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A Critical Analysis of the Effects of Digital Technologies (DTs) on Energy Efficiency and Environmental Sustainability: Assessing the Extended Effects on the Overall Housing Quality in the UK

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Annotation

This research work critically analyzed the effects of digital technologies (DTs) on energy efficiency and environmental sustainability with extended effects on the overall housing quality in the UK. It engages qualitative research techniques in investigating the application of DTs for promoting sustainable housing practices inthe UK, with a view to highlighting the effect of DTs for promoting sustainable housing initiatives in UK. The specific objectives of this study are to: identify the key DTs driving sustainable housing initiatives in UK, explore the effects of these DTs on energy efficiency, environmental sustainability, and overall housing quality in the UK, assess the challenges and problems associated with the implementation of DTs for promoting sustainable housing in the UK, and determine the enablers and strategies for effective integration of DTs for promoting sustainable housing practices in UK. The study adopted Thematic Analysis assumptions in its data analysis. The method of data collection were through semi-structured interviews as primary sources. Other information were drawn from extensive literature reviews of journals, textbooks, printed publications, internet sources and write-ups relevant to the study, from secondary sources. The result from the data analysis shows that there are various DTs that aid sustainable housing practices. To acknowledge the roles these DTs play in promoting sustainable housing practices in the building industry, the knowledge of their application and in-depth understanding on their use is critical. The study recommends that future research should focus on addressing key barriers to the implementation of DTs for sustainable housing worldwide since the present study focuses on DTs application for promoting sustainable housing in the UK.

Keywords: Digital Technologies, Energy Efficiency, Environmental Sustainability, Overall Housing Quality and United Kingdom.

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Introduction

Recently, there has been an upsurge in the rate at which researches are conducted on construction industry such as sustainable development and construction projects delivery. Also, the rapid

growth of the global population, together with significant rural-urban migration resulting from the increased rate of poverty, contributed greatly to an unprecedented rise in resource consumption, exacerbating climate change, leading to multifaceted socioeconomic and environmental challenges worldwide. Consequently, a lot of countries of the world are faced with the challenges of building projects delivery, especially in the area of promoting sustainable housing, using digital technologies (DTs) available. These challenges menace the balancing of economic viability, social acceptability, technical feasibility, and environmental compatibility, which characterize good sustainable housing. They also hinder the utilization of modern conventional housing delivery method like the application ofDTs for promoting sustainable housing. Thereby causing numerous housing projects that cost too much and take longer time to complete. No wonder why Lewis and Conaty (2012) contend that there is need for urgent and coordinated global action to handle the escalating threat coming from climate change to both present and future generation. They explained that government of countries of the world are faced with the challenges of balancing economic development with environmental sustainability, confronting issues of climate change mitigation and adaptation in both developed and developing nations. The focus of this research work is therefore, to examine the application of DTs for promoting sustainable housing in the United Kingdom (UK) with particular reference to the objectives of the study.

Sustainable housing encompasses various dimensions, such as functional, economic, social, cultural, environmental, and ecological. It must meet the criteria of economic viability, social acceptability, technical feasibility, and environmental compatibility (Choguill, 2007). Also, Guertler and Smith (2006) include construction quality, affordability, psychological impacts, and eco-efficiency as factors to be considered under sustainable housing. Moreover, the UN-HABITAT (2012) establishes a multifaceted description, characterizing sustainable housing as homes that are healthy, durable, safe, affordable, and environmentally friendly. These homes should be resilient to natural disasters, equipped with efficient energy and water systems, and integrated into their communities while enhancing social, cultural, and economic aspects. The working definition of sustainable housing in this work is taken to include homes that offer decency, security, privacy, healthiness, should be able to meet the criteria of affordability, legal tenure, habitability, accessibility, and proper integration with services and infrastructure.

Aim and Objective

1. Explore the effects of these DTs on energy efficiency, environmental sustainability, and overall housing quality in the UK.

Research question

1. What are the effects of DTs to enhancing energy efficiency, reducing carbon emissions, and improving the overall sustainability of housing in the UK?

Conceptual Review

Sustainable Housing and Digital Technologies

Sustainable housing ideology can be traced back to the 1987 Brundtland's report and 1992 Rio Earth's definition of sustainable development, which is meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). Sustainable housing aims to reduce energy and water use, employ ecologically friendly building materials, and incorporate renewable energy sources like solar panels (Department of Communities and Local Government (DCLG), 2006; Almusaed & Almssad, 2022). Choguill (2007) asserts that for a housing to be considered sustainable, it has to be affordable, socially acceptable, technically practicable, and environmentally suitable. Almusaed (2004) emphasizes the use of environmentally friendly materials, recycling systems, and clean energy in sustainable housing. Again, Almusaed and

Almssad (2022) define sustainable housing as houses that reduce their environmental impact both throughout the construction process and during operation; such dwellings are intended to be long-lasting, easy to live in, and passed down to future generations. They blend in smoothly with their surroundings, utilizing resources such as light and water to cut energy use and household expenditures. From the foregoing, it is gathered that sustainable housing encompasses homes that are purposefully built and designed to minimize their environmental footprint, both during the building process and operation phase.

The UK Government in bid to encourage housing sectors to adopt more sustainable approaches in new building construction to improve the energy efficiency of new homes, introduced the Code for Sustainable Homes (CSH) in 2007 (DCLG, 2013a). However, DCLG (2013b) contends that since the code's establishment, very few homes have been built to the higher standards of the Code, and those that have the vast majority have been public housing. The housing sector is failing to deliver zero-carbon homes in advance to meet the UK government's 2050 net zero-carbon home's target. These developments have caused an increase in research into finding new innovative strategies to produce sustainable housing in the UK and beyond.

DTs, which are electronic instruments, systems, devices, and resources that create, store, or process data have been identified by many scholars as vital means of improving sustainable housing. Some of these DTs identified include among others, smart home solutions, BIM, IoT, and BD (Al-Emran & Griffy-Brown, 2023; Rane, 2023). They assert that smart technologies optimise energy consumption and minimise waste, BIM allows collaboration in design and construction, IoT devices collect real-time data for analysis, while BDprovides insight from sustainable housing data through analysis. Though this study supports their ideas, it agrees with Al-Emran and Griffy-Brown's (2023) claim that modern DTs have both positive and negative effects on sustainability. As a result, getting a full understanding of how these technologies could be used by individuals and organisations is critical for achieving improved sustainability outcomes.

From the above considerations, it is gathered that evaluating the use of DTs for promoting sustainable housing initiatives in the UK is critical because, it will help in determining the actual effect of DTs on sustainability metrics such as energy consumption, carbon emissions, and resource efficiency. Its evaluation will help identify technical, economic, environmental, and social hurdles to the successful implementation of DTs for sustainable housing projects inUK. Understanding these difficulties will enable policymakers and industry stakeholders in the UK to devise strategies and incentives to address them.

Effect of DTs on Energy Efficiency, Environmental Sustainability and Housing Quality

Studies have shown the numerous benefits of incorporating DTs such as BIM, IoT and AI into construction processes, which range from increasing energy efficiency to boosting environmental sustainability, ensuring improved housing quality. BIM models, for instance, provide a comprehensive platform for optimizing resource utilization and energy efficiency in construction projects by allowing for precise planning and simulation. BIM facilitates the identification of optimal construction supplies and equipment, contributing to improved energy performance (Diaz-Sarachaga, Jato-Espino& Castro-Fresno, 2017; Manzoor, Othman, Gardezi& Harirchian, 2021). Similarly, AI, and other DTs play important roles in promoting environmental sustainability and improved housing quality. This it does through the provision of AI-powered systems data analytics, to provide actionable insights for reducing energy consumption and optimizing resource usage throughout a building's lifecycle (Junge& Straube, 2020; Nishant, Kennedy & Corbett, 2020; Samuel, Lucivero & Somavilla, 2022). These experts' perspectives portray DTs' transformative potential for revolutionising the building sector to achieve higher energy efficiency, environmental sustainability, and housing quality.

In contrast, Manzoor et al. (2021) argue that the adoption of these DTs has significant environmental repercussions that must be considered. These environmental repercussions include significant carbon dioxide emissions from the energy-intensive processes coming from data generation and processing; material environmental impact, observed in data centre construction and the extraction and manufacturing of technological components, and e-waste disposal (Lepawsky, 2018). Consequently, the growing number of data-driven solutions may have a rebound effect increase rather than decreasing long-term demand for DTs, data storage, and analysis, thereby, posing challenges to sustainability efforts (Alcott, 2005; Hilty, Köhler, Von Schéele, Zah& Ruddy, 2006; Takahashi, Tatemichi, Tanaka, Nishi& Kunioka, 2004). Hence, the need to explore the effect of these DTs on energy efficiency, environmental sustainability, and overall housing quality worldwide and in UK in particular to evaluate their significance, and detrimental effect on attaining the UK government's 2050 net zero greenhouse gas (GHG) emission objective.

Effect of DTs on Energy Efficiency

Energy efficiency is defined as the ratio of energy services produced to energy input. It entails making the most of each unit of energy produced or consumed (Herring & Roy, 2007). DTs have a significant impact on energy efficiency for sustainable housing in the UK and across the world, providing multiple opportunities for energy optimization. Several researches have looked into the role of DTs in improving energy efficiency in buildings, showing their potential benefits and uses. Home automation systems, which include smart home technology, give consumers more visibility and control over their energy consumption patterns by monitoring and controlling various home attributes such as lighting, air conditioning, indoor air quality, entertainment systems, and appliances (Darby, 2006; Sun, Yu, Kochurov, Hao& Hu, 2013). This greater insight into energy use patterns enables targeted interventions and behavioural changes, which can result in large energy savings over time.

However, Frondel (2004) and Herring and Roy (2007) argue that as energy services become more cost-effective due to efficiency improvements, consumers may respond by increasing their use of energy services, either by using them for longer periods of time or by upgrading to higher-quality services. This indicates that investing on DTs to improve efficiency may not necessarily result in the desired degree of energy savings if consumers respond by increasing their energy consumption in other ways. As a result, measures such as policy formation are required to help regulate the amount of acceptance and implementation of DTs for enhancing the energy efficiency of sustainable buildings in UK and globally.

Effect of DTs on Environmental Sustainability

Wong and Zhou (2015) state that the concept of environmental sustainability has prompted revolutionary changes in the built environment, resulting in a lower rate of energy consumption and natural resource depletion than were required in traditional construction lifecycles. Samuel et al. (2022) contend that DTs have their own environmental effects. These include high carbon dioxide emissions from the energy required to generate and process substantial amounts of data; the effecton the material environment (for example, where data centres are built); the effects of unsustainable practices for extracting minerals for technological components and manufacturing these components; and e-waste disposal (Marks, 2014; Lepawsky, 2018). While DTs present opportunities for improving environmental sustainability in sustainable housing initiatives in the UK and across the world, it is critical to address and reduce their own environmental footprint to ensure a genuinely sustainable approach to technology implementation in the sustainable built environment.

Effect of DTs on Housing Quality

The incorporation of DTs has a substantial effect on home quality for sustainable housing initiatives across the world, and in the UK. Residents can gain remote control over indoor conditions such as air quality, humidity, heating, lighting, and security systems, using smart home automation systems such as IoT sensors and energy monitoring systems, improving comfort and safety (Al-Fuqaha et al., 2015; Ullah et al., 201). Also, BIM software ensures accurate design and construction, reducing waste and errors while improving building quality (Azhar, 2011). Besides, digital twins allow for virtual simulations and testing of construction methods, materials, and maintenance strategies, which leadto higher housing quality (Lu et al., 2020).Observationally, these technologies can collectively improve housing standards within sustainable housing efforts across the world and in the UK, creating better living environments for residents.

Enablers and Strategies for Effective Integration of DTsfor Promoting Sustainable Housing Practices

This section of the study identifies the major enablers and strategies crucial to the successful integration of DTs for sustainable housing practices in UK. Enablers, in the context of gaining effective integration of DTs for promoting sustainable housing practices, provide legal power or enabling resolution to achieving a successful integration strategy for promoting sustainable housing practices through DTs. Also, it investigates the roles of government policies, industry collaboration, research and development initiatives, capacity building programmes, public awareness campaigns, regulatory frameworks, incentives, and monitoring mechanisms to provide insight into the key components of a successful integration strategy for promoting sustainable housing practices through DTs in UK and across the globe. Hart, Adams, Giesekam, Tingleyand Pomponi's (2019) classification of circular economy enablers in the built environment concept was employed to conduct an in-depth examination and understanding of the enablers driving the use of these DTs to promote sustainable housing practices. The classification includes cultural, regulatory, financial, and sectoral enablers, which are discussed below.

Cultural Enablers

Cultural enablers encompass leadership, environmental culture, teamwork, and a system thinking approach, all of which contribute significantly to the use of DTs for promoting sustainable housing practices (Hart et al., 2019). Hart et al. (2019) study holds that strong leadership at all levels enables for supportive policies, resource allocation, and the establishment of goals to prioritise sustainability in housing projects, which is critical for promoting the adoption of DTs for sustainable housing practices. It is gathered from their study that organisations that promote an environmental culture based on leadership, resource efficiency, and innovation are more likely to adopt DTs for sustainable housing.

The collaboration among stakeholders, such as architects, engineers, developers, policymakers, and community members, is critical for the successful application of DTs for sustainable housing. Besides, effective teamwork makes it easier to share knowledge, co-create solutions, and align interests around common sustainability goals. However, a systems thinking approach takes into account the interconnection of many components in the housing environment. It focuses on comprehensive solutions that address the social, environmental, and economic dimensions of sustainability. By adopting a system thinking mentality, stakeholders can gain a deeper understanding of the intricacies of sustainable housing and use DTs to optimise overall system performance. In this regard, cultural enablers foster a climate that encourages innovation, collaboration, and continuous improvement in the quest of sustainable housing solutions worldwide, especially in UK.

Regulatory Enablers

Regulatory enablers are tagged by scholars like Haines and Mitchell (2014) as crucial driver of DT implementation for enhancing global sustainability. Hart et al. (2019) defines regulatory enablers as policy support, regulatory reform and incentives that support skills development and innovation, the establishment of metrics for measuring sustainability and embodiedthe removal of obstructive regulations, and tax breaks on refurbishment projects and other fiscal incentives. In general, these regulatory enablers establish the required structure and incentives to encourage the incorporation of DTs into sustainable housing practices. Through aligning regulatory policies with environmental objectives, governments can create an environment conducive to innovation and collaboration in the building industry, eventually accelerating the transition to more sustainable housing options in UK and globally.

Financial Enablers

Financial enablers (FEs) are part of the circular economy enablers in the built environment used to access and understand the use of DTs for promoting sustainable housing practices. Studies such as Haines and Mitchell (2014) and Wilson, et al. (2015) have revealed access to supportive financing channels and specific strategies, which are vital drivers for the integration of the use of DTs to promote sustainable housing practices. Such supportive financial channels include among others, public co-funding of large-scale projects and preferential permitting for developers who commit to digitally enabled sustainability certifications. Also, Hart, et al. (2019) contend that FEs promote the use of DTs and sustainable practices in housing projects by incentivizing cost-effective solutions, aligning financial interests with environmental goals, and leveraging collaborative approaches to overcome barriers. These enablers help to ensure the economic feasibility and long-term sustainability of DT-based housing projects in the UK.

Sectoral Enablers

Hartet al. (2019)define sectoral enablers (SEs) as initiatives within the construction industry that aim to facilitate the integration of DTs for promoting sustainable housing practices through improved evidence-base and communication, clear vision and frameworks, collaboration and design tools, research and development, and reverse logistics infrastructure. They alsoobserved that SEs work to develop a strong evidence basis through enhanced case studies and transparent information dissemination. That notwithstanding, these programmes enable industry stakeholders and policymakers understand the benefits and practicality of implementing such technologies. Again, SEs collaborate to define effective frameworks and principles for incorporating DTs into housing developments, providing guidance and direction to industry professionals.

Hartet al. (2019) in their own contribution, state that SEs help research and development initiatives focus at identifying novel DTs, materials, and building processes that could enhance the sustainability performance of housing projects. In their findings, SEs encourage the creation of standards and assurance schemes that create guidelines for the use of DTs in building construction while assuring compliance with legal requirements and industry best practices. Besides, SEs work to build reverse logistics networks, such as materials marketplaces and recycling facilities, aid effective collection and repurposing of materials following demolition and renovation activities. Hence, SEs play an important role of supporting the adoption of DTs to promote sustainable housing practices by offering guidance, support, and resources to industry stakeholders. These initiatives help to overcome implementation bottlenecks and expedite the global shift for more sustainable and environmentally friendly housing solutionsin the UK.

Empirical Studies

Some scholars have contributed to the scope of Building Technology in cross-building technologists' studies, which include the application of DTs for promoting sustainable housing

initiatives. Depicted in Figure 1is a reoccurrence analysis of the keywords in literature that emanated from some of these scholars' contributions that relates to this research work scope (culled from NVivo 14).

Figure 1: Reoccurrenceanalysis of the keywords in this research literature

Source: NVivo 14

Ibem and Aduwo(2015) examine a framework for understanding the different facets of sustainable housing to aid sustainable housing policy formulation and practical actions, using a systematic review of existing literature. They posit that sustainable housing can be realized through interventions at the levels of housing processes, products, and services. In their findings, they established the importance of proficient management skills and adequate resources among housing developers and managers that could effectively implement and evaluate sustainable housing initiatives. Also, they identified practical steps and strategies essential for achieving sustainable housing, with a primary emphasis on fostering a collective commitment among all stakeholders within the housing sector, including architects and other built environment professionals, to embrace sustainability principles throughout the entire lifecycle of housing projects.

Ibem and Aduwo's study is related to this present study in the sense that both studies are interested on measures or strategies that can facilitate sustainable housing initiatives globally maintenance, though, this present research is focused on the UK. This delimitation, instantiate their difference. The two studies also differ in their method of gathering data for the study. While Ibem and Aduwo's (2015) data for their study is through a systematic review of existing literature only, the study at hand, in addition to review of existing literature, collected data from semi-structured interviews and multiple case studies. However, both studies recommend strategies for the implementation of sustainable housing practices in the building construction industry worldwide.

Methodology

This study adopts and adapts Saunders, Lewis, and Thornhill's (2009) concept of the research onion. This study adopts an interpretivism research philosophy. Saunders et al. (2009) identify different types of research strategies, which are experimental, surveys, case studies, action research, grounded theory, ethnography, and archival research. This study adopts qualitative research technique. This study uses both primary and secondary data sources. Semi-structured interview with four AEC experts that specialised in DTs and sustainable housing were employed to serve as the primary data sources for this project, as well as the instrument for data collection. After gathering the data for the study through semi-structured interview and case studies, the researcherconfirms facts; the researcher also transcribes, collates, categorises, juxtaposes them, and then, subject them to analysis, using thematic analysis (TA) assumptions.

Case Studies Analysis

DTs Integration – Effect on Energy Efficiency, Environmental Sustainability, and Housing Quality

The Forge project used modern DTs such as BIM, IoT, and digital twins to achieve net zero carbon commercial buildings. Also, innovative construction approaches, such as Design for Manufacture and Assembly (DfMA) were used to reduce material waste, lower embodied carbon emissions, and improve construction efficiency. Again, the project utilized IoT, BIM and digital twins to incorporate advanced building systems such as highly efficient air-source heat pumps for heating and cooling, renewable electricity generation through solar panels, and passive design measures to optimize energy performance, reduce environmental impact, and improve project quality. Despite the above considerations, the use of digital modelling tools such as design for performance, which bases on the concept of digital twins and BIM, enabled accurate prediction and optimization of operational energy use, leading to the achievement of the project's sustainability objectives. Therefore, the integration of innovative technologies (BIM, IoT and digital twins) and design strategies into the Forge project, improves indoor environmental quality, energy efficiency, occupant comfort, and well-being, leading to a more desirable sustainable housing outcomes in the UK.

The 80 Charlotte Street case study demonstrates significant technology integration, notably in terms of sustainability. This study draws from the information provided by UKGBC (2022), which states that through the application of DTs such as IoT, big data, cloud computing, and AI enabled the incorporation of smart systems such as air source heat pumps for heating and cooling, solar thermal panels for hot water, and Light-Emitting Diode (LED) lighting systems into the project, which contributed to energy efficiency and carbon emission reduction. Similarly, the project utilized BIM to facilitate efficient design and coordination, which aid in the implementation of sustainable practices, thereby improving the project quality while reducing environmental footprint. Recognizably, the application of DTs such as IoT, BD, cloud, and BIM in the 80 Charlotte Street project is consistent with claims made by scholars such as Azhar (2011), Al-Fuqaha et al. (2015), and Rane (2023) that these DTs help to enhance energy efficiency and overall sustainable housing results both in the UK and beyond.

Findings and Discussion

The findings of this study disclose the effect of DTs on energy efficiency, environmental sustainability, and housing quality for sustainable housing initiatives in the UK and globally. The findings discovered that DTs, such as home automation systems and smart technology, enable energy monitoring and control, leading to significant energy savings over time, while acknowledging concerns about potential rebound effects. Besides, DTs offer opportunities to minimize carbon footprints, but also pose environmental challenges such as high energy consumption during data processing and e-waste disposal. Again, it was discovered that DTs

improve housing quality through the remote control over indoor conditions and accurate design and construction facilitated by BIM software and digital twins.

The two case studies explored in this research work highlight the effect of DTs on energy efficiency, environmental sustainability, and housing quality in the UK and beyond. The Forge, and the 80 Charlotte Street project case studies unveil how the application of DTs such as IoT, BIM, AI, digital twins, big data, cloud computing, innovative construction approaches and smart systems enable both building projects meet their sustainability objectives – net zero carbon commercial buildings, improved indoor environmental quality, energy efficiency gains, occupant comfort, and well-being.

Also, the study's interviews with AEC professionals further consolidated the positive effects of DTs on energy efficiency, environmental sustainability, and housing quality in the UK and worldwide. P1 and P4respectively explain that:

…DTs such as AI, IoT, and Big Data have a positive impact on energy efficiency, environmental sustainability, and housing quality in sustainable housing projects. Through leveraging these technologies to generate, record, and analyse data on completed and in-use sustainable houses, we were able to reduce energy consumption and improve overall environmental sustainability and housing quality...(P1).

…DTs I think greatly improve energy efficiency, environmental sustainability, and housing quality through bridging the performance gap between planned and actual building performance. Also, accurate energy predictions during the design stage allow for the formation of feedback loops, which inform subsequent projects and improve performance…(P4).

However, P3 contends that:

…the effect of DTs on energy consumption, environmental sustainability outcomes, and housing quality vary based on the maturity level of companies and the availability of dedicated resources for research and development...

Despite the above positive effectsof DTs on energy efficiency, environmental sustainability and housing quality in the UK and beyond, this study agrees with Frondel (2004) and Herring and Roy (2007) argument that while DTs can enhance energy efficiency in sustainable buildings, there is a tendency that cost-effective energy services may lead consumers to increase their overall energy consumption, possibly offsetting the intended energy savings. The result of the finding of this study advocates the need to show concern about the environmental footprint of DTs, citing factors such as high CO_2 emissions from data processing, unsustainable mineral extraction for technological components, and e-waste disposal. In this regard, there is need for policy measures to regulate the acceptance and implementation of DTs to ensure effective energy efficiency improvements and mitigation of the environmental footprint of DTs in sustainable buildings both in the UK and globally.

Conclusion

Discussed also in this study are the effect of DTs on enhancing energy efficiency, reducing carbon emissions, and improving the overall sustainability of housing in UK. the study presents research justification and gave as well insight into the concept of sustainable housing, establishes the key DTs driving sustainable housing initiatives in UK, highlights the effect of DTs on energy efficiency, environmental sustainability and housing quality

Recommendations

The study recommended that the application of DTs for promotion of sustainable housing practices is an active means of advancing housing sustainability in the UK. Therefore, it is important for the industry to have an in-depth understanding of the use of DTs as that will help in

promoting sustainable housing development in the UK. Besides, a sound knowledge of DTs and their usage will help students of Building Technology appreciate the effect of DTs in advancing sustainable housing development fully. However, having acknowledged that this work cannot exhaustively cover all the issues surrounding DTs processes involved in promoting housing sustainability practices in the UK,

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