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Review

Integrating Digital Twins with BIM for Enhanced Building Control Strategies: A Systematic Literature Review Focusing on Daylight and Artificial Lighting Systems

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Abstract: In the architecture, engineering, and construction industries, the integration of Building Information Modeling (BIM) has become instrumental in shaping the design and commissioning of smart buildings. At the center of this development is the pursuit of more intelligent, efficient, and sustainable built environments. The emergence of smart buildings equipped with advanced sensor networks and automation systems increasingly requires the implementation of Digital Twins (DT) for the direct coupling of BIM methods for integral building planning, commissioning, and operational monitoring. While simulation tools and methods exist in the design phase of developing advanced controls, their mapping to construction or post-construction models is less well developed. Through systematic, keyword-based literature research on publisher-independent databases, this review paper gives a comprehensive overview of the state of the research on BIM integration of building control systems with a primary focus on combined controls for daylight and artificial lighting systems. The review, supported by a bibliometric literature analysis, highlights major development fields in HVAC controls, failure detection, and fire-detection systems, while the integration of daylight and artificial lighting controls in Digital Twins is still at an early stage of development. In addition to already existing reviews in the context of BIM and Digital planning methods, this review particularly intends to build the necessary knowledge base to further motivate research activities to integrate simulation-based control methods in the BIM planning process and to further close the gap between planning, implementation, and commissioning.

Keywords: building information modelling; digital twin; integral control strategy; daylight and artificial lighting; simulation

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1. Introduction

1.1. The Aspect of Integral Control Strategies

In recent decades, the intersection of sustainable building design, energy efficiency, and technological innovation has catalyzed significant advancements in the field of integrated building control strategies. Among the most promising and impactful aspects of integrated building control strategies is the harmonization of natural daylight and artificial lighting control systems. This integrated approach not only enhances occupant comfort and well-being but also plays a pivotal role in reducing energy consumption and environmental impact [1,2].

Buildings account for a third of global energy consumption and a quarter of CO_2 emissions [3]. Around 75% of emissions and costs over the entire life cycle are generated during operation, making the optimization of building performance increasingly urgent. Consequently, there has been a surge in research and development efforts aimed at improving the interplay between architectural design, lighting systems, and control strategies. Until now, many studies have investigated the individual merits of daylight harvesting and advanced artificial lighting control [4–7], but a comprehensive exploration of their integration and the status of this integration within the BIM planning process is a subject of growing interest and relevance.

Various control strategies, technologies, and approaches that have been proposed and implemented in the context of sustainable building design have been analyzed and reviewed by [8]. As a follow-up, this review aims to highlight the current state of integration of control strategies within the BIM planning process and their further mapping into construction and operational models, known as Digital Twins, which hold the promise of streamlining and optimizing the design and operation of buildings from concept to occupancy.

To achieve these targets, set on the European level in the Energy Performance of Buildings Directive [9] for the reduction of energy consumption as well as CO_2 emissions, continuous optimization during the design process, but especially during the operational phase of a building, is of utmost relevance.

1.2. From the BIM Model as a Digital Shadow towards a Fully Integrated Digital Twin

After decades of critical discourse, pitfalls, and differing viewpoints regarding the introduction of BIM as the most significant innovation in the architecture, engineering, and construction (AEC) sector since its inception, its future significance in this domain is now virtually indisputable [10]. Authorities and construction companies worldwide are convinced of BIM as a future planning method. Meanwhile, the UK, France, Poland, Austria, Russia, and Switzerland define it as a required standard method for public building construction [11–13].

Nowadays, buildings can be considered as highly complex infrastructures due to the involvement of multiple disciplines and technologies. Numerous experts are involved in creating a cost-efficient but technologically optimized solution in terms of operational energy demand and user comfort. The need for multiple iteration cycles during the different planning phases seems obvious to meet these requirements. In this context, it is important to distinguish between digital models, digital shadows, and digital twins, which are summarized in Table 1.

Table 1. Definition of the terminology of the digitalization of construction.

Digital model	A 3D CAD model as a simplified approximation or a 1-1 detailed model that contains a significant amount of meta-data; the information flows from the digital model to a physical object in one direction.
Digital shadow	It is the reflection of a physical object with a high level of detail in the form of its digital shadow; the flow of information goes from the physical world to the digital representation.
Digital twin	Its origin lies in a digital model or a digital shadow to capture or initiate it; the information flows not only from digital assets to the physical world but also loops back; information from construction and asset management merges with the digital model.

To achieve this, a BIM model as a single data source and acting as a so-called Digital Twin, coupled with powerful coordination workflows and mature tool interoperability, is highly desired. Nevertheless, this scenario is still beyond the latest state-of-the-art research, particularly as interchange and interoperability capabilities are of the highest relevance to achieve this goal in the future (c.f. Figure 1).

While building management systems (BMSs) are well-established for communicating with the different installed building systems (artificial light, shading, thermostats, etc.), integrative building controls are hindered in their ability to connectively communicate through the prevalence of proprietary system solutions. Another barrier is the incapacity to have all pertinent information at a single location during the design phase. With the BIM method as a so-called Digital Shadow of a building and its evolution in the building realization process towards a Digital Twin, an appropriate digital method already exists to technically enable this integrative process of designing, optimizing, and implementing integral building controls.

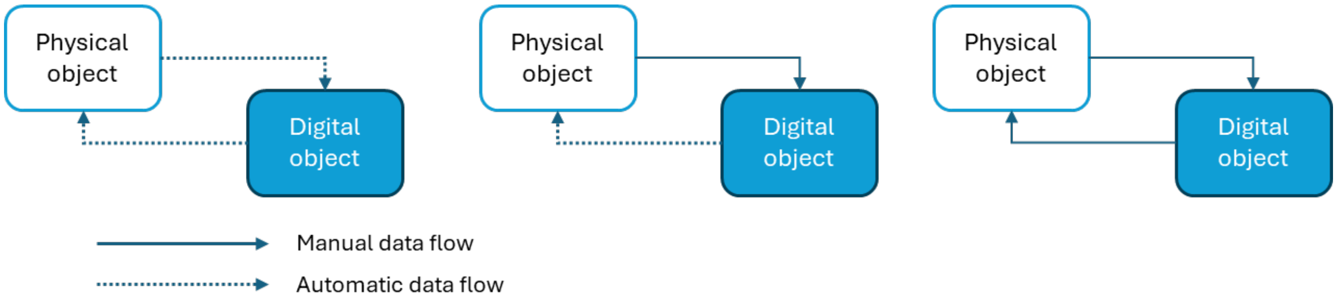

Figure 1. Flow of information in digital models, shadows, and twins [14].

However, BIM not only seminally provides the means for such an integrative process. BIM implements virtually integrated design, construction, and operation (ViDCO), thereby comprising object-based modelling, model-based collaboration, and network-based integration [15]. This vision of BIM exhibits a strong resemblance to the notion of a DT [16–18], a model-based, virtual replica of a cyber-physical system with bidirectional data exchange between the two [19]. We conjecture that the successful application of BIM paves the way for the gestation of a DT for the AEC domain [17,18]. The tight resemblance between BIM and DTs radically epitomizes in linking BM with IT [20].

DTs are commonly generated from the BIM model and fed with live data from sensors, devices, and other origins, subsequently replicating and imitating the actions, qualities, and circumstances of the physical entity in a digital environment. DTs are not simply a compilation of 3D models or simulations. They integrate real-time data, machine learning, and other technologies to offer a nearly real-time depiction of the physical object [21,22]. By virtue of their well-recognized potential, the AEC domains are specifically interested in utilizing DTs to improve project design, planning, simulation, construction management, and facility operations, with the hopes of enhancing collaboration, saving costs, and optimizing asset performance over the entire building life cycle.

For this reason, it was also crucial for this review, focusing on the mapping of daylight and artificial lighting controls, to consider not only the BIM model-based planning phases but also their implementation and operation in the DT application. This continuous connection offers decisive added value, particularly in the control area.

1.3. Objectives and Their Research Questions

This review paper provides a comprehensive examination of current research in integrating BIM models with building control systems, specifically focusing on coordinating daylight and artificial lighting controls. The primary objective is to critically evaluate the effectiveness, hurdles, and prospects associated with merging building control strategies into BIM planning processes. Leveraging bibliometric keyword screening from the Elsevier's ScienceDirect literature database, this work presents an overview of the latest peer-reviewed research papers in the field. It delves into published ideas concerning communication and interoperability interfaces while emphasizing the role of DTs in both the overall building design process and operational phases. Furthermore, it explores parallel domains where DTs have gained traction, such as fault detection in HVAC (Heating, Ventilation, and Air Conditioning) and applications in fire risk management, aiming to draw insightful connections.

By starting from the initial planning phase towards the realization of the building, this review addresses the whole planning process with the attempt to give insights into (1) existing methods to map integral control strategies in a BIM model; (2) existing approaches and workflows on how to better integrate the control development phase into existing planning processes and tools; and (3) how to bridge the gap between the final design of an integral control strategy in a BIM model and the implementation in a real building towards a full DT.

This leads to the following research questions, which are raised in this review work and will be addressed later in the discussion section:

1. In terms of mapping integral control strategies in a BIM model and a DT, respectively:
   - ➢ What approaches currently exist in BIM to map lighting controls and building control systems in general?
   - ➢ How can control input data (static and dynamic) be linked and integrated into the BIM model?
   - ➢ Can current limitations in realizing integral controls be resolved by moving the controls planning towards the BIM level?
2. In terms of existing approaches and workflows to design and elaborate integrative controls:
   - ➢ What interfaces and exchange workflows exist in the literature to bridge BIM with building energy modelling (BEM)?
   - ➢ How can integral controls currently be simulated on the BIM level?
   - ➢ Are there workflow procedures in the existing literature to derive controls from a simulation?
3. In terms of transferring integral control approaches from a BIM model to real buildings ("BIM2control"):
   - ➢ What are the core features of intelligent commissioning based on existing examples and how would these be anchored in the context of integral control strategies?
   - ➢ Are there workflow procedures in the existing literature and what is the current state of research?

2. Existing Reviews on BIM and Its Applications in Design and Commissioning

2.1. Application of BIM in the AEC Industry

While BIM has made significant strides, there are ongoing needs and challenges in the AEC industry. These encompass further enhancing interoperability between tools and processes during the design phase, refining data exchange protocols, and promoting cross-disciplinary collaboration. As the demand for smarter, more sustainable buildings continues to rise, the current developments in BIM do not stop at design and commissioning, but push towards the realization of DTs, post-construction monitoring, and continuous fault detection to optimize the operation. This might help to close the performance gap between planning and operation and support the facility manager in the proper maintenance of the building.

In a building's lifespan, the application of BIM can include the pre-construction, construction, and post-construction phases of a project. While the pre-construction phase is mainly dedicated to building design and optimization, the post-construction phase includes the monitoring and smart operation of building status data (e.g., temperatures, CO_2-levels, etc.) and the building service states of HVAC components (e.g., chillers, pumps, valves, etc.) via the use of IoT technologies [23].

2.2. Application of BIM in the Design and Construction Phases

In [24], a comprehensive literature review on the different application levels of BIM, starting from early design to commissioning and beyond, is given. During the planning phase, a special focus is on the integration of tools for energy performance and life-cycle analysis. The study appoints interoperability issues between BIM and real-time data, primarily due to a wide variety of existing communication protocols between proprietary systems. The review emphasizes the importance of integrating dynamic data more effectively in the future in order to further develop the BIM concept into adaptive DTs.

In [15], a literature review on the multifaceted applications of BIM during the construction phase is given and identifies its limitations. While BIM provides a standardized way to represent building components and systems semantically, the concept of a DT takes a more holistic approach by emphasizing the interaction between physical and digital data streams. However, according to Boje et al., BIM methods currently have major limitations in the integrability of control strategies, sensor networks, or social systems, especially when it comes to the incorporation of dynamic data at various levels.

In addition, [25] offers an extensive overview of research trends on designing and commissioning smart buildings in the BIM context. Through scientometric analysis, the paper categorizes the reviewed BIM research into six main topics, covering BIM adoption, BIM-aided management, progress monitoring, interoperability, life cycle analysis, and energy simulation, while a special focus is given on methods for integrating BIM with BEM. As a main result, developed applications in this field mainly focused on building envelope design, which creates a gap of missing applications related to building systems design and control, as well as tasks from the operational phase such as fault detection and diagnosis as well as model predictive control (MPC). The review underscores the need for future research to explore how BIM-to-BEM processes can facilitate the implementation of integrative control strategies in the different areas of building operations.

2.3. Application of BIM in the Post-Construction Phase

In the post-construction phase, most relevant studies in this field address the challenge of effective asset management, particularly in the context of monitoring and maintaining buildings [26–29]. Most presented analyzing methods are based on the dynamic integration of energy simulation methods coupled with actual consumption data to achieve a more efficient building operation as well as improved fault detection. Through this, the research focus has also more and more shifted from the mainly static BIM model in the planning phase towards the more dynamic DT model with a linked-data paradigm in recent years. The current trends of IoT and AI assets (e.g., machine learning, data analytics, etc.) allow an even more realistic integration of a building's operational status and dynamic processes into a DT compared to more physical-based approaches.

Lastly, for the upcoming aspect of anomaly detection in building service assets (currently mainly HVAC systems) and methods for operational monitoring and maintenance, the importance of a DT in the AEC industry is virulent. In [30], a literature review is given on current research in operation and management (O&M) approaches as well as anomaly detection processes, which distinguishes between point anomalies and contextual anomalies. It also introduces a DT-enabled anomaly detection system for asset monitoring, supported by an extended industry foundation classes (IFC) data integration method. This method enables the extraction of monitoring data from building DTs, which contain diagnostic information about asset operations.

3. Methodology Applied for This Review

3.1. Identification of the Thematically Relevant Literature

For the thematic overview of the scientific literature, a publisher-independent search was carried out via Web of Science and a supplementary search via ScienceDirect. These searches are based on the use of suitable search strings. Based on the research questions in Section 1.3 regarding the mapping of lighting controls in the DT, their evaluation and derivation from system simulations, and their transferability to the physical building hardware, a collection of main keywords including synonyms has been defined and combined into required search strings for the individual search engines (see Table 1). Including "office" as a building context in the keyword list as a relevant building sector in the global energy demand filters the search results to office applications. Even though the focus is on the lighting trade, this review also aims to highlight the transferability of workflows and functionality to other trades (i.e., an assessment of the cross-trade applicability of the concepts). Therefore, different fields of HVAC are also included in the list of synonyms. For the search in the literature databases, each main keyword was logically OR-linked with the corresponding synonyms. The resulting OR terms were logically AND-linked.

As the ScienceDirect search is limited to eight Boolean operators, in addition to the first three main keywords, i.e., the most thematically relevant keywords, only the synonyms that returned the most hits were used. The subset of keywords used leads to a superset of results from the full search string. The literature selection includes both research and review articles and was applied to both full-text and title-abstract keywords (TAK) using the defined search strings according to Table 2.

Table 2. Overview of the main keywords used and their synonyms. Elements marked with * represent placeholders that stand for a random character sequence, here as a word ending.

Main Keyword	BIM	Control	Lighting	Smart Commissioning	Building *
Synonyms	Building Information Modelling	Strategies	Light	Intelligent commissioning	Office *
	Building Information Modeling	Strategy	Artificial lighting	Implementation	Bureau
	IFC-Model	System *	Daylighting	Automated commissioning	
	Digital Twin	Building automation	HVAC	Automated start-up	
		Logic	Heating	Planning	
			Ventilation	Simulation *	
			Cooling	Software application	
			Air conditioning	Tool *	

The first review was carried out by evaluating the abstract for suitability regarding the research questions set. To ensure a high degree of topicality, the search was limited to the period from 2015 to 2023. There was no geographical restriction. An initial search was carried out in January 2023. The articles were updated in September 2023, resulting in a total of 118 publications after excluding duplicates and unavailable articles. An in-depth full-text review of each individual article followed the research question and sought to find answers to the following specific objectives:

(1) What approaches currently exist to map lighting control systems and their logic on the BIM side?
(2) What approaches are there to designing (integral) control strategies for the BIM planning process, simulating them, and deriving them from the simulation?
(3) What roles do advanced commissioning and CAFM play?
(4) Which BIM software environment is used?
(5) Can the current limits of integral controls (interface between trades, responsibilities) be removed by shifting to the BIM level?

Upon the significance of the contents, the paper pool of 118 in total was categorized into three groups of relevance (high, medium, and low). If a paper turned out to be irrelevant, it was finally discarded at this stage. The reasons for this were either missing a clear focus on controls or being in context with BIM but with no clear contribution to the aforementioned objectives. This subsequent full-text review led to the exclusion of 61 papers, leaving 57 articles for detailed analysis, shown in Table 3, which is the basis for the bibliometric analysis.

Table 3. List of search strings used to identify the suitable literature (TAK: Title, Abstract, or Author-specified keywords; TS: Title, Abstract, Author Keywords, Keywords Plus®); publication plus duplicates in brackets. Elements marked with * represent placeholders that stand for a random character sequence, here as a word ending.

Database/Search Engine	Search Methodology	Filter	Transfer to Detail Search, January 2023	Transfer to Detail Search, September 2023	Subtotal of Paper, before Detailed Evaluation	Remaining after Detailed Evaluation
Web of Science	**TS:** (BIM OR IFC-Model OR "Digital Twin" OR "Building Information Modelling" OR "Building Information Modeling") AND (Control * OR Strategies OR Strategy OR "Building automation" OR System *) AND (Lighting OR Artificial lighting OR Light OR Daylighting OR Daylight OR HVAC OR Heating OR Ventilation OR Cooling OR "Air conditioning") AND (("Smart Commissioning" OR "Intelligent commissioning" OR Implementation OR "Automated commissioning" OR "Automated start-up") OR (Planning OR Simulation * OR "Software application" OR Tool *)) AND (Building * OR Office * OR Bureau)	2015–2023 All Databases	40 (42)	--	40 (42)	20
Elsevier (Science Direct)	**Full text:** ("BIM" OR "IFC-Model" OR "Digital Twin" OR "Building Information Modelling") AND ("control" OR "building automation" OR "lighting" OR "daylight" OR "HVAC")	2015–2023 Research article The first 100 with relevance	22 (22)	5 (5)	27 (27)	16
Elsevier (Science Direct)	**Full text:** Building OR Office OR Bureau **TAK:** (BIM OR IFC OR "Digital Twin" OR "Building Information Modelling") AND (control OR lighting OR daylight OR HVAC OR logic)	2015–2023 Research article The first 100 with relevance	49 (59)	2 (2)	51 (61)	**21**
			111 (123)	7 (7)	118 (130)	**57**

3.2. Manual Evaluation Criteria and a Supplementary VOSviewer Analysis

To answer the research questions, the identified publications were filtered and critically analyzed using manual evaluation criteria. These filter criteria include the BIM-side mapping of building control systems and their communication architecture, which also includes interfaces and data semantics, associated development environments, and fields of application. Furthermore, the role of BEM in the context of building control systems is elaborated upon and existing methods and concepts in the digital twin are highlighted in detail, especially their advantages and challenges for the integration of control configuration and parameterization. This is intended to identify the need for future research.

In addition to the qualitative literature analysis, a supplementary bibliometric analysis was carried out. The VOSviewer, version 1.6.19 [31], was used for this purpose. In addition to the occurrences of individual keywords, represented by the node size, the focus is particularly on identifying connections between individual thematic keywords. The relevant evaluation parameters of the bibliometric correlations are the links between individual keywords, whose value is displayed in the VOSviewer via link strength and cluster. To differentiate between keywords that were used for the search in the literature databases and keywords for the bibliometric analysis, the latter are referred to as items in accordance with the VOSviewer nomenclature [31]. To limit the VOSviewer output to thematically relevant items and to avoid falsification of the output by synonyms, related items are merged manually via the VOSviewer thesaurus file (MapFile of 231 items limited to 26 thematically relevant items).

4. Bibliometric Analysis of the Existing Literature

Based on a VOSviewer analysis that included all 57 selected articles, a clustering of the resulting main keywords (circles) and their interrelations (connection lines) is shown in Figure 2. In this, the size of the circles as well as the thickness of the connecting lines within the network are representatives for the number of occurrences.

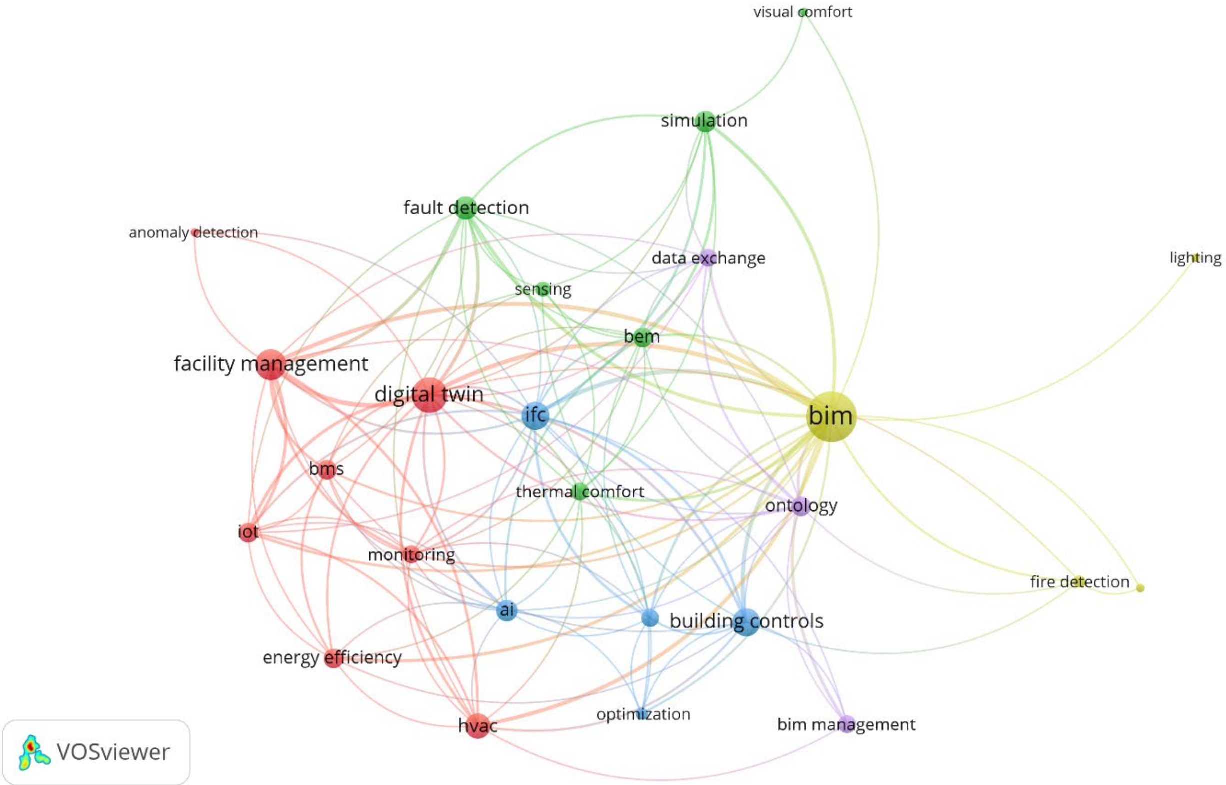

Figure 2. Network Visualization applied to 57 articles (VOSviewer details: Keyword-based, Binary Counting, Minimum number of Occurrences: 1, thesaurus file used to merge synonyms).

BIM, as the main topic of the literature search, is highlighted as the largest item, which reflects the categorical search around this subject area and effectively highlights the directly related topics. Therefore, a strong relationship exists between BIM—Digital Twin—Facility management (FM), whereas both build up their own cluster (red) which includes, as an interesting aspect, the sub-items of BMS, Monitoring, IoT, Energy efficiency, and HVAC. From this, it can be clearly seen that in the literature, energy efficiency measures and methods are mostly in connection with operational monitoring, via BMS and IoT in the application of HVAC systems.

In this context, anomaly detection also plays a small part, which is connected as a sub-item to this cluster. A relatively strong connection between DT and FM is also given to the green cluster, which builds up the topic of fault detection. Interestingly, this cluster also includes “simulation”, “BEM”, “sensing”, and comfort aspects. Thus, simulation-assisted analysis in the BIM/DT environment is mainly connected to fault detections, indirectly influencing the comfort performance of a system. Consequently, integration of simulation-based methods for energy optimization and controls, directly incorporated in the digital twin, is not state-of-the-art, which can be stated as a major outcome for the purpose of this review.

Building controls, as a main topic in this review work, also builds up its own cluster in blue, which includes the sub-items “IFC”, “AI”, and “optimization”. Individual interconnections between the subitems of the blue, red, and green clusters exist; therefore, close relationships and partly integrated methods show up in the existing research to some extent. Data management, communication, and ontology concepts are also clustered around the topic of BIM as more generous, methodological aspects (violet cluster). In there, "ontologies" might be a relevant topic, especially for control integrations, while "data exchange" shows a closer relationship to the simulation and BEM fields.

As another especially interesting aspect for this review, the sub-item "lighting", directly linked to "BIM", shows no connection at all to other clusters. This underpins another major result for the purpose of this review, showing that lighting controls and their consideration in DT applications are highly underrepresented.

As a second trend analysis, two key journals out of the selected pool of 57 publications can be mentioned as being Automation in Construction from Elsevier (17 selected papers) and Energy and Buildings from Elsevier (six selected papers), while the rest of the published works are spread very diversely among numerous journals in the fields of Construction, Sustainability, and Building Science. In addition, within the pool of publications, six conference papers are included from renowned conferences in the field (IBPSA, CISBAT, and EuroSun).

A third trend analysis of the reviewed literature focuses more on the timescale, where the number of relevant publications per year is shown in Figure 3.

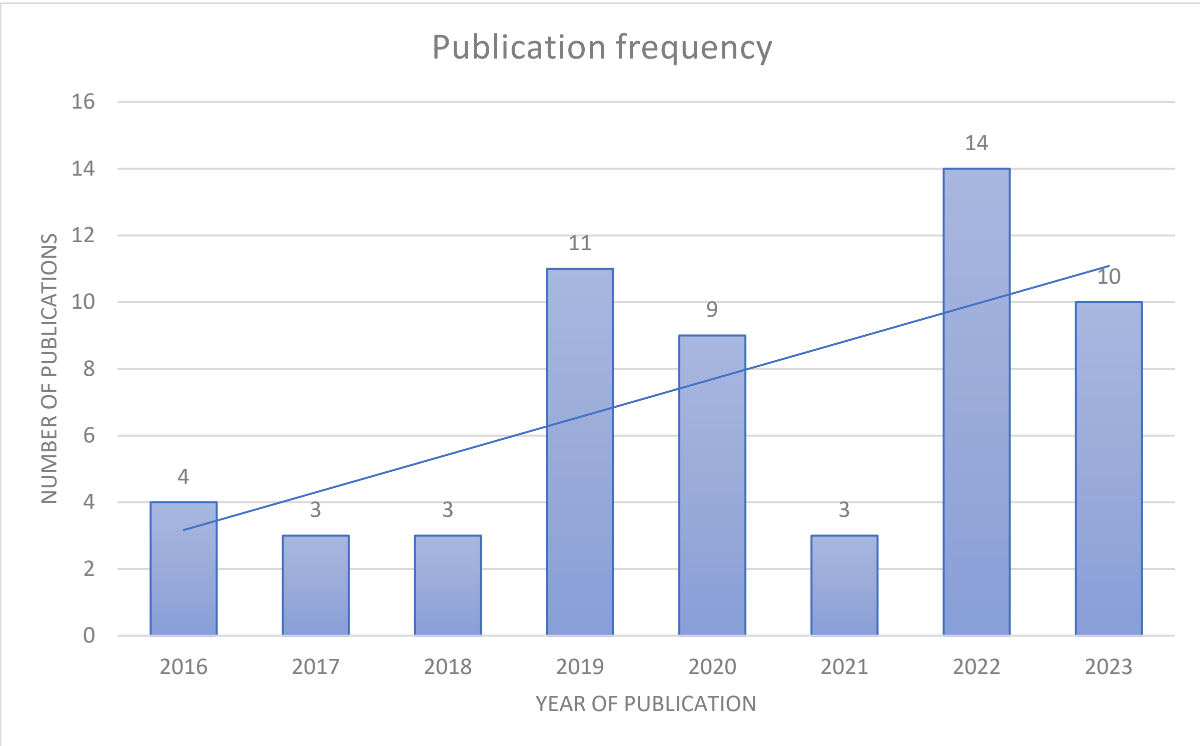

Figure 3. Distribution of the number of publications within the search period (2015–2023).

According to the distribution of publications, a clear upward trend in the relevance of the topics in recent years can be shown, especially in 2022 and 2023 when there was a strong focus on the topics of DT integration, dynamic data collection, virtual sensing, multi-objective, and predictive control. In 2020 and earlier, research on improving data exchange, interfaces, and the establishment of the first interchange platforms was the focus. The temporary decline in 2021 may be linked to reduced publication activity during the first year of the coronavirus pandemic due to harsh lockdowns and delays in the review process. In addition, the highest number of publications was recorded in 2022, which will also be due to delayed submissions.

In the following chapters, these trend results will be described in more detail by highlighting the individual aspects of the reviewed papers. In Section 5, the state of representation of integral control strategies in FT will be discussed, while in Section 6, the already established field of DT integration is highlighted as an example. Section 7 points out the relevant findings from the literature regarding the state of research in integrating integral controls in a DT environment.

5. Dimensions of a Representation of Integral Control Strategies in a Digital Twin Environment

As already mentioned in Section 2, Digital Twins can be used for the energy efficiency management of the entire life cycle of building energy systems. These systems encompass a wide spectrum of components, from heating, ventilation, and air conditioning to lighting, renewable energy sources, and building automation. The energy efficiency of these systems is of paramount importance as it directly affects operational costs, environmental sustainability, and occupant comfort. Intensive research outcomes from recent years show that DTs have emerged as a game-changing concept in the domain of building energy systems [23,27,28,32,33].

The main requirements when it comes to the realization of integral control strategies involving different trades can be addressed by a DT. This includes (1) the digital representation of control logic for different trades in the BIM model; (2) the integration of sensors, physical or virtual as well via IoT technologies; and (3) the ability to communicate between different modeling tools and appropriate environments. In the following subchapters, examples and any relevant literature are highlighted for each requirement, pointing out those aspects in more detail.

5.1. The DT as an Integrative Solution for Controls Mapping

Traditionally, the design and operation of building energy systems have been disparate, often lacking a comprehensive, real-time connection between the virtual representation and the actual, physical systems in place. This disconnect has limited the ability to optimize energy efficiency throughout the entire lifecycle of a building.

Digital Twins can bridge this gap by creating a dynamic, real-time mirror image of the building energy systems. This twin, which is essentially a digital replica of the physical system, can provide computer continuous data and insights that enable more effective energy management. It facilitates the monitoring, control, and fine-tuning of these systems in response to changing conditions, occupancy patterns, and external factors such as weather.

In the context of the entire lifecycle of building energy systems, DTs play a pivotal role in ensuring that these systems not only meet their intended performance but continuously adapt and improve their efficiency over time. This dynamic, holistic approach has become a cornerstone in the quest for energy-efficient and sustainable buildings.

Exemplarily, the paper by Chen et al. [23] introduces an innovative approach using real-time HVAC simulation of chillers to compare digital twin models' real physical systems. A new framework is presented to prepare these models so that they can be run in real-time and integrated into a digital twin for operational optimization. The DT model of the HVAC system is based on a broad learning system to solve the problem of real-time interactive and associated symbiosis, which is the most important aspect of DT. Traditional chiller models often lack real-time updating capabilities, making them unsuitable for real-time interactions with physical systems. The paper presents an intelligent DT framework for HVAC systems, featuring equipment, data, simulation, and application layers, which can build a basic concept for other trades (e.g., daylight and artificial lighting controls).

To enable BIM-based monitoring, control, and fault detection, Tan et al. [28] developed an office building's existing surveillance system and lighting system and proposed a digital twin-based intelligent lighting system that can adaptively provide appropriate lighting quality and minimize energy consumption. The proposed system consists of three main parts: a visualized operation and maintenance platform for the digital lighting system based on dynamic BIM, a framework for environmental perception based on computer vision mechanisms, and an occupant detection system based on model training and prediction using the YOLOv4 training algorithm. The goal was to aid the timely adaptivity of the digital twin during operation to achieve a more realistic lighting situation.

5.2. The DT as a Communication, Visualization, and Interchange Platform

Building Information Modeling, as an innovative technology, can be considered as an opportunity for the AEC industry to move to the digital era and improve collaboration among stakeholders by applying Information and Communication Technologies (ICT). The seamless exchange of information within a BIM framework is vital for effective collaboration in the construction industry. This interoperability ensures that data can be understood by different BIM applications and reduces the need for different file formats and documents. However, challenges arise when semantic data has multiple definitions across different disciplines or when incompatible proprietary information models are used.

While standard data models such as IFC (Industry Foundation Classes) have been proposed as a solution, inconsistencies and semantic gaps persist, limiting their effectiveness for information exchange. Consequently, there is a growing interest in research aimed at improving BIM interoperability, particularly through the open-BIM data model IFC. In the review work of [25], BIM-aided management, progress monitoring, and interoperability were identified as one of the six main topics where research is ongoing.

In terms of an integrative building design, collaboration and communication play a decisive role in the process, whereas Building Information Modelling provides the necessary technology. Nevertheless, this core aspect of BIM is mostly a major challenge to be resolved in a functional way. Important standards such as ISO 19650 [34] are defined to harmonize the data management in BIM projects, as described by the Common data environment (CDE). The standard proposes the approach of keeping partial models for different disciplines (such as Architecture, Structure, and HVAC), which are coordinated by well-defined collaboration cycles to achieve a coherent design in the end. However, Esser et al. [35] clearly highlight the practical limitation of this concept when it comes to large-scale models and highly frequent iteration cycles. Therefore, Esser proposes a novel digital collaboration method based on object-level synchronization, which is graphically based and follows the representation of a BIM model as well as their changing property graph structures [36].

As shown in Figure 1, IoT plays a major role in the integration of facility maintenance into BIM by integrating continuously updated operation data from the building site through sensors, physical as well as virtual. This allows visualization of operational data directly on a digital twin model as well as the implementation of a maintenance management system to continuously improve the process. Recent research activities are trying to address this aspect. In Villa et al. [37], the aim was to integrate an alerting system through the continuous monitoring of the building site and to visualize them virtually in a digital twin. A digital framework using IoT as well as an open-source cloud platform was realized for real-time analysis and fault detection. The platform also enables the facility manager to keep a good overview of the building's current operational status and to optimize indoor conditions in terms of comfort and temperature.

BIM provides all of the required tools and automation to achieve end-to-end communication, data exchange, and information sharing among collaborators. Accordingly, virtual 3D models, created by the BIM process, are delivered as physical assets, monitored in real-time, and managed using Building Management Systems (BMS). They can also adopt Internet of Things (IoT) designs and services. In this way, ref. [38] proposes an alternative approach for a system design that employs blockchain technology as a measure to secure and control the framework that involves integrated IoT and BIM technologies. While the system design is exemplarily applied in a smart museum, the authors point out that design tends to be generic and therefore also applicable to other building categories.

In [39], the need for efficient sensor failure management in sensor-based facility management within IoT environments is addressed. It emphasizes the use of BIM as a visual model and data repository for integrating sensor data across a building's operational lifecycle. The work illustrates that using this BIM-based system can enable timely responses to sensor failures, ensuring minimal disruption to monitoring services. Additionally, the paper suggests potential enhancements, such as incorporating occupancy sensors and machine learning, to further improve sensor maintenance and predictive planning. Therefore, the approach presented in this paper provides valuable insights into bridging the gap between BIM and sensor-based support tools for more effective facility management.

5.3. DT Enables Interoperability by Providing Interfaces and Workflows

Interoperability encompasses the ability of different software tools and platforms to understand, interpret, and effectively exchange data. In the context of BIM, it ensures that information flows smoothly between the diverse applications used at different stages of a construction project. This capability is essential for fostering collaboration, reducing errors, and enhancing overall efficiency within the AEC sector.

In the work of [40], the integration of Building Energy Modelling with Building Information Modelling has been studied. The investigation uncovers several interoperability challenges between BIM and BEM, highlighting that BIM-based energy modeling holds promise for sustainable and low-energy building design. However, it also reveals that the BIM-to-BEM process lacks standardization, leading to variations from one modeler to another, which may slow down adoption and introduce uncertainties for professionals in the field.

To improve the interoperability issues, the AEC industry is shifting towards cloud-based Common Data Environments (CDEs) that link BIM models, marking the move towards BIM maturity level 3. The authors in [41] introduce a CDE named Virtual Commissioning (VC), capable of commissioning HVAC systems before their physical installation. A so-called FSC diagram to represent HVAC BIM models in the VC CDE (Common Data Environment) and the Revit to the FSC exporter for serialization is being developed.

In addition, [42] addresses the challenges in preparing Building Energy Performance Simulation (BEPS) models, which often involve manual operations leading to data losses and errors. The proposed solution suggests a standardized method of information exchange between Building Information Modeling (BIM) and BEPS tools using the Information Delivery Manual (IDM) and Model View Definition (MVD) methodologies. This approach utilizes use cases to identify exchange requirements for BEPS tools, translating them into the Industry Foundation Classes (IFC) schema. The goal is to facilitate the transfer of information from IFC-based BIM to various BEPS tools, enabling the full potential of BIM-based simulation and providing a reliable IFC subset for energy simulation software.

For the BIM-based development of integral daylight and artificial lighting control strategies, existing linkages between established daylight modelling and energy modelling tools to the BIM environment are of high relevance. In the published work by Miller et al. [43], the first direct integration of the web tool DALEC [44] into Revit 2022 through its own plug-in was realized. In a current follow-up research project, BIM2BEM-Flow [45], a continuous parameter workflow from early-stage design until commissioning is going to be established, starting with initial parameter management (parameter definition, trade assignment, and specification of normative requirements and default values), followed by continuing parameter workflow management for various simulation tools in the field of energy and daylight simulation (assignment of responsibilities and workflows), and finally, the creation of a dashboard for comparing different design variants [46].

As an outlook beyond the results from the literature review, there are numerous ongoing national and international standardization and harmonization activities trying to address the aspect of improved data interoperability between the different disciplines in the construction sector. While Building Smart International strives to provide a standardized file format with IFC as well as a standard property set via the buildingSMART Data Dictionary (bSDD), several initiatives on different national levels strive for their own "ground truth", especially by involving the relevant national standards and requirements. While those activities help to achieve individual steps towards understanding and international harmonization, the CEN/TS 17623:2021 [47] was recently published, which defines parameter items to describe lighting objects (including luminaire, controls, electronics, and geometry) in a high level of detail on the BIM level. Based on these new parameter standards, the new Global Lighting Data Format (GLDF) [48] was recently published and has already been implemented in the latest releases of DIALux evo 12 and Relux Desktop 2024.1. It addresses the issue of interoperability in the lighting sector and should help to build a new basis for a BIM-based description of lighting objects.

6. Overview of the Established Fields with Applied DT Integration

Despite the fact that the establishment of integrative control strategies in the BIM environment for daylight and artificial lighting systems is not yet well developed according to the existing literature, other related fields already show a significant amount of published research. One example is the field of fault detection for HVAC systems, which requires a broad system information level due to the system complexity, whereas BIM can provide a powerful environment as a single source of information. In addition, the field of fire protection comes up with plenty of research activities, whereas BIM can also build a perfect environment to localize and control fire- or smoke-detecting sensors in facility management. The following sections highlight the processes and concepts of relevant work to provide useful input for daylight and artificial lighting control applications.

6.1. Fault Detection for HVAC Systems

During the operational phase of a building, the heating, ventilation, and air conditioning (HVAC) systems are the main contributors to excessive energy consumption if they are not properly designed or if sufficient maintenance is not performed. In addition, problems with HVAC systems can heavily impact the occupant's thermal comfort. Therefore, identifying the root cause of HVAC problems is essential for facility managers to plan preventive and corrective maintenance activities. However, due to the complex interaction between different devices and the lack of data integration between FM systems, they do not provide the necessary information to identify the cause of HVAC problems.

In Golabchi et al. [49], a BIM HVAC tool is being developed that uses a fault detection and diagnosis (FDD) algorithm to automate the process of detecting faulty heating, ventilation, and air conditioning (HVAC) systems. The algorithm connects to a complaint ticket database and automates BIM to identify potentially damaged HVAC system components and develop an appropriate action plan for facility inspectors.

In addition, Hosamo et al. [26] describe the development of a digital twin framework for automated fault source detection and predictions for improved user comfort. It was developed by integrating building information modelling with real-time sensor data, integrating user feedback via surveys as well as probabilistic models based on Bayesian networks. Within several real-case example buildings, numerous sensors have been installed to get data about the building operation. A Revit plugin was developed to access the live data and to maintain the BIM model. As it was not always possible to extract sensor data from the existing BMS systems, an additional Restful API was implemented as an additional layer in the system hierarchy. Apart from HVAC fault detection, the developed method addresses the occupant's comfort, including indoor air quality, acoustic quality, and lighting quality. Furthermore, the digital twin enables the prediction of maintenance cycles and tasks for the next two months to prevent the system from malfunctioning, using the Bayesian networks.

In the work of Alavi et al. [50], a decision-making framework is developed, which helps the facility manager to evaluate the reason for the improper functionality of an HVAC system. The framework is organized in the form of a sequential checklist workflow, evaluating if the indoor unit capacity of the installed systems is higher or lower than the thermal load of the room. While the unit capacity can be determined by databases, the thermal load can be calculated based on the existing building model. In general, fault detection and diagnosis methods can either follow a data-driven or knowledge-based approach.

To provide efficient maintenance services for building systems, the research by Villa et al. [37] proposes the creation of an IoT network for facility managers to monitor HVAC system components and detect their failure. A cloud-based user interface with integrated IoT technology feeds the 3D BIM model of the building with information on room temperature, humidity, and brightness, as well as the operating status of the fan coil units. At the edge of the system, this integrated fault detection methodology notifies and sends alerts to facility managers when an anomaly is detected. In addition, maintenance staff can easily find the location of the faulty component in the 3D BIM model of the building by room ID or room name, both of which are integrated into the application.

In the work by Andriamamonjy et al. [51], the objective was to facilitate and partially automate the implementation and use of model-based FDD. This was demonstrated by the development of a BIM-based method for automated implementation and commissioning of fault detection for ventilation systems. The elaborate process also includes a BIM2BEM workflow to obtain energy modelling data from the BIM model by entering extended IFC properties into a Modelica model.

While fault detection is not a main concern of daylight and artificial lighting controls at first glance, the methods presented in the reviewed works concerning system data interoperability and model-based control, as well as the approaches around feeding measured data into an existing BIM model, are also of high relevance for lighting controls. In addition, HVAC control systems and lighting control systems have been established as independent trades for a long time, whereas a joint integration of both in the BIM environment can provide a significant piece of the puzzle to take integral HVAC and lighting controls a realistic step further.

6.2. Fire Protection for Built Facilities

A lot of research has already been carried out in the fields of BIM application and IoT in fire risk management, as it is of great significance to building operations that comprise fire protection design, fire/smoke spread limitation, fire extinguishment, and escape probability. Although fire safety is not the topic of this review, the existing literature in this context has been screened. Learned lessons and interesting concepts applicable to the building controls field have been identified.

In the work of Jian et al. [52], the use of digital twins and semantic web technologies is described for the intelligent control of building fire protection systems and their efficient operation. For the description of the fire protection system, a novel ontology is considered in the semantic model and as the basis for the integration of static building geometry data with dynamic sensing data during operation. To keep the digital twin model up to date with the physical space during the operational phase, rules and process methods are developed and implemented.

In Zhou et al. [53], a cloud-based fire alarm warning system based on BIM is proposed. The system platform and software architecture are developed. On the platform, all plans (BIM/IFC, sensor positions, CAD) are uploaded, located, and mapped using GPS. A sensor-BIM alignment module links sensor data via an NLP algorithm to the location where the sensor is installed and stores it in the BIM model. The CloudFAS software includes static data (model data) and real-time data (sensors, cameras) and processes the data in a cloud-based monitoring software. Although no control strategies are implemented in this paper, methods on how to connect real sensors with a digital twin environment show potential similarities to the implementation and localization of controls for daylight and artificial lighting systems.

7. The State of Research in Integrating Controls in a DT

7.1. Existing Approaches to Develop and Optimize Integrating Control Approaches

Existing research in control development and integration within the BIM environment predominantly focuses on HVAC systems, with limited attention given to integral daylight and artificial lighting. This scarcity may stem from a lack of widespread awareness in the construction industry, leading to an underestimation of optimization potential. Alternatively, the complexity of practical implementation may hinder progress, exacerbated by the fragmented nature of the lighting industry. Consequently, the demand for large-scale solutions and current research in this area remains relatively low.

Despite these challenges, the urgency for solutions has increased in the face of issues such as summer overheating, elevated user comfort expectations, and the growing prominence of low-energy building concepts. While existing research articles outline strategies for incorporating controls within the BIM process, they predominantly pertain to HVAC and general building energy systems. This article emphasizes the importance of extending these strategies to integral daylighting and artificial lighting controls, recognizing their applicability and potential for addressing contemporary challenges in construction and building performance.

A highly relevant work in this context by Sporr et al. [54] shows a complete conceptual design and mapping of an HVAC control system in IFC. An integral approach to designing HVAC controls is being implemented and virtually set up by using theoretical component models and derived building data (and system data were available) from an IFC model. Automated control configuration is envisioned, while lighting is not yet included.

Another work by Sporr et al. [55] focuses on defining ventilation control strategies using building model data also derived from an IFC file. In this work, IFC is firstly also used to define new control algorithms, while an integral approach including different trades is not envisioned so far.

In Benndorf et al. [56], a control strategy is created that includes a boiler, a thermal storage tank, a ventilation unit, and a floor system. Starting from the definition of a heating curve, the schedules for the ventilation unit, and the supply temperature for the heating circuit, an overall control system is configured. HVAC elements are firstly exported from Revit to IFC as IfcDistributionFlowElement or IfcDistributionControlElement. Subsequently, these elements are supplemented with additional information outside Revit, using a new tool based on IfcOpenShell. After that, the IFC is converted via IfcOWL into an ontology, which converts the IFC via IFC2RDF into an RDF and is then queried via SPARQL by the controlling tool. Unfortunately, the theoretical concept shown is not applied to any test example in the published work. Nevertheless, as novel information, the paper contains a detailed description of how controllers, actors, and sensors are managed and networked in the IFC and how dependencies are mapped.

To close the performance gap that results from inconsistencies between the different planning phases, Jakobi et al. [57] present a workflow promoting extended commissioning, demonstrated by using a PV system in combination with a heat pump and passive solar heating. The simulation model is continuously updated based on changing conditions, which allows the predicted energy demand to be kept in close range to the real operation. In addition, the paper shows the principles of how to pair a real building project with a digital twin model to set up predictive maintenance services.

Similarly, the paper by Nytsch-Geusen et al. [32] describes a simulation-based method for the design and evaluation of building control strategies, using a combined method of a digital twin, real building data, and the HVAC system modelled in Modelica v3.2.3. For the implementation of building control strategies, the software package openHAB release 2.4 (open Home Automation Bus) is used, which works bi-directionally and in real-time. Thus, control strategies can be developed and optimized under dynamic boundary conditions during the design phase. A digital twin represents the building behavior, which is continuously enhanced to reduce the performance gap to reality, until it is substituted by the built building and the control system behaves almost similarly without additional changes.

A work that is also promising for application in the field of daylight and artificial lighting controls is published by [33]. It presents a conceptual framework for developing real-time weather-responsive control systems in combination with BEMS (Building Energy Management Systems). The controls are developed based on typical building energy control patterns, which are generated using weather data. The method allows elaborate control patterns for the two dominant energy use controls in buildings and daylight and artficial lighting, as well as HVAC operational schedules. The BIM model is used to collect the required building geometry data for the thermal and lighting simulation models as input. For the lighting part, a daylight intensity database is pre-calculated. For the thermal part, apart from the geometry itself, combined effects such as solar radiation intensity and glazing properties are considered for pre-evaluation using CFD.

Even if the area of daylight and artificial lighting control is still underrepresented in the concepts and approaches shown, many methodological approaches from the HVAC sector can certainly be transferred to the daylight and artificial lighting sector. This literature review identifies all existing approaches, regardless of the device, and thus defines a common state of the art for the further development steps that are to take place as part of the TwinLight research project.

7.2. The Role of BEMS in the Development of Control

The increasing focus on energy efficiency during a building's operational phase highlights the importance of continuous energy consumption control. Building Energy Management Systems (BEMS) play a crucial role in achieving optimal indoor environmental quality while minimizing energy costs. However, most existing BEMS systems mainly monitor and collect building energy usage data, track real-time energy intensity, and identify abnormal energy consumption. They are mostly lacking in integrated control systems and do not consider detailed building geometric information, which makes accurate prediction and analysis of energy usage challenging. Recent advancements in BEMS are geared towards real-time energy management using data from weather conditions and energy usage patterns. While this approach enhances accuracy, it tends to underestimate energy use set points due to occupant behavior effects, particularly concerning room temperature and heating/cooling loads.

However, at the same time, research in building energy performance management and control is rapidly evolving as shown in the literature review above, driven by increased energy conservation efforts in the construction sector worldwide. Recently, BEMS has been integrated with control systems to enhance energy consumption control and prevent anomalies. Researchers have proposed that various BEMS can be integrated with BIM to improve accuracy and reliability. BIM data can support Model Predictive Control (MPC) and simulation-based control systems.

To further address these emerging trends, the ongoing research project TwinLight [58] aims to develop a conceptual framework for a real-time building energy simulation-based BEMS that accounts for occupant behavior and energy-efficient building operation, specifically regarding optimized control of daylighting and shading systems for windows as well as daylight-linked artificial lighting controls for energy-efficient indoor illumination. The control concept will utilize a simulation-based control routine, considering building model data, real-time occupant data, and weather data for time-efficient control evaluation. This literature review builds the scientific basis to build up new developments on the current state of research.

8. "Lessons Learned" and Derivations for the BIM Implementation of Integral Lighting Controls

The highlighted application fields of control strategies in Section 6 for HVAC systems, fire protection, and Building Energy Management Systems (BEMSs), and their reviewed research articles, underpin the strong trend towards a proactive integration of BIM models not only during the construction phase but increasingly also to continuously consider them in the operational phase as digital twin applications.

In the realm of HVAC systems, several research articles propose BIM-based tools for fault detection, predictive maintenance, and occupant comfort improvement. Fire protection explores intelligent control systems using digital twins and cloud-based approaches, with potential applications to lighting control systems. Nevertheless, the current emphasis on control development primarily centers around HVAC systems within the BIM environment, leaving a gap in the research for integral lighting controls. Therefore, there is not evidence to make a clear conclusion on the application of Digital Twin approaches in the field of daylight and artificial lighting.

Nevertheless, "lessons learned", achievements so far, and research results from the different articles can be used to derive several trends in connection to the following research questions.

Focus 1: Mapping integral control strategies in a DT

➢ What approaches currently exist to map lighting controls in BIM and to make them usable for all construction stakeholders?

Notably, IFC is frequently mentioned in conjunction with an open-BIM approach, while closed-BIM solutions predominantly involve Revit or related developments within the Revit environment (such as Dymola, Revit families, Revit to FSC diagrams, or integrated plugins in Revit).

When it comes to communication architecture and protocols for real implementation, Modbus, BACnet, CAN, and Ethernet are commonly cited. In the realm of sensor integration, technologies such as WiFi, Bluetooth, RFID, ultra-wideband, and IoT are frequently discussed. IFC-related communication platforms encompass IFC2RDF, ifcOWL, and SPARQL, utilizing MSSQL, Python, and JSON as programming languages or Restful APIs for communication. Due to the wide variety of technologies and languages available now, there is the risk that interoperability is not always guaranteed due to the greater variety of communication platforms and protocols. Therefore, standardization is required at this point.

Moreover, contemporary trends include IoT and cloud-based monitoring services, which facilitate the collection of linked data from diverse sources (such as building-based and weather data). This, in turn, enables the adoption of data-driven modeling approaches for the establishment of control routines. While many models still adhere to physical-based white-box or grey-box paradigms, there is an emerging inclination towards data-driven models, particularly in the context of control-oriented routines.

With the published work of Tan et al. [28], a best-practice example for a digital twin-based intelligent lighting system can be highlighted, providing highly relevant insights relating to this aspect.

➢ Can the current limitations of integral controls be removed by moving planning to the BIM level?

The current trend in implementing model-based control algorithms is increasingly aligned with digital twin approaches, particularly in terms of connectivity to CAFM or failure detection analysis. However, a significant divide still exists between various trades. While only a limited number of reviewed papers explicitly focused on developing new control strategies, six papers delved into research articles dedicated to daylighting and artificial lighting, while HVAC applications and other domains were the focus of seventeen and seven research papers, respectively.

In the realm of developing new control strategies, thermal dynamic simulation tools were cited in six papers, with lighting simulation featuring in only three relevant works. Notably, in the HVAC field, Modelica v4.1.0 and Simulink were mentioned for thermal simulation applications, while EnergyPlus v23.2.0, TRNSYS v18, and IDA ICE v4.6 were highlighted in the energy envelope modeling domain. Therefore, it is evident that BEM tools are becoming more closely integrated into the BIM environment by incorporating relevant simulation data. Currently, this is mostly restricted to plain geometry information, but it will include more and more metadata such as material specifications or occupant-related information such as user feedback, occupancy models, and user requirements.

The integration of simulation routines at the BIM level, whether for energy performance or daylight simulation, represents a crucial initial step in overcoming current obstacles and limitations in integrating different trades. However, active research and the standardization of interfaces must be pursued to further diminish the boundaries between different disciplines.

In this context, the research work published by [38] can be mentioned as an informative work, proposing an alternative approach for a system design based on blockchain technology, which also aims to improve interoperability between the trades and provide solutions for secure version control of different development statuses between different planning versions.

Focus 2: Existing approaches and workflows to designing and expanding integrative controls

- ➢ What interfaces and exchange workflows exist between BIM and BEM? Where are the boundaries here?
- ➢ How can integral controls currently be simulated in a digital twin environment?
- ➢ Are there workflow procedures to derive controls from the simulation?

The literature review reveals the absence of an established standard for simulating integral controls across various trades within the digital twin environment. Numerous research articles showcase fragmented developments, underscoring the need for cohesive efforts to achieve the goal of developing and simulating integral control routines within a digital twin framework. Nevertheless, the following significant points relevant to the raised research questions can be highlighted:

In the realm of Computer-Aided Facility Management (CAFM), the implementation or optimization of control played a subordinate role. From the analyzed papers, fault detection took precedence in 10 articles, while monitoring was highly relevant in 11 articles. Notably, ref. [28] addresses BIM-based monitoring, control, and fault detection, encompassing an office building's existing surveillance and lighting systems along with a proposed digital twin-based intelligent lighting system. This system adaptively provides purpose-fit lighting quality while minimizing energy consumption.

Ref. [27] focused on monitoring, utilizing measured sensor data to generate forecasts for diverse control options, including daylight and artificial light, as well as HVAC. EnergyPlus serves as the energy modeling kernel. While specific control logistics were not specified, simulations were employed to optimize implemented control routines. The study also delves into building data collection for refurbishment projects, discussing linked data and the utilization of various sources to gather relevant information.

Similarly, in [23], promising model-based optimization of HVAC applications is demonstrated on a real system. This work also focuses on the operational phase instead of developing controls in the pre-installation phase, which can be integrated during the BIM planning process.

Focus 3: Transferring integral control approaches from the DT to the real building

- ➢ What are the core features of intelligent commissioning based on existing examples and how would these be anchored in the context of integral control strategies?
- ➢ Which BEM2Control possibilities exist or could be used, where is there a need for development?

Upon reviewing the research paper list, a primary objective was to identify various approaches addressing intelligent commissioning. This entails formulating an integral control strategy during the design phase within the BIM environment, subsequently translating it directly into a digital twin. The pivotal research question centers on the mechanism for this seamless transfer. However, scarcely any reviewed papers serve as a definitive "blueprint" for an intelligent commissioning methodology. Thus, no current method can guarantee fully automated commissioning, including the assurance of knowing about adoptions taken during the construction process compared to the final planning stage. This is a significant hindrance when it comes to the ability to design a proper building control in the pre-construction phase based on a planning model.

In the work by [23], a method is introduced that specifically tackles real-time HVAC simulation, focusing on chillers. The aim is to prepare these models for real-time execution and integration into a digital twin for operational optimization. While the emphasis remains on HVAC components, the chosen approach aligns closely with prevalent concepts in the realm of daylight and artificial lighting control. It involves obtaining real sensor data from the system, assessing it in real-time using a real-time-capable model, and implementing optimizations. However, it is worth noting that the model's optimization is not automatically fed back to the system; instead, manual adaptation is required for system adjustments.

9. Conclusions

Based on a publisher-independent search of scientific literature carried out via Web of Science and a supplementary search via ScienceDirect, a thematic overview on the current state of research in the field of developing, integrating, and maintaining integral control concepts for the application of daylight and artificial lighting was produced. Supported by a bibliometric analysis using VOSviewer, thematic focal points and their interrelationships were graphically processed and analyzed.

The literature research shows that development priorities have crystallized in the areas of fault detection, building control, and facility management. While published work on controls-related content shows a clear focus on HVAC applications, a strong trend from the recent work can be extrapolated in pursuing the DT approach by developing interdisciplinary interchange platforms and new interfaces for improved data flows and communications.

Challenges and barriers in the practical implementation of integral controls for daylight and artificial lighting systems are manifold: (i) interoperability issues between BIM and software tools in the planning phase due to missing standardizations, (ii) shortcomings in data accuracy and consistency due to missing execution workflows and binding responsibilities between different trades and planners, and (iii) obstacles in accurately modelling as-build systems due to missing specification data as a consequence of insufficient BIM property sets, especially when it comes to daylighting systems. This leads to mistrust regarding the further use of transmitted data and, in turn, causes a lot of unnecessary pre-/post-processing work. It also hinders smooth communication via existing building management systems, especially between the existing proprietary control systems which are widely used in the market.

In-depth research should therefore continue to focus on the continuous improvement of the above-mentioned interoperability and compatibility issues, which are essential as technological bases for an integrative mapping of building control strategies in BIM and DT applications. Future research steps should therefore focus on the aspects of refining control strategies using more and more planning data from existing BIM models, incorporating real-time data, and improving the interoperability of DTs with different building management systems. This development is crucial to further close the so-called performance gap between design and operation and will have a significant impact on energy-efficient building practices, user comfort, and sustainability in the construction industry.

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