Title: Healthy BIM: The feasibility of integrating architecture health indicators using a Building Information Model (BIM) computer system.

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Author Name: Louis Rice

Affiliation:

Department of Architecture and the Built Environment,

University of the West of England, Bristol,

UK

Louis.Rice@uwe.ac.uk

01173283014

Healthy BIM: The feasibility of integrating architecture health indicators using a Building Information Model (BIM) computer system.

The Covid-19 pandemic has forced billions of people into lockdown; foregrounding the important relationship between architecture and health. In this context, there is heightened urgency for the construction sector to improve the healthiness of buildings. Accordingly, the research identifies the feasibility of measuring various building health indicators (BHI) through the use of a Building Information Management (BIM) model. The research seeks to find optimal strategies for integrating the near ubiquitous use of BIM with a range of health indicators related to building design. A systematic literature review was undertaken to identify potential Building Health Indicators for use in BIM models. The research then undertook a Delphi technique in order to test the hypothesis. Three rounds of questionnaire-based surveys were undertaken with expert participants. The research identifies three different levels of BIM complexity in order to achieve the integration of health indicators. The most simple strategy suggests BHI can be directly measured using existing BIM models; the next level of sophistication requires 'plug-in' software to BIM models; the final level would require additional sensors and detectors in a 'smart' building. The research is significant for users of BIM, building designers, public health advisors, construction professionals, healthcare providers, social prescribers, architects and clients. The integration of BHI into the architectural design process is an important step towards the construction sector improving health and wellbeing. The research provides for the first time a rigorous identification of the most viable mechanisms through which BIM may be used to measure the healthiness of a building.

Keywords: architecture; BIM; health; wellbeing; building information modelling; smart buildings, Covid-19.

Introduction

The importance of including health indicators when designing a building is of growing importance. As Covid-19 devastates the health of millions of people globally, the connection between the environment in which we live and our health has been forefronted as never before. Covid-19 has impacted the health of majority of the world's population within a few months of its onset (deSantis, 2020). Governments are implementing radical changes to spatial, social, economic and cultural structures in order to contain the virus. The principal mechanism for dealing with Covid-19 has been some form of quarantine particularly 'lockdown' into homes. This pandemic has placed architecture at the heart of this medical and public health issue. Billions of people are restricted to their own homes (or other residential forms of accommodation). The role that the design of buildings performs in shaping our health (and/or ill-health) is forefronted by this pandemic. However, Covid-19 is not the only health concern that is associated with architectural design. The majority of the global population now suffers from ill-health and the prevalence of disability is increasing (Abubakar, Tillmann and Banerjee, 2015). The main driver behind the majority of ill-health is linked to the growth in non-communicable diseases (NCDs) associated with factors including: obesity, sedentary lifestyles, junk food, depression, loneliness and anxiety (ibid). With society now spending 90% of its time indoors (Samet and Spengler 2003); the importance of architectural design to health is even more important than ever. It has become increasingly incumbent on a range of professions to address the emerging health crisis – including building designers and the construction industry (Rice 2019a; Jones, Rice and Meraz 2020). There is an urgent need for the design profession to consider human health more fully and rigorously in the design process, particularly in light of the issues emerging during the Covid-19 pandemic (Salama 2020; Rice, 2020a). The hypothesis tested is whether building health indicators (BHI) can be integrated into a Building Information Management (BIM) model to automatically measure and assess the healthiness of a building. The research identifies the feasibility of measuring and evaluating various BHI through the use of a BIM model. Given the availability and use of health indicators related to the design of buildings and the widespread adoption of BIM in the construction industry, the research seeks to integrate the two. However, to date, it is not clear whether it is feasible to achieve this goal. The objective is, through the use of Delphi technique, to identify experts' opinions on the mechanisms for measuring health indicators through the development of a BIM model. This article addresses a broader aim of identifying BHI that can be measured using BIM in order to evaluate and improve health outcomes.

BIM

BIM is a computerised simulation of architectural design with additional information and data related to the entities included within the model. The National BIM Standard (United States) defines BIM as a: '*digital representation of physical and functional characteristics of a facility*' (National Institute of Building Sciences 2015, 1). The use of BIM has become widespread in the construction sector globally; there is widespread use in higher-income economy nations, with growing usage in low-middle income countries (Jung and Lee 2015; Bui, Merschbrock and Munkvold 2016). Building Information Modelling (BIM) has been mandated on all government-funded building projects in the UK since 2016. BIM has already enabled innovation and delivered efficiencies in a variety of aspects of building design including: financial control, material waste, carbon footprint and sustainability performance. There has been a proliferation of research into the use of BIM for a variety of factors, particularly sustainability and financial costings, however there has to date been very little research into the use of BIM for evaluating human health. Healthy BIM (HeBIM) is still in its infancy; there are no available tools to automatically integrate health indicators into BIM (Lu et al 2017). This article establishes, for the first time, mechanisms through which BIM can be used to measure a number of different health issues that are associated with the design of buildings.

BIM, sensors and smart buildings

The use of BIM to calculate complex data such as health indicators, has become more feasible with recent advances across a range of intelligent digital technologies and sophisticated 'smart' buildings and 'smart' cities (Vito, Berardi and Dangelico 2015). BIM models have traditionally been 'static' models in that the data is input manually by designers or managers; and typically do not show dynamic changes occurring in completed buildings (Volkov and Batov 2015). However, the growth of smart buildings and smart cities is beginning to change this (Jia et al 2019). There is a rapid increase in deployment of intelligent sensors, metres, and detector within buildings to track real-time changes within the environment, particularly for heating, ventilation and lighting levels (Panteli, Kylili and Fokaides 2020). These sensors can be linked to intelligent control systems for boilers, air conditioning etc to respond to the changing conditions. Whilst sensors such as thermostats have been used for some time, there is now a much greater range of detectable devices, particularly through the expansion on the Internet-of-Things and wearable devices (Rashid, Louis and Fiawoyife 2019). The integration of BIM models with the wider proliferation of intelligent digital devices is seen as the next step in the development and utility of BIM. Accordingly, the research examines how smart buildings can aid in the measurement of various health indicators as part of a BIM model.

Health Indicators

An indicator can be described as *'something that provides useful information about a physical, social, or economic system, usually in numerical terms'* (Farrell and Hart 1998, 7). The terms indicators, tools and indices are often used interchangeably; for simplicity this article adopts the term 'indicator' to refer to each specific issue that is being investigated, measured, monitored or evaluated. Indicators are used to measure a variety of issues, partly lead by political imperatives, economics and/or accountability, for example, the United Nation's Sustainable Development Goals have a range of indicators to allow evaluation of nation's progress to date. On a smaller scale, hospitals are monitored for their care provision, schools are audited for their exam results and industrial organisations have energy efficiency assessments. Indicators are widely used in healthcare, architectural design and the construction industry. The measurement of the effect of the design of a building on human health through the use of BHI is relatively new. As human health is a mix of physical, mental and social wellbeing; it is necessary to measure a range of aspects of the built environment that can determine health outcomes (WHO, 1946). Diseases and illnesses are often linked to specific qualities of architectural design (Rice, 2019b). For example, 'air quality' is the indicator measured because it is linked to illnesses such as bronchitis and other related respiratory health conditions. Other indicators such as 'acoustic insulation' are measured due to its connection with a range of illnesses, for example unsuitable acoustics can result in poor sleep, which may contribute to a number of health conditions including depression, diabetes, obesity and coronary heart disease (Buysse 2014). Different aspects of the design of building environments are associated with determining various health outcomes. The health map (see figure 1) provides an illustration of how aspects of building design interact with health determinants (Rice, 2019b). The health map breaks the complex aspects of health into four domains involved in the design of buildings: *materials, spatial, agency and behaviours.* These four domains cover all aspects of the identified BHI and encompass physical, mental and social health qualities.

Figure 1: Health map for architecture (Image credit, Louis Rice, 2019b). Note: Image adapted from a health map by: Hugh Barton and Marcus Grant, 'A Health Map for the Local Human Habitat,' The Journal for the Royal Society for the Promotion of Health 126, no. 6 (2006): 252-253. Developed from a concept by: Goran Dahlgren and Margaret Whitehead, Policies and Strategies to Promote Social Equity in Health (Stockholm: Institute for future studies. 1991).

Indicator Selection

The building health indicators selected were derived from a systematic literature review. The objective of the review was to systematically identify BHI. A 'Preferred Reporting Items for Systematic review and Meta-Analysis Protocol'(PRISMA-P) approach was adopted to aid consistency in the approach to reviewing evidence. PRISMA-P is a well-established methodological and analytical approach and is a frequently used protocol for systematic reviews (Moher et al 2015). The review consisted of three phases: phase one involved a meta-analysis of literature to identify studies for inclusion; phase two extracted BHI from the meta-data; phase three involved the extraction of the most frequently used BHI. It is necessary to undertake such a rigorous literature review, as one of the '*key weaknesses in Delphi analysis has always been that certain questions were not asked; they did not seem important when the study started*' (Linstone, Simmonds and Bäckstrand 1997). In order to reduce this weakness in the Delphi technique the systematic literature review identified a full set of BHI in advance (note: a fuller account of this systematic literature review is available in: Rice and Drane, 2020b).

The systematic literature review identified 14 health indicators that are used in the construction industry: thermal comfort, volatile organic compound (VOC), formaldehyde concentration, thermal zoning and controls, daylight factor, sound insulation, indoor ambient noise level, room acoustics, security, safe access, outside space, views of nature, sedentary lifestyles and illuminance levels (bid). The majority of these health indicators can be measured easily, quantitatively and have relatively straightforward relationships to health outcomes, (such as air quality and bronchitis) (ibid). However, some health determinants are harder to measure than others; particularly the more qualitative indicators. Whilst these indicators are sometimes used within the construction industry, they are not calculated within BIM models. When BHI are used, they typically part of more complex evaluative toolkits such as: BREEAM, LEED, SB Tool, CASBEE or Greenstar. These toolkits tend to include a small number of AHI as part of a much larger inventory focusing on energy efficiency and sustainable construction. The aim of the research is to attempt to ascertain the feasibility of integrating BHI into BIM, thereby bypassing the need for additional, often expensive and complex toolkits to calculate the healthiness of buildings.

Quantifying the cost of Ill-health

Health covers a vast array of mental, social and physical factors, and there are now sophisticated methods for calculating the 'relative value' of different illnesses and diseases (Gallopin 1997). There is agreement within the medical and public health professions on how best to provide an equitable framework within which to do this comparison (Changik 2014; Byford, Torgerson and Raftery 2000). Models such as 'value of statistical life', 'value of lost output' 'disability adjusted life years' and 'cost of illness' are well-developed models used to prescribe the economic value of specific illnesses, disabilities or mortalities (Per-Olov 2001). The World Health Organization describe Disability Adjusted Life Years (DALYs) as: 'the sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability' (WHO 2011a). The loss of one year of healthy life is equivalent to one DALY. Each specific illness can be ascribed a DALY, for example, 13% of all DALYS are related to mental health; whereas one tenth of all DALYs are attributable to cardio-vascular disease (WHO 2011b). With models of health and illness, such as DALYs, a rigorous evaluation of various heterogeneous illnesses can be quantified and compared. The sophisticated DALYS model can be integrated with BHI to ensure that architects and construction professionals can comprehensively assess a range of health outcomes related to the design of buildings.

Methodology

The research undertook a Delphi technique in order to test the hypothesis. Delphi has been developed as a means of measuring the level consensus of opinion amongst a group of experts (Dalkey and Helmer 1963; Sourani and Sohail 2015). The Delphi technique is a 'unique method of eliciting and refining group judgement' (Kaynak and Macaulay 1984) and is 'effective in allowing a group of individuals as a whole to deal with a complex problem' (Linstone and Turoff 1975). The measurement of building health indicators using a BIM model is a 'complex problem' for which the use of Delphi is an appropriate strategy for investigating this subject. Delphi has previously been used in the architectural and construction sector for evaluation of design process decisions, value hierarchies and criteria identification (Manoliadis, Tsolas and Nakou 2006; Gunhan and Arditi 2005; Giel and Issa 2016; de la Cruz, del Caño and de la Cruz 2006). The Delphi technique is used here to identify the congruence of opinion of BIM experts on the research hypothesis.

Expert participants

The Delphi technique is predicated in the opinions of 'experts' therefore non-probability purposive sampling was undertaken in order to selectively target participants with a significant knowledge of BIM systems (Flick 2018). Previous studies have found that an optimal number of experts required to participate in a Delphi technique is in the range of 8 to 30 participants (Griffith et al 2007; Mullen 2003; Okoli and Pawlowski 2004; Crichter and Gladstone 1998). As the Delphi requires several rounds, there is a tendency for some of the participants to drop out, therefore it is prudent to choose a sample size large than necessary to allow for non-completion across three separate surveys. The participants were composed from a non-stratified sample of 15 individuals and the sample size of the three rounds was as follows: n=15, n=9, n=9. It is critical for an appropriately knowledgeable expert panel to be selected to ensure the procedure is valid and rigorous. Participants were chosen according to two key criteria; a detailed knowledge of BIM systems and expertise in the construction industry. All of the panellists have worked and/or conducted research in a number of countries and continents and have a wealth of experience to enable the work to be relevant globally to research in BIM, public health, architectural design and the construction industry. Four of the expert participants had more than 11 years of experience one had 6-10 years' experience, two had 2-5 years and one participant had 0-1 years two had 2-5 years working with BIM models. There was a range of expertise amongst the group; some participants have experience in the BIM in the construction industry whilst other participants were University employees conducting research in the field of BIM.

Delphi process

The experts were asked to verify the feasibility or otherwise of specific health indicators to ascertain the degree of agreement. The first round involved questions concerning the 14 specific indicators identified from the literature review [thus : thermal comfort, volatile organic compound (VOC), formaldehyde concentration, thermal zoning and controls, daylight factor, sound insulation, indoor ambient noise level, room acoustics, security, safe access, outside space, views of nature, sedentary lifestyles and illuminance levels. Whilst all of the participants are experts in the construction industry and would be expected to have a good working knowledge of these criteria; in order to reduce the possibility of confusion or misinterpretation, brief definitions of each AHI were provided. For example, the indicator 'illuminance level' had the accompanying definition: ''*Illuminance (lux) level' is defined as a measurement of the light intensity at any point within a building (lumens per square metre)*'. Full ethical approval was granted before the research was undertaken and all responses were anonymised. The first-round survey asked expert participants closed-ended questions to ascertain whether it is feasible for a specific BHI to be measured with a BIM model. If a BHI were considered not feasible, the respondents are prompted to give a brief explanation thereof and this indicator be removed from the subsequent survey. If a BHI were deemed feasible then it would be included in the subsequent surveys. Furthermore, if the respondent answered affirmatively; they were then requested to suggest a method for measuring this indicator within a BIM model. The reasoning behind this approach was to reveal new ideas or techniques from BIM experts who have a high level of expertise of BIM models that perhaps had not hitherto been evident or available in the existing literature. The intention here was to reveal greater insight, particularly from a technical perspective, this group of experts could contribute to the topic. There was also one additional question that asked more broadly '*Do you think it is feasible to use a BIM model to measure the health of building occupants?'* in order to get an overview of the feasibility of integrating BHI into BIM.

The second-round survey included statements on the feasibility of each BHI to be measured in a BIM model and participants asked to rate each statement. In the second and third round surveys, each participant was shown the group response for each item. The results of the previous round were presented to the participants at the start of the survey and each participant was given the opportunity to reflect, compare and, if appropriate, revise their responses in light of the other experts' responses. A 7-point Likert scale was used to enable participants to quantify the degree of agreement or otherwise with the statements. A rating of 1 indicating they 'strongly agree' and 7 indicating they strongly disagree' that that a BHI could feasibly be measured in BIM model. For each of the indicators a follow-up question was included; for example a first question: '*The health indicator 'thermal comfort' can be measured in a BIM model?*' had a follow-up question (for those who agreed with the first question) of: '*The health indicator 'thermal comfort' can be measured in a BIM model through the integration of additional wearable sensors for users in the completed building?'*.

The third and final round of the survey asked the same questions as the second round and gave respondents the opportunity to change their decision or further confirm their original choice. Whilst two rounds of the survey may suffice in some instances; in this study three iterations of the survey were necessary in order to confirm consensus amongst expert participants. Three rounds were undertaken and no further were necessary due to the high level of congruence amongst the expert's decisions. As Delphi is predicated on a relatively small number of experts, there is generally little merit in performing extensive statistical modelling on the results (Kaynak and Macaulay 1984; Rowe and Wright 1999). Relative scoring is used to reveal the decision tendencies amongst the expert group.

Results

The findings go through each of the BHI in turn. Beginning with the broader question on whether the experts believe that it is feasible to use a BIM model to measure the health of building occupants. Eight of the nine respondents agreed, with one respondent in disagreement, that BIM can be used to measure BHI. This evidences a strong consensus among the professional and academic experts that a BIM based approach is feasible for measuring health indicators.

Thermal comfort.

The experts agreed that the health indicator 'thermal comfort' can be measured in a BIM model, by a ratio of eight of the nine participants. The follow-up question on whether thermal comfort can be measured in a BIM model through inputting multiple criteria (such as: U-Values, location/orientation of building, proportion of glazing etc) and using e.g. Dynamo to calculate safe levels for the building received unanimous agreement. A further question relating to the measurement of thermal comfort through the integration of additional wearable sensors for users in the completed building was agreed by eight of the nine respondents (one respondent neither agreed nor disagreed). This shows that there is very high level of consensus that thermal comfort can be measured in a BIM model, and that there are a variety of means through which BIM could achieve this.

Volatile Organic Compounds

The majority of respondents (eight of the nine) agreed that the health indicator 'Volatile Organic Compound' (VOC) can be measured in a BIM model. On the follow-up question on whether VOC can be measured in a BIM model through inputting the VOC level for each material, appliance and product in the building (and using additional software e.g. Dynamo to calculate safe levels for the building) was agreed by 8 of the 9 respondents (one respondent neither agreed nor disagreed). All respondents unanimously agreed that VOC can be measured in a BIM model through the use of additional VOC sensors in the completed building. The results reveal a high level of consensus for the use of BIM to measure VOC levels.

Formaldehyde Concentration

All respondents unanimously agreed that 'formaldehyde concentration' can be measured in a BIM model through the use of additional sensors in the completed building. Eight of the nine respondents agreed that 'formaldehyde concentration' can be measured in a BIM model through inputting the formaldehyde level for each material, appliance and product in the building (and using e.g. Dynamo script to calculate safe levels for the building); one respondent neither agreed nor disagreed. This shows that there is very high level of consensus that formaldehyde concentration can be measured in a BIM model, and that there are a number of mechanisms through which a BIM model could achieve this.

Daylight Factor

All experts unanimously agreed that the health indicator 'daylight factor' can be measured in a BIM model. In addition, there was unanimous agreement that daylight factor' can be measured through the integration of additional BIM plug-in software to calculate appropriate levels for the building. Eight of the nine respondents agreed that 'daylight factor' can be measured in a BIM model with additional 'daylight level' sensors in the completed building, with one respondent disagreeing with this. The results indicate that there is a high level of consensus that daylight factor' can be measured in a BIM model, and that there are a number of means through which a BIM model could contribute to this.

Illuminance Levels

There was agreement amongst the experts that the health indicator 'illuminance levels' can be measured in a BIM model. Furthermore, the respondents unanimously agreed that illuminance levels can be measured in a BIM model with additional sensors in the completed building. The majority (eight of the nine experts) agreed that illuminance levels can be measured in a BIM model through the integration of additional plug-in software to calculate appropriate levels for the building; one respondent neither agreed nor disagreed. The results indicate a strong degree of consensus for the use of BIM to measure illuminance levels.

Thermal Zoning and Controls

The majority of respondents agreed that the health indicator 'thermal zoning and controls' can be measured in a BIM model. Eight of the nine respondents agreed that 'thermal zoning and controls' can be measured in a BIM model through the integration of additional Dynamo scripts (one respondent neither agreed nor disagreed). Again, eight of the nine respondents agreed that thermal zoning and controls can be measured in a BIM model with additional detectors and sensors in the completed building; with one respondent disagreeing with this. The results indicate a good degree of consensus for the use of BIM to measure thermal zoning and controls.

Sound Insulation

All respondents agreed that the health indicator 'sound insulation' can be measured in a BIM model. Eight of the nine respondents agreed that sound insulation can be measured a BIM model through the use of additional acoustic sensors in the completed building; one respondent disagreed with this. All respondents unanimously agreed that health indicator sound insulation can be measured in a BIM model through inputting the sound insulation level for each material, appliance and product in the building and using e.g. Dynamo to calculate appropriate levels for the building. The results indicate a strong degree of consensus for the use of BIM to measure sound insulation.

Indoor Ambient Noise Level

Respondents agreed that the health indicator ‘indoor ambient noise level’ can be measured in a BIM model. Seven of the nine respondents agreed that indoor ambient noise level can be measured in a BIM model through inputting the acoustic qualities for each material, appliance and product in the building and using plug-in software e.g. Dynamo to automatically calculate appropriate levels; the remaining two respondents neither agreed nor disagreed with this. All respondents unanimously agreed that indoor ambient noise level can be measured in a BIM model with additional ambient noise sensors to the completed building. This finding reveals that there is a high level of consensus that indoor ambient noise level can be measured in a BIM model, and that there are several ways through which a BIM model could achieve this.

Room Acoustics

There was agreement amongst the experts that the health indicator ‘room acoustics’ can be measured in a BIM model. Seven of the nine respondents agreed that through inputting the acoustic properties for each material, appliance and product in the building and using e.g. Dynamo to automatically calculate appropriate levels; however one of the respondents neither agreed nor disagreed with this, whilst one expert disagreed. On the follow-up question eight respondents agreed that room acoustics can be measured in a BIM model with additional acoustic sensors in the completed building; one respondent disagreed. The results indicate a strong degree of consensus for the use of BIM to measure room acoustics levels, although not to such a high degree of agreement as the previous indicators.

Security

Whilst there was overall agreement amongst the experts that the health indicator ‘security’ can be measured in a BIM model, there was no clear agreement amongst the experts on how to achieve this. When asked of the feasibility of whether the health indicator ‘security’ can be measured in a BIM model by using a binary rule-based code (e.g. a compliance checking script in Dynamo) against prescribed criteria (e.g. ‘Secured by Design’); there was a mixed response. Secured by Design is one of the most well-known and widely used toolkits for designers for integrating predetermined principles for safe and secure architectural design (Cozens, Pascoe and Hillier 2004). Five experts agreed this was possible, whilst two neither agreed nor disagreed and two disagreed entirely. The results reveal that whilst in principle security might be measurable using BIM, there is less clarity over which might be the best approach.

Safe Access

There was overall agreement amongst the experts that the health indicator 'safe access' can be measured in a BIM model. However only seven of the nine respondents agreed that safe access can be measured in a BIM model by using a binary rule-based code (e.g. a compliance checking script in Dynamo) against prescribed criteria (e.g. Employer Information Requirements); one of the respondents neither agreed nor disagreed with this, whilst one expert disagreed. Employer Information requirements are commonly used by certain building clients and client advisors, with safe access forming one of these requirements. The results reveal that there is agreement that safe access could be measurable using BIM, and there was a broad consensus on how to achieve this with a software plug-in.

Outdoor Space

There was no strong consensus on whether the health indicator 'outside space' can be measured in a BIM model by inputting external space qualities using a rule-based code (e.g. a compliance checking script in Dynamo) against prescribed criteria. Four experts agreed with this approach, two of the respondents neither agreed nor disagreed with this, whilst three experts disagreed. Whilst there was full agreement that this indicator could be measured in principle; no overall agreement on how to best achieve this in a BIM model.

Sedentary Lifestyles

Seven respondents agreed that the health indicator 'sedentary lifestyles' can be measured in a BIM model. Seven experts agreed (with two disagreeing) that sedentary lifestyles can be measured in by connecting to e.g. fitbit sensors and wearable technologies to a BIM model. Similarly, seven experts agreed (with two disagreeing) that sedentary lifestyles can be measured in a BIM model with additional behaviour/activity-detecting sensors in the completed building. The same experts agreeing that sedentary lifestyles can be measured in a BIM model by calculating average activity levels for each building layout and room type.

Views of Nature

There was majority agreement amongst the experts that the health indicator 'views of nature' can be measured in a BIM model in principle. However, there was no consensus on whether the health indicator 'views of nature' could be measured in a BIM model by using plug-in software e.g. Dynamo to calculate (for each room/window) the amount of greenspace in the surrounding context. Four experts agreed with this approach, one of the respondents neither agreed nor disagreed with this, whilst four experts disagreed. Similarly, there was lack of agreement over the feasibility of 'views of nature' being measured in a BIM model through a qualitative assessment by an expert consultant. Three experts agreed with this approach, two respondents neither agreed nor disagreed with this, with four experts disagreeing. Whilst there was agreement that this indicator could be measured in principle; no overall agreement was arrived at for achieving this in a BIM model.

Discussion

The first and most important finding is the broad consensus amongst experts that BIM can be used to measure BHI. This is the first time that a consensus of this nature this has been achieved. It provides a platform for a more detailed and developed approach to measuring healthiness of buildings using BIM computer models. Further research is required to convert this into reality, with greater testing of the individual variables required, as well as evaluation of the careful weighting of composite scores. The results also reveal that BIM is deemed an appropriate platform for measuring a full range of BHI. This is perhaps surprising as many of the indicators are subjective and complex; it could be anticipated that as BIM is a highly quantitative system it would not lend itself amenable to qualitative BHI. The experts unanimously agreed that BIM could be developed to cover a wide range of different health issues that are prevalent in society. There was some divergence over the most effective route through which this might be achieved using BIM.

Using existing BIM software as it is, each of the fourteen BHI identified, could be measured to some extent. For more sophisticated analysis of certain health indicators, current BIM platforms would need to be augmented through the use of additional plug-in software, such as Dynamo, to calculate the more complex algorithms required. Additional software would support the integration of the following BHI: thermal comfort, Volatile Organic Compounds, formaldehyde concentration, daylight factor, illuminance levels, thermal zoning and controls, sound insulation, indoor ambient noise level, room acoustics and safe access. Furthermore, in order to better evaluate selected BHI, additional sensors or detectors would need to be installed in a ‘smart’ building and integrated with a dynamic BIM model. The BHI requiring additional smart sensors are: thermal comfort, Volatile Organic Compounds, daylight factor, illuminance levels, thermal zoning and controls, sound insulation, indoor ambient noise level, room acoustics and sedentary lifestyles. This approach would require a dynamic BIM model to be integrated with ‘smart’ building technologies.

The BHI identified cover a wide range of factors linked to a number of common health issues prevalent in society today. However, it is noticeable that the majority of the BHI mostly relate to prevention of communicable diseases. Whilst this is an important set of health issues, this must be set within a context where relatively few people die of communicable diseases (particularly in nations where BIM is used most extensively). As non-communicable diseases are the most common cause of morbidity and illness globally, there is arguably a need for more BHI to be made available to capture a fuller picture of human health determinants, especially non-communicable diseases. Nonetheless, this is more a reflection of the indicators available than the capacity of BIM models.

In relation to the four domains of the health maps identified earlier: materials, spatial, agency and behaviours; there is also an imbalance across the four domains. Most of the available BHI would translate into the ‘material’ qualities of a building, that is the actual fabric from which the building is constructed. Many of the BHI are directly or closely associated with the physical construction materials, for example volatile organic compound (VOC) and formaldehyde concentration are closely associated with the material composition of building components. Similarly, thermal comfort, sound insulation, indoor ambient noise level and room acoustics are also a function of the material qualities of the construction materials. Daylight factor and illuminance levels are partly a function of the material qualities, i.e. the amount of glazing in the external envelope; but they are also related to the spatial qualities of the design, in terms of how the building is laid out on the site. Views of nature, outside space are also associated with the ‘spatial’ domain, requiring care at the design stage to fully consider these aspects optimally. There are fewer BHI that focus on ‘agency’ specifically; however the following indicators: access to outside space, security and safe access all have some association with this domain. Furthermore, user control (particularly for lighting and thermal) are corelated with agency, depending on the degree to which human users have control or whether the building is ‘smart’ and automatically controls e.g. heating and cooling. As buildings incorporate more ‘smart’ technologies and the control of different aspect become automated, there is a real risk that human users of buildings lose control and agency, which would typically reduce levels of wellbeing. There is a need therefore to be mindful of the widespread implementation of smart technologies without due consideration of the impacts on human health. The final domain of the health map is ‘behaviour’ and this relates most directly to the BHI sedentary lifestyles. In order to measure this domain the use of sensors, metres, detectors and wearable technologies as part of a smart building approach would be beneficial.

Conclusion

The research provides new insights into how BIM might be used in the architectural design process to improve analysis of health. This is particularly pertinent as the relationships between human health and the design of buildings is heightened by the Covid-19 pandemic. The research assists in the development of processes and systems using BIM models for designing healthier buildings. As BIM becomes increasingly used as part of the design system in the construction industry, the research is significant in providing, for the first time, insight into the mechanisms through which healthier buildings can be delivered. The health indicators are derived from a systematic literature review into medical, epidemiological and public health literature related to the design of the built environment. Using a Deplhi technique, the research finds that there is almost unanimous consensus amongst the experts that BIM can be used to measure health indicators. The research highlights the potential for BIM models to be used in three different strategies. The first, and most straightforward strategy, establishes how BHI can be measured using standard BIM computer models. The second strategy would require greater sophistication and necessitate additional plug-in software and/or third-party computer programming to do the requisite, complex calculations. The final strategy would involve an even higher level of BIM sophistication and complexity as part of a ‘smart’ building approach; requiring additional sensors, metres and detectors to be installed in the completed building. This smart building strategy would need a more dynamic BIM that would communicate with the ongoing data collection by the sensors. Further research is required to develop these BHI into a fully comprehensive system that holistically quantifies the full impact of building design on human health. The research establishes for the first time a rigorous identification of the most viable mechanisms through which BIM can be used to measure the healthiness of a building.

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