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AUSTRET: An Automated Step Response Testing Tool for Building Automation and Control Systems

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Abstract: Building energy consumption is still one of the main contributions to global carbon emissions. With the overall digitalization in the building sector, building automation and control systems (BACS) are to play a more important and key role in improving the building sector performance. A well-designed BACS at the building design phase with a high level of control functionalities is not a guarantee for efficient building operation and successful control and management strategies in the operational phase. Thus, a systematic automated initial and retro-commissioning process is key to test the performance of the automation system and the response of the integrated HVAC systems. This is an arduous and time-consuming task susceptible to human errors. As an alternative, the current study proposes a methodological framework to automate step response testing of BACS and to optimize the different steps of this process in a cost-effective way. In addition to newly built buildings, the framework can be applied in existing or retrofitted medium to large-sized buildings that have a building management system capable of receiving actuator commands and responsible to provide updates of several state variables. Based on the proposed framework, a first-of-its kind tool "AUSTRET" for building automated step response testing of BACS is designed and developed. The tool provides the necessary input configuring parameters, building system selection, and output results for each performed test. The framework aims to act upon ventilation, room heating and cooling, and water heating and cooling modules in a building. The implementation and demonstration of the AUSTRET in a medium-sized building case study for two different building systems are presented and evaluated: (1) Ventilation/fan, (2) Room heating. The results show the different dynamic responses on these two systems and how misleading input parameter configuration can invalidate step response tests. The preliminary results highlight the capability of using AUSTRET as a key component in both building initial and retro-commissioning applications.

Keywords: step response; test; building automation; auditing; control; software

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Citation: Santos, A.Q.; Liu, N.; Jradi, M. AUSTRET: An Automated Step Response Testing Tool for Building Automation and Control Systems. *Energies* **2021**, *14*, 3972. https://doi.org/10.3390/en14133972

Academic Editor: Wolfgang Kastner

Received: 27 May 2021
Accepted: 21 June 2021
Published: 2 July 2021

1. Introduction

To reduce the climate change impacts, more ambitious energy and climate goals are being proposed [1]. The European Union, EU, has devoted huge efforts towards reducing energy consumption and decreasing the greenhouse gas emissions. Recently, the EU commission proposed new climate policies, known as the 'Clean Energy for all Europeans' package [2]. The directives aim to unify the existing energy markets and improve energy efficiency through better management of the existing infrastructure, while providing energy flexibility [3]. This will allow the integration of flexible demand and renewable energy to provide a cleaner and steady energy supply to EU's country members. More ambitious energy and climate goals can pose a significant stress on the current energy systems. The results of national and international pressure towards the integration of renewable energy sources (RES) is forcing conventional solutions into a new paradigm [4]. It is expected that by 2050 most of EU members will have the largest share of its energy supply provided by RES. This will result in an intensified focus on different instruments to implement energy efficiency measures to various components in the existing energy sector. The goal is to overcome technical limitations of the existing energy infrastructure models and help produce the conditions that move the energy paradigm into the next era. Herein, seen the large-scale implementation of smart grids and the flexibility measures on residential, commercial and industrial applications.

In the center of this scenario, buildings will play a key role on management and provision of energy-efficient solutions and flexible provision of services to balance the intermittent energy sources and the peak energy consumption of different applications. The building sector is responsible to consume 40% of the overall energy resources, worldwide, and contributes to an average of 30% of global carbon emissions [5]. This situation was a catalyst to upgrade the previous Energy Performance in Buildings Directive (EPBD) and impose more strict guidelines and standards to enhance energy efficiency in buildings and hence reduce consumption and the corresponding emissions [6].

How to automate step response testing of BACS applied to medium to large-sized buildings? This is the underlying question that this paper aims at answering. Overall, building performance auditing and commissioning has been a hot topic in the recent decades, both in terms of theoretical assessments and evaluations and experimental implementations and practical applications [7,8]. Most of such investigations targeted the overall building performance auditing and commissioning, including both initial and continuous commissioning, to reduce energy performance gap between the design and the actual performance and to ensure a proper building operation from day one and throughout its life cycle. In addition, a large block of studies has targeted building constructions and materials auditing and evaluation [9] as well as building components including heating, ventilation and air conditioning (HVAC) units [10], devices and various services [11], aiming to improve the design and optimize the operation. Although building performance auditing and commissioning is not a new topic, very few investigations concentrated on the building automation and control system auditing and commissioning, evaluating its structure and operation patterns.

As more and more BACSs are installed with various characteristics and functionalities, one of the major challenges facing the smart buildings sector is the assumption at the design stage that the building management system will perform as expected and claimed in the design documents [12]. However, a large block of investigation has highlighted recently that such assumptions and claims which are not supported by testing and proper commissioning have led to large energy performance gaps and to buildings that are operating under suboptimal conditions [13,14]. One of the main causes of these performance gaps is the unproper design and testing of the BACS system and failures on different levels of control of various building components including HVAC units and services [15,16]. In most of the developed countries, there is a requirement in the building regulation for manual performance testing and initial commissioning prior to the building handover [17]. However, most of these tests are done on the level of the whole building with no concentration on the building brain, the BACS. In addition, such auditing and performance testing processes are mainly performed manually [18], with no guarantee for the owner that they are performed in the right way and that it has the required quality. This manual auditing and commissioning process is very time and resources consuming and thus very expensive to conduct and prone to errors. Most of such errors and failures will be propagating throughout the operational phase leading to an inefficient operation at various levels and to expensive maintenance and repair costs. This pattern is not related only to newly built buildings but also common and could be even more expensive and inefficient in retrofitted buildings. This includes buildings which exhibit building services, upgrade, new automation and control devices installation, management strategies modifications, and the BACS software and hardware components upgrades. In any of these cases, implementing an automated BACS performance testing on different levels is vital to ensure proper BACS operation as well as well-interconnected and controlled energy systems.

Most of the studies and investigations reported in the literature deals with optimizing the design of building automation and control systems and enhancing their functionalities and services. As mentioned above, a well-designed building automation system at the building design phase with a high level of control functionalities is not a guarantee for efficient building operation and successful control and management strategies in the building operational phase. Thus, a systematic automated initial and retro-commissioning process is key to test the performance of the automation system and the response of the integrated HVAC systems. This will ensure not only an upgraded and well-installed BACS, but also a smooth integration and interaction with all the energy systems around the building.

The first contribution of the paper is to provide a methodological framework to automate step response testing of BACS applied to medium to large-sized buildings. This is the first initiative towards the design and development of an innovative automated step response testing application for building automation systems. The methodology and design of the step response testing algorithms is presented along with the application design and development with all the different hardware and software components. A second contribution of the paper is to develop a first-of-its-kind tool "AUSTRET", implementing the proposed framework. In addition, the application implementation for two different types of tests, ventilation/fan and room heating test is performed and reported. The work is carried out under the 'Automated Auditing and Continuous Commissioning of Next Generation Building Management Systems' (BuildCOM) research project aiming to develop and demonstrate innovative set of tools for automated building management system auditing and continuous building commissioning [19], and aid the establishment of a methodical auditing and evaluation process for the design of next generation building management systems.

2. Building Automation System Auditing and Evaluation

Although multiple national and international schemes have been developed and presented in recent decades dealing with a whole-level building certification including LEED [20], DGNB [21], and BREEAM [22], very few schemes are presented for auditing and evaluation of building automation systems. One of the well-defined and widely used BACS auditing and evaluation methodologies in Europe is the 'eu.bac System' methodology [23]. The framework for this auditing system was developed by the European Building Automation and Controls Association (eu.bac) representing a large group of leading manufacturers of building automation and control equipment in Europe [24]. In terms of the auditing methodology, the eu.bac employs the European standard EN 15232 "Energy performance of buildings—impact of Building Automation, Controls and Building Management" [25]. The standard defines multiple building classes associated with the corresponding level of automation and control, spanning from A (best) to D (worst). The eu.bac System certification criteria is mainly devoted to quantifying the energy efficiency in buildings and is based on a point-scoring basis, with a range from 0 to 100. In auditing and evaluating the building automation and control system, the eu.bac uses an excel-based platform with 10 domains, each targeting one of the building services and systems [23].

Although the eu.bac system framework aims at evaluating and auditing the design of the BACS considering energy efficiency as the only criterion, another BACS auditing scheme was introduced recently, the Smart Readiness Indicator (SRI) [26], developed by the European Commission and allowing much broader assessment and auditing of the BACS considering the larger picture. Although it also uses a point grading system, the SRI methodology aims at evaluating the BACS considering multiple criteria. Along with energy efficiency, it includes maintenance and fault prediction, comfort, convenience, health and wellbeing, energy flexibility and storage and information to the occupants [27]. The SRI overall score highlights the level to which the building satisfies user needs, allows energy-efficient operation and enhances grid flexibility. Similar to the eu.bac scheme, the SRI methodology also targets multiple building services and domains including the HVAC systems and the controls. The technical domains, the impact criteria and the corresponding explicit weightings of the EU SRI framework are shown in Figure 1 [28].

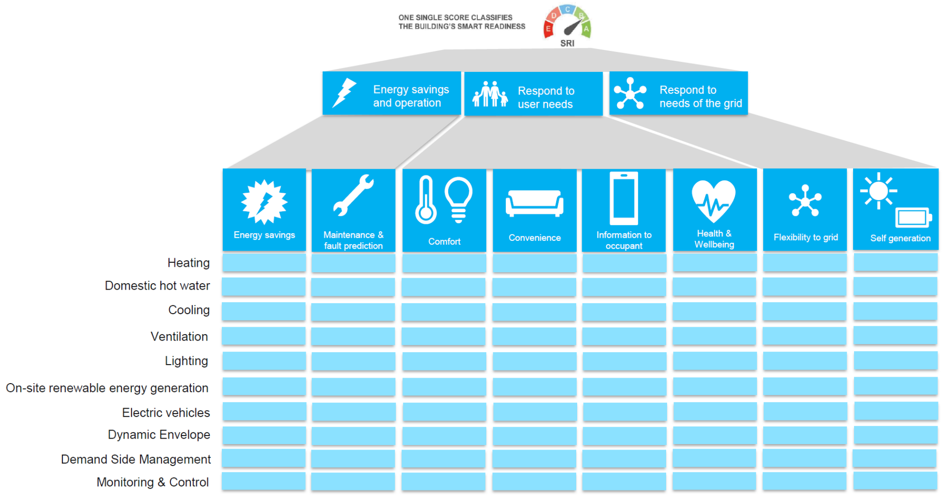


Figure 1. The technical domains, the impact criteria and the corresponding explicit weightings of the EU SRI framework [28].

Building up on the two aforementioned schemes, the eu.bac system and the SRI framework, an interactive tool for building automation and control systems auditing and smartness evaluation (IBACSA) was recently developed and presented [23]. IBACSA is intended to form a comprehensive, yet user friendly and easy to use tool for BACS auditing and evaluation and could serve as an instrument for buildings initial and retro-commissioning. In terms of the auditing and evaluation methodology, it employs a hybrid qualitative-quantitative multi-criteria holistic framework, targeting eight major building domains: Heating, Hot Water, Cooling, Ventilation, Lighting, Dynamic Envelope, Electricity and Monitoring and Control [29]. In auditing the various services and functionalities of each of the mentioned listed domains, IBACSA also relies on the European Standard EN15232 guidelines. The total number of services included is 60, and each is associated with multiple control functionalities and levels. The scoring with respect to each impact criterion is based on the EN15232 standard for building automation systems' performance and expert knowledge from the SRI framework. The evaluation impact criteria highlighted in IBACSA are (1) Energy efficiency, (2) Maintenance and fault prediction, (3) Energy flexibility, (4) Comfort and (5) Information to occupants.

In addition to the building automation and control systems auditing schemes presented above, a large block of studies has been presented in the recent years dealing with improving the design and implementation of BACS in buildings as well as investigating and evaluating of BACS design and the corresponding specifications for optimized operation. A multitude of investigations has considered the European Standard EN 15232 and the associated methodology, evaluating and analyzing the compliance of case study buildings with the standard and the level of functionalities used as a basis for control and automation [30]. Mancini et al. [31] carried out a large-scale analysis considering 412 buildings in Italy. Data on the energy consumption was gathered and an assessment on the energy savings when BACS was implemented in the buildings was carried out. Based on the analysis and evaluation performed, three major modes of control and automation were highlighted as optimal under the considered specific boundaries and conditions. In addition, the results showed that a proper BACS design enables large potentials of demand response applications and flexibility upgrade in buildings as a key condition for future smart grids interaction. In a related study, Ożadowicz et al. [32] studied different demand-side management scenarios and claimed that effective and well-designed BACS with upgraded functionalities will unlock large possibilities of flexibility in buildings along with active demand-side management opportunities.

In their study, Ippolito et al. [33] highlighted that the proper design of BACS is a crucial milestone towards energy-efficient and smart building operation. They considered a case study in Italy and implemented the BAC factor method to evaluate the impacts of the automation and control system implementation on the overall building performance. On the technical side, they reported an improvement in the building operation patterns when a well-designed BACS is installed, along with an upgrade in the EPC class. However, a major challenge highlighted is the high cost of implementation and the variation in the economic savings due to BACS implementation which was attributed to different parameters including the country of application, the building in use, climatic conditions and the HVAC systems installed. Ożadowicz et al. [34], studied the design and implementation of a BACS in a case study university building in Poland. The European standard EN15232 was used to evaluate the design and application of the BACS, and the results attained highlighted a proportional relation between the BACS functionalities and the energy efficiency levels and thus the reduction in energy consumption. However, major questions were raised regarding the scalability and generalization of the results. Moreover, multiple studies recently have highlighted failures in BACS operation, improper controls and management techniques, lack of automation in operation as major causes of building energy performance gaps, leading to a reduction in the overall building energy efficiency [35,36]. Therefore, it was highlighted that a special consideration should be given not only to the design of BACS but also its operation, which needs to be considered to be a major component in buildings initial and retro-commissioning processes. In this regard, Motamed et al. [37] developed and implemented a self-commissioning approach focusing on a rule-based control logic and aiming to enhance the automation level of shading and lightning systems. The implementation of the self-commissioning approach has led to major positive impacts including higher visual comfort, less energy consumption and a smoother control methodology.

The extended review carried out for some of the major schemes for building automation and control systems auditing and evaluation along with the block of studies targeting various aspects of the BACS shows that the large multitude of theoretical and practical investigations have aimed towards ensuring an optimal design of the BACS, auditing its features and functionalities and making sure that the design complies with the national or international automation and control standards. Considering that the BACS operation and the actual integration with various building components and HVAC systems is as important as the design functionalities, this study will present a first-of-its kind tool for automated step response testing of BACS considering interactions with energy supply systems in buildings. The tool will serve as a key component in both building initial and retro-commissioning applications.

3. Methodology

Figure 2 illustrates a generic system behavior during a unit step response testing. In the first curve, the input changes instantaneously from a specific reference base to a new configuration value. Usually, the input is normalized to a step changing from zero to one unit. The input will depend on the type of system, and which controlled variable is used in the automated control. Then, the output is observed to check possible deviations and the long-term steady state is registered.

One of the most important parameters in a step response test is the settling time. It measures the elapsed time from the start of the input change, until the output has entered and remained close to the setpoint reference. Because "close" is an imprecise and relative measure, a deadband (interval) around the setpoint value is defined, and usually highlighted as a percentage of the setpoint value.

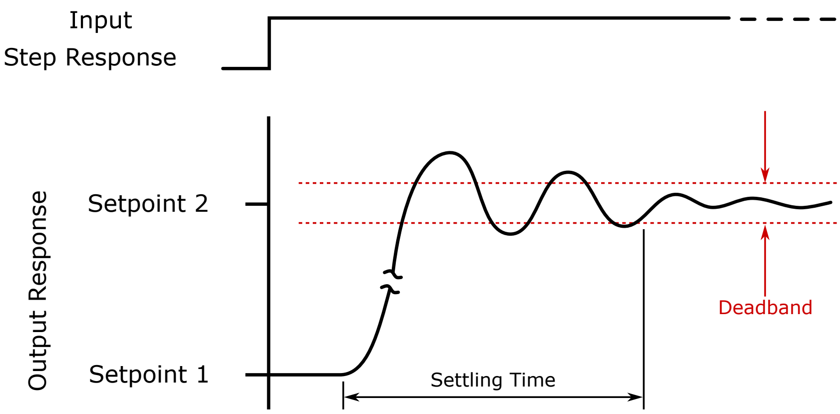


Figure 2. Step response.

Common challenges in step response tests are related to how the output signal behaves after the input change. Different systems have different dynamic behaviors. It is not possible to define a specific duration time which is suitable for all types of tests. For example, for fast response systems, the tests can take a couple of seconds, while slow response systems, can take several days until a feasible response is shown. In addition, undershoot and overshoot values needs to be taken into consideration because if they are not controlled, instability issues may occur. Moreover, the used sample rates can affect the final result of the system. Faster response systems need higher sample rates, otherwise, the number of measured samples would not be enough to decide if stability is achieved. Finally, false positive and false negative response may occur, if the parameters of the step response are not well configured or are not in agreement with the size and the physical nature of the system under testing.

Figure 3 illustrates the methodological framework we propose in this work to implement automated step response testing. The overall structure is divided into two main modules: (1) Building management system, and (2) AUSTRET module for automated step response testing. This shows the dependence of AUSTRET on having an operational BMS system capable of receiving actuator commands and responsible to provide updated state of several state variables. The overall goal is to develop a series of steps that ensures the right sequence of actions, and to enable flexible and automated step response tests over buildings.

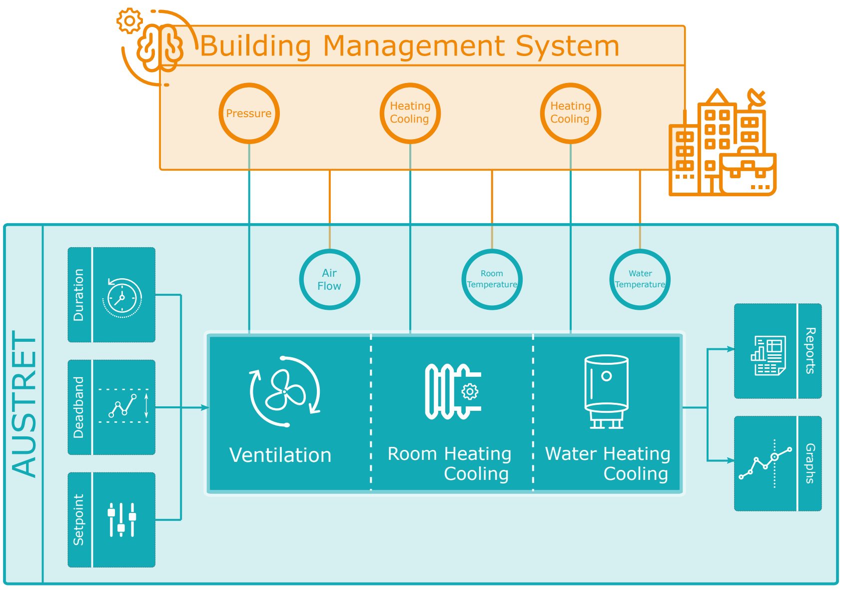


Figure 3. AUSTRET methodology.

3.1. Inputs

The inputs of the unit step response tests are related to the parameters necessary to configure time and precision. It is used to establish internal and external boundaries for the test, as well as relevant constraints. Three parameters stand out when designing generic tests:

1. Setpoint: It is the desired or target value for the output of the controlled variable;
2. Deadband: It is the interval precision defined around the setpoint;
3. Duration: It is the total duration of the test.

3.2. Subsystems

BMS systems are responsible to control and monitor mechanical and electrical equipment such as Heating, Ventilation, and Air Conditioning (HVAC), lighting, shading, windows and door opening, fire and security systems, etc. It is often used for multi-objective goals, such as high comfort level, energy savings, air quality, etc. the pilot case consists of three main modules:

1. Ventilation
2. Room heating/cooling
3. Water heating/cooling

Several modules can be integrated later into the system. The idea is to provide a framework responsible to configure the most important parameters and to generate necessary information and analysis for the step response system. In Section 5, we present a case study with two of the aforementioned subsystems: (1) Ventilation/fan and (2) Room heating.

3.3. Outputs

The proposed methodology needs to perform the unit step response test and collect the necessary data for further analysis. This can be done in two ways. Either reports can be generated with tables and text describing the results of the test or graphs can be generated showing how the controlled variable behaved along the duration of the test. A similar behavior presented in Figure 2 is expected.

An indication of success or failure in the test can also be provided. This can be quite challenging because it depends on several assumptions and correct configuration of the test. Basically, the system can show if the controlled variable signal stayed within the deadband interval until the end of the test, i.e., if the system presented stability response for the considered test. Another approach is to execute the unit step response test and let the user decide if the result achieved stability. In this case, the last step is not automated, but it is more accurate.

4. AUSTRET: Automated Step Response Testing Tool

4.1. Design

Based on the proposed methodology in the previous section, an automated step response testing (AUSTRET) tool is designed and developed in this work. In this context, AUSTRET will have two major features. One is to establish communication with BMS and the other is to automatically manipulate BMS values based on users' wishes. A RESTful BMS Gateway is involved to facilitate the communication between AUSTRET and BMS. The infrastructure of involved RESTful BMS Gateway provides the ability of configuring RESTful endpoints for BMS and serves the REST resources to AUSTRET. Then AUSTRET schedules and performs various HTTP requests to the REST resources to achieve the automation based on the parameters configured by users via AUSTRET interface.

Moreover, AUSTRET also provides a visualization platform where overall results of step response tests can be presented and viewed. All the logged data archives on users' file system in terms of JSON format [38] and will be used for drawing overall report with a visualization library.

AUSTRET presents a friendly user portal where users can be step-by-step guided to configure all the parameters for executing a step response test. On AUSTRET, an executable step response test includes inputs, outputs and several parameters. Table 1 explains all AUSTRET configurable options with their usages.

Table 1. Inputs, outputs and parameters used by AUSTRET.

Inputs and Outputs	Parameters
• Inputs: BMS parameters whose values will be changed and logged during step response test. • Outputs: BMS parameters whose values will be logged during step response test.	• Name: Characters that refers to the name of step response test. It will be shown on report. • Type: Select options that refers to the type of step response test. Different types of step response test will be provided with different default parameters. • Supplied value: The new value that the input is to be changed to from its initial state during the step response test. • Duration: The time in seconds from which the values of inputs are changed until they are returned to their initial values. • Intervals: The frequency of data logging during step response tests in seconds. • Deadband: Percentage number that is used to calculate the upper boundary and lower boundary with supplied value. Two boundaries form the stability areas of step response test and will be drawn on the report. • Start time: This is the time at which the step response test starts to change the values of inputs.

4.2. Workflow

Figure 4 shows the workflow of AUSTRET from a user perspective. To access the main portal, users need to log in with their username and password from log in page. AUSTRET uses PostgreSQL database [39] to manage users and by default a user named "Admin" is created on the database. After successfully logging in AUSTRET, before any performance can be attempted, an authentication is required. This is because AUSTRET establishes communication with BMS throughout a RESTful BMS Gateway that serves BMS data in a RESTful manner. Thus, all the requests sent via the tool to the RESTFul APIs should include credentials in forms of access tokens. The information required for obtaining the access token are username and password of a user who has been created on BMS. Moreover, the host information where the RESTful resources is hosted is also required.

Once an access token is successfully issued from the BMS, users can then start using AUSTRET to customize a step response test. On one hand, the tool provides "search" functionality where users can search out BMS values by keyword they desire. The searched results are structured as a list and consist of all BMS values whose name contains the provided keyword. Then users can select the values they desire and save them as inputs or outputs for the step response test. Figure 5 provides an example of AUSTRET's searching interface. In this example, the user performed a search using "Spt" as keyword and obtained all values from BMS whose name contains "Spt".

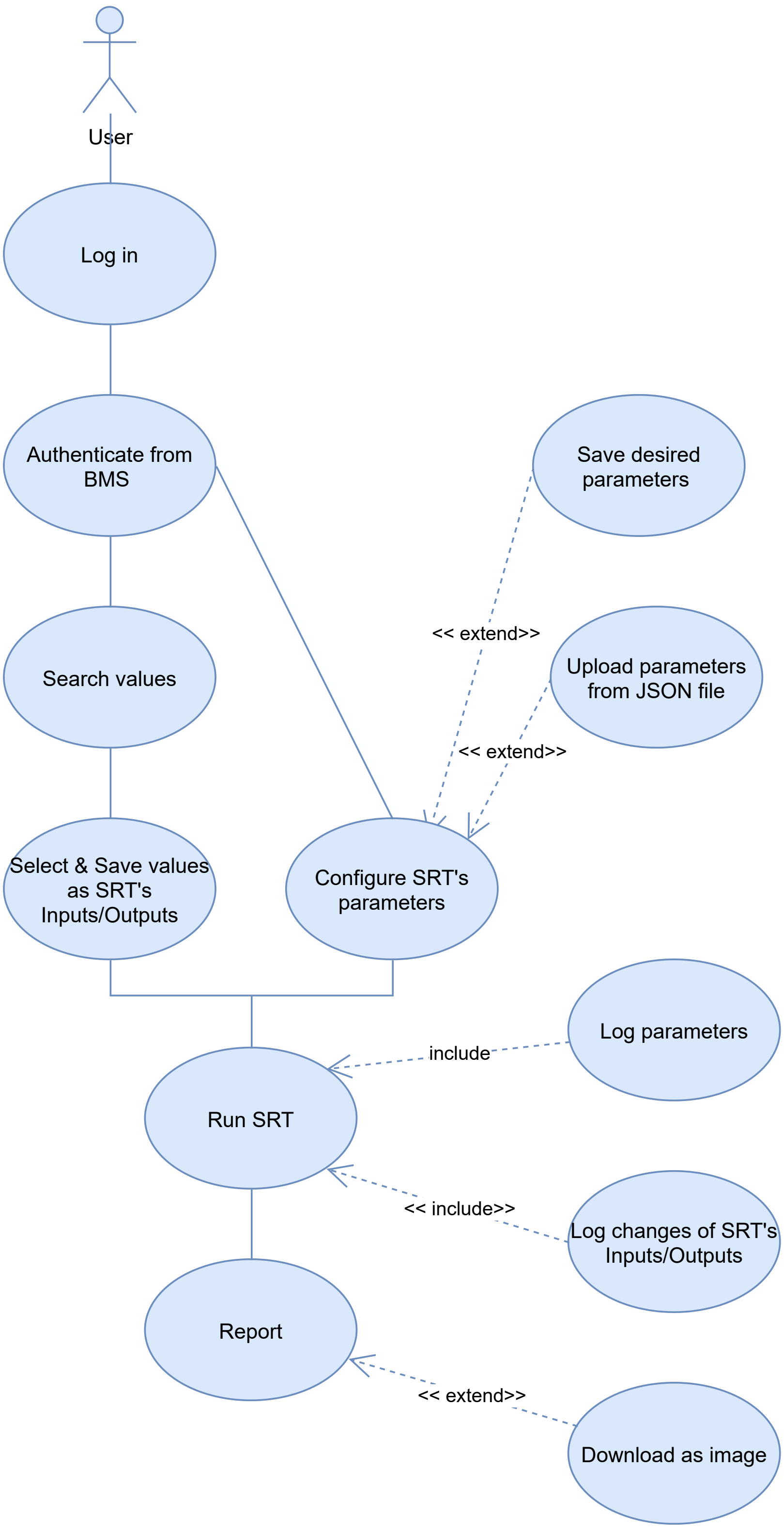
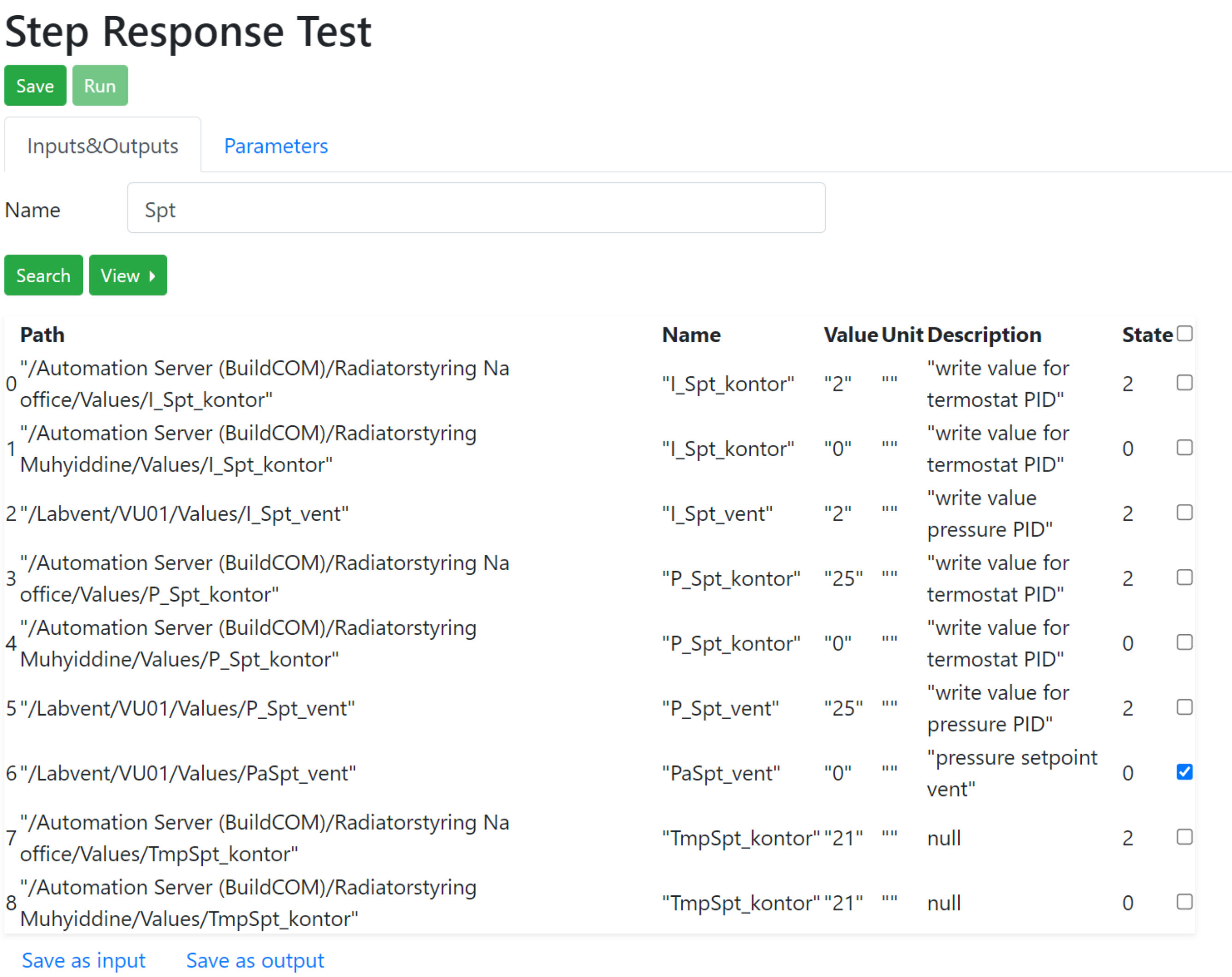


Figure 4. AUSTRET workflow diagram.



	Path	Name	Value	Unit	Description	State	
0	"/Automation Server (BuildCOM)/Radiatorstyring Na office/Values/I_Spt_kontor"	"I_Spt_kontor"	"2"	""	"write value for termostat PID"	2	☐
1	"/Automation Server (BuildCOM)/Radiatorstyring Muhyiddine/Values/I_Spt_kontor"	"I_Spt_kontor"	"0"	""	"write value for termostat PID"	0	☐
2	"/Labvent/VU01/Values/I_Spt_vent"	"I_Spt_vent"	"2"	""	"write value pressure PID"	2	☐
3	"/Automation Server (BuildCOM)/Radiatorstyring Na office/Values/P_Spt_kontor"	"P_Spt_kontor"	"25"	""	"write value for termostat PID"	2	☐
4	"/Automation Server (BuildCOM)/Radiatorstyring Muhyiddine/Values/P_Spt_kontor"	"P_Spt_kontor"	"0"	""	"write value for termostat PID"	0	☐
5	"/Labvent/VU01/Values/P_Spt_vent"	"P_Spt_vent"	"25"	""	"write value for pressure PID"	2	☐
6	"/Labvent/VU01/Values/PaSpt_vent"	"PaSpt_vent"	"0"	""	"pressure setpoint vent"	0	☑
7	"/Automation Server (BuildCOM)/Radiatorstyring Na office/Values/TmpSpt_kontor"	"TmpSpt_kontor"	"21"	""	null	2	☐
8	"/Automation Server (BuildCOM)/Radiatorstyring Muhyiddine/Values/TmpSpt_kontor"	"TmpSpt_kontor"	"21"	""	null	0	☐

Figure 5. Example of searching in AUSTRET.

On the other hand, AUSTRET also provides users with a simple and practical interface to quickly configure parameters of a step response test. It facilitates the parameters' configuration in two ways. First, for different types of step response test, it provides users with different default parameters for their references, while users still can have the opportunity to customize the parameters based on their own wishes. Secondly, users can save their desired parameters as JSON file and load it or share it with other users later. The shared JSON file can be then uploaded with AUSTRET's file uploading interface for a quick setup. Figure 6 shows the configuration interface via AUSTRET. Moreover, users can also validate their configurations before running the step response test, to check for any error in the typing, inputs or time introduced. This step is very important, especially when dealing with large buildings and complex energy systems. After completing all the configurations and passing all the validations, users will be able to run step response tests. During the testing itself, AUSTRET first converts and saves all the parameters to JSON file. Then the main thread starts handling tasks related to update BMS values while another thread is also scheduled to handle data logging for every change of inputs and outputs. After running, the logged data are converted and saved to JSON file that serves as a basis of the final report.

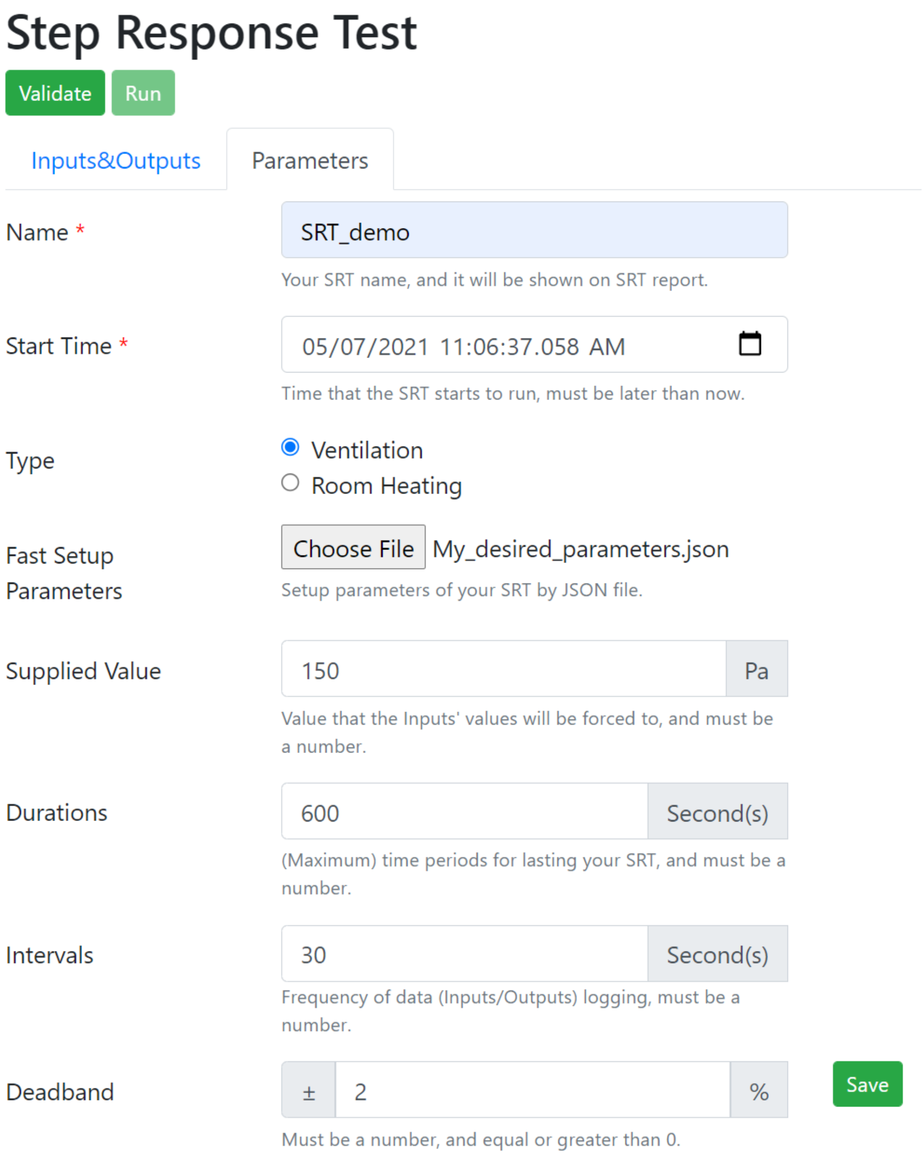


Figure 6. Interface for configuration of the parameters.

AUSTRET has the capability of dynamic reporting with drawings and figures, employing a Java Script for drawing. Some layout variables are pre-defined, such variables as axis width, legend orientation, font, etc. Other layout variables such as report title is dynamically retrieved from the configuration file. Additionally, the layout variables for drawing the two boundaries with dashed lines that define an area interval for stability determination are calculated from deadband and supplied value that are also retrieved from the configuration file. Moreover, for drawing the plots that illustrate the changes of inputs and outputs during step response test, AUSTRET dynamically retrieves data from the data logging file, then the retrieved data are sorted and converted to the data type that can use for plotting based on x axis and y axis. Report examples will be shown in Section 6.

5. Case Study

To test and assess the implementation of AUSTRET, two testbeds were built: (1) Heating system and (2) Fan system, being two common modules in HVAC applications. Moreover, they represent two dynamic systems with their own parameters and configurations. On the other hand, the time response characteristics of the two systems are very different. Both systems are controlled via BMS that is responsible for integrating different components and operation control.

5.1. Heating System

To assess a heating system step response, a small office, located at the Odense Campus of the University of Southern Denmark, is considered to be a case study. The MMMI building [40] was built in 1995 with an energy class C rank based on the Danish building standards. The facility has a multipurpose application with several room types including offices, laboratories, teaching rooms, workshops, meeting, and seminar rooms. The heating is provided by an indirect district heating loop used to feed the radiators and domestic hot water supply.

One of the office rooms was chosen. It has an area of 15 m^2 and 2.5 m in height. Figure 7 shows the heating control system mounted. The system is a typical radiator apparatus that uses water to heat the indoor environment air mass. Several sensors and actuators were installed to provide control and measurement access of different parameters. The thermostat is connected directly to the control unit and regulates the inlet and outlet water heat flow. There is also a heat flow sensor that measures the supply and return temperature of the radiator.

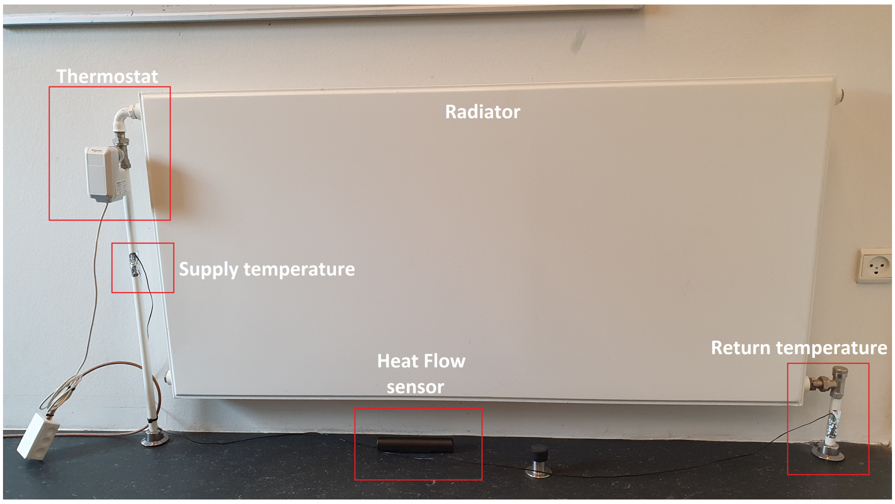


Figure 7. Heating testbed with its components.

Table 2 describes the schedule tests designed for the heating test bed. The idea of these tests is to study how the indoor temperature of physical zone changes depending on several factors. The steps were created to cover most of the parameter variations found in real heating control setups, independent of the technology used. However, the system parameters are very dependent on several conditions, such as the external environment temperature or the building insulation. The tests were executed in December of 2020 and represent the winter conditions in a typical city in Denmark.

Table 2. Heating system schedule tests.

Test	Description	Duration	Setpoint
1	Minimum temperature.	3 day	−10 °C
2	Maximum temperature.	3 day	+30 °C
3	Minimum-maximum excursion	1 day	Minimum to maximum.
4	Increasing steps	2 days	[17:23] °C
5	Initial increasing steps	1 day	[20:23] °C
6	Decreasing steps	2 days	[23:17] °C
7	Initial decreasing steps	1 day	[20:17] °C
8	Sensor location	1 day	Minimum to maximum
9	Occupancy	1 day	from [18:20] °C
10	Stress	1 day	from [18:20] °C

The first parameter to be obtained is the minimum and maximum temperature we can attain by controlling the radiator and are represented by tests one and two. The objective is not to obtain an absolute value, but instead take an approximation value. Test three established how long a test can run, showing what is the maximum observation time to consider. It is an important parameter to define the maximum time necessary to obtain necessary stability in the system. In tests from 4 to 7, several time steps responses are observed. They simulate the common changes found on scheduled control systems or when manual configuration is executed. Tests 8 and 9 evaluate how the location of the sensor and occupancy affects the indoors temperature behavior. Test 10 is a stress condition where doors and windows are kept open to measure the interference of the internal environment with the external environment.

5.2. Fan System

A simple exhausting fan control system was built to apply the step response tests. Figure 8 shows the mounted apparatus. The system is not a real ventilation unit, and the inlet and outlet air are located at the same room. Therefore, parameters such as temperature, humidity and CO_2 concentration are not considered. The main aim of the test is to consider the main active component of air-based cooling/heating systems or ventilation units, which is the supply or exhaust fan.

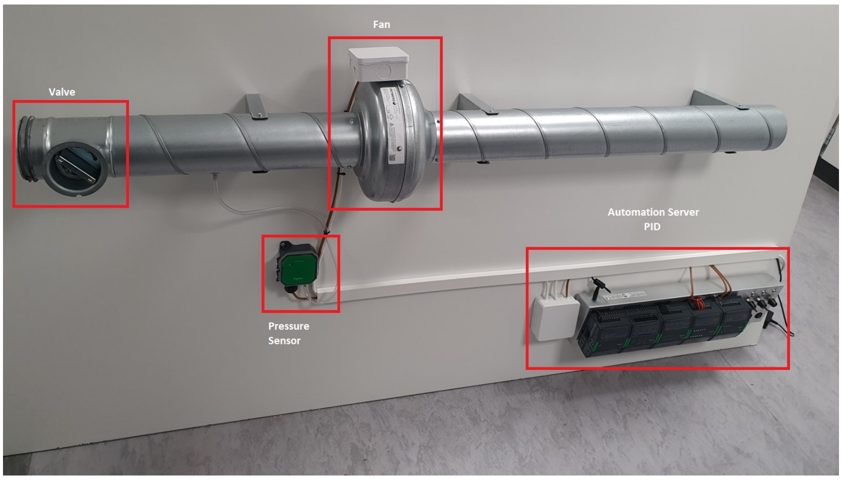


Figure 8. Overview of the fan testbed with its components.

The fan can spin at variable speed, and it is controlled indirectly by the static pressure inside the duct. Therefore, a pressure setpoint is configured and the fan speed will change accordingly. The apparatus also has a valve to simulate the interaction between outdoor and indoor environments. The valve helps to adjust the pressure limits inside the duct to values close to the ones found on real systems. It is a circle damper that can turn 180 degrees on both directions and controls the amount of air that are supplied to the outlet system.

As with the step response test of the heating system, Table 3 describes the schedule tests designed for the fan test bed. A different context is presented in this case. This scenario is a controlled prototype that simulate some features of a ventilation system. Therefore, parameters such as temperature, CO_2 concentration, humidity, etc., need to be disregarded. The experiment is done in a way that we control the pressure inside the duct by increasing or decreasing the fan rotational speed. It is an indirect way of controlling how much air flow pass through the duct.

The schedule tests of Table 3 are very similar to the ones previous defined. However, the observed time is significantly lower. Although the temperature tests could take several days to execute, five minutes are enough to run each fan test. The sensor measurements and the final result have also different magnitudes. No stress tests were possible to be performed with the current setup due to missing the real environment factor.

Table 3. Fan system schedule tests.

Test	Description	Duration	Setpoint
1	Minimum rotation.	5 min	0 Pa
2	Maximum rotation.	5 min	600 Pa
3	Minimum-maximum excursion	5 min	Minimum to maximum
4	Increasing steps	5 min	[0:400] Pa
5	Initial increasing steps	5 min	[200:400] Pa
6	Decreasing steps	5 min	[400:0] Pa
7	Initial decreasing steps	5 min	[400:200] Pa

6. Results and Discussion

6.1. Heating System

The presented results in this section are based on the two testbeds presented in Section 5. Figure 9 shows the results of one step response test scenario carried out for the heating system case. The temperature setpoint was changed from 22.5 °C to 23.5 °C. The deadband is configured within an interval of 2% [23, 24] °C. The heating system can keep the final temperature within the deadband interval after a couple of hours. The temperature will change according to the ambient temperature: rising during day and decreasing during night. Accordingly, the valve position in the radiator will provide more or less openness depending on the time of the day. In particular, it is possible to analyze the actuation of the automatic PID control when the temperature rises close to the maximum border of the deadband in the second day. In this case, the valve closes totally to avoid any additional heating into the system.

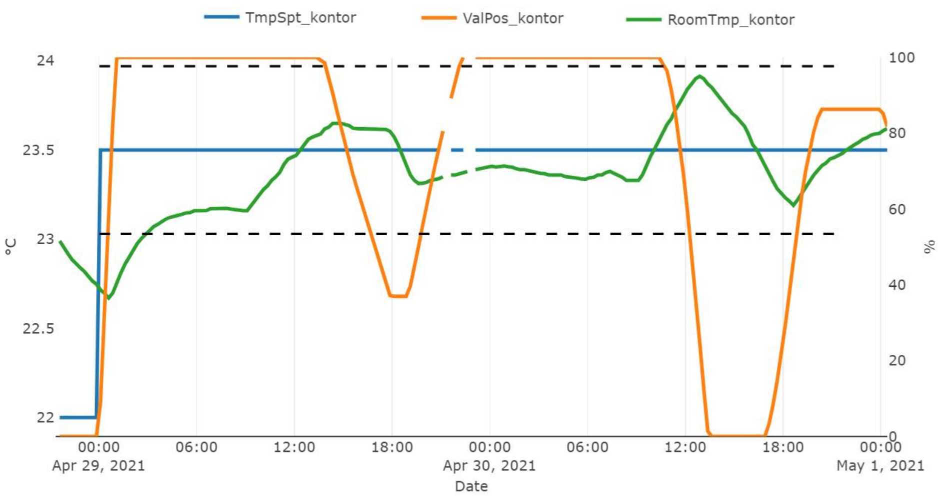


Figure 9. Time step response of the temperature setup.

Figure 10 shows the inlet temperature (External probe 1) and outlet temperature (External probe 2) that are installed in the radiator extremities. A temperature sensor is also installed close to the radiator (Internal probe). Comparing this result with Figure 9, it is possible to verify how the energy provided by the radiator follow the indoor climate temperature in the office.

Figure 11 represents the maximum temperature that can be achieved during winter months. To keep the valve open 100% all the time, a setpoint temperature was configured to 26 °C. The building has a central heating system that control the flow of heating to all offices. That means, we cannot achieve high levels of thermal heating, especially very high temperatures during winter months. This is done to save energy while still providing a pleasant environment for everyday work. The deadband was configured to 2% but we did not expect the temperature values to achieve the defined interval around the setpoint. The maximum temperature obtained was 21 °C, far away from the configured setpoint.

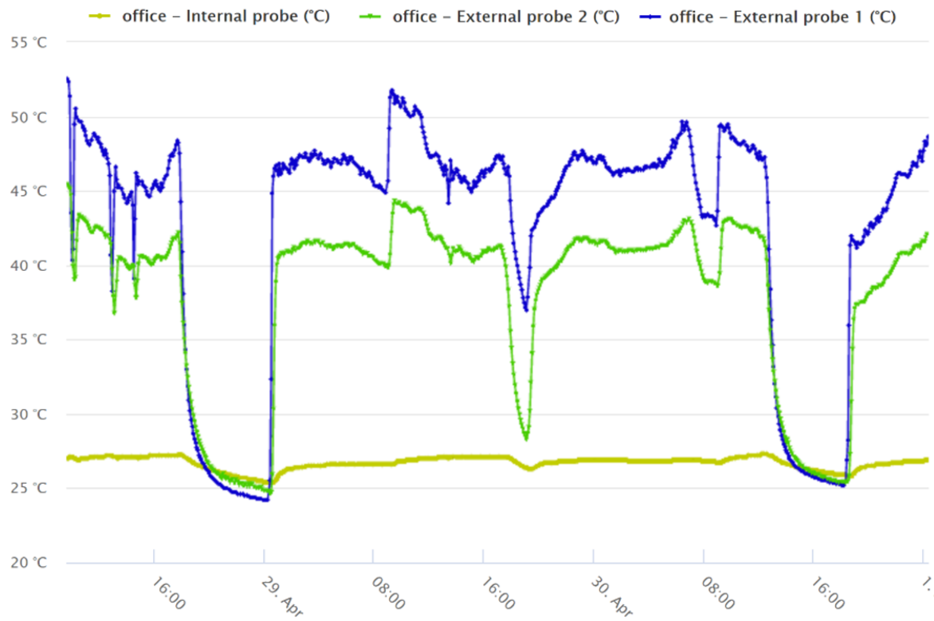


Figure 10. Inlet and outlet temperature from the radiator.

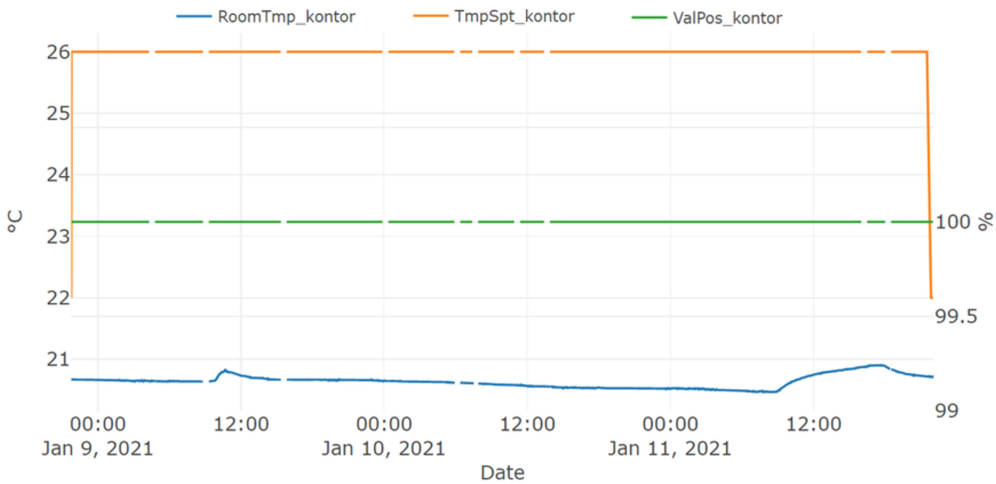


Figure 11. Time step response of the temperature setup: maximum temperature.

During the two days test, the outside temperature changed between 0 and 5.5 °C, as shown in Figure 12. It is also possible to see that the small peaks in the ambient temperature also provided a small increase in the indoor temperature of Figure 11.

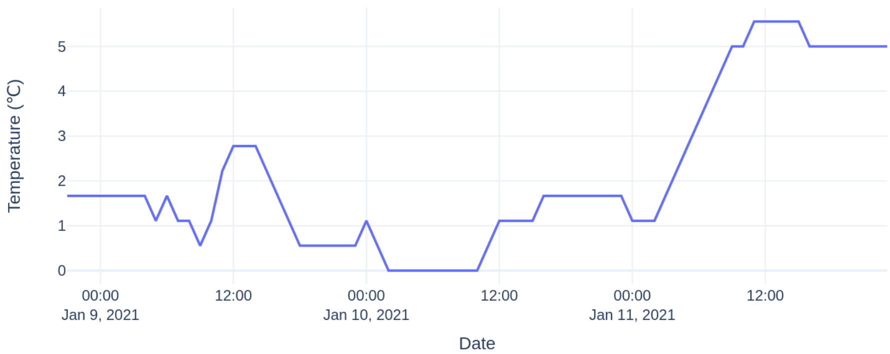


Figure 12. Ambient temperature.

6.2. Fan System

The fan system presented, in general, faster response when compared with the heating setup. While the heating can take several hours, the fan system could have a stable solution in a matter of minutes. Most of the cases presented stability within the interval of [5,10] min. Nonetheless, it is critical to understand the behavior of any systems and avoid misconfiguration of input parameters. Some cases could not achieve stability or the initial time frame was not enough to establish any meaningful conclusions. In all cases a ±2% deadband was adopted: $setpoint - 2\% \leq value \leq setpoint + 2\%$.

Figure 13 shows a successful time step response test. Three signals are shown. *PaSpt_vent* is the air pressure setpoint value in Pa that we aim at achieving, *Pa_vent* is the current air pressure value in Pa, and *Fanspeed* is the rotational velocity of the fan in percentage, where 0% means no rotation and 100% means full speed run. The pressure setpoint was changed from 0 Pa to 100 Pa and maintained for 10 min. The deadband is represented by the dashed lines. The successful criteria are based on the condition to establish a stable response inside the deadband. In this case, this condition is achieved after four minutes.

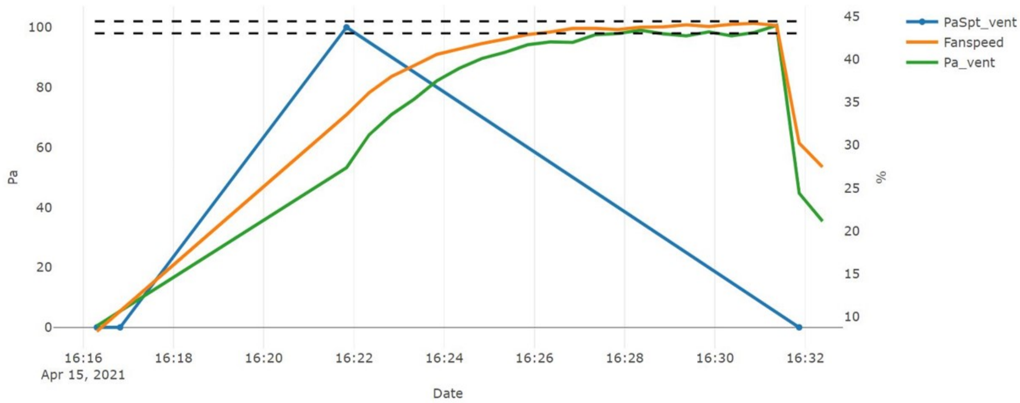


Figure 13. Time step response of the ventilation setup: stable condition.

Figure 14 shows how different input parameters can affect the final result of the tests. In this case, the test duration was changed to five minutes. Shorter tests rise concerns about the final step response stability. It is possible to see that only two readings are inside the deadband interval. The issue is that it is not possible to establish a steady state behavior only with the presented short duration. Longer time is needed to support any conclusions.

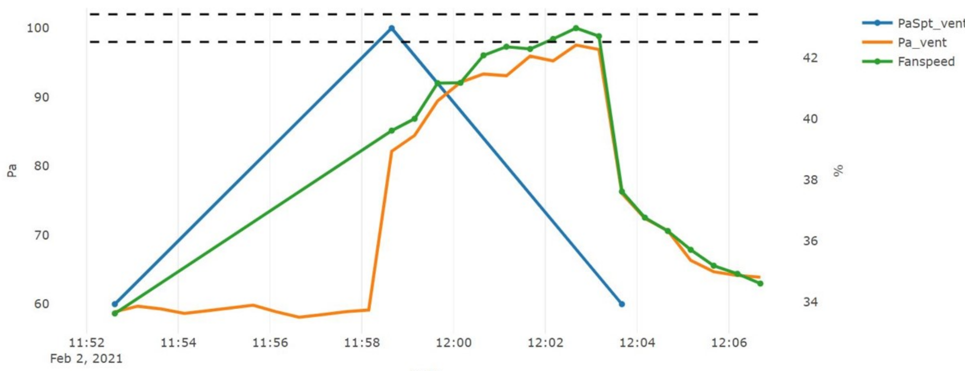


Figure 14. Time step response of the ventilation setup: short stability.

Figure 15 is an extrapolation of physical parameters for the specific test setup. The pressure is changed from 0 Pa to 450 Pa. The result shows that the system cannot achieve this pressure level, even though it is very close to the lower boundary of the deadband interval. This shows the importance of knowing the different capacities and properties of the physical system before applying any step response tests. It is vital to present feasible input parameters, so the final test result has proper meaning. In this specific case the duration of the test would not matter in the final result. The system has a physical limitation to achieve such high pressure even though the fan is spinning with 100%. capacity for the whole duration of the test.

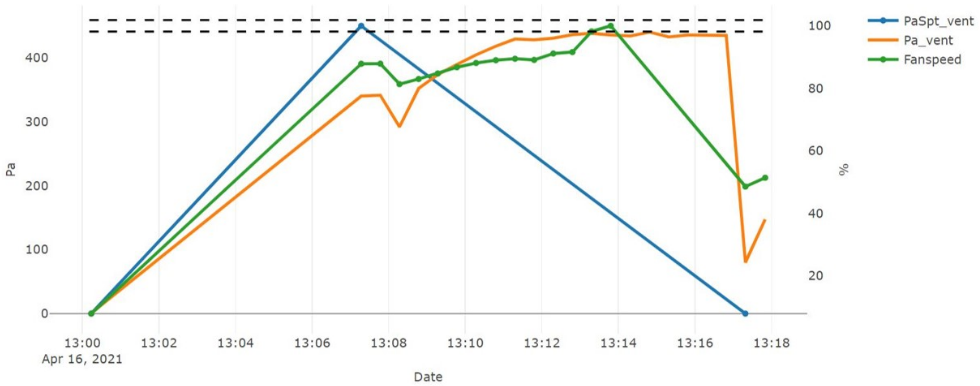


Figure 15. Time step response of the ventilation setup: unstable condition.

7. Discussion and Future Work

In this section, we discuss some relevant topics related to the proposed framework and the implementation of AUSTRET. Some considerations for future work will also be described to improve the current status of the solution.

The framework initially proposes three main modules: (1) ventilation, (2) room heating/colling and (3) water heating/colling. Other subsystems can still be integrated, such as lighting, shading, windows and door opening, fire and security systems, etc. However, this is out of the scope of this paper and will be investigated in a future work. The same happens with the case study that evaluates only two out of three modules. It is still necessary to investigate the dynamics of water thermal mass.

The room control is controlled by a radiator that provides heating energy to the environment. No cooling systems were available to test in our case study. Cooling systems are more appropriated to specific applications or warm countries. In Denmark, where the case study was performed, it is not common to have cooling systems on office buildings. Considering the heating test, it is important to investigate further the influence of weather conditions and the building envelope in the overall performance of AUSTRET. This kind of analysis shows how difficult is to provide pre-defined parameters for automated tests and facilitate step response tests on generic buildings.

The fan prototype built for the second step unit testing is not a real ventilation system. The inlet and outlet air flow has the same source. Therefore, it is not possible to control common variable, such as CO_2 or humidity concentration. We can work with a real ventilation system soon. The results obtained with the fan prototype are very important to be applied on the real system.

AUSTRET integration with the building and prototype subsystems can only be done using the building's proprietary protocols. To establish a flexible solution, open protocols integration needs to be implemented. We envision the usage of OPC UA as the main connection framework because is one of the most flexible solutions for the Industry 4.0 transformation. More effort will be done in the near future to make AUSTRET more flexible to connect with different BMS providers.

As future work, we plan to validate the usage of AUSTRET on real commercial buildings to include the analysis of a complete ventilation system, as well as water heating and cooling. We would also like to implement an OPC UA communication module to be able to connect our current solution to generic subsystems.

8. Conclusions

As a first contribution, we propose a methodological framework for automated response testing of BACS, allowing flexible and fast configuration of auditing tasks in medium to large-sized buildings. This is the first initiative towards the design and development of an innovative automated step response testing application for building automation systems. The framework initially consists of three main modules: (1) ventilation, (2) room heating/colling, and (3) water heating/colling. As a second contribution, the methodology was implemented through the development of the first-of-its-kind AUSTRET tool. The third contribution is the testing of AUSTRET in a case study with two dynamic systems: (1) ventilation/fan, (2) room heating The results show the feasibility of the proposed method. The heating system presented a slower step response and allowed us to configure a lower sample rate. Duration was a critical parameter in this test because longer time was necessary to achieve stability. The fan system presented a faster step response and needed higher sample rates. The duration of this system could be reduced drastically, but still it was important to define the ideal interval to be used. Manual and time-consuming tasks can be replaced by automated solutions, reducing most of the common misconfiguration errors. Although different dynamic responses were obtained by the study cases, their analysis and control were abstracted by AUSTRET tool. The proposed framework and its implementation contributes to the area of building auditing solutions, especially for the new generation of automated solutions envisioned by smart building applications. This solution can help in the digitization transition we are currently facing on new building technologies, especially when considering the modernization and retrofitting most of the building are going through. The society also benefits from this transition by having more energy-efficient structures and, lastly, significantly reducing the human environment impact. The tool will serve as a key component in both building initial and retro-commissioning applications. In addition, more research will be developed to accommodate the integration between BMS and new applications, responsible to automate every single step of the building operation. AUSTRET will be configured on a complete HVAC system setup in a real case study building to be tested in near future.

Author Contributions: Conceptualization, M.J.; methodology, A.S.; software, N.L.; validation, A.S. and N.L.; formal analysis, A.S., N.L., M.J.; resources, M.J., A.S., N.L.; data curation, A.S., N.L.; writing—original draft preparation, A.S., N.L., M.J.; writing—review and editing, A.S.; supervision, M.J.; project administration, M.J.; funding acquisition, M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Energy Technology Development and Demonstration Program (EUDP) grant number 64019–0081.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Acknowledgments: This work is carried out under the "BuildCOM: Automated Auditing and Continuous Commissioning of Next Generation Building Management Systems" project, funded by the Danish Energy Agency under the Energy Technology Development and Demonstration Program (EUDP), ID number: 64019–0081.

Conflicts of Interest: The authors declare no conflict of interest.

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