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# Designing Smart Building Management Systems for Sustainable and Cost-Efficient Housing

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**Abstract**

The growing demand for sustainable and cost-efficient housing solutions has spurred the development of Smart Building Management Systems (SBMS), which leverage advanced technologies such as Internet of Things (IoT) devices, artificial intelligence (AI), and data analytics to optimize building performance. This paper explores the design, implementation, and impact of SBMS on promoting energy efficiency, resource management, and overall cost reduction in housing. The study highlights key design principles, including the integration of smart technologies, the use of sustainable materials, and the optimization of control systems like HVAC, lighting, and waste management. Additionally, it examines common challenges in SBMS implementation, such as technological, financial, and regulatory barriers, and proposes solutions like innovative financing models, public-private partnerships, and updated regulatory frameworks to facilitate broader adoption. The paper also identifies gaps in existing research, such as the need for more studies on technology integration, scalability, and user engagement. Finally, the paper concludes by offering recommendations for future research, focusing on the development of emerging technologies, policy frameworks, and user behavior studies to enhance the efficacy of SBMS in achieving long-term sustainability and cost-efficiency in housing.

**Keywords:** Smart Building Management Systems, Sustainability, Cost-Efficiency, IoT Devices, Energy Optimization, Regulatory Frameworks

## 1. Introduction

### 1.1 Overview of the Challenges in the Housing Sector

The housing sector faces several persistent challenges that hinder the achievement of sustainability and cost-efficiency. Rapid urbanization, population growth, and increased demand for affordable housing have placed immense pressure on existing infrastructures. Traditional building designs often fail to meet the growing need for energy-efficient, environmentally sustainable, and cost-effective solutions (Onukwulu, Fiemotongha, Igwe, & Ewim, 2023) [55]. Consequently, energy consumption in buildings remains a significant contributor to global carbon emissions, particularly in the residential sector. Furthermore, the high operational costs of maintaining housing systems such as heating, cooling, and lighting further exacerbate the economic strain on homeowners and tenants, particularly in urban areas where living expenses are already rising (Abisoye *et al*.; Gil-Ozoudeh, Iwuanyanwu, Okwandu, & Ike).

In addition to environmental concerns, there is an increasing demand for smart technologies that improve the quality of life for occupants while reducing operational expenses. Aging housing infrastructure, limited access to capital for refurbishment, and outdated building management practices present significant barriers to integrating modern technologies. These challenges demand the exploration of innovative solutions that balance sustainability, cost-efficiency, and occupant satisfaction. As housing becomes an increasingly scarce and expensive resource in many parts of the world, the integration of advanced building management systems presents a viable strategy to address these critical issues (Afolabi & Akinsooto, 2021; Igwe, Eyo-Udo, & Stephen, 2024b) [9, 40].

Smart Building Management Systems (SBMS) are integral to addressing the challenges of sustainability and cost-efficiency in housing. These systems leverage advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics to optimize the operation of building infrastructure. SBMS integrate various building functions, including heating, ventilation, air conditioning (HVAC), lighting, energy management, and security, through a centralized platform. By utilizing real-time data and predictive algorithms, these systems can dynamically adjust settings to enhance energy efficiency, reduce waste, and lower costs (Paul, Ogugua, & Eyo-Udo, 2024b) [62].

The relevance of SBMS to the housing industry lies in their ability to enhance the environmental and economic performance of buildings significantly. With growing concern over climate change and resource depletion, housing needs to adopt sustainable solutions that minimize energy consumption and reduce environmental footprints. SBMS offer the potential to achieve these goals by integrating energy-efficient technologies, such as smart meters, automated energy-saving strategies, and sustainable energy sources like solar panels (Agbede, Akhigbe, Ajayi, & Egbuhuzor; Olufemi-Phillips, Igwe, Ofodile, & Louis, 2024 [46]).

In addition to the environmental benefits, SBMS improve occupant comfort, security, and overall building performance, making them an attractive option for developers, homeowners, and tenants alike (Basiru, Ejiofor, Onukwulu, & Attah, 2022; Olufemi-Phillips, Ofodile, Toromade, Igwe, & Adewale, 2024) [21, 47]. As the demand for smart homes and sustainable housing solutions increases, SBMS present a crucial component of the future housing landscape. The application of such systems ensures that buildings can meet regulatory requirements for sustainability while providing cost-saving opportunities for owners and operators (Onukwulu, Fiemotongha, Igwe, & Ewin, 2024) [56].

### 1.2 Main Objectives of the Paper

The primary objective of this paper is to examine the role of Smart Building Management Systems (SBMS) in advancing sustainable and cost-efficient housing solutions. This exploration will involve a detailed analysis of the design principles behind SBMS, highlighting their key components, such as sensors, automation, data processing systems, and integration with renewable energy sources. By understanding these design principles, the paper aims to offer a comprehensive framework for the implementation of SBMS in residential buildings, focusing on their contributions to environmental sustainability and cost reduction.

Additionally, this paper will explore the practical application of SBMS within the housing sector, providing insights into how their integration can optimize energy use, reduce operating costs, and enhance the quality of life for residents. It will assess both the technological advancements that make SBMS effective and the potential challenges associated with their adoption, such as initial capital investment, technological complexity, and user acceptance. By focusing on the intersection of technology, sustainability, and cost-efficiency, this paper seeks to offer evidence-based recommendations for policymakers, urban planners, developers, and building managers. The goal is to inform decisions that lead to the development of smarter, more sustainable housing solutions. Ultimately, the research will contribute to a broader understanding of how SBMS can help reshape the housing sector, providing tangible benefits to the environment and occupants while supporting the global transition towards more sustainable living practices.

## 2. Literature Review

### 2.1 Review of Existing Research on Smart Building Technologies

The integration of smart building technologies has been a key area of research in the past decade, driven by the need to optimize energy consumption, enhance operational efficiency, and reduce environmental footprints. Smart buildings utilize automation technologies, such as sensors, actuators, and control systems, to adjust and manage building operations based on real-time data. These systems are often linked through Internet of Things (IoT) networks, which provide continuous feedback on various parameters like temperature, lighting, air quality, and occupancy (Paul, Ogugua, & Eyo-Udo, 2024a) [61].

One critical area of research has been energy efficiency. Studies indicate that smart buildings can significantly reduce energy consumption by optimizing heating, ventilation, and air conditioning (HVAC) systems based on occupancy and weather forecasts (Onukwulu, Agho, Eyo-Udo, Sule, & Azubuike, 2024b) [53]. Automation technologies enable buildings to adapt to fluctuating energy demands, avoiding unnecessary heating or cooling during off-peak hours. Smart energy management systems also incorporate renewable energy sources, such as solar panels and wind turbines, by efficiently managing the generation, storage, and distribution of energy within the building (Abisoye & Akerele, 2022 [2]; Chisom Elizabeth Alozie, Olanrewaju Oluwaseun Ajayi, Joshua Idowu Akerele, Eunice Kamau, & Teemu Myllynen).

Resource management is another key component of smart building systems. Research highlights the importance of water and waste management systems integrated with building automation. Smart meters and water-saving technologies, for instance, can detect leaks and optimize water usage, thereby contributing to sustainability goals (Eyo-Udo *et al*., 2024) [33]. Additionally, smart waste management solutions, such as automated sorting and recycling systems, help reduce the environmental impact of buildings while promoting sustainable practices. The growing body of research underscores the potential of smart building technologies to revolutionize energy consumption patterns and resource management, making them crucial to addressing global sustainability challenges (Chisom Elizabeth Alozie, Olarewaju Oluwaseun Ajayi, Joshua Idowu Akerele, Eunice Kamau, & Teemu Myllynen).

### 2.2 Previous Studies on the Implementation of SBMS in Housing

Several studies have demonstrated the successful implementation of Smart Building Management Systems (SBMS) in the housing sector, particularly highlighting their role in promoting sustainability and cost-efficiency. For example, research has shown that the integration of SBMS in residential buildings leads to a reduction in overall energy consumption, contributing to significant savings in utility bills (Adewoyin, 2022) [8]. Automated systems, such as adaptive lighting and climate control, adjust energy use based on real-time occupancy data and environmental factors, ensuring that energy is not wasted. This has proven especially beneficial in large housing developments where energy costs can be substantial (Daramola, Apeh, Basiru, Onukwulu, & Paul, 2023; Oluokun, Akinsooto, Ogundipe, & Ikemba, 2024d) [26, 51].

Furthermore, studies have explored the economic benefits of SBMS, emphasizing the long-term cost savings associated with reduced operational expenses. Although the initial investment in SBMS can be high, the payback period is often relatively short due to the energy savings and operational efficiencies achieved through automation (Onukwulu, Agho, Eyo-Udo, Sule, & Azubuike, 2024a) [52]. For instance, one study of a smart residential complex found that the integration of smart meters, energy-efficient lighting, and automated HVAC systems resulted in a 20% reduction in energy consumption within the first year of operation. Additionally, the integration of renewable energy sources, such as solar panels and battery storage, has further enhanced cost-saving outcomes by reducing dependency on the grid and lowering energy costs for residents (J. O. Basiru, C. L. Ejiofor, E. C. Onukwulu, & R. U. Attah, 2023c; Oluokun, Akinsooto, Ogundipe, & Ikemba, 2024c) [24, 50].

The sustainability outcomes of SBMS implementation have also been significant. Numerous studies indicate that smart building systems play a key role in reducing carbon footprints. For instance, a study of a mixed-use development with integrated smart systems found that it reduced its carbon emissions by over 30% annually (Kokogho, Odio, Ogunsola, & Nwaozomudoh, 2024a) [41]. Moreover, the ability of SBMS to monitor and optimize water and waste management further aligns these systems with sustainability objectives. However, despite the promising results, challenges remain in the widespread adoption of SBMS, including the high upfront costs and the need for specialized technical expertise for installation and maintenance (Egbuhuzor, Ajayi, Akhigbe, & Agbede, 2024) [30].

While existing research provides valuable insights into the potential of Smart Building Management Systems (SBMS), several gaps remain that need to be addressed. One of the primary challenges is the integration of various technologies within a unified system. SBMS typically require the seamless connection of diverse components, including sensors, actuators, energy meters, and building control systems (Ajayi, Agbede, Akhigbe, & Egbuhuzor, 2023) [13]. The integration of these systems often involves complex technical challenges, such as ensuring interoperability between devices from different manufacturers and handling vast amounts of real-time data. Current research tends to focus on individual technologies rather than their integration into a holistic, scalable solution for residential buildings (Adeniyi & Adelugba, 2024; Egbuhuzor, Ajayi, Akhigbe, & Agbede, 2022) [6, 29].

Another critical gap lies in the scalability of SBMS. Many of the successful studies in the existing literature focus on small-scale implementations or pilot projects. While these studies offer promising results, they often lack scalability in terms of cost, infrastructure, and implementation across larger housing developments. There is a need for more research on how SBMS can be adapted for use in a variety of housing types, from single-family homes to large-scale apartment complexes. This includes exploring how these systems can be scaled up economically while maintaining performance standards and sustainability outcomes (Ajayi, Akhigbe, Egbuhuzor, & Agbede, 2022; Onukwulu, Fiemotongha, Igwe, & Ewim, 2022) [15, 54].

User behavior is another area that has received limited attention in the literature. Even with the best technology, the success of SBMS depends on the willingness of residents to adopt and interact with the system. Studies on user behavior are crucial to understanding how occupants interact with smart technologies and how these interactions can be optimized to achieve better energy efficiency and sustainability outcomes. For example, a smart thermostat might reduce energy use, but if residents manually override the system or fail to use it correctly, the potential benefits could be diminished. Research on user education, incentives, and behavioral psychology is needed to maximize the impact of SBMS (Ajayi *et al*., 2023; Fiemotongha, Igwe, Ewim, & Onukwulu, 2023b) [13, 37].

## 3. Design Principles for Smart Building Management Systems

### 3.1 Key Design Principles

The core design principles of Smart Building Management Systems (SBMS) revolve around efficiency, automation, and optimization through technology. One of the primary principles is data-driven decision-making, which underpins much of the functionality of SBMS. These systems rely on continuous data collection from a variety of sensors, meters, and devices installed within the building. This data is then analyzed in real-time to make informed decisions about how the building should operate. For instance, data about occupancy levels, temperature, lighting, and external weather conditions can be used to adjust indoor climates automatically, ensuring comfort while minimizing energy consumption (Fiemotongha, Igwe, Ewim, & Onukwulu, 2023a; Paul, Abbey, Onukwulu, Agho, & Louis, 2021) [36, 60].

The integration of IoT devices is another key design principle in SBMS. The Internet of Things (IoT) refers to the network of connected devices that communicate with each other and with central management systems. In the context of SBMS, IoT devices include smart thermostats, energy meters, sensors that detect movement or occupancy, and automated lighting systems. These devices gather data and send it to a central platform where it can be processed and used to optimize building performance. For instance, sensors detecting low occupancy in a room can signal the lighting system to dim or turn off, reducing energy consumption without compromising comfort or convenience (Odio *et al*., 2021) [43].

The integration of artificial intelligence (AI) algorithms enhances the capabilities of SBMS by providing predictive and adaptive responses based on historical and real-time data. AI can analyze patterns in energy usage, predict future demand, and adjust systems proactively. For example, AI-powered algorithms can optimize heating and cooling schedules based on weather forecasts and historical occupancy data, ensuring that energy is not wasted when a building is unoccupied. These AI-driven systems also have the potential to learn and evolve over time, continuously improving their efficiency as they gain more data (Oyekunle, Adeniyi, & Adeeko, 2024) [59].

### 3.2 Requirements for Sustainable Materials, Energy Systems, and Water Usage in the Design of SBMS

For Smart Building Management Systems to meet sustainability goals, it is essential to integrate sustainable materials, energy systems, and water usage into their design. Sustainable materials play a vital role in reducing the environmental impact of buildings. In the context of SBMS, the selection of materials that are durable, low-maintenance, and energy-efficient can contribute to the overall sustainability of the building. For example, incorporating materials with high insulation properties, such as recycled or low-emission insulation materials, can reduce the demand for heating and cooling, enhancing energy efficiency (Adeniyi & Adeeko, 2024; Sule, Eyo-Udo, Onukwulu, Agho, & Azubuike, 2024) [5, 12].

Energy systems in SBMS are designed to minimize energy consumption while maximizing the use of renewable energy sources. A key requirement is the integration of smart energy management systems that can track energy production and consumption in real-time. For instance, smart meters can monitor electricity use and provide feedback to building managers or residents, enabling them to adjust their consumption patterns (Achumie, Oyegbade, Igwe, Ofodile, & Azubuike, 2022; Okeke, Alabi, Igwe, Ofodile, & Ewim, 2024a) [4, 44]. Moreover, renewable energy sources such as solar panels or wind turbines are often integrated with the SBMS, allowing the building to generate its own clean energy and store it in batteries for later use. The smart energy system can prioritize the use of renewable energy, reducing the building's reliance on the grid and decreasing its carbon footprint (Adeniyi & Adeeko, 2024; Sule *et al*., 2024) [5, 63].

Water usage is another critical aspect of sustainable building design. The SBMS must incorporate smart water management systems that reduce consumption and prevent waste. These systems can include water-efficient fixtures, sensors to detect leaks, and automatic adjustments to water usage based on occupancy or weather conditions. For instance, if a smart irrigation system detects rainfall, it can automatically adjust the watering schedule, reducing unnecessary water consumption. In addition to water conservation, the system may also optimize the use of rainwater harvesting systems and greywater recycling to reduce demand on municipal water supplies further (Eyieyien, Idemudia, Paul, & Ijomah, 2024b) [32].

### 3.3 Various Control Systems

A critical feature of Smart Building Management Systems (SBMS) is their ability to optimize the operation of various control systems, such as HVAC (heating, ventilation, and air conditioning), lighting, and waste management. The optimization of these systems is vital to enhancing cost-efficiency and minimizing energy consumption while maintaining occupant comfort (Kokogho, Odio, Ogunsola, & Nwaozomudoh, 2024b) [42].

The HVAC system is one of the largest consumers of energy in buildings, and optimizing its operation is essential for cost-efficiency. SBMS can improve HVAC performance through smart thermostats and demand-controlled ventilation. For example, a smart thermostat adjusts the temperature based on occupancy patterns, ensuring that heating or cooling is only active when needed (Afolabi & Akinsooto, 2023; Ezeanochie, Afolabi, & Akinsooto, 2021) [10, 34]. Moreover, SBMS can use data from occupancy sensors to adjust air circulation in rooms, reducing energy use when rooms are unoccupied. In addition to temperature control, SBMS can integrate with building-wide air quality management systems to ensure healthy indoor environments while optimizing energy use. The integration of AI-based predictive algorithms can also allow HVAC systems to anticipate changes in weather and adjust accordingly, avoiding unnecessary energy consumption (J. O. Basiru, C. L. Ejiofor, E. C. Onukwulu, & R. U. Attah, 2023b; Igwe, Eyo-Udo, & Stephen, 2024a) [23, 39].

Lighting systems in SBMS are similarly optimized to enhance cost-efficiency. Advanced smart lighting systems adjust brightness based on natural light levels or occupancy, ensuring that lights are only on when needed. For example, motion sensors can detect when rooms are occupied and automatically adjust the lighting accordingly (Okeke, Alabi, Igwe, Ofodile, & Ewim, 2024b) [45]. Moreover, integrating LED lighting with smart controls can further reduce energy consumption, as LEDs consume less power than traditional incandescent bulbs and have a longer lifespan. Additionally, SBMS can use daylight harvesting, where the system adjusts artificial lighting based on the amount of natural light entering the building, further reducing energy costs (Otokiti, Igwe, Ewim, Ibeh, & Sikhakhane-Nwokediegwu, 2022; Umoga *et al*., 2024) [57, 64].

Waste management systems are another important aspect of SBMS. Efficient waste management is crucial for both environmental sustainability and cost-efficiency. Smart waste management systems use sensors to monitor waste levels in bins and optimize collection schedules. By doing so, SBMS can reduce the frequency of waste collection, lowering transportation and disposal costs. Moreover, these systems can be integrated with recycling and composting processes, allowing for better waste sorting and diversion from landfills. In addition, SBMS can monitor and reduce water waste in areas such as kitchens and bathrooms by using sensors to detect leaks or overuse (Abisoye & Akerele; J. O. Basiru, C. L. Ejiofor, E. C. Onukwulu, & R. U. Attah, 2023a) [22].

## 4. Implementation Challenges and Solutions

### 4.1 Common Challenges in the Design and Implementation of SBMS

The implementation of Smart Building Management Systems (SBMS) faces several significant challenges, which can hinder their widespread adoption and effectiveness. Technological barriers are among the most prominent, particularly in integrating diverse systems and devices from various manufacturers. Achieving seamless interoperability between these technologies requires standardized communication protocols, which are not always readily available, especially when retrofitting existing buildings with new smart technologies (J. O. Basiru, L. Ejiofor, C. Onukwulu, & R. U. Attah, 2023) [20]. Additionally, the complexity of managing and processing the large amounts of data generated by smart systems often presents challenges in terms of data storage, analysis, and security. The reliance on the Internet of Things (IoT) also introduces potential vulnerabilities to cyberattacks, which raises concerns about the privacy and security of building data (Ajayi, Agbede, Akhigbe, & Egbuhuzor, 2024; Daramola, Apeh, Basiru, Onukwulu, & Paul, 2024) [14, 27].

Financial barriers present another challenge, as the initial cost of implementing SBMS can be high, particularly for large-scale projects. The expenses related to the installation of smart devices, sensors, and systems can be prohibitive for both developers and building owners. Moreover, the financial returns from energy savings may take years to materialize, which can discourage investment in the technology (Oluokun, Akinsooto, Ogundipe, & Ikemba, 2024a) [48]. Regulatory barriers also pose obstacles, as existing regulations may not be conducive to the adoption of new technologies. Many cities and countries lack clear guidelines or incentives for smart building implementation. The regulatory landscape must evolve to accommodate the unique needs of smart buildings, encouraging innovation while ensuring compliance with safety, security, and environmental standards (J. O. Basiru, C. L. Ejiofor, E. C. Onukwulu, & R. Attah, 2023; Oluokun, Akinsooto, Ogundipe, & Ikemba, 2024b) [20, 49].

### 4.2 Proposed Solutions to Overcome These Challenges

To overcome the challenges in SBMS implementation, several solutions can be proposed. One promising approach is the development of innovative financing models that reduce the upfront financial burden of adopting smart technologies. Energy-as-a-Service models, for example, allow building owners to lease smart building technologies and pay for them over time, based on the energy savings achieved (Otokiti, Igwe, Ewim, & Ibeh, 2021) [58]. This arrangement can make the transition to smart systems more financially feasible by spreading out the costs and aligning them with the expected returns from energy efficiency improvements. Additionally, green bonds or sustainability-linked loans can offer lower financing costs to building owners who implement environmentally sustainable practices, making SBMS more attractive from a financial perspective (Adewoyin, 2021; Ajiga, Hamza, Eweje, Kokogho, & Odio) [7, 17].

Another solution involves public-private partnerships (PPP), where government entities collaborate with private companies to fund and implement smart building technologies. Governments can provide incentives such as tax credits, subsidies, or grants to reduce the financial risks associated with SBMS adoption. In return, private companies bring in expertise, technology, and capital to accelerate the rollout of smart systems. PPPs also facilitate the establishment of pilot projects that demonstrate the long-term benefits of SBMS, helping to build public confidence and stimulate market demand (Agho, Eyo-Udo, Onukwulu, Sule, & Azubuike, 2024; Eyieyien, Idemudia, Paul, & Ijomah, 2024a) [12, 31].

Finally, regulatory frameworks must be updated to support the widespread deployment of SBMS. Governments can introduce policies that offer incentives for building owners to adopt energy-efficient and sustainable technologies. These could include financial subsidies, tax rebates, or preferential treatment in zoning and building permits for projects that meet specific sustainability criteria. Additionally, the establishment of clear technical standards and guidelines for smart building technologies would ensure compatibility and ease of integration, encouraging more building owners to invest in smart solutions (Ajiga, Hamza, Eweje, Kokogho, & Odio; Durojaiye, Ewim, & Igwe, 2024 [28]; Ezeanochie, Afolabi, & Akinsooto, 2024 [35]).

## 5. Conclusion and Future Directions

This paper has explored the design, implementation, and impact of Smart Building Management Systems (SBMS) on creating sustainable and cost-efficient housing. The findings emphasize that SBMS represent a transformative approach to building management by integrating data-driven decision-making, automation, and intelligent control systems. The key advantages of SBMS, such as energy optimization, real-time monitoring, and resource management, make them invaluable tools for reducing energy consumption, improving environmental sustainability, and enhancing operational cost efficiency in buildings. The integration of IoT devices, AI algorithms, and renewable energy sources allows SBMS to not only lower operating costs but also improve occupant comfort and reduce the carbon footprint of buildings. Additionally, sustainable design principles—such as the use of eco-friendly materials, energy-efficient systems, and water conservation technologies—are crucial in ensuring that smart buildings meet modern environmental goals.

While the potential benefits of SBMS are clear, the paper also identified several challenges in their design and implementation. Technological complexities, high upfront costs, and regulatory barriers are among the primary obstacles hindering the widespread adoption of these systems. However, proposed solutions such as innovative financing models, public-private partnerships, and updated regulatory frameworks provide promising pathways to overcome these challenges, making the adoption of SBMS more feasible for stakeholders in the housing industry.

As the demand for sustainable and cost-efficient housing continues to grow, several areas require further research and development. One critical direction for future research is the exploration of emerging technologies that can enhance the capabilities of SBMS. For example, advancements in blockchain could offer improved security and transparency in managing building data, while 5G networks could enable faster communication and more efficient real-time data processing, enhancing the responsiveness of smart systems. Additionally, the integration of machine learning with SBMS could lead to more adaptive and predictive systems, capable of learning from historical data to optimize building performance even further.

Another area for development is the creation of more robust regulatory frameworks that incentivize the adoption of SBMS. Future policies could focus on creating a standardized certification for smart buildings, similar to energy efficiency certifications like LEED (Leadership in Energy and Environmental Design), ensuring that buildings meet minimum requirements for sustainability and performance. Governments should also consider expanding financial incentives, such as tax breaks or grants, for buildings that adopt smart technologies, helping to lower the initial capital expenditure and encouraging more widespread adoption of SBMS. Moreover, research into user behavior and occupant engagement is crucial for the future success of SBMS. Many of smart buildings' most effective energy-saving opportunities depend on user input or habits. As such, understanding how occupants interact with smart technologies and how to increase their engagement with energy-saving behaviors can enhance the overall efficiency of SBMS.

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