Digital system interaction test: quality assurance of system functions through standardized tests

Rebekka Benfer [a], Ralf Ulmer [a], Eike Hinck [a], Jochen Müller [a], Samuel Rischmüller [b], Stefan Plesser [b],

[a] Institute of Building Services Engineering, Faculty of Process Engineering, Energy and Mechanical Systems, TH Köln - University of Applied Sciences, Cologne, Germany, rebekka.benfer@th-koeln.de, ralf.ulmer@th-koeln.de, eike.hinck@th-koeln.de, jochen.mueller@th-koeln.de.

[b] synavision GmbH, Bielefeld, Germany, rischmueller@synavision.de, plesser@synavision.de.

Abstract. Technical building systems are becoming increasingly complex, more diverse and more strongly networked through building automation systems. As a result, resource-saving and energy-efficient operation can be achieved. In practice, however, faults and deficiencies often exist in the systems that prevent the most efficient plant operation possible. The deficiencies include, for example, an incorrect parameterization of systems, controller settings that are not matched and optimized to the system, and inadequate cross-plant automation functions. In practice, various methods are used to identify these deficiencies and ensure the quality of automation functions. These include visual inspection of the plant to be tested by certified testing experts. In addition, applications of monitoring and commissioning as well as user-oriented test sequences can be used for fault detection and quality assurance of automation functions. However, the aforementioned procedures are associated with time and configuration effort, which result in costs for their usage and configuration. In addition, they are not based on any generally valid and standardized procedure. Based on these findings, this paper describes the conceptual development of digital system interaction tests that can be used to check different cross-plant automation functions. On the one hand, the focus of the process is on implementing the test procedure as automatically as possible. On the other hand, it should be standardized and generally applicable. Due to the low configuration effort, time and costs for the use of the procedure can be reduced. The standardization of the test procedure enables the application to be used in different technical building systems and creates a transparent form of testing.

Keywords. Energy efficiency, Quality assurance of building services, Automated and low configuration functional tests, Standardized test procedures.
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1. Introduction

Technical building systems are becoming increasingly complex due to their networking. At the same time, the demands on installers and operators are increasing due to the requirement for demand-oriented and energy-efficient operation [1]. In 2019, the energy consumption of the building sector was 35% of the total global energy consumption [2]. [3] have shown that various deficiencies in building systems can be observed in operation. These deficiencies can result in energy not being used optimally and thus the possible energy savings potential not being fully exploited. Future remediation of these deficiencies can lead to increased efficiency and reduced energy consumption in the building sector.

The detection of deficiencies with the aim of quality assurance and optimization of technical building systems, is currently carried out using various methods. Examples are expert inspections, monitoring or commissioning processes and user-oriented test procedures, which are explained below.

Expert inspections

In Germany, expert inspections ensure the effectiveness and operational safety of systems subject to mandatory inspection, as well as the proper interaction of various systems. [4, 5] The inspection is carried out during commissioning, after major modifications and at specified intervals during operation. [4] Tests are executed on site at the plant and include visual inspections of the components, display of the operating states, but also defined functional tests of frost protection, damper control and flow monitoring for the example of an air handling unit (AHU). Building permits and functional descriptions of the systems serve as the basis for testing. [6].

A weakness of expert inspections is that tests take place on site, which creates expense. In addition, the selection of tests specified in the test principles does not include a review of plant efficiency, but only of the effectiveness of selected functions [6].

Monitoring

Plant monitoring aims at the recording and analysis of operating states for function control, operation optimization and analysis of fault conditions. For fault detection various methods can be used for example limit value monitoring, process models or plant simulations. [7]

Due to the fact that data from building automation can be used for plant monitoring [7], remote plant monitoring of analyzable data is possible. In addition, the detection of errors [8, 9] in the operating states enables to eliminate them and thus improve the energy efficiency of the systems. However, since the tests are based on the operating states of the plant, this prevents the verification of the chronological sequence of automation functions. Other disadvantages of the current monitoring systems are the manual integration of data points into test scenarios and that selection of test scenarios is not standardized. Test scenarios are usually created individually for each plant, which results in manual effort. In addition, monitoring is a process without intervention in the plants. If certain load situations do not occur within the monitoring period, they cannot be checked.

Commissioning

Commissioning is the process of ensuring components operate to code and planning. It also includes the optimization of plant parameters under real load conditions to achieve an optimal operating condition. Energy management and information systems or at the plant level building automation systems can be used as tools for this purpose. [10] Continuous or monitoring based commissioning represents the ongoing commissioning in building operation with recording of plant data and evaluation of performance [7]. In [11], due to the increasing complexity of BACS, the need for automated process for commissioning building automation systems is described but not the process itself.

Similar to plant monitoring, energy savings can also be achieved through commissioning [10, 12, 13] However, here too, no test procedures and test scopes are defined in advance.

User-oriented certification

The aim of user-oriented certification [14] is to test the correct functionality of user-specific efficiency programs for technical building services. The configuration effort for testing can be kept low, since test scenarios are adapted to the user requirements and can thus be used for testing all of his systems. In addition, the system is manipulated during the test sequence by means of synthetic values, which means that a check under simulation of different load conditions can be carried out in a short time.

An evaluation of efficiency programs in the municipal environment has shown that only 30% of the efficiency programs tested perform their required function. Identifying these deficiencies and correcting them can save energy, as with monitoring and commissioning. Nevertheless, the configuration effort cannot be completely avoided, since the selection of suitable data points and their integration into the testing process is done manually.

The possibilities for quality assurance and operational optimization of building automation have been described in the previous sections. However, all of the above-mentioned methods involve configuration efforts that are time-consuming. In addition, the test mechanisms differ depending on the system to be tested, which reduces both the transparency and the traceability of the test results. In comparison to the previously described methods, this paper presents a method that is intended to guarantee automated quality assurance and operational optimization of building automation by using uniform test methods and minimizing the manual configuration effort.

2. Research method

This section describes the concept of an automated, digital system interaction test. Its aim is a standardized and transparent testing and quality assurance of automation functions. The test procedure is structured in such a way that it runs uniformly and as automatically as possible. This results in the benefit of minimizing the manual configuration effort prior to the use of test methods such as those described in section 1. In addition, the procedure can be applied to various building services due to its standardized process. The sub-aspects of the test procedure considered are divided into:

- User inputs
- Exploration of the building automation and control network
- Generation of a BACnet [15] data point file for the edge device
- Design of an explorable MQTT [16] topic structure
- Component-based creation of a digital twin
- Generation of a MQTT data point file for the edge device
- Generation of a dispatch file for the edge device
- Component-based test configuration
- Execution of the test scenarios
- Evaluation of the test results

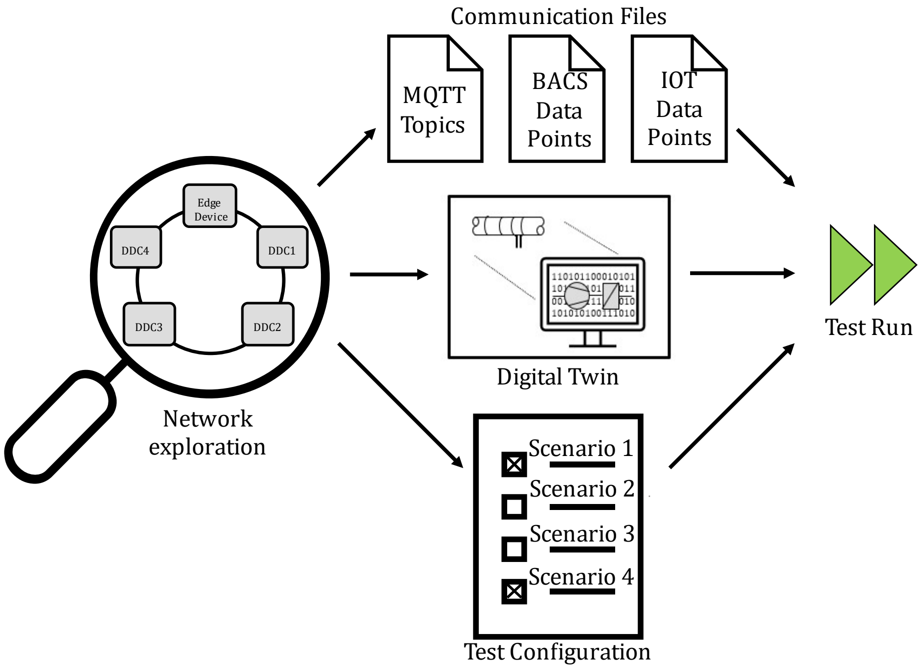

Fig. 1 - Overview of the sub-aspects of digital system interaction tests

In the following sections, the aforementioned sub-aspects of a digital system interaction test will be explained using an exemplary use case of building services. In the first part the general conditions for the use case are defined and followed by separate sections which explain the different aspects of the test procedure in more detail.

Use case assumptions

The scenario shown in Figure 2 is assumed as an example to describe the method of a digital system interaction test.

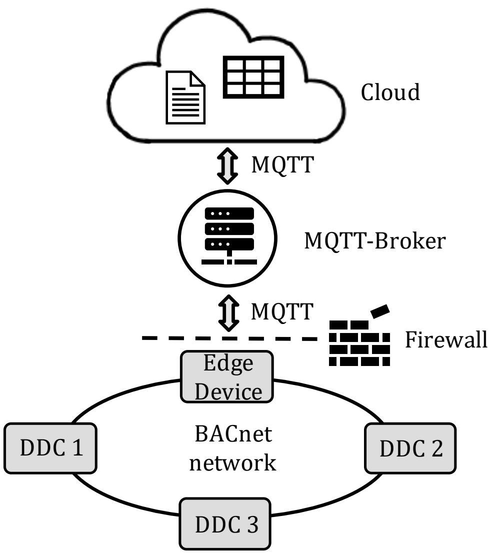

Fig. 2 - Implementation of the communication between protocols of BACS networks and the IoT on the example of BACnet and MQTT using an Edge-Device and an MQTT-Broker

The communication within the building automation and control systems (BACS) network of a property owner is realized via the BACnet protocol [15]. The automation and control of various plants, for example an AHU, is carried out by a programmed automation station (DDC). The existing data points of the plants were designated according to a standardized, defined user address system (UAS). In addition, an edge device has been installed in the same network. It is used to translate between different BACS protocols, explore BACS networks and communicate with IoT protocols. An often used messaging transport system for IoT communication is the Message Queuing Telemetry Transport protocol (MQTT) [16]. An established MQTT broker is used as an interface for a cloud connection. This enables the data transfer between a BACS network and a cloud platform. The data stored in the cloud is available for analysis and evaluation in IoT applications.

User inputs

The process is started by the inspector giving general information about the inspection. It is necessary to specify which plant is to be subjected to a test. This information is based on the plant designation according to the UAS. According to [17], the user input could be "FAC01" (full air-conditioning system). Furthermore, it is necessary to specify the Ida of the BACnet devices which contain information about the plant to be tested.

Exploration of the building automation and control network

The next step is the automated exploration of the BACnet network and data filtering. A BACnet scan is performed by the edge device. It is initiated by an MQTT topic that is published to the MQTT broker by the application for digital system interaction test and subscribed by the edge device. The payload contains the IDs of the BACnet devices to be scanned. The results of the scan are published to the MQTT broker under an MQTT topic created specifically for each BACnet device, for example in XML or JSON format. [18]

After the BACnet scan, the application subscribes to the result topics of the scan using the device IDs in order to be able to further use the detected data points. The payloads of these topics are stored in a database. Since the results of the BACnet scan can be used to test multiple assets, the payload files are duplicated. In the process of the digital system interaction test, only the data points of the plant to be tested are required. To filter the required data, a comparison of the BACnet data point designations with the plant designation defined in section "User inputs" is performed using the duplicates for all BACnet objects from the scan result. All data points whose designation do not include the plant designation are deleted from the XML or JSON files.

Generation of a BACnet data point file for the edge device

Based on the explored and filtered data points described in the previous section, a BACnet data point file is generated. This file contains an entry with specific information from the BACnet scan for each BACnet object of the plant to be checked. This information includes the ID of the BACnet device on which the object was found, the object type and the object instance. This is used to ensure that each entry within the BACnet data point file can be uniquely assigned to a BACnet object. Depending on the structure used by the edge device, every data point looks as follows:

<deviceID>.<objectTyp>_<objectInstance>

If there is, for example a BACnet Object with the object type “binary-input” and the object instance 12 found on the BACnet device with device-ID 25001 the entry would look as follows:

25001.BI_12

In the further process of the digital system interaction test, the BACnet data point file is used as the basis for generating an MQTT data point file for communication with the IoT. BACnet and MQTT data point file are used in the context of this paper by the edge device for communication between protocols of the BACS network (here BACnet) and protocols of the IoT (here MQTT). The description of the implementation is given later in section "Generation of a dispatch file for the edge device".

Design of an explorable MQTT topic structure

In order to be able to implement the further steps of the digital system interaction test as automatically as possible, it is necessary to design an explorable MQTT topic structure. For this purpose, an MQTT topic is designed for each BACnet object based on its data point designation, which also uses the structure from the already defined UAS. This ensures that each MQTT topic is unique and can be assigned to the associated BACnet object.

Component-based creation of a digital twin

In the application, a digital twin is derived from the real plant. It is represented by the information model of the asset administration shell (AAS) [19] and is based on a predefined template depending on the plant type. In the use case "Digital system interaction test", the AAS contains the submodels "Components" and "Test descriptions" (Fig. 3). The submodel "Components" is used to identify the components of the real system. It consists of several SubmodelElementCollections (SMC) for all possible components of an AHU and their designs. In each SMC, properties (Prop) are defined whose values contain MQTT topics. These MQTT topics can be used to indicate the installation of the component described by the SMC in the real system under test. For example, with regard to the preheater of an AHU, the submodel „Components“ contains SMCs for a water preheater and an electric preheater. By matching the explorable MQTT topics of the real system with the values of the properties, it is possible to identify which component is installed in the system. The instance of the digital twin depends on the structure of the real system. For example, if a preheater pump (HEA/PUM) exists in the MQTT topics of the real system, it can be concluded that the preheater is a water preheater.

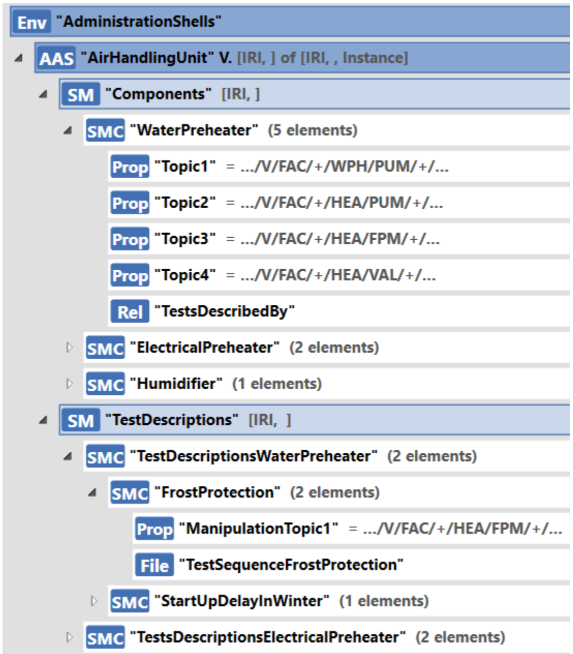

Fig. 3 - Excerpt of the template of an AHU for the instantiation of a digital twin based on a real system

Legend: V – ventilation, FAC – full air conditioning system, WPH – water preheater, PUM – pump, HEA – heater, FPM – frost protection monitor, EPH – electrical preheater, VAL - valve

As a result, only the SMC WaterPreheater of the submodel „Components“ and the SMC “TestDescriptionsWaterPreheater” of the submodel “TestDescriptions” are considered when instantiating the digital twin. In the SMCs of the submodel "Components", RelationshipElements (Rel) refer to the test descriptions associated with the components, which are contained in the SMC of the submodel "Test descriptions". This submodel describes the scope of the tests required to check the subcomponents of the AHU. For each test there is a separate SMC in which the associated test sequences are stored as files and the topics to be manipulated are described. Using the example of a water preheater, the test comprises the check of the frost protection and the winter start-up circuit as shown in Figure 3.

Generation of an MQTT data point file for the edge device

From the information of the instantiated AAS for the system under test described in the previous section, an MQTT data point file can be generated, analogous to the creation of the data point file of the BACS network. This file is used by the edge device for communication with the IoT.

For the purpose of time series data collection, an entry is created for each data point of the system under test, which contains the MQTT topic of the respective data point defined in section "Design of an explorable MQTT topic structure". This topic is supplemented by a suffix, e.g. “/measure”. The suffix is used to inform that the entry contains a data point with information from the BACS network. The edge device is used to send the BACS information to an MQTT broker that is part of the cloud platform. So the sent data can be used for evaluation in the IoT.

In addition, entries are created in the file for data points that have to be overwritten for checking purposes. These depend on the structure of the system under test and its components. The information which data points have to be manipulated are stored in the submodel “TestDescriptions” of the AAS. For each test the

topics used for manipulation are stored in the values of the properties of the according SMC. To indicate that the MQTT topic is used for manipulating the system, it is supplemented with the suffix “manipulate”. This suffix informs that the entry contains a data point with information from the IoT that has to be subscribed from the MQTT broker by the edge device. After this step the information of the IoT is available in the BACS network.

Generation of a dispatch file for the edge device

In order to map the BACnet and MQTT data points to each other, a dispatch file is generated automatically using the described data point files of BACnet and MQTT. In the first step, the topic of each entry in the MQTT data point file is compared with the data point designations of the BACnet data point file. If the MQTT topic contains the BACnet data point designation, an entry for a data point mapping is created in the dispatch file. The structure of the entry, as shown in Figure 4, depends on whether it is an MQTT topic for time series data collection of the system from the BACS network or one for manipulating system data for testing purposes. An indication of this is the suffix of the MQTT topic under consideration described in the previous section.

In the case of an MQTT topic for time series data collection with the suffix "/measure", data from the BACS network has to be transmitted by the edge device to an MQTT broker and thus made available to the IoT. The entry in the dispatch file contains the entry from the BACnet data point file as the information source and the entry from the corresponding MQTT data point file as the destination (compare Figure 4).

In the case of an MQTT data point topic for manipulation of plant data with the suffix "/manipulate", test sequences have to be transmitted from the MQTT broker to the BACS network using the edge device. In the dispatch file, the entry from the MQTT data point file is used as the information source and the one from the BACnet data point file as the destination (compare Figure 4).

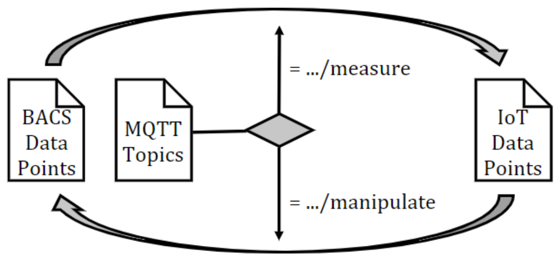

Fig. 4 - Dispatch mechanism for mapping BACnet data points and MQTT data points

Component-based test configuration

This section describes the automated configuration and compilation of test scenarios to be run through as part of the digital system interaction test. This depends on the plant and its components. The results of section "Component-based creation of a digital twin" can be used as a basis for the compilation. Each SubmodelElementCollection (SMC) of a component includes a RelationshipElement, that references to a SMC which contains information about the required tests. (Figure 3) For example the SMC “WaterPreheater” includes the RelationshipElement “TestsDescribedBy” that references to the SMC “TestDescriptionsWaterPreheater”. This SMC contains the required information for a test of frost protection and start-up delay in winter for a water preheater. An excerpt of required tests for different components is shown in table 1. Column 1 contains the component to be tested. In the second column, the test is designated. The third column contains the components that have to be included in the test, depending on their availability. In table 1, the water preheater of an AHU is considered as an example. If a water preheater is available, the triggering of the frost protection monitor and the start-up delay in winter should be checked. These are used to protect the system in order to prevent the heater from being damaged by frost at low outdoor air temperatures. In addition to the preheater, it is also necessary to check the control of the dampers and fans of the system. If the preheater is an electric preheater instead of a water preheater, the triggering of the temperature monitor or the run-on time of the fans in case of system shutdown have to be checked to ensure system safety. By means of the principle presented, all necessary test mechanisms can be selected automatically, depending on the components recognized in section "Component-based creation of a digital twin".

Execution of the test scenarios

Based on the compilation of required tests described in the previous section, setpoints for schedules or indoor air temperatures, for example, are first transferred from the BACS network. These are required for a subsequent target-actual comparison. This is followed by the execution of the test sequences. They are called according to the functions under test together with the associated time series for data points that need to be overwritten during the test process of the function. This time series data are stored in the AAS of the plant under test. Every SMC of the submodel “TestDescriptions” that describes function tests of a component contains a File with the used time series data. Parameters such as climatic environmental influences, measured values or specified setpoints are changed and the reaction of the plant is observed.

In the following, the sequence for testing the frost protection function of a water preheater in an AHU will be explained as an example using table 2. For this purpose, the data point of the frost protection monitor is manipulated in such a way that the system is simulated to be triggered (column "manipulation"). In case of a correctly implemented frost protection function, the system should be switched off. This will cause the closing of outdoor and exhaust air dampers and the switching off of fans. In addition, the preheater should be heated up completely, for which purpose the preheater pump has to be switched on and the preheater valve has to be opened completely (columns "expected reaction"). The actual behavior of the components is recorded using time series data acquisition and published to an MQTT broker by the configured edge device. The data is stored in a cloud database and thus made available for evaluation in the IoT.

Evaluation of the test results

The test sequences defined in table 2 of section "Execution of the test scenarios" represent not only the required manipulation but also the target behavior of the system. Its actual behavior is captured by the records of the test-relevant data points that have been stored in a cloud database. Target and actual behavior are compared with each other. The tests are evaluated component-by-component. If, for example, the outdoor and exhaust air dampers in the example of the frost protection function only react after several minutes, the reaction of these is documented as not corresponding to the target behavior and thus represents a deficiency. For each test, a key performance indicator (KPI) is created that describes the fulfillment of the target state. It comprises a scale from one to ten. If the value of the KPI for the frost protection test is ten, this indicates that all components exhibited the expected target behavior at all times during the test. If the value of the KPI is three, this means that all components together have fulfilled their target behavior over a period of 30% of the tested time.

Tab. 1 - Excerpt of required test scenarios depending on existing plant components using the example of different heater types

Component	Test designation	Components to be tested (according to availability)
Water preheater	Frost protection control	Dampers, fans, heater
Water preheater	Start-up delay in winter	Dampers, fans, heater, control release
Electrical preheater	Overheating control	Heater, fans
Electrical preheater	Fan run-on during system shutdown	Fans

Tab. 2 - Example test sequence for testing the frost protection function of a water heater
t = time unit, *bef = expected plant behavior before test, *man = manipulation, *er = expected reaction, *af = expected plant behavior after test

Component	*bef	*man	*er			*man	*af		
	t = -1	t = 0	t = 1	t = 2	t = 3	t = 4	t = 5	t = 6	t = 7
Frost protection monitor	0	1	0	0	0	0	0	0	0
Outdoor and exhaust air damper	Min-100	-	0	0	0	-	Min-100	Min-100	Min-100
Fans	1	-	0	0	0	-	1	1	1
Heater pump	0/1	-	1	1	1	-	0/1	0/1	0/1
Heater valve	0-100	-	100	100	100	-	0-100	0-100	0-100
Acknowledgement	0	-	-	-	-	1	-	-	-

3. Discussion and conclusion

The possibilities for detecting deficiencies and saving energy have already been presented in the introduction by the methods of monitoring, commissioning and user-oriented certification. The advantages of the method presented in this paper primarily relate to the savings in configuration effort and the standardization of test procedures.

Savings in configuration effort

Compared to the described expert inspection, access to the building automation network reduces the effort for on-site inspections. By using a unified UAS and incorporating a gateway, building automation networks, in this case BACnet, can be explored automatically and the available data points can be transferred into a UAS oriented MQTT topic format. This reduces the configuration effort compared to monitoring applications, commissioning processes or user-oriented certification. With these methods, the data points still have to be explored and mapped to the test scenarios manually. The converted MQTT data points, described in this paper, are standardized by templates of the submodel “Components” of a digital twin and are used for configuration-free selection of test scenarios. This is based on the actual plant structure, its components and their subtypes mapped in the digital twin. The inspector-independent and component-dependent selection thus made possible is not considered in previous monitoring and commissioning applications.

Standardization

Standardization is achieved through component-based test selection and predefined test scenarios. The test scenarios contain synthetic data for triggering specific plant states, so that functions can be checked completely independent without being influenced by real load conditions.

Various stakeholder of the building benefit from the described process. Building owners benefit from time and associated construction cost savings due to increased productivity of executing companies during the commissioning phase. For inspectors of technical systems, the advantage is that inspections can be digitized and automated. Uniform, standardized testing procedures are available that can be used with little configuration effort.

During the operating phase, owners and tenants in particular benefit from the procedure, because detected deficiencies can be eliminated which contributes to energy savings and thus to the reduction of energy costs.

This could lead to a broader application of the described inspection procedure, which would reveal more operational faults and non-energy-saving plant operating conditions. The energy consumption of the building sector can be permanently reduced by eliminating the detected deficiencies and causes an increase in energy efficiency in the operation of technical equipment.

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Data Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.