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## Improving healthcare design with BIM-based tools

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## Improving healthcare design with BIM-based tools

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**Abstract.** It is well known that the quality of healthcare facilities can contribute to health and wellbeing. Healthcare design is complex due to the large amount of information involved, with sometimes conflicting requirements which evolve over time. Therefore, strategies to deal with such complexity and volume of information is key. These include requirements from clients, stakeholders and regulations, structuring and storing design data and also verifying if design solutions are compliant to the briefing and to the regulatory framework. Despite the reported benefits of BIM, there are still gaps on the use of BIM tools in practice to support healthcare design. The aim of this paper is to discuss the benefits and limitations of commercially available BIM tools to support requirements management in general, and rule checking (also referred to as code checking, i.e. regulatory compliance checking) specifically. Design Science Research is the method adopted in this investigation. An empirical study was conducted in collaboration with an institution responsible for Primary Healthcare buildings in the UK. The results discuss the role that two tools (dRofus and Solibri Model Checker) have in supporting requirements management and code checking in healthcare design, their benefits and limitations. A framework is proposed, exploring relationships between the main features of the two BIM tools addressed in this paper and their potential impact on healthcare design. This paper demonstrates that improvements in healthcare design can be achieved by using BIM tools, which might benefit the quality of buildings designed and built, leading to positive health outcomes.

### 1. Introduction

The healthcare built environment includes operational and functional spaces supported by technology. The quality of the healthcare environments affect services delivered within these facilities and, ultimately, can positively impact health outcomes [1]. Healthcare design involves a large amount of information [2], partially because of the multiple stakeholders involved and the need to balance their needs, preferences and requirements [3,4], but also due to the related medical knowledge and the combination of healthcare services and technologies to be delivered in the building [5,6]. Thus, these requirements represent needs from people and organizations involved or impacted by a project, and



relate to how needs and expectations are translated into functions, attributes and other features in the product (i.e. the healthcare building) [7].

Healthcare systems are dynamic due to the unpredictable, interdependent and evolving tasks [8–10]. In order to deal with this dynamism and variability, there is a need for flexibility, so that buildings can adapt to changing services and needs [11]. This represents a challenge for the design of healthcare facilities, which should be able to allow flexible solutions [12], at the same time all requirements are also considered and fulfilled [13]. Thus, managing requirements in such projects constitutes a challenge of the utmost importance [2,14].

The use of information technology (IT) to support requirements management has been suggested over 20 years ago [15]. IT is able to support the management of large amounts of data, including its creation, communication and documentation [15]. In recent years, important changes in the design process have happened due to the support of different types of Building Information Modelling (BIM) processes and software tools [16]. This has led to benefits related to improving building quality and relying on more accurate processes [17]. However, there are only a few applications of BIM reported by literature in healthcare requirements modelling [18,19]. Hence, there is a need to further investigate the use of BIM tools to support healthcare building design.

This paper starts by presenting a literature review of the use of BIM in healthcare design. It explores the main benefits and limitations of using BIM to support both requirements management and automated code/rule checking. The method adopted in this investigation is then presented, leading to the discussion of the main findings. It is understood that by improving the healthcare design process, there can be benefits on the way buildings will be used. This can contribute to better healthcare outcomes for patients and better quality of life for staff, which are amongst the global challenges addressed by the United Nations (UN) sustainable development goals. In fact, the use of digital technologies through automation and improved data management are also key strategies for the future the UK construction industry [20]. Using digital approaches across all stages of a building design can ultimately lead to improved construction and operation processes.[20].

## **2. BIM in healthcare design**

In the last decades BIM has been adopted to improve all phases of a building lifecycle [16]. According to Pikas et al. [17], by using BIM, there is an opportunity to improve a building project by enabling early contribution of different stakeholders on decision-making for planning, designing and constructing healthcare facilities, through an evidence-based processes. While using BIM, information becomes the fundamental asset, through the development of semantic-rich databases [21]. Whereas this evidences the need to make information explicit to support better decision-making, requirements must be structured in a way compatible to BIM, to achieve such benefits in practice [2]. This can be done through the adoption of digital and systematic requirements management strategies which, in turn, can also support design assessment and regulatory compliance checking through automated rule checking [22]. In the following, the main uses of BIM for requirements management and rule checking are discussed.

### *2.1. Requirements management in healthcare design*

The requirements management process consists of managing, controlling and refining requirements throughout the project life cycle [23]. It should be understood as a systematic process of fulfilling requirements across all phases of a project, acknowledging that requirements change and/or refinements are needed over time [18,24,25]. This can be supported by BIM, which enables registering and handling data in a more flexible and reliable manner, by linking it to building models [14].

The use of BIM for modelling and managing requirements contributes to the visualisation and communication of requirements [18]. Requirements modelling using BIM also has a positive impact on assessment. The connection between requirements and the model facilitates visualisation and verification, and thus contributes to reduce the time spent on design analysis and approvals [22,26]. Therefore, storing structured requirements in object-oriented tools, contributes to promote a construction industry that is more focused on the clients and their needs [14,16,26,27]. BIM tools such as dRofus and

Solibri Model Checker have been developed for this purpose [26]. Both allow the connection between requirements and different parts of the building model by using the IFC Open Standard, in order to ensure that the design solutions satisfy requirements [28].

The design of healthcare buildings is complex, involving the coordination of all stakeholders, such as, policy makers, community, design teams, construction companies and end users [29,30]. Such complexity, added to conflicting requirements and changes over time, make the processes of managing design information difficult [1,27,31]. Despite the support of BIM through advances in information management, manipulation, storage and data exchange techniques, difficulties of coordinating and managing information still occurs in practice [32]. Moreover, processes related to communication, capturing and traceability of requirements are often still fragmented, hence difficult to manage in healthcare projects [32].

### *2.2. Automated rule checking in healthcare design*

Automated rule checking has been subject of research for a number of years [22,33]. Previous research focused on incorporating automated approaches to deal with building compliance to regulations [21,33,34]. This involves using information from building codes and other regulations as an input for rule creation and execution. Most developments aim to alleviate issues and inconsistencies of the manual compliance process [22,34,35].

The introduction of a degree of automation in design assessment can lead to many benefits. It is often difficult to assess design compliance due to the complexity of the regulatory framework associated to healthcare buildings [36]. Quantifiable and objective regulatory requirements can be easily verified in building models by using commercially available software, such as Solibri Model Checker. The main benefits are time savings, as well as its user-independent character [22], which avoid the negative effects of individual biases and misunderstandings while assessing building designs [21,36]. Moreover, the use of automated rule checking is scalable, as checking routines can be replicated [34].

The main issues relate to the way these approaches have been developed over time [37] and to limitations in dealing with subjective requirements [36,38,39], which hampers its practical adoption [22,33]. Most developments are limited and have emerged from very specific research initiatives, leading to fragmented solutions [37]. Moreover, solutions tend to include hard-coded approaches [22,33], which makes it difficult to adapt those to contexts other than the ones for which they were originally developed [33].

### *2.3. Summary*

The use of BIM to support requirements management and automated rule checking has been extensively discussed across the literature. Despite their important contribution, it is evident that most of the issues are still recurrent in practice. While the main benefits indicate potential improvements to the design process by using BIM, practical results appear to be limited. These limitations are mostly due to the inconsistencies between information used to support the design, based on subjectivity, and technological constraints from software. Issues in dealing with subjective requirements could be alleviated with the introduction of semi-automated approaches, enhancing design through combining human inputs and computer-processed data [39]. Moreover, BIM tools need to have an easy-to-use interface [40] and must be integrated, so they allow interoperability across different domains [41]. Thus, the discussion of the benefits and limitations of existing software is important to support the improvement of existing tools or the development of new software, considering the scope of this paper.

## **3. Research method**

This paper reports preliminary findings from ongoing research investigating opportunities to improve healthcare design through better requirements management. Design Science Research (DSR) was the methodological approach adopted in this investigation. This approach consists of developing solution concepts (also known as artefacts) with the aim of solving classes of problems with practical and theoretical relevance [42,43]. The outcomes of DSR are typically constructed through cycles of analysis,

understanding, development and refinement [44]. It is important to highlight that results presented in this paper do not include the final artefact of this research study. Findings here presented are limited to the initial stages of the research, i.e. understanding of the problem.

An empirical study was developed during the design of a primary healthcare building. This was in collaboration with an institution responsible for primary healthcare buildings across the England. Results presented in this paper are based on the literature review, and insights from the empirical data are used to support the analysis presented. The main sources of evidence are: (i) literature review on requirements management and automated rule checking in healthcare design; (ii) analysis of design documents, such as briefing documents, schedule of accommodation, 2D drawings, building models and assessment reports; and (iii) use of software (dRofus and Solibri Model Checker) to support requirements management and automated rule checking, respectively.

The findings explore how BIM can support healthcare design through better requirements management and regulatory compliance checking. The use of dRofus focuses on managing both clients and regulatory requirements in a structured database, linked to the virtual building model. Solibri Model Checker was used to incorporate information from the British healthcare regulatory framework as an input to rule creation and model checking. Thus, Solibri was used to automatically verify if the Primary Healthcare building was compliant to a set of (quantitative) regulatory requirements.

During the research further data was also collected through (i) interviews with multiple stakeholders and (ii) visits to four operating health centres. Even though the evidence collected through this is not presented in this paper, it influenced the analysis here presented.

## 4. Key findings

### 4.1. Using dRofus for healthcare requirements management

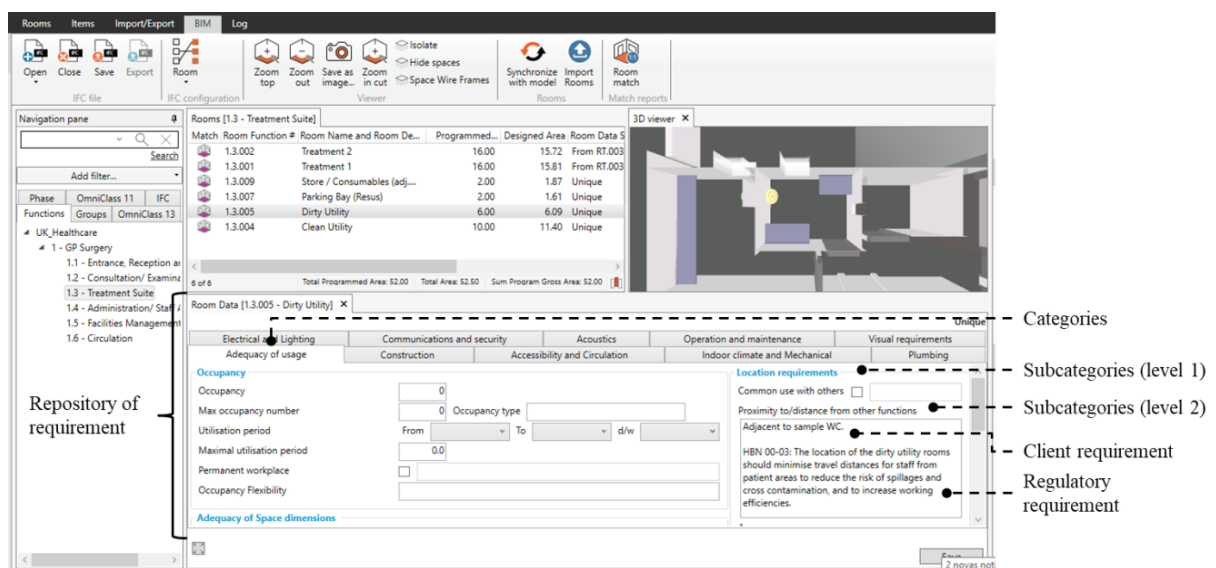
Storing requirements in a systematic way assists in the development of an integrated and broad database, with the aim of supporting decision-making and the selection of design alternatives. Client requirements collected during visits, interviews and regulatory requirements were included in a database within dRofus. Hence, the tool was used to structure and store requirements hierarchically. Initially, information from clients and regulatory requirements was stored in a spreadsheet and grouped according to affinity, e.g. requirements related to the dimensions of spaces; subsequently, it was organised into categories and subcategories of requirements. These categories and subcategories were based on Kiviniemi's framework [14], as well as on the existing structure of dRofus. As a result, the requirements' structure used includes 12 categories (Table 1), 48 subcategories (level 1 in Table 1) and 225 subcategories (level 2 in Table 1).

Capturing, analysing and structuring requirements was done manually, which took a substantial amount of time and effort. Requirements' modelling in dRofus focused on the storage of requirements structured according to the categories described in Table 1, and its connection to the digital building model. The building model was developed using Autodesk Revit. Therefore, dRofus was used to model client and regulatory requirements, developing a central information repository, which supported the visualisation and communication of requirements (Figure 1). Modelling is beneficial as it involves the creation of a generic and reusable information repository, as some requirements are similar across different healthcare projects.

The main benefit of dRofus was to make requirements information easily available and traceable during design. This enables the control of requirements during design development, as well as the process of assessing whether those requirements have been fulfilled in the design solution. Some limitations were also identified: (i) the software does not enable designers to easily understand the impact of a requirement's change in other requirements; (ii) the tool does not support capturing or analysing requirements; (iii) subjective requirements are difficult to categorize, as requirements may belong to more than one category. Subjective requirements need further processing to be understood by project teams and also by computer systems; and (iv) dRofus is not suitable for modelling process requirements, which are requirements to accommodate or support user activities [28].

**Table 1.** Structure of 12 categories and examples of subcategories adopted in this investigation.

Categories	Subcategories (level 1)	Subcategories (level 2) / Requirement
1. Adequacy of usage and functionality	Occupancy	Occupancy; Max occupancy number; Occupancy type;
	Adequacy of space dimensions	Standard required area; Programmed area; Designed area;
2. Construction	Walls/ partitions	Protection of privacy; Walls / Partition flexibility
3. Accessibility and Circulation	Doors	Door opening; Glass in doors; Sliding doors; Dimensions
	Space Accessibility	Accessibility for handicapped; Accessibility for hearing impaired;
4. Indoor climate and Mechanical	Heating and Cooling	Individual room temperature control; Heating system flexibility;
	Ventilation	Possibility to overrule ventilation; Ventilation control;
5. Plumbing	Water supply	Water temperature requirements; Water supply flexibility
6. Electrical and Lighting	Electrical System	Normal supply - single outlets; Electrical system flexibility
	Lighting	Light dimmer; Zone divided lighting;
7. Communications and security	Communication and transmittal	Hearing Loop; Local signal transmission; IT network and telecom flexibility
	Surveillance, security and alarm	Camera surveillance; Special fire alarm;
8. Acoustics	Sound insulation	Doorless partition walls: $R'w[dB] >$ ; Partition walls with door: $R'w[dB] >$
9. Operation and maintenance	Cleaning	Special detergents; Special cleaning methods; Cleaning frequency
10. Visual requirements	Overview	Overview of patients; spaces or functions overview
	Wayfinding	Signalling escape routes; Colours for spatial orientation
11. Finishing requirements	Product information	Product name; Finish; Colour;
	Dimensions	Width; Height; Thickness
12. Equipment and furniture requirements	Max dimensions and weight	Width; Depth; Height; Weight; Loud on (Floor, Wall, Ceiling)
	Ergonomics	To be placed on: Floor; Surface; Allow Height adjustment



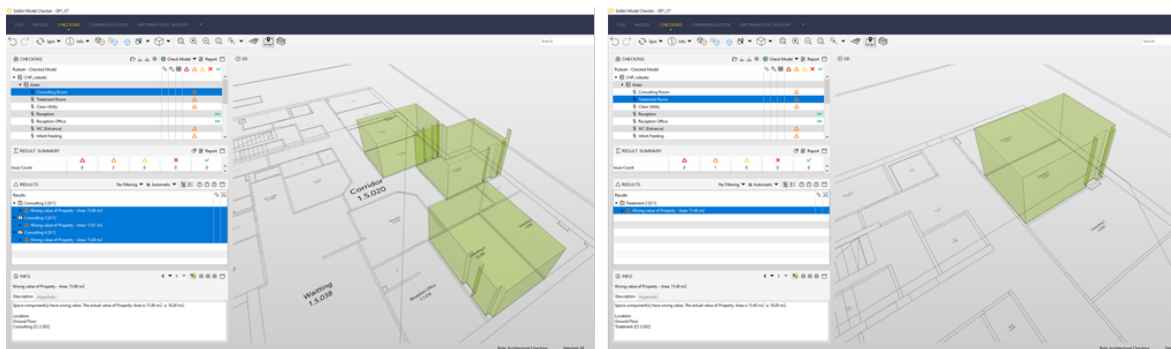
**Figure 1.** Example of application of dRofus – Storage of requirements in the Room Data

#### 4.2. Using Solibri Model Checker to support automated rule checking

Regulatory requirements were incorporated into Solibri through the software's ruleset manager. The process of translating information from regulations was manual and demanded a considerable amount of time. This is because information is presented in regulatory documents through text, tables, sketches and diagrams. Therefore, their translation to Solibri was done by browsing the software rule library and choosing the pre-programmed rule structure which could be more easily adapted to verify each requirement. Every rule structure has different parameters that can be modified, however there is limited flexibility from the software in terms of rule creation.

The application of Solibri was successful for quantitative requirements related to size, such as area and height. Moreover, qualitative requirements such as determining if specific objects or sets of objects are included into certain spaces could also be verified by using this tool. These are common types of requirements included in the healthcare regulatory framework.

Results from the assessment process are easily generated and incorporated to reports and datasets, so it provides feedback to designers with ease. Figure 2 is an example of how Solibri was used to verify if the designed spaces were compliant to requirements related to their minimum dimension. Although the verification has pointed out inconsistencies due to spaces being smaller than required, the clients involved in the decision-making process would define whether the designed area is acceptable or if the regulatory requirement should be derogated.



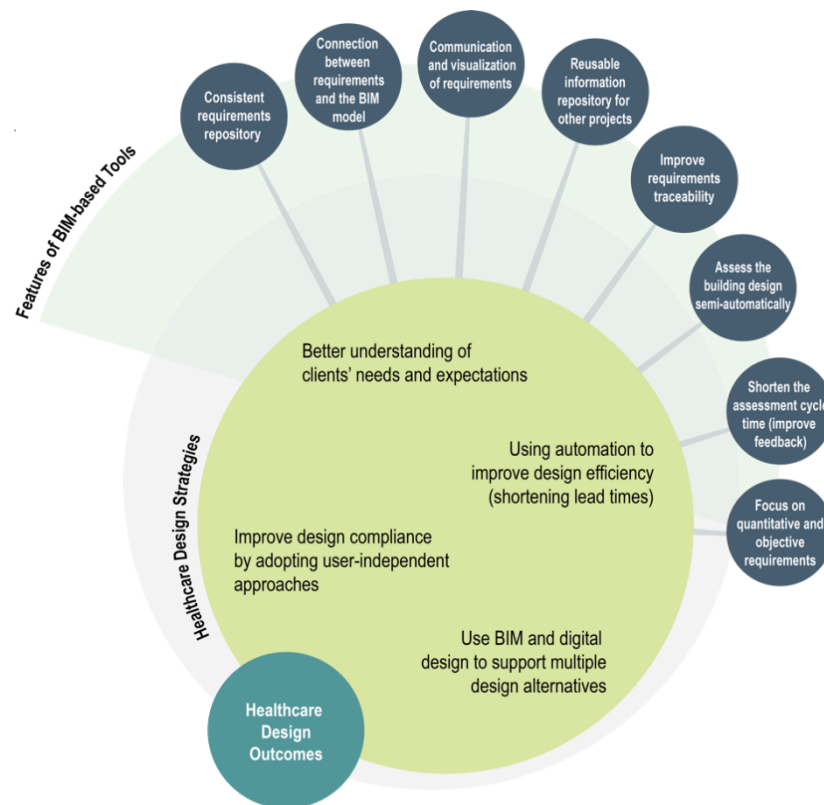
**Figure 2.** Example of application of Solibri – Assessment of areas

Using Solibri for automated rule checking also had limitations. These relate to the way information needs to be processed to be used as an input for rule creation e.g. the “black-box effect”, as rule processing is not completely transparent to users. This was already identified in the literature [35,45] and is a major issue. The software deals relatively well with typical quantitative and objective requirements (which are fundamentally related to measurements and counting), but incorporating subjective regulatory requirements (e.g. related to flexibility and adaptability) was not possible in Solibri in this research.

#### 4.3. Discussion

From the application of the BIM tools, it is possible to identify their benefits and limitations in use. dRofus has been successful to manage and model requirements, with limited application of automated checking, performed mostly under a semi-automated approach. On the other hand, Solibri enabled automated rule checking of some specific types of requirements, mostly related to objective and quantitative information. By using a combined approach between these tools, different features can be identified. These are represented in Figure 3, in the proposed a framework.

This framework explores relationships between (i) the main features of BIM tools identified in this paper and (ii) their potential impact on healthcare design strategies. These, in turn, can contribute towards better healthcare design outcomes. The framework is discussed as follows, according to proposed healthcare design strategies.



**Figure 3.** Framework healthcare design strategies with support of BIM-based tools

*4.3.1. Better understanding of clients' needs and expectations.* The use of the BIM tools described in this paper support the identification of clients' requirements and their use across the healthcare design process. This consists of a systematic and reliable approach to identify, organise and store information, enabling its use to support decision making. BIM tools support introducing a degree of automation in some of these operations, which contribute towards dealing with large amounts of data in the design process. The overall quality of the built environment can potentially be improved by: making sure that clients' needs are fulfilled and that buildings are compliant to regulations. This is relevant specially in healthcare design because of the many stakeholders involved in this process and the potential disconnection regarding their design awareness. The use of BIM can aid non-technical users to understand the building and how it will function (e.g. patient pathway), contributing towards meeting their needs.

*4.3.2. Using automation to improve design efficiency (shortening lead times).* The use of semi automated routines enables time savings due to the elimination repetitive operations. From the tools explored in this paper, both dRofus and Solibri are based on automated operations, which support processing data in a faster and more reliable way. The use of automated rule checking also supports reducing the time designers spend on design assessment. This can enable them to focus more on value-adding activities, which rely on creativity and unique reasoning. Ultimately, this approach might lead to improved design quality by better use of designers' time and efforts.

*4.3.3. Improving design compliance by adopting user-independent approaches.* The use of automated rule checking to support the building compliance process is based on its user-independent character. Hence, there is non-involvement of humans while assessing a design proposal, automatically judging its conformity to a set of regulations. This has the potential to improve design outcomes by avoiding



subjectivity due to individual biases and misunderstandings that could happen in the assessment process, if humans are in charge of this task.

*4.3.4. Using BIM and digital design to support multiple design alternatives.* The use of BIM can support exploring different healthcare design alternatives. This is a direct consequence of using automated routines, which enable cost and time efficient explorations of design. Both tools explored in this paper are not directly associated to generating multiple design alternatives, but they support validating proposals in terms of accordance to different types of requirements.

By demonstrating the benefits and limitations of using digital and BIM-based tools for healthcare design it might be possible to contribute towards the development of public and governmental policies to support these advancements. The underlying reasoning expressed by this framework is that by improving healthcare design, there is a potential to provide better healthcare environments and infrastructure for services to be delivered. This can contribute towards achieving the UN sustainable development goals i.e.: (i) goal 3: ensure healthy lives and promote well-being for all at all ages; and (ii) goal 9: build resilient infrastructure, promote sustainable industrialization and foster innovation.

As previously described, there is an important relation between the built environment and how it supports healthcare service delivery, which impact health outcomes. The quality of the built environment impacts directly how patients react and sense the spaces, but it also has a major impact on staff. This is because medical staff tend to stay in these spaces for long shifts, most of the times under pressure. Therefore, approaches described in this paper have the potential to better incorporate their needs into design solutions. This can contribute to better working environments in the future.

Moreover, the analysis carried out highlights that updating and revisiting all the healthcare regulatory framework is needed. This is because regulations should be updated to allow a wider use of automated approaches. This can potentially alleviate some of the limitations identified during the empirical phase of this research.

## **5. Final remarks**

The use of BIM tools to support healthcare design, such as dRofus and Solibri, has been explored in this paper. Benefits and limitations of each software have been identified. A framework was proposed exploring relationships between the main features of BIM tools investigated and their potential impact on healthcare design. This stemmed from the practical application of BIM tools to better support requirements management and rule checking.

The analysis carried out in this paper evidenced that improvements in healthcare design emerging from automation would have a positive impact in the quality of buildings designed and built. This is because exploring design through this perspective facilitates the visualisation, traceability and communication of requirements, by connecting these to the digital model. Requirements modelling using BIM also contributes to reduce the time spent on design assessment and approvals, as well as preventing the negative effects of individual biases and misunderstandings during the assessment process. In addition, the use of BIM can provide benefits to healthcare design by replicating rulesets and also generic requirements across different projects.

The use of BIM in healthcare design was considered in this paper, but it can also support the building across its lifecycle. BIM can support change management within the building during its operational use, as healthcare systems evolve and asset management is fundamental to deal with their emerging needs. This paper demonstrated that advancements in healthcare design emerging from BIM tools and automation might positively impact design solutions, ultimately contributing towards improved operations and health outcomes.

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