ISEC 2024 – 3rd International Sustainable Energy Conference
Solutions for Energy Efficiency
https://doi.org/10.52825/isec.v1i.1217

Published: 12 Apr. 2024

Towards a Digital Representation of Building Systems Controls

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Abstract. Energy monitoring and performance optimization processes play a significant role in ensuring energy-efficient building operation. However, the current implementation of these processes requires substantial time and effort due to the fragmented and non-digital nature of technical building equipment information. To address these challenges, we demonstrate the application of the PLCont methodology within an ongoing monitoring process in a real building. PLCont utilizes Semantic Web Technologies and established RDF ontologies to describe the control topology. The digital representation of control functions aligns closely with the IEC standard 61131-3, and the PLCont ontology establishes a connection between the topology and the control functions. We compare the conventional approach and the PLCont methodology using the supply air temperature control of an Air Handling Unit (AHU) as a use case. A graphical user interface built upon the PLCont backend provides a comprehensive representation of the system's functionality. It displays the system topology as a digital HVAC schema, the function code exported from the PLC, time-series data plots, and textual descriptions of implemented functions. We demonstrate how this approach enhances transparency and facilitates the identification and elimination of faulty system behavior, ultimately contributing to the optimization and energy efficiency of building systems.

Keywords: Building Information Modeling (BIM), Building Automation Systems (BAS), Semantic Web Technologies (SWT), Programmable Logic Controller (PLC), Digitization

1. Introduction

The German federal government has set the goal of achieving a nearly climate-neutral building stock by 2050 [1]. In order to accomplish this, the level of energy efficiency in buildings needs to be increased. Energy monitoring and performance optimization processes can help ensuring that buildings are operated in an energy-efficient manner. However, currently, carrying out these processes requires a significant amount of effort and time since the required information on technical building equipment is often distributed across various domains and actors and is only available in heterogeneous and non-digital formats. Enhancing digitization in the design, commissioning, and operation phases of systems like Heating, Ventilation and Air Conditioning (HVAC) systems can help tackle these issues by providing a consistent, up-to-date, and machine-understandable documentation to different stakeholders, which can ultimately lead to an increase in the quality and speed of performance optimization processes. Therefore, in the German funded research project EnergieDigital, we have proposed, developed, and demonstrated a method for an integral, digital description of the building equipment, which uses and links BIM (Building Information Modelling) information and common data formats from individual domains.

In this paper, we focus on the digital representation of building system controls within the overall approach. Ensuring a high quality in the design, the documentation and the programming of controls is crucial to achieve energy-efficient operation of buildings as controls directly impact the performance of building systems such as HVAC systems. For example, an incorrectly programmed heating curve in a heat pump system, which controls the heating water supply temperature based on the outdoor air temperature, can significantly impact the heat pump performance, resulting in higher energy consumption and CO2-emissions. Corrective measures can only be efficiently implemented if the initial situation is correctly captured and understood. Therefore, it is crucial to provide maximum transparency and quality to building managers through access to a digitized, easily accessible, and consistent documentation of the designed and implemented control concepts. In Germany, the VDI 3814 guideline provides recommendations to automation designers on the documentation of building system controls including a textual function description, a building automation schema, and a function list of the control of building systems [2]. Function descriptions are usually developed in the design phase by planners and provided as free text in a non-standardized and hardly machine-readable form, such as PDF files. Automation specialists then implement the control functions in programmable logic controllers (PLC) based on the function description. However, since the descriptions are not standardized, the final implementation can differ considerably between different automation systems and automation engineers. Furthermore, the function descriptions are often not updated after changes in the control strategies in the PLC. A systematic synchronization of the programmed functions with the textual function descriptions is lacking. Thus, existing functional descriptions often only represent the design status, and the actual implemented functions can only be found in the code of the PLCs. This situation hinders an effective application of monitoring and optimization processes. To efficiently carry out these processes, a comprehensive understanding of the building system controls and therefore, an unambiguous and up-to-date digital control function representation is required. In relation to this, the PLCont methodology, which is utilized in this paper, has been developed and described in previous works [3], [4]. This paper focuses on the demonstration of the methodology within an ongoing monitoring process in an existing building.

2. Methodology

PLCont is based on a hybrid approach, where the control topology - which includes controllers, sensors, actuators, and their connections - is described using Semantic Web Technologies (SWT) and established RDF ontologies such as SOSA [5], SEAS [6], and CTRLont [7]. Additionally, the digital representation of control functions aims to adhere to the IEC standard 61131-3 [8] to closely align with the actual implementation in PLCs used in building automation systems (BAS), thereby avoiding the need for additional conversion processes. The PLCont ontology establishes the connection between the topology and the control functions implemented on the PLC. By utilizing SWT and existing RDF ontologies, the digital representation of the control can be linked with the system topology of the corresponding system. Figure 1 shows the schematic overview of the methodology.

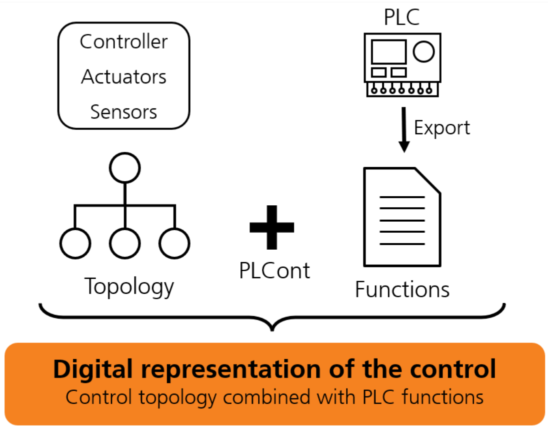

Figure 1. *Schematic overview of the digital representation of the building systems controls (PLCont methodology).*

The digital representation can be enriched with information from the design phase to the operational phase, enabling a comprehensive digital description of building systems within a BIM framework and in alignment with existing standards. Additionally, the implemented control functions can be accessed in an "as-programmed" version without the need to directly access the PLC. This facilitates the identification and resolution of faulty system behavior.

3. Demonstration

The developed approach is being showcased at the 2023 inaugurated seminar center of the Viega company in Germany. We evaluate the method by comparing the conventional approach with our PLCont based methodology. To achieve this, we analyzed textual function descriptions and time-series data to identify possible discrepancies and inconsistencies. We demonstrate the application of the PLCont methodology on an Air Handling Unit (AHU) of the seminar center with heat recovery, heating and cooling functions and show how the digital representation of the controls can facilitate the monitoring process and the energetic performance optimization.

3.1 Comparison of the measurement data with the textual functional descriptions

The supply air temperature of the AHU is controlled by an outdoor air temperature-dependent heating curve, which includes adjustments for summer and winter. Additionally, upper and lower temperature thresholds are defined, as well as a room air temperature compensation if most of the air temperature values in the supplied rooms are lower or higher than their setpoint. The textual function descriptions as found in the design documents of the AHU are given in Table 1.

Table 1. *Function description of the control of the supply air temperature of an AHU.*

Function description	
Lower limit supply air temperature	18 °C
Upper limit supply air temperature	22 °C
Heating Curve (supply air temperature in dependency on the outdoor air temperature OAT)	22 °C at 5 °C OAT 19 °C at 24 °C OAT
Room air temperature compensation	If the majority of the connected rooms in comfort mode are warmer or colder than their set temperature, the supply air temperature will be adjusted within the min-max limits.

The measurement data of the actual value and the setpoint of the supply air temperature, as well as the calculated heating curve, are displayed in Figure 2. The following observations could be made:

- The supply air temperature setpoint values range from 18 °C to 23 °C, with most points around 21 °C.
- The actual supply air temperature values generally follow the setpoint, except for a few outliers for outside air temperatures below 10 °C and above 23 °C.
- Both the setpoint and the actual value deviate from the heating curve.

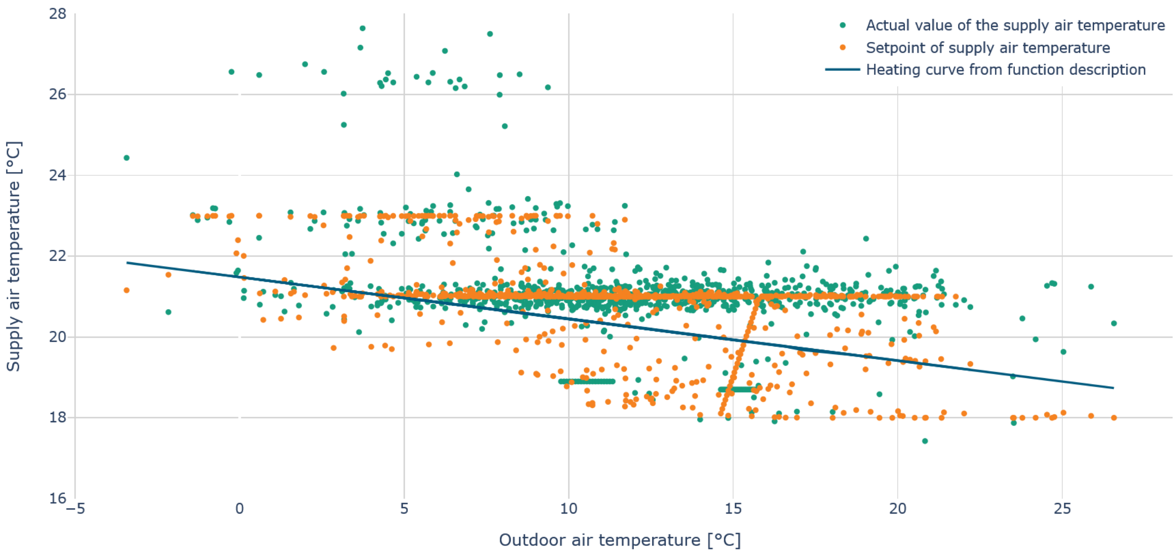

***Figure 2**. Measurement data of supply air temperature setpoint, actual value, and calculated heating curve depending on the outside air temperature.*

The implemented thresholds and the expected distribution of the supply air temperature set point values deviate from the function description: The upper limit of the supply air temperature seems to be at 23 °C instead of 22 °C and it is unclear why for the majority of time steps the setpoint of the supply air temperature is at 21 °C although neither the value nor an additional (seasonal) threshold is mentioned in the function description. Additionally, the supply air temperature setpoint has only a weak dependency on the outdoor air temperature. The function description and the measurement data alone do not provide the necessary insight into the system's functionality to explain or resolve these uncertainties.

3.2 PLCont Application

In this chapter, we show how the process could be facilitated by accessing the PLC code as a function block diagram and visualizing the contents of the PLCont methodology through a specifically developed graphical user interface (GUI) built upon the PLCont backend (see Figure 3). The PLCont GUI enables a comprehensive representation of the system's functionality by displaying the system topology as a digital HVAC schema and the function code exported from the PLC. Additionally, the application displays time-series data plots and provides a textual description of the implemented functions.

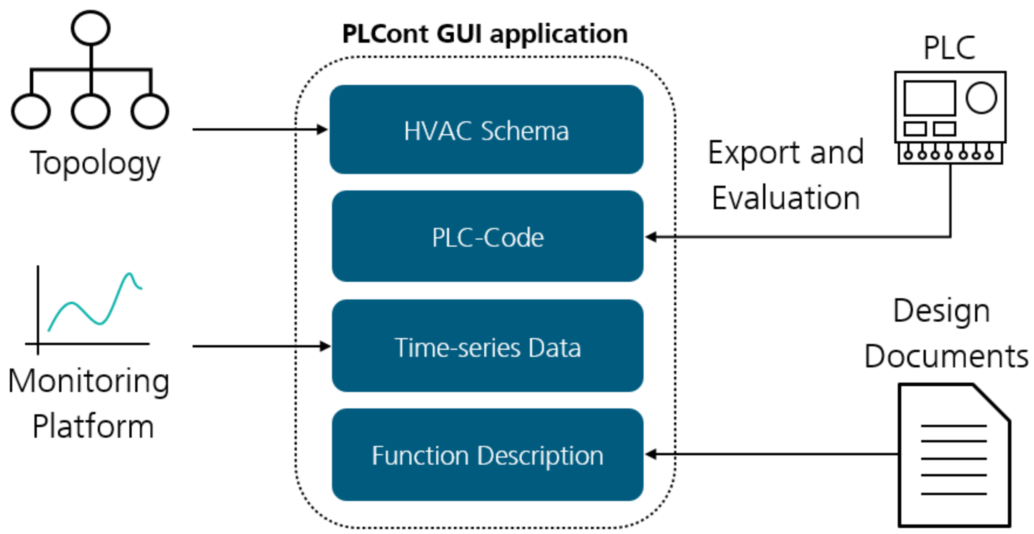

Figure 3. *Structure of the prototype PLCont GUI application.*

The HVAC schema is derived from an IFC file and subsequently linked to the control topology [9]. The PLC code is exported from the PLC using the XML exchange standard [8], and the XML file is connected to the control topology and the entire system topology through the PLCont ontology. The XML representation of the control functions is then analyzed to generate a graphical representation of the function block diagram. Additionally, the system variables and their corresponding unique identifiers are mapped in a post-processing step enabling an automated query of time-series data from a monitoring database. We then utilized the PLCont GUI for the use case of supply air temperature control of the AHU presented above. In Figure 4 the GUI is shown: the digital schema of the AHU, an excerpt of the control functions of the supply air temperature control and time-series data plots of the variables used in the supply air temperature control.

In a subsequent step, the PLCont GUI enabled us to display all relevant information to analyze the PLC code and the time-series data of the variables used in the control functions. Based on this, we could draw the following conclusions:

- Many supply air temperature set point values in Figure 2 hover around the 21 °C line because this value is hardcoded as a lower threshold in winter or upper threshold in summer without being mentioned in the function description as can be seen in the function block diagram in Figure 4.
- The room air temperature compensation is calculated in a separate control sequence based on the difference of the setpoint and the actual value of the averaged room temperature. Since this function block is part of a proprietary library of the automation company, we were only able to access its inputs and outputs but not the complete source code.
- For the winter period (see exemplary days in the time-series plot in Figure 4): The temperature calculated based on the heating curve is below the lower limit of the supply air temperature in winter (21 °C) for most timestamps. If the difference of the set point and the actual value of the averaged room temperature is below zero (i.e., on average the rooms are too warm) the room temperature compensation is also negative and the supply air temperature setpoint defined as the sum of the heating curve temperature and the room air temperature compensation is set to the lower limit of 21 °C. If the difference of the set point and the actual value of the averaged room temperature is above zero (i.e., on average the rooms are too cold), the room air temperature com-

pensation quickly increases to above 2 K and the supply air temperature setpoint increases to the upper limit. As a result, the supply air temperature setpoint in the winter period is either at 21 °C (lower limit) or at 23 °C (upper limit) for most timestamps.

- For the summer period a similar behavior can be observed where the supply air temperature setpoint is set to the upper or lower limit based on the room temperature compensation for most timestamps.

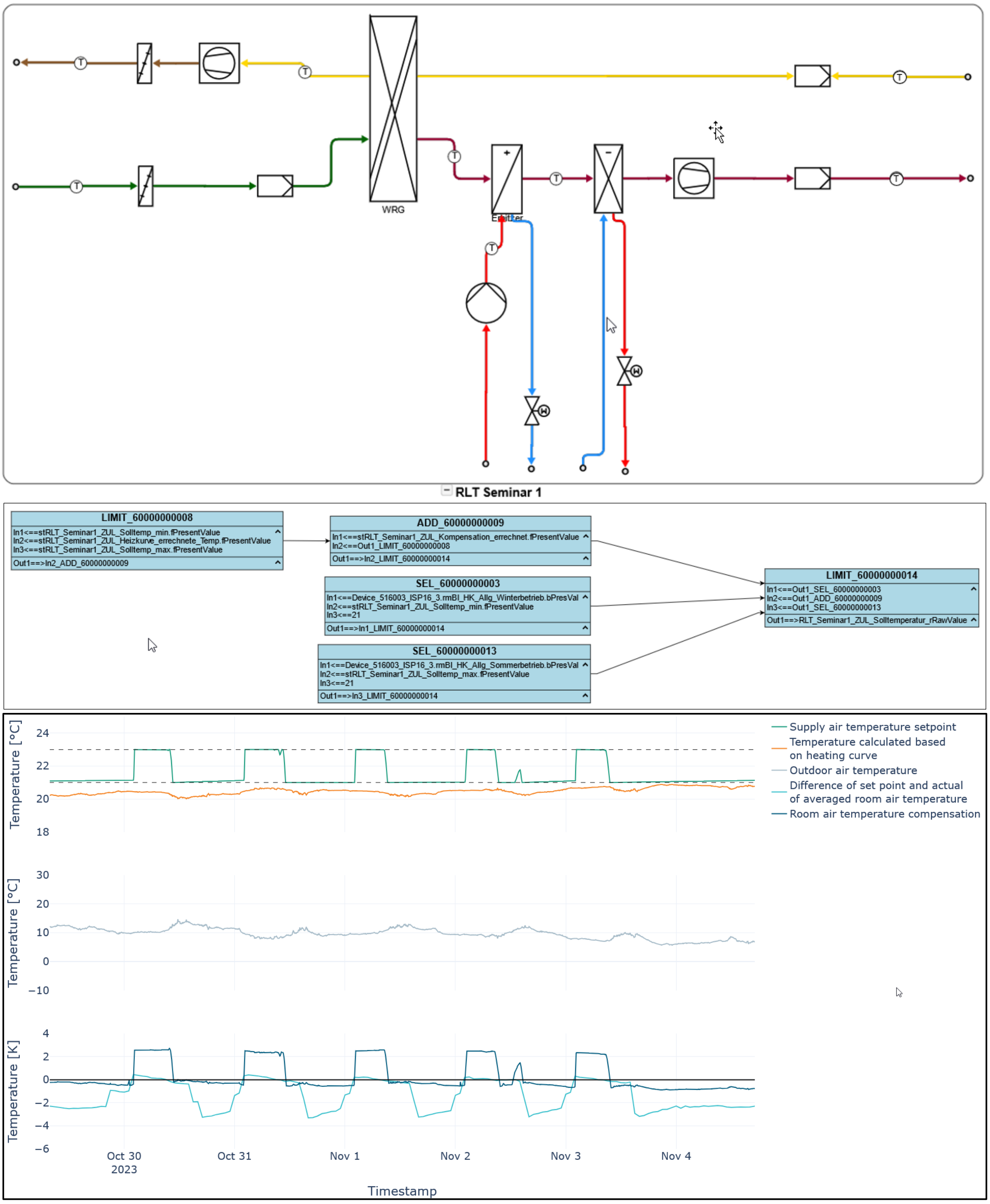

Figure 4. *PLCont GUI for the use case of the supply air temperature control. Top: Digital HVAC Schema. Middle: Excerpt of the control function representation. Bottom: Time-series data for data points that are part of the chosen supply air temperature control.*

As a result, in the winter and the summer period, the supply air temperature setpoint is mostly independent on the calculated heating curve temperature which leads to the assumption that the control sequence used to calculate the room air temperature compensation is incorrectly parametrized.

4. Discussion

The application case examined in this paper highlights the difficulties that can arise in processes for energy monitoring or performance optimization. We have shown that function descriptions can be:

- error-prone (incorrect parameter values, copy-paste errors)
- not up to date (parameters differ from implementation)
- ambiguous (functions are not clearly described)
- incomplete (not all functions are described)

As a result, they do not satisfactorily reflect the implemented control. The presented PLCont methodology circumvents this issue by representing the control based on the functions exported from the PLC. The post-processing routines applied to the XML representation of the PLC code can generate a simplified representation of the implemented control, which can be accessed outside of a PLC and easily kept up to date. When the code is updated, only a new XML export needs to be performed, and the evaluation routines can be run again. The additional connection to the time series data via the developed PLCont GUI facilitates the analysis of the control code.

We have also shown that the automated evaluation of PLC code has limitations. Even if the representation of the PLC code and the corresponding time series data could be evaluated automatically, except for a few manual pre-settings, a more in-depth analysis was not possible due to the use of closed proprietary function blocks. Since each manufacturer and automation company usually uses proprietary functions, the XML export does not represent the complete implemented control functions. These circumstances hinder an in-depth evaluation of PLC code and result in a lack of transparency required in monitoring and optimization processes.

Furthermore, although the representation of the implemented control functions shown here as a function block diagram provides a simplified view compared to the development interface of the PLC, the setup of the PLCont and interpretation of the function block diagram can be time-consuming compared to reading textual function descriptions, especially for complex controls. Clear, up-to-date, and error-free textual function descriptions are required. In the future, the emergence of Generative Pretrained Transformer (GPT) models in the field of large language models could help generating function descriptions based on PLC code and vice versa.

Finally, the PLCont methodology shown here primarily aims to depict the actual implementation status of the controls, without proposing a standard for the code implementation. To address the same problem from a different perspective, other research initiatives are focused on developing a standardized function description and automating the translation of these descriptions into PLC code leading to a reduction of errors and time consumption in the implementation process [10], [11].

5. Conclusion

To unlock the substantial energy efficiency potentials during the operational phase of buildings, building managers and monitoring specialists need a higher transparency of the implemented functions in BAS. This necessitates digital models that provide consistent and up-to-date descriptions of the implemented control functions for HVAC systems. The PLCont methodology presented here addresses this issue by utilizing Semantic Web Technologies and incorporating established ontologies, along with the developed PLCont ontology, to describe the control topology and the control functions exported from PLCs in accordance with the IEC standard 61131-3. We have demonstrated that the implementation of the PLCont methodology, along with its display within the PLCont GUI, enables a quick access to essential information and programmed functions of HVAC systems. Additionally, by linking PLC code to time-series data, we facilitated the identification and resolution of faulty system behavior, which represents the first step towards an optimized and energy-efficient operation of building systems. Furthermore, we have shown that technological and market driven barriers are remaining that hinder the transparency and deployment of third-party solutions capable of optimizing the energy-efficient operation of buildings. The emergence of new, more open systems that preserve the know-how of automation companies while providing consistent information to different stakeholders involved in the operation phase of buildings as well as the recent developments in artificial intelligence with the promising advancements in the field of Natural Language Processing can be enabler for future user-oriented and intelligent BAS.

Data availability statement

The data used in this study was provided under a Non-Disclosure Agreement (NDA) and as such, cannot be publicly disclosed or made available.

Author contributions

Moritz Ihlenburg: Conceptualization, Methodology, Software, Writing: Original Draft, Editing. Nicolas Réhault: Conceptualization, Supervision, Writing: Review & Editing. Sebastian Herkel: Supervision. Gesa Benndorf: Conceptualization, Writing: Review & Editing.

Competing interests

The authors declare that they have no competing interests.

Funding

These works have been carried out within the project EnergieDigital funded from the German Ministry for Economic Affairs and Climate Action (BMWK) under grant agreement no. 03ET1611.

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