

Enhancing Building Energy Efficiency Through IoT Integration

Dhanush M.¹, Shivashankar Hiremath^{2,*}, Subramanya R. Prabhu B.²

Abstract

Building management systems featuring Internet of Things (IoT) technology provide a revolutionary way of maximizing user comfort and improve the use of energy. This study presents a comprehensive analysis of various components within an IoT subsystem utilized in building management, including Smart IoT Gateways, temperature and humidity sensors, lightweight database systems such as Tiny DB, and cloud communication platforms like Twilio. Each component plays a vital role in facilitating real-time monitoring, control, and data analysis, ultimately leading to informed decision-making and improved operational efficiency. A detailed examination of recent studies highlights the impact of daylight supplementation on user experience in office environments, showcasing positive user feedback regarding the integration of horizontal light pipes (HLP). Furthermore, the implementation of static pressure management in HVAC systems demonstrates significant potential for energy savings, with reductions exceeding 50% in certain scenarios. The study also addresses critical methodologies for ductwork calculations, emphasizing the Minimal Energy Dissipation Principle (Min EDP) as a robust alternative for analyzing airflow in duct networks. Additionally, various control techniques for air handling units (AHUs) are classified, ranging from classical methods to advanced strategies, underscoring the need for flexible and adaptive control mechanisms in HVAC systems. The findings underscore the importance of a well-implemented IoT framework, which not only enhances energy efficiency but also prioritizes user satisfaction and comfort in modern building environments. By synthesizing insights from various studies and practical applications, this research contributes to the ongoing discourse on sustainable building practices and the effective integration of IoT technologies in the quest for energy-efficient solutions.

Keywords: IoT, energy efficiency, smart IoT gateway, Tiny DB, Twilio, HVAC systems

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INTRODUCTION

In recent years, the escalating concern over energy consumption and environmental sustainability has led to a paradigm shift in how buildings are designed and managed. A significant portion of global energy is consumed in the construction and maintenance of buildings, driving academic and business experts to explore innovative solutions for improving energy efficiency. One possible approach to overcoming such obstacles is the incorporation of Internet of Things (IoT) equipment into building management systems. The Internet of Things, or IoT is a network of linked devices that can exchange data and communicate with others, thereby facilitating better automation, control, and monitoring of numerous systems.

In the context of buildings, IoT technologies facilitate real-time data collection and analysis, allowing for informed decision-making regarding energy use and occupant comfort. This capability is particularly critical in the management of heating, ventilation, and air conditioning (HVAC) systems, which are major contributors to energy consumption in commercial and residential buildings.

This study aims to explore the various components of an IoT subsystem employed in building management, including Smart IoT Gateways, temperature and humidity sensors, lightweight database systems like Tiny DB, and cloud communication platforms such as Twilio. Each of these components plays a pivotal role in creating a cohesive system that not only improves energy efficiency but also enhances the overall user experience.

In addition, the study reviews relevant literature on building energy efficiency, ductwork calculations, and air handling unit (AHU) control techniques. By synthesizing insights from these areas, the research highlights the potential of IoT integration to optimize building operations and contribute to sustainable practices in the construction industry. The findings underscore the importance of adopting IoT technologies in creating intelligent buildings that meet the demands of modern society while minimizing their environmental footprint.

DIFFERENT COMPONENTS USED IN IOT SUBSYSTEM

Smart IoT Gateway

The SIG (Smart IoT Gateway) device provides a reliable and scalable solution for IoT deployment, enabling real-time online monitoring of RS-485 MODBUS data. It reads the MODBUS memory map of RS-485 MODBUS devices and transmits the data to a cloud server for storage and analysis. The SIG device incorporates GSM, Wi-Fi, or LoRa communication features, dual SIM slots for redundancy, alarm set-points, relays, a buzzer, LED indicators, and various connectivity options. It seamlessly integrates with cloud-based systems, offering a graphical LCD, pen drive interface, SMS/email notifications, and MQTT protocol support. Figure 1 showcases the Smart IoT Edge Gateway employed in our project, while Figure 2 illustrates the interfaces and online data visualization trends associated with the Smart IoT Edge Gateway.

Temperature and RH Sensor

The 85XX+ is an upgraded version of the successful 85XX model, offering enhanced capabilities for various industrial applications. It features multiple serial ports, an Ethernet port, Profibus-DP, a USB port, improved scanning speed, and an alphanumeric display. The modular architecture of the 85XX+ allows for easy expansion with 5 I/O slots that can accommodate a mix of analog input, digital input, open collector output, analog output, or relay output, catering to different requirements in industries such as power, water, pipelines, and infrastructure. Field inputs are connected directly to panel terminals using prefabricated cables, simplifying the wiring process. Configuration of the 85XX+ is user-friendly with the mSCAN+ software, and it can also be edited using the front keyboard and display. Numeric



Figure 1. Smart IoT Edge gateway employed in the project.

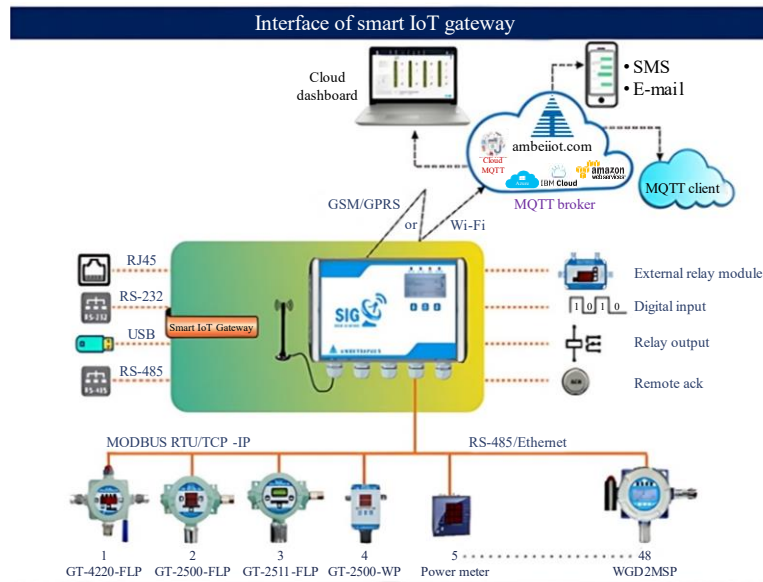


Figure 2. Illustrates the interfaces and online data visualization trends of the Smart IoT Edge Gateway utilized in our project.



Figure 3. Temperature and humidity measuring sensor.

and alphanumeric displays provide value and tag information, while discrete LEDs on the front fascia indicate alarm, trip, and control status. Figure 3 shows the temperature sensor used. The unit offers flexible mapping of 8 relays and 24 open collector outputs for alarm/trip or control set points.

Tiny DB

In our project, we have utilized the Tiny DB library, which can be installed by running the command shown in Figures 4 and 5 which showcases the significance of Tiny DB as a lightweight file-based database system, employed for efficient data storage and retrieval. This library has proven to be highly effective, offering a user-friendly and adaptable solution for managing data without the complexities associated with traditional database systems. With Tiny DB, we were able to create tables or collections, employ key-value data format, and benefit from its filtering and querying capabilities. The system ensured data persistence, thanks to its built-in serialization and deserialization mechanisms. Moreover, Tiny DB's suitability for small to medium-scale projects, coupled with its open-source nature, allowed us to customize and extend its functionalities according to our specific project requirements.

Twilio

Twilio, a cloud communication platform, is integral to our AHU project, providing seamless messaging capabilities. By integrating Twilio, we establish a connection between our system and the cloud, enhancing AHU monitoring and control. The process involves signing up for a Twilio account, creating a messaging service, and configuring our system for message exchange. Incoming messages are parsed and processed, enabling actions and data storage. Leveraging Twilio's cloud-based messaging capabilities enables real-time communication, optimizing AHU management. Figure 6 depicts the step-by-step procedure for Twilio account signup, token ID generation, and obtaining an online phone number, facilitating effective communication in our project.

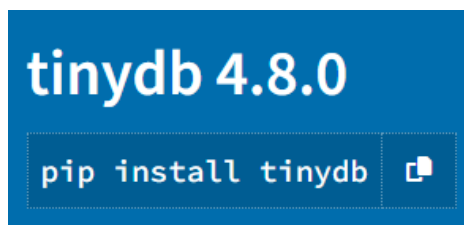


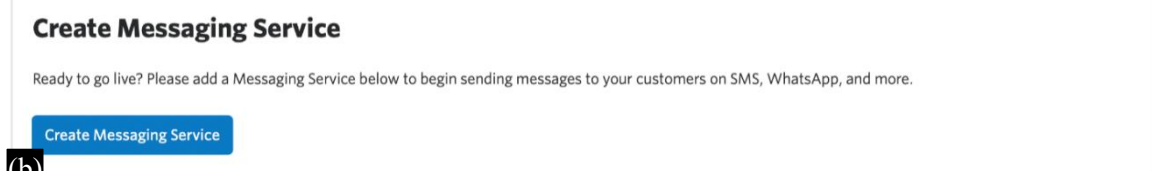
Figure 4. Tiny DB tiny database management system.

```
>>> from tinydb import TinyDB, Query
>>> db = TinyDB('path/to/db.json')
>>> User = Query()
>>> db.insert({'name': 'John', 'age': 22})
>>> db.search(User.name == 'John')
[{'name': 'John', 'age': 22}]
```

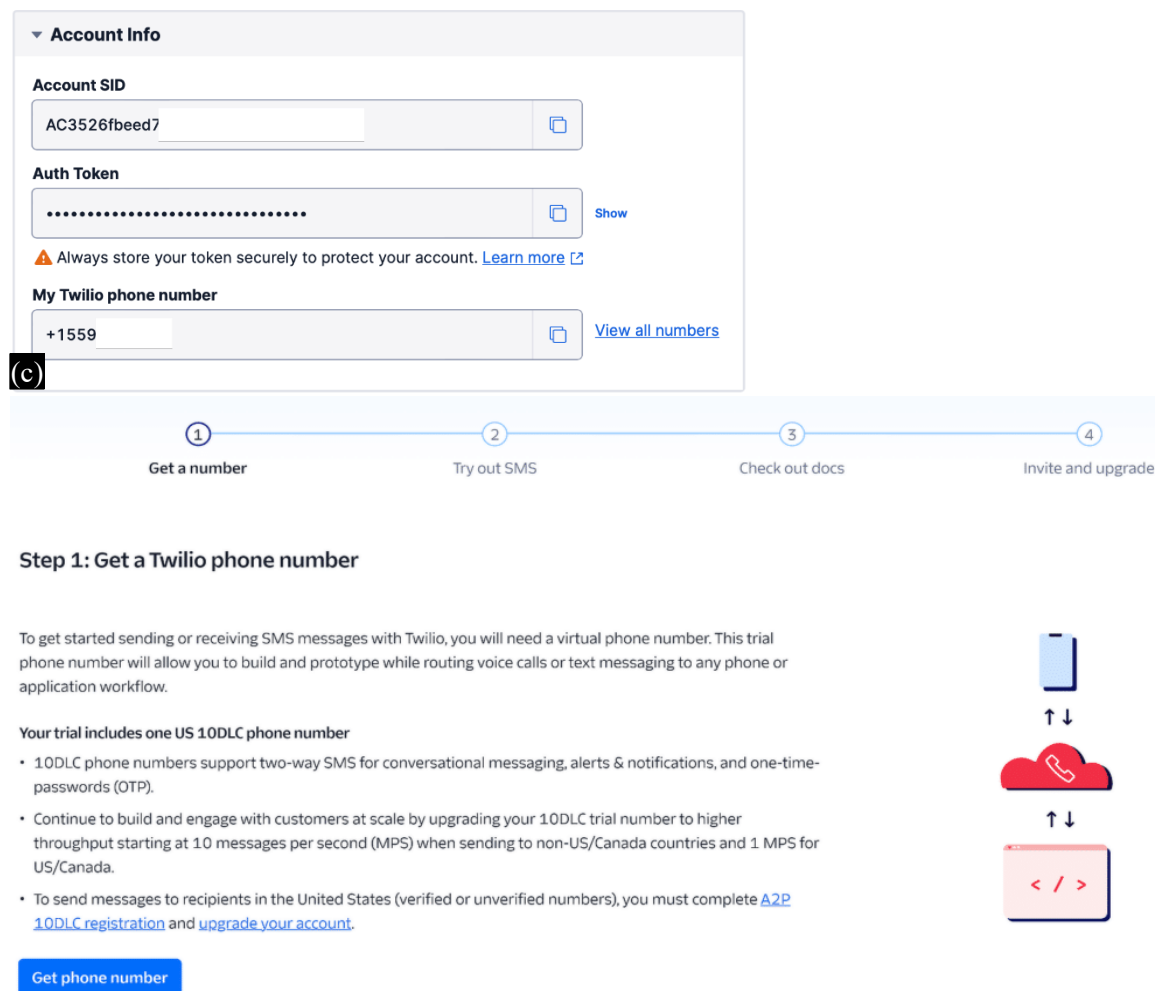
Figure 5. Example code to write a query in Tiny DB.



(a)



(b)



(d) **Figure 6.** (a)–(d) Illustrates the step-by-step process for signing up for a Twilio account, generating a token ID, and obtaining an online phone number.

BACKGROUND THEORY

Building Energy Efficiency

The papers highlighted in this summary focus on various aspects of daylight supplementation and its impact on user experience in office environments. Gao *et al.* conducted a qualitative study to investigate users' opinions of daylight supplementation via a horizontal light pipe (HLP) in a test office in southern Norway [1]. Their findings shed light on the positive appraisal of the office when daylight supplementation was noticeable through the HLP. However, users had negative perceptions of higher light variability in both indoor and outdoor illuminance levels. This study emphasizes the potential benefits of implementing HLPs in building design beyond energy savings, considering user satisfaction and comfort.

The study conducted by Shim *et al.* aimed to explore the effects of a horizontal light pipe (HLP) on user perception of daylight replenishment in a workplace located in southern Norway [2]. Their research also focused on assessing the performance of a VFD-motor-fan system with different static pressure management approaches, highlighting the potential for significant energy savings through static pressure reset. The modelling results demonstrated that implementing static pressure reset could lead to electrical power savings exceeding 50% under conditions where the zone thermal load diversity is moderate. However, the study found that reducing the minimum airflow ratio from 30 to 10% did not result in substantial power savings due to energy losses during low load and speed conditions. Notably, the abstract did not provide further details on the test results comparing the three alternative control systems.

The study conducted by the Ahmed *et al.* aimed to evaluate various technologies used in retro- and ongoing commissioning of HVAC systems in existing buildings. The objective was to identify practical tools for fault detection, energy consumption analysis, and end-user evaluation. Three tools were analyzed in the study [3]. Notably, the Emma-CTA tool demonstrated exceptional performance in detecting and diagnosing faults in air handling units (AHUs). On the other hand, the PECEI Guide proved to be particularly useful in retro-commissioning procedures. Additionally, the IMPVP tool was highlighted as a global standard for energy service companies (ESCOs) in terms of measurement and verification practices related to energy savings. The findings of this study provide valuable guidance to ESCOs, technical organizations, and research institutions in selecting the most suitable instrument based on their specific requirements and objectives.

The study conducted by Hossain *et al.* presents a case study conducted in a French industrial pharmaceutical facility, which identified HVAC systems as a significant contributor to carbon emissions [4]. In response to this issue, the article proposes a comprehensive methodology comprising four steps: air volume reduction, air treatment time optimization, efficient air treatment design, and efficient air treatment management. The methodology suggests the implementation of innovative strategies, including the use of electronically commutated motors instead of conventional motors, to achieve carbon emissions reduction. The study emphasizes that the proposed methodology meets quality, environmental, health, and safety criteria without compromising the overall performance and thermal efficiency of HVAC systems. The case study provides practical evidence of how HVAC systems in industrial settings can effectively decrease carbon emissions. Furthermore, the suggested methodology offers a framework for selecting the most suitable HVAC systems or upgrading existing ones to minimize carbon emissions while adhering to necessary environmental standards.

Ductwork Calculation

The study conducted by Soto-Francés *et al.* addresses the limitations of conventional duct network analysis in HVAC air-duct systems, particularly in relation to head losses at branched junctions. The authors argue that ignoring these head losses can lead to numerical issues and inaccuracies [5]. In response, they propose the Minimal Energy Dissipation Principle (MinEDP) as an alternative method for analyzing flow networks, including HVAC air-duct systems. The MinEDP offers several advantages, including rapid operation and the ability to handle negative head losses without requiring ad hoc modifications or prior knowledge of the solution's nature. While alternative models based on physical principles have been proposed, the authors advocate for the Min EDP as a technique suitable for studying the steady state of any flow network, even those involving shear work at junctions. Overall, this research highlights the significance of accurate and effective methods for analyzing HVAC air-duct systems to ensure optimal performance.

Different AHU Controlling Techniques

The study conducted by Afram *et al.* explores and categorizes various control methods for HVAC systems [6]. The classification includes classical control, hard control, soft control, hybrid control, and other control techniques. Classical control methods, such as on/off control and PID control, are commonly used but have limitations in terms of accuracy and tuning [6]. Hard control techniques, such as gain scheduling, nonlinear control, robust control, optimal control, and Model Predictive Control (MPC), provide more advanced strategies for HVAC system control, addressing disturbances and optimization goals. Soft control techniques, including Fuzzy Logic (FL) control and Artificial Neural Network (ANN) control, offer flexibility in control actions, auto tuning, and nonlinear modelling. Hybrid control approaches combine both hard and soft control techniques to leverage their strengths and tackle complex control problems in HVAC systems. The study briefly mentions other control techniques like direct feedback linear control, pulse modulation adaptive control, pattern recognition adaptive control, preview control, two-parameter switching control, and reinforcement learning control. The research highlights the benefits, challenges, and applications of each control approach in the context of HVAC systems, providing valuable insights for energy-efficient control of AHUs and other HVAC processes.

Classification of Algorithms and IoT Devices

The research conducted by Afram *et al.* presents a comprehensive analysis and classification of various HVAC system control strategies [6]. Their study categorizes control techniques into classical control, hard control, soft control, hybrid control, and other control methods. Classical control techniques, such as on/off control and PID control, were found to have limitations in terms of accuracy and tuning [6]. On the other hand, hard control approaches, including gain scheduling, nonlinear control, robust control, optimal control, and Model Predictive Control (MPC), offered more advanced strategies to address disturbances and optimize HVAC system control. Soft control methods, such as fuzzy logic (FL) control and artificial neural network (ANN) control, provided flexibility in control actions, auto tuning, and nonlinear modelling. The study also briefly mentioned other control techniques like direct feedback linear control, pulse modulation adaptive control, pattern recognition adaptive control, preview adaptive control, two-parameter switching adaptive control, and reinforcement learning adaptive control. The research provides valuable insights into the benefits, challenges, and applications of each control strategy in the context of HVAC systems. These findings contribute to the development of energy-efficient control strategies for AHUs and other HVAC processes.

The study conducted by Balasubramanian *et al.* [7] focuses on developing a diagnostic framework for air handling units (AHUs) by utilizing statistical-based approaches and machine learning models for failure detection and diagnosis (FDD) methodologies [8]. Statistical approaches such as Fisher Discriminant Analysis (FDA) and Principal Component Analysis (PCA) were employed for fault diagnosis, contrasting PCA models with pre-defined thresholds based on prediction errors. Machine learning techniques, including support vector machines (SVM), wavelet analysis with artificial neural networks (ANNs) were also used for AHU FDD. Balasubramanian *et al.* presented a diagnostic methodology that encompasses data preparation, decision tree induction, evaluation, and interpretation, utilizing integrated decision tree algorithms with pruning based on cost-complexity criteria and residual features [7].

In their paper, Omer Ali *et al.* discuss real-time object detection and classification using Microsoft Custom Vision multi-class Machine Learning (ML) model at the IoT edge [9]. They explore the use of virtual dockers or containers for enhanced security and isolation, running multiple applications on a single hardware. The experiments conducted on emulated IoT devices on Microsoft Azure IoT platform validate the accuracy and implementation of the model for future Smart City surveillance.

In their paper, Tarjan *et al.* introduced a low-cost hardware module that facilitates the integration of traditional industrial machines into Industry 4.0 through the IoT. The module enables synchronization of machine measurements and states with a cloud server, without requiring the machine to have advanced communication protocols [8]. A dedicated smartphone app allows remote monitoring and control of the machine via the cloud, and offers additional capabilities for data storage, processing, and analysis. The solution was successfully validated on a conveyor belt system controlled by a programmable logic controller and variable-frequency drive.

In the context of the Internet of Energy (IoE), the paper by Yifeng *et al.* proposes a decentralized IPT cloud/fog architecture for the distributed energy resources management system (DERMS) [9]. This architecture connects IPT fog and cloud nodes to achieve time synchronization accuracy of less than 1 μ s and improved performance in terms of system layers, real-time capacity, construction speed, and availability. The proposed architecture is verified with a wastewater treatment virtual power plant (VPP) application case.

In their paper, Zhu *et al.* proposed an enhanced robust model-based optimal control strategy for cooling water systems in air-conditioning systems [10]. It uses fuzzy c-means clustering and fuzzy inference to predict model output errors, leading to improved energy performance. Validation with real operation data and simulations demonstrates its effectiveness, saving up to 0.9% in the presence of model errors and up to 3.22% with measurement bias errors. Although computation time increases, it remains feasible for implementation in practical building automation systems.

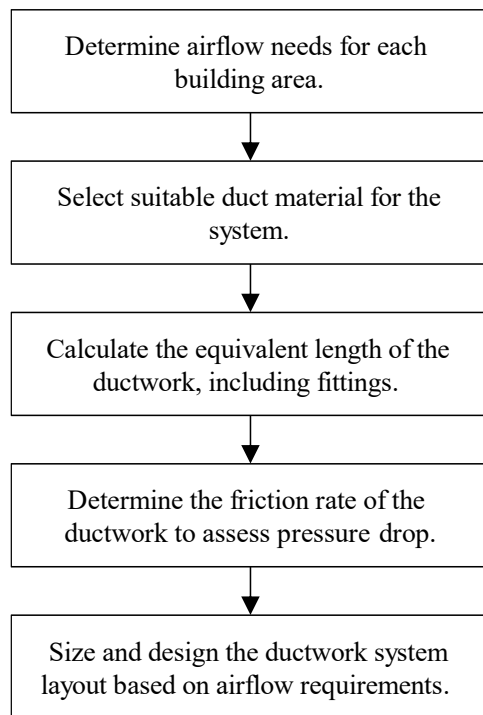


Figure 7. Block diagram to represent steps involved in ductwork calculation.

METHODOLOGY

Theoretical Discussion

The process of designing the ductwork system for a building involves several key steps. Firstly, the airflow requirements for each area are determined. Next, an appropriate duct material is chosen, and the equivalent length of the ductwork is calculated, considering fittings and bends. The friction rate of the ductwork is then determined to assess pressure drop. Using the airflow requirements, equivalent length, and friction rate, the duct size is calculated to ensure optimal performance. The ductwork system layout is designed, specifying sizes, lengths, and fittings. Finally, simulation software is used to verify the design, ensuring that airflow requirements are met, and pressure drop is within acceptable limits. Figure 7 shows the block diagram showing the steps to do ductwork calculation.

CONCLUSION

An important step toward raising occupant comfort and attaining energy efficiency is the incorporation of Internet of Things (IoT) equipment into building administration systems. This study has explored various components of an IoT subsystem, including Smart IoT Gateways, temperature and humidity sensors, lightweight database systems like Tiny DB, and cloud communication platforms such as Twilio. Each component contributes uniquely to a holistic approach that optimizes building operations through real-time monitoring, control, and data analytics.

The review of current literature emphasizes the importance of daylight supplementation and advanced HVAC control techniques in improving user experience and achieving substantial energy savings. Studies have shown that implementing strategies such as static pressure management in HVAC systems can lead to power savings exceeding 50%. Additionally, the Minimal Energy Dissipation Principle (Min EDP) offers an effective method for ductwork calculations, ensuring that airflow is optimized while minimizing energy losses.

Additionally, the organization of different AHU control techniques emphasizes how important it is to be adaptable as well as flexible while reducing building systems. By employing a combination of

classical, hard, soft, and hybrid control methods, building managers can address complex challenges while maximizing energy efficiency. To sum up, this study's findings reveal how IoT technologies have the ability to completely transform building management methods.

As the demand for sustainable solutions continues to rise, the integration of IoT systems in buildings will play a crucial role in promoting energy efficiency, reducing operational costs, and enhancing occupant satisfaction. Future research should focus on further optimizing these technologies, exploring new applications, and addressing any challenges associated with their implementation. Ultimately, embracing IoT in building management paves the way for intelligent, sustainable environments that cater to the needs of modern society while contributing to environmental conservation.

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