the value written at a higher priority level, permitting the controller to use the value at the next highest priority level. If values used for testing are not removed when testing is finished, the controller will be left in a state where it will not operate properly. The FPTM will reset the values associated with any write events when exiting, but it may be necessary to reset the values manually, such as when modifying one or more individual events, re-running a test, or loading a new script file after running a previous one. A reset can be directed to all applicable events or to a specific event. The steps to reset all events are:

1. Start the FPTM and load a series of events, either manually or through a script file as previously directed.
2. Run the test either to completion or until it performs one or more write events.
3. When the test has stopped, select **Runtime Options→Reset Values**. This will reset all events with a write action.

The steps to reset an individual event are similar:

1. Repeat steps 1 and 2 from above.
2. Click in the Line number box for the event to be reset. This will open a window with prompts to delete the event or reset the event. Follow the prompt to reset the event.

6.5 Evaluation of Results

After the execution of a sequence, the results are stored in a log file previously specified by the **Set Log File** command or specified in a script file. The log file includes information on the values read or written, the time/date, and FPTM configuration options. These results must be reviewed manually to determine if any particular test passed or failed.

After each test is completed, the user should use the menu **Runtime Options→Reset Values** to reset the BACnet objects overwritten during the test. This will restore the values that the objects were set to before the test was executed, by writing a NULL value at the priority level used for testing, and by resetting objects to their previous out-of-service status. Note that if a BACnet object was set to out-of-service before testing, this state will be retained. If the device address, object, or instance information is changed after a test but before a reset the FPTM will not be able to reset the correct value. **It is very important to reset values as without being reset the system may be left in an unstable state**.

7 References

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