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Framework for the UK construction industry transition to net zero design: a Delphi techniques and structural equation model approach

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ABSTRACT

The shift towards net zero design for the construction industry poses complex challenges, which can be likened to a three-headed hydra embodying energy, water, and carbon emissions. The industry stakeholders have grappled with addressing the challenges due to an ineffective reductionist approach that targets each head (energy, water, and carbon) separately. Recognizing their interdependence, this study proposes a holistic panacea approach to facilitate the industry's transition to net zero design. This was achieved using a mixed (quantitative and qualitative) research methodology. The qualitative study was conducted using a three-stage Delphi technique involving 13 experts. Structural equation modeling was used for the quantitative involving 200 construction stakeholders selected randomly. The study discovered that net-zero design integrates sustainability concepts, such as net-zero energy, water, and carbon aimed at ensuring a sustainable built environment. Factors like innovation, organizational culture, and construction project management were identified as pivotal in steering the construction industry toward net zero design. The transition to net zero design can be impeded by poor cost management and restrictive organizational cultures. The study recommended that stakeholders in the construction industry should embrace a culture that supports the commitment to net zero design.

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Carbon emission; innovation; net zero; project management; UK

Introduction

The UK construction industry is a crucial player in the growth of the nation's economy, as it has a significant impact on the GDP (Ajayi et al. 2016). The industry is also one of the major employers of labour globally as it accounts for half of the labour force (Dainty et al. 2001). The UK construction industry is also responsible for providing housing and public facilities that can improve the quality of life for people in the community (Lovell and Smith 2010; Fulcher et al. 2022). In the same vein, Li et al. (2022) affirmed that the construction industry employs nearly 10% of the working population as well as providing the roads, housing, and infrastructure that form the foundations of today's society and the built environment. These opinions demonstrate the importance of the construction industry to the advancement of the UK economy.

Despite the importance of the construction industry, it is carbon intensive, accounting for approximately 40% of the UK's total emissions (Shubbar et al. 2021). Construction and greenhouse gases are closely related concepts in the context of sustainability and environmental impact. Killip (2013) affirmed that global carbon emissions, due to the activities of the construction industry, have increased exponentially since the beginning of the twentieth century. Construction, as an industry, is a major contributor to greenhouse gas (GHG) emissions due to the use of energy-intensive materials, processes, and equipment (Karlsson et al. 2020a). GHGs, such as carbon dioxide, methane, and nitrous oxide, trap heat in the Earth's atmosphere and contribute to climate change (Li et al. 2022).

Bazazzadeh et al. (2021) affirmed that long-term climate change is responsible for the increase in energy consumption of buildings. Climate change and building energy consumption are interconnected in many ways. The energy used to heat, cool, and power buildings is a significant contributor to global greenhouse gas emissions, which is a major cause of climate change (Barrett et al. 2022; Li et al. 2022). For example, as temperatures rise, the need for air conditioning increases, leading to higher energy consumption. Similarly, more frequent, and intense heat waves may increase the need for cooling, which in turn leads to increased energy consumption. At the same time, the effects of climate change, such as increased storm activity and rising sea levels, can cause damage to buildings, which can lead to additional energy consumption as repairs are made or the buildings are replaced (Chance 2009). To reduce the impact of building energy consumption on climate change, it is important to design and construct buildings that are energy-efficient and environmentally friendly (Bazazzadeh et al. 2021).

The need for constructing or designing buildings that are both energy efficient and environmentally friendly led to the adoption of the net zero concepts for the construction industry. The review of literature such as (Voss et al. 2011; Gassie et al. 2016; Crosson 2018; Deutch 2020) revealed that net zero could be applied to carbon, water, or energy within the construction industry. Thus, this study identified net zero as the group of activities or design that ensures a building produces no more

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than the carbon dioxide, energy, and water it consumes and needs. This implies that net zero energy, net zero water, and net zero carbon are all related concepts that promote sustainability and have a positive impact on the environment. In support of this assumption, Galvin (2022) and Khalifa et al. (2022) affirmed that the transition to net zero in 2050 would require tackling both energy-related and non-energy-related factors like water and carbon simultaneously. Thus, this implies that a holistic approach and objectives are needed for a nation that desires to transition to net zero design.

In 2008, the United Kingdom (UK) was among the nations in the world to enshrine a net zero objective into law (Shubbar et al. 2021; Li et al. 2022). The purpose of this law was to reduce emissions within the UK and force the transformation of the economy towards a net zero design. Despite the legislation the UK construction industry is currently struggling to achieve net zero in line with the 2050 target (Karlsson et al. 2020b). Nonetheless, researchers such as Ohene et al. (2022a) and Obobisa (2022) still believe that the construction industry is vital for the UK to achieve net zero owing to its carbon-intensive nature. This in return has led to numerous researchers embarking on establishing innovative solutions that support the construction industry transition to net zero. Pless and Torcellini (2010), Su et al. (2022), and Obobisa (2022) evaluated the adoption of renewable energy as the solution for the construction industry transition to net zero. Zhang et al. (2017), Ohene et al. (2022b), and Tirelli and Besana (2023) examined the critical factors for low-carbon development. Englehardt et al. (2016) and Srb et al. (2023) focused on innovative solutions for transitioning to net zero. A common phenomenon emanating from the findings of the aforementioned research is that a reductionist approach was adopted for achieving net zero design.

The reductionist approach emanated from the research focus on only achieving net zero carbon, energy, or water. Thus, this created a gap in research and practice that provides a holistic approach for the UK construction industry in achieving net zero carbon, water, and energy simultaneously. This study fills the gap by creating a model that supports the transitioning of the UK construction industry to net zero water, carbon, and energy. This model will function as a guide for stakeholders in the construction industry in designing infrastructures capable of ensuring net zero water, carbon, and energy simultaneously. The findings from this research will contribute to ensuring that the construction industry contributes to promoting environmental conservation. This study will also contribute to the UK construction industry achieving net zero in line with the 2050 target.

Net zero design

The notion of 'net zero' has been widely embraced as a commonly understood concept in contemporary society. Only two decades ago, its definition and significance were largely unfamiliar, but today it is a term that we come across frequently in various forms of media. Net zero is a term that has gained increasing prominence in recent years as individuals and organizations seek to promote sustainable living. According to Loveday et al. (2022), the earliest recorded instance of the term 'net zero occurred in an academic paper with an environmental focus in 1991. It is worth noting that the paper referred to the utilization of biomass fuels, rather than any effort to lower emissions on a broader scale. Thus, it can be implied that there are now numerous interpretations and ideas stemming from the concept of net zero.

A common phenomenon about the numerous interpretations is that net zero is focused on achieving a state of balance between resource consumption and resource generation, typically in the areas of energy, water, and carbon emissions. Net zero energy, for example, involves generating as much energy as it is consumed over a given period (Pless and Torcellini 2010). This is typically accomplished through the use of renewable energy sources such as solar, wind, and geothermal power, as well as through the implementation of energy-efficient technologies and practices (Naveen Chakkaravarthy et al. 2018; Obobisa 2022). Galvin (2022) believed that by balancing energy consumption with energy generation, net zero energy buildings and communities can significantly reduce their environmental impact and promote a sustainable future. Net zero carbon, on the other hand, involves achieving a state of carbon neutrality over a given period (Mohan et al. 2022). This involves reducing carbon emissions through the use of renewable energy sources and energy-efficient technologies, as well as offsetting any remaining emissions through the purchase of carbon credits or other means. Thus, it can be deduced that net zero energy, water and carbon are interrelated which implies that combination of the principles shown in Tables 1 and 2 can ensure net zero design.

To achieve net-zero design, all three of these concepts as shown in Figure 1 must be integrated and implemented in a complementary way. For example, this study prescribed that the energy generated through renewable sources in a net-zero energy building can also power water treatment systems for net-zero water. In support of the assertion, Mohan et al. (2022) opined that reducing energy consumption can also lead to a decrease in carbon emissions, helping to achieve net-zero carbon. By integrating net- zero energy, water, and carbon concepts into building design and operations, we can ensure a more sustainable future for our built environment (Thiel et al. 2013; Khalifa et al. 2022). Achieving net-zero buildings and construction will help reduce our impact on the environment, conserve resources, and support a more sustainable future (Hughes et al. 2011; Khaddour et al. 2023).

Net zero design principle for the UK construction industry

This sub-section discusses the principles or solutions extracted from literature capable of supporting the transitioning of the UK construction industry to net zero design by 2050. The review of literature like Chance (2009) and Oktay (2022), reveals that the principles have been adopted in the UK for the development of BedZED in London. The BedZED development utilized local and recycled materials, as well as energy-efficient techniques to reduce energy consumption once built. McLeod et al. (2012) and Glasziou et al. (2024) revealed that the enhancement of policies was another principle for transitioning to net zero. Notable among these policies is the UK 'Zero Carbon Homes Policy' which required all new homes to be net zero energy buildings by 2016. The policy received widespread praise from environmental campaigners, as the UK was the first country to make such a commitment (McLeod et al. 2012).

Another principle for achieving net zero design in the construction industry is setting ambitious goals and developing a plan to reach them (Das and Ghosh 2023). This involves goals directed at investing in renewable energy sources, such as solar panels or wind turbines, as well as implementing energy-efficient technologies, such as LED lighting or smart thermostats (Patrizio et al. 2021; Ko et al. 2022). It also involves making changes to daily habits and practices, such as reducing energy and water

Table 1. Principles for NetZero design in the construction industry.

Principle	Definition	Source
Energy efficiency	Designing buildings to be highly energy-efficient is a key principle of net zero design. This includes optimizing building orientation, minimizing air leakage, and using high-performance insulation and glazing.	Song et al. (2014) and Oktay (2022)
Renewable energy	Incorporating renewable energy sources, such as solar panels or wind turbines, can help buildings generate their own energy and reduce reliance on fossil fuels.	Su et al. (2022) and Obobisa (2022)
Material selection	Using low-impact materials and sustainable construction practices that can help reduce the carbon footprint of a building.	Song et al. (2014)
Water conservation	Incorporating water-efficient fixtures and systems, such as low-flow toilets and rainwater harvesting systems, can reduce water consumption and associated carbon emissions.	Srb et al. (2023) and Song et al. (2014)
Life-cycle analysis	Considering the life-cycle impacts of building materials, systems, and operations can help identify opportunities for reducing carbon emissions over the building's entire lifespan.	Thiel et al. (2013)
Building automation	Using smart building automation systems that can help optimize energy use and reduce waste, while also improving occupant comfort and productivity.	Hughes et al. (2011)
Sustainable Transportation	Designing buildings with access to public transportation and encouraging sustainable commuting options for occupants can help reduce the carbon footprint associated with transportation.	Zaman (2023)
Legislation	The development of policies and laws that supports the transition to net zero.	Shubbar et al. (2021)
Airtight building	The construction of building that prevents air and heat loss with the focus of conserving energy and reducing carbon emission. This form of construction is sometimes called passive building.	Moreno-Rangel et al. (2020)
Carbon emission	The development and construction of infrastructures that supports the zero emission of carbon throughout its life cycle.	Karlsson et al. (2020a)

Source: authors review of literature.

Table 2. Variables supporting construction industry transition to net zero.

Classification	Transitionsolution	Citation
Innovation	Building simulations	Nelson and Allwood (2021) and Ohene et al. (2022a,b)
	Alternative fuels	(Peckyte, 2021), (Gorski, 2021), (Cameron, 2021)
	Carbon pricing tools	McLeod et al. (2012) and Mohan et al. (2022)
	Offsite manufacturing	Pless and Torcellini (2010)
	Low carbon construction materials	Karlsson et al. (2020a) and Zhang et al. (2017)
	Building automation	Hughes et al. (2011) and Nelson and Allwood (2021)
	Renewable energy technology	Su et al. (2022) and Pless and Torcellini (2010)
	Building optimisation technology	Alirezaei et al. (2016) and Nelson and Allwood (2021)
	Biomass	Sindhwani et al. (2022)
Construction project administration	Financial incentives	Sindhwani et al. (2022) and Obobisa (2022)
	Cost management	Leach et al. (2014) and Torcellini et al. (2015)
	Risk management strategies	Englehardt et al. (2016)
	Engineering standards	Chisale and Mangani (2021)
	Life cycle analysis	Thiel et al. (2013)
	Decarbonisation methods	Dixon et al. (2022) and Das and Ghosh (2023)
	Waste management	Chuenwong et al. (2022) and Englehardt et al. (2016)
Organisational culture	Leadership	Ko et al. (2022)
	Behavioural change	Nelson and Allwood (2021)
	Training and education	Marteau et al. (2021)
	Communication	Valiulahi et al. (2023)
	Collaboration	Nelson and Allwood (2021)
	Commitment to sustainability	Zaman (2023)
	Research and development	Dixon et al. (2022)

Source: author's review of literature.

consumption and promoting sustainable transportation options (Olmos and Loge 2013). Mandel et al. (2023) affirmed that applying the principles of net zero design for the construction industry offers a promising path toward a more sustainable future. It is believed that a sustainable future is achieved in a state of balance between resource consumption and resource generation. Achieving a net zero in the construction industry can significantly reduce their environmental impact and promote a

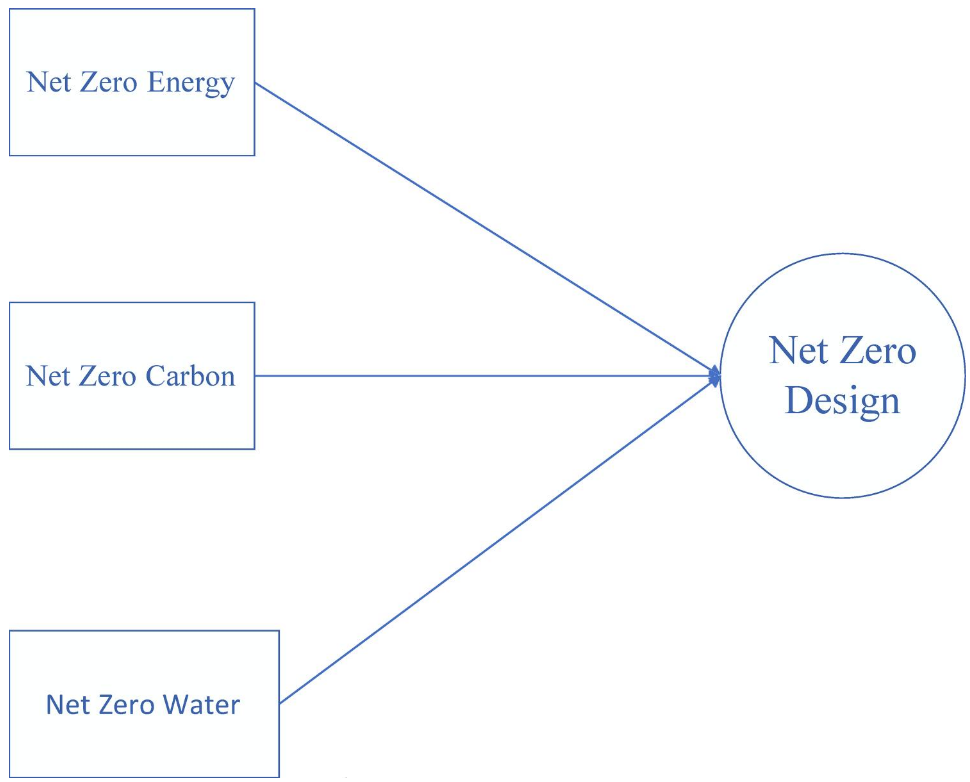

Figure 1. Component of net zero design.

more sustainable world (Su et al. 2022; Ohene et al. 2022a). While the journey towards net zero may be challenging, the principles for net zero design as shown in Table 1 can foster the transition of the construction industry to net zero.

It can be deduced from the summary of the principles for net zero design for the construction industry as shown in Table 1 extend beyond the traditional carbon and energy reduction. A recent principle is an airtight building which ensures that air is not lost within the building (Moreno-Rangel et al. 2020). Santin et al. (2021) opined that the airtight principle is one of the core philosophies supporting the development and rise of Passivhaus construction. Wagner (2023) and Santin et al. (2021) discovered that Passivhaus also known as passive construction supports the transition to net zero by ensuring airtight building and reducing energy efficiency. Moreno-Rangel et al. (2020) opined that the energy is reduced by adopting a passive solar design that supports incorporating oversized south-facing windows that allow solar radiation to penetrate directly into the southern rooms. As a result, the floors and walls, which are constructed to be sufficiently thick, can absorb and store a substantial amount of heat during the day for use at night. This is because the house can generate and retain heat using natural solar energy, there is less reliance on artificial heating systems such as electric heaters and gas boilers.

Transition to net zero design for the construction industry

According to Su et al. (2022), the construction industry is not moving at the expected rate on its own toward a net zero transition. Thus, this implies that the stakeholders within the construction industry must create an innovative way to foster the transition to net zero. Unfortunately, researchers like Marteau et al. (2021), Galvin (2022) and Khalifa et al. (2022) agreed that there is no single solution that will help the construction industry deliver the UK's 2050 net zero emissions target. Tirelli and Besana (2023) identified effective leadership as a solution for moving toward net zero-carbon buildings. Likewise, Ohene et al. (2022a) also advocate for the private sector to take the lead in driving the transition. Mandel et al. (2023) avowed that the construction industry can transition to net zero by focusing on the utilisation of a building as a tool for decarbonising the environment. Obobisa (2022) indicated that building can only be used for decarbonising the environment through the alteration of standard construction techniques.

Unfortunately, the standard construction techniques used by the majority of the industry are insufficient to achieve net-zero design, as noted by Karlsson et al. (2020a). Thus, it is apparent that organizations must explore new and innovative technologies to overcome the industry's traditional challenges and achieve this goal. If the industry fails to adopt innovative solutions that reduce emissions, it will be unable to deliver net-zero design (Hughes et al. 2011; Galvin 2022; Li et al. 2022). Mehta and Ashish (2020) and Adhikary et al. (2022) recommend innovations like green concrete, waste glass, agricultural straw, and husk biomass straw to prevent the negative impact of the construction industry on the environment. Therefore, it is crucial to transition from existing innovative solutions to those that are environmentally friendly. Innovative solutions include the adoption of new technologies and technical practices that support the reduction of carbon emissions, energy efficiency, and water conservation. Table 2 presents some innovative transitions or solutions like alternative fuels, building simulations, carbon pricing tools, and others.

Another crucial factor for transitioning to net zero is project administration (Leach et al. 2014; Torcellini et al. 2015). Construction project administration establishes a structure for managing and executing a project, clarifying the responsibilities of individuals for specific deliverables (Joustra and Yeh 2015). According to Ohene et al. (2022a), for the construction industry to achieve net zero emissions by 2050, substantial alterations need to be made to its conventional project administration or governance structures and their management processes. Some of these administrative solutions shown in Table 2, such as decarbonization methods and waste management, have already begun to be implemented, whilst others still require further work if they are to be delivered. Nelson and Allwood (2021) related the further work needed to transition to net zero in the construction industry to cultural changes. On the other hand, construction is not usually regarded as particularly forward-thinking when it comes to the industry's culture. It is seen as an industry that is averse to cultural change (Osunsanmi et al. 2022). Table 2 presents some organizational culture practices that are currently practiced in ensuring net zero design. This study postulates that the approach toward achieving net zero design must include a combination of innovation, organizational culture, and construction project management. The effective implementation of such changes would deliver a version of net zero design that could allow the industry to meet the 2050 target.

Research methodology

The activities of the United Kingdom's (UK) construction industry contribute to the nation's economy, by employing about half of the global labour force and providing essential infrastructure (Lovell and Smith 2010). Unfortunately, its activities contribute approximately 40% of the UK's total emissions, accelerating climate change (Mandel et al. 2023). To sustainably advance the economy, it is vital to address the environmental impact of the construction industry while benefiting from its activities. This study proposes the development of a model capable of supporting the transitioning of construction industry to achieve a net zero design as a solution to addressing the environmental impact of the construction industry.

In achieving the objectives of this study, the research methodology was broken down into three stages as shown in Figure 2. The methodology was guided by the use of a pragmatism epistemology which supports the use of both quantitative and qualitative methodology (Maarouf 2019). This methodology was adopted because the objective of this study cannot be achieved without construction experts' inputs in the form of providing constructs that support the design of net zero in the UK construction industry. Also, the constructs provided by the experts should be validated using a scientific method. The validation and extraction of the constructs from the experts require a pragmatism epistemology that emphasizes the practicality or validation of new ideas (Maarouf 2019). Tashakkori and Creswell (2008) and Kelly and Cordeiro (2020) avowed that pragmatist epistemology believes that knowledge is not fixed but is constantly evolving based on new observations. Thus, this study adopted a Delphi study in seeking new observations regarding the transition to net zero design.

Delphi study

The qualitative aspect of this study was achieved by using a Delphi Study which is a forecasting tool used for solving complex issues from an expert viewpoint (Alomari et al. 2018). A Delphi study is a research method used to obtain a group consensus on a particular topic by gathering expert opinions through a series of iterative surveys or questionnaires (Osunsanmi et al. 2022). The consensus for this study was achieved after three iterations with each iteration being used for developing the next iterations. The question for the first iteration was discovered from the review of literature shown in Table 2. The responses were collected and analyzed using an Excel spreadsheet and then used to develop a second round of questions, which were then sent back to the experts for further review and refinement. This process was repeated until a consensus was achieved.

Delphi experts' selection and consensus determination

Before achieving the consensus the most crucial step for achieving the objective is the selection of Delphi experts. Keeney et al. (2001) and Aghimien et al. (2020) affirmed that the reliability of expert selection is the main bane of the Delphi study. This problem was addressed in this study by adopting the criteria-based system as used in past studies like Alomari et al. (2018), and Aghimien et al. (2020). The criteria-based system supports the creation of certain criteria for selecting the experts needed for a study. The system recognized that an expert must have a distinct feature to make them eligible to participate in the study. The criteria selected are extensive professional experience (above 5 years) within the UK construction industry, being a faculty member of an institution, member of a professional body, and possession of a higher degree. A criteria value of 50% was selected as the cut-off point as recommended by Alomari et al. (2018). A total of 33 experts met the criteria but only 15 made it to the last iteration. Thus, the consensus in this study was achieved among 13 experts. About 53.8% of the experts have a Ph.D. degree as their highest qualification and the remaining (46.2%) have a master's as their highest educational level. Concerning their working experience 46.1% have a working experience of above 20 years in the UK construction industry. Their position spanned lecturer, construction project manager, quantity surveyor and environmental specialist. Equation 1.0 presents the formula used for calculating the consensus.

$$D_i = [x_i - m(X)] \qquad \text{Equation 1.0}$$

where:

D_i = Absolute deviation x_i = Panelist rating
$m(X)$ = Measure of central tendency

Consensus is a vital aspect in the successful completion of a Delphi study, as affirmed by De Villiers et al. (2005) and Jones (2018). To achieve consensus in this study, the deviation of all responses from the group median and interquartile range of deviation (IQD) was determined, except for one unit, due to the 10-point Likert scale used. The deviation was calculated using Equation 1.0, which is also known as the absolute median, and the IQD was determined using the difference between the 75th and 25th percentile. The 25th, 50th, and 75th percentiles are also known as the first, second, and third quartiles, respectively. The IQD was used to determine consensus in this study, in line with previous literature by Hsu and Sandford (2007) and Aghimien et al. (2020). Consensus is defined in this study as a formal measure of agreement between experts, and it was also used as a medium for stopping the Delphi rounds. The scale of consensus adopted for this study is provided below.

- Strong consensus- median 9-10 mean 8-10 and IQD ≤ 1
- Good consensus- median 7-8.99, mean 6-7.99 IQD $\geq 1.1 \leq 2$

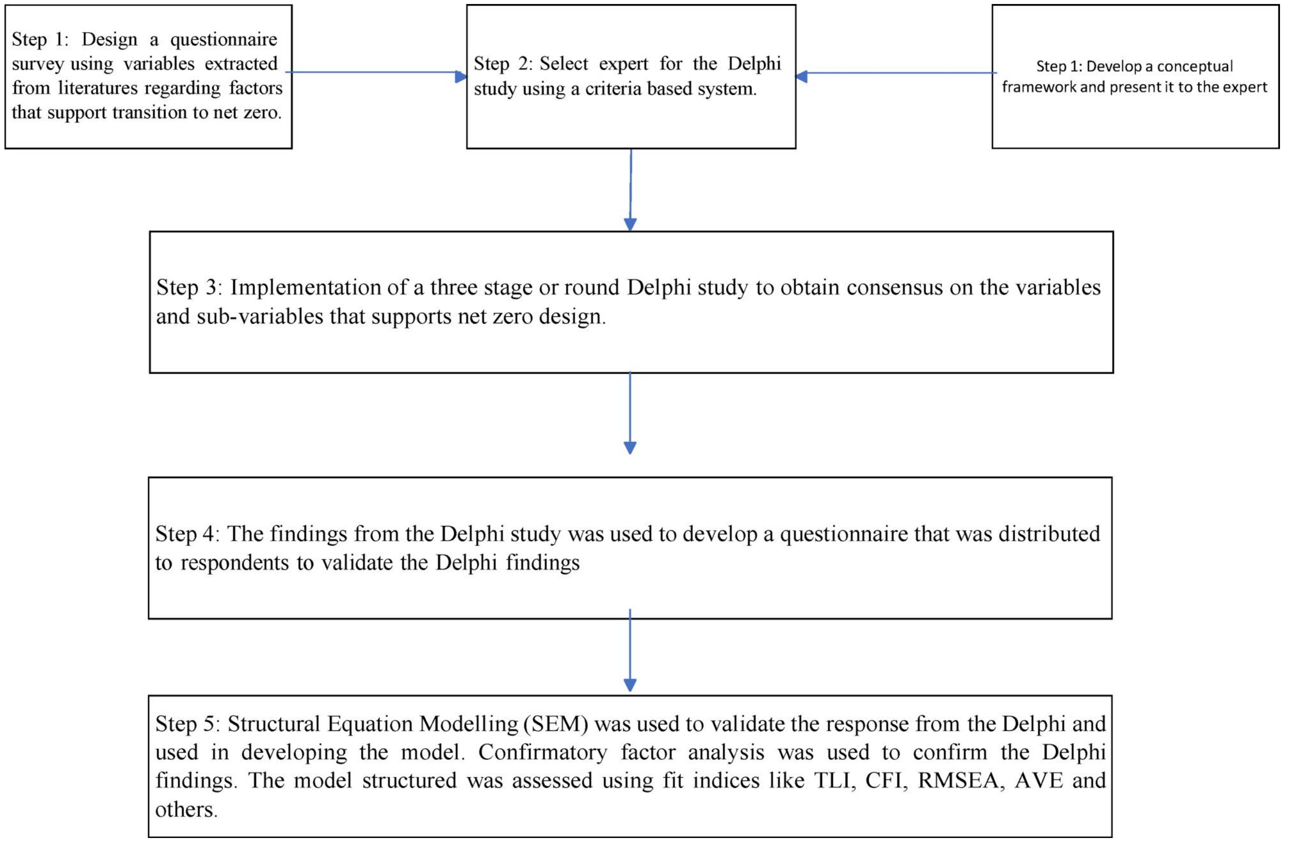

Figure 2. Methodology framework.

- Weak consensus median $\leq$ 6.99, mean $\leq$ 5.99 and 1QD $\geq 2.5 \leq 3$

Structural equation modeling

The findings from the Delphi study were used as the basis for designing the questionnaire which forms the quantitative aspect of this study. During the Delphi study, the respondents (experts) provided new variables in addition to the already existing variables shown in Table 3. The questionnaire used in this study was broken down into three sections. The first section of the questionnaire focused on the respondents' personal information and the last three sections focused on the capacity of the three constructs in ensuring the transition to Net Zero Design. After employing Cochran's formula with a 90% confidence level and a margin of error of 0.5%, a total of 216 respondents were randomly selected from the list of registered construction professionals in the United Kingdom. The population size was determined to be accurate by reviewing similar studies conducted in the UK (Seed 2015). However, only 200 provided accurate responses to the questionnaire, which was administered *via* an online platform (Google Forms). To ensure the questionnaire's reliability, a Cronbach Alpha was calculated, resulting in a value of 0.764, which exceeds the recommended threshold of 0.70 (Tavakol and Dennick 2011). Therefore, it can be concluded that the data derived from the questionnaire is reliable and accurate.

The data collected from the questionnaire was in turn subjected to structural equation modeling. The covariance-based modeling (CB-SEM) structural equation modeling was an approach used in this study. The confirmatory factor analysis (CFA) was the first step in conducting CB-SEM. The aim of conducting a CFA was to ensure the accuracy and sufficiency of the variables about each construct (Osunsanmi et al. 2023). Amos Graphics version 27 was utilized to perform the CFA, and various tests including discriminant validity, composite reliability (CR), and average variance explained (AVE) were carried out. The CFA was conducted based on the guidelines proposed by Schreiber et al. (2006) and Hair et al. (2017). These scholars recommended that the loadings of each variable within a component should be at least 0.70 to achieve the best-fit model. In addition, for discriminant validity, a CR value of 0.70 to 0.95 is considered valid according to the Fornell-Larcker criterion, and the AVE should be above 0.5. The last stage of SEM includes validating the framework of this study while using bootstrapping in the AMOS function to determine the impact of the constructs for transitioning to net zero.

Discussion of findings

Delphi study

The findings from the Delphi study are presented in this section. The findings from the Delphi were used to inform the framework that serves as a guide for developing the model. The Delphi passed through three rounds with consensus achieved in the third consensus. The first round was designed after conducting an extensive review of literature related to achieving net zero that revealed the set of main and sub-attributes that are essential to efficient net zero design for the UK construction industry. The extracted attributes from the literature as shown in Table 2 were presented as an open and closed- end questionnaire to the respondents in the first round.

After the first round, the feedback was collated, and it was discovered that consensus was not achieved for the majority of

Table 3. Delphi findings.

Classification	Transitionsolution	SEM Coding	M	x̄	σX	IQD
Innovation	Building simulations	IN01	7	7.31	1.06	0.00
	Alternative fuels	INO2	8	8.08	0.56	0.00
	Carbon pricing tools	INO3	6	7.00	1.68	1.00
	Offsite manufacturing	INO4	5	5.62	1.19	0.50
	Low carbon materials	INO5	9	8.69	0.62	0.50
	Building automation	INO6	7	6.77	1.13	1.00
	Renewable energy technology	INO7	9	8.77	0.41	0.00
	Building optimization technology	INO8	7	7.23	0.77	0.50
	Energy storage	INO9	7	6.85	1.26	1.00
	Smart building design	INO10	7	7.38	0.82	0.50
	Biomass	1NO11	6	6.54	0.99	0.50
Construction project administration						
	Financial incentives	CPA1	7	6.87	0.64	0.50
	Cost management	CPA2	9	8.67	0.62	0.50
	Risk management strategies	CPA3	8	8.20	0.94	0.00
	Engineering standards	CPA4	6	6.20	0.86	0.00
	Life cycle analysis	CPA5	7	7.20	1.15	1.50
	Energy auditing	CPA6	8	8.13	0.74	0.00
	Decarbonisation methods	CPA7	9	8.53	0.92	0.00
	Waste management	CPA8	8	8.28	0.70	0.50
	Continuous monitoring and reporting	CPA9	8	8.00	0.93	0.00
Organisational culture	Leadership	OGC1	8	8.27	0.59	0.00
	Behavioural change	OGC2	8	7.80	1.32	1.00
	Training and education	OGC3	8	7.73	1.22	1.00
	Communication	OGC4	9	8.87	0.52	0.00
	Commitment to sustainability	OGC5	10	9.73	0.46	0.50
	Research and development	OGC6	8	7.93	0.80	0.00
	Collaboration	OGC7	8	8.20	0.68	0.00
	Stakeholders involvement with net zero design	OGC8	8	8.07	0.80	0.00
	Accountability	OGC9	6	6.13	0.52	0.00
	Transparent	OGC10	7	7.47	0.83	0.50

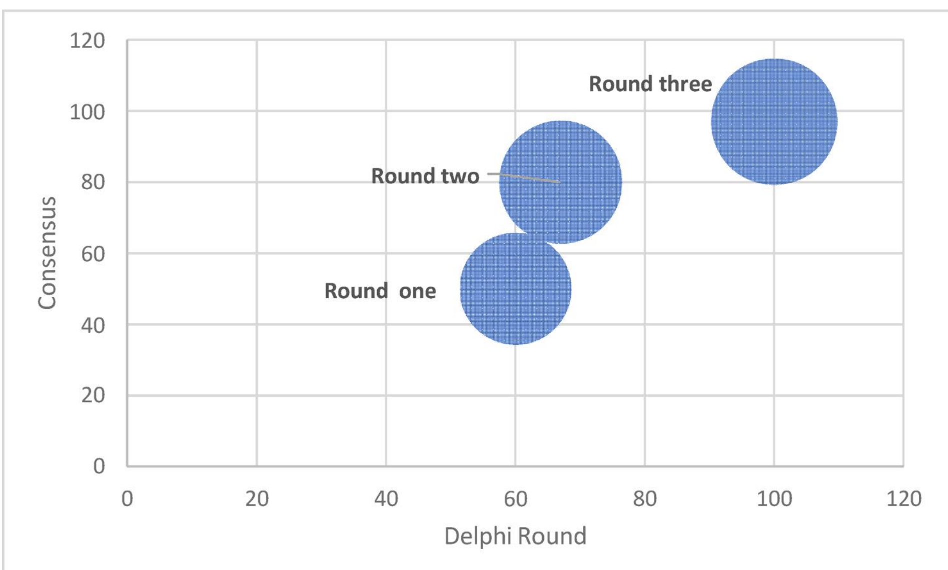

Figure 3. Summary of Delphi rounds.

the variables. The summary of all the rounds was presented in Figure 3 and it revealed the average consensus for the second and first rounds were below 80. In addition, the experts introduced new variables to the questionnaire for each attribute. The variables are energy storage and smart building design for innovation. While for construction project administration the experts included energy auditing, continuous monitoring, and reporting. Finally, for organizational culture, the experts added stakeholders' involvement with net zero design, accountability, and visibility. Aghimien et al. (2020) and Ginigaddara et al. (2021) affirmed that the ability to add new variables to an existing framework is a crucial advantage of the Delphi study. In the second round consensus was achieved for most of the variables including the idea that organizational culture, project administration and innovation contributes in achieving net zero design.

However, Figure 4 revealed that consensus was achieved for all the variables and sub-attributes that determine net zero building design in the third round. After analyzing the responses from the third round, the main and sub-attributes that have a significant impact on achieving net zero building design were organized to create a more complete picture of these attributes. The attributes were organized and presented in Table 3 using mean, median, and interquartile deviation (IQD). According to Jiang et al. (2017), a consensus is achieved with 100% of the

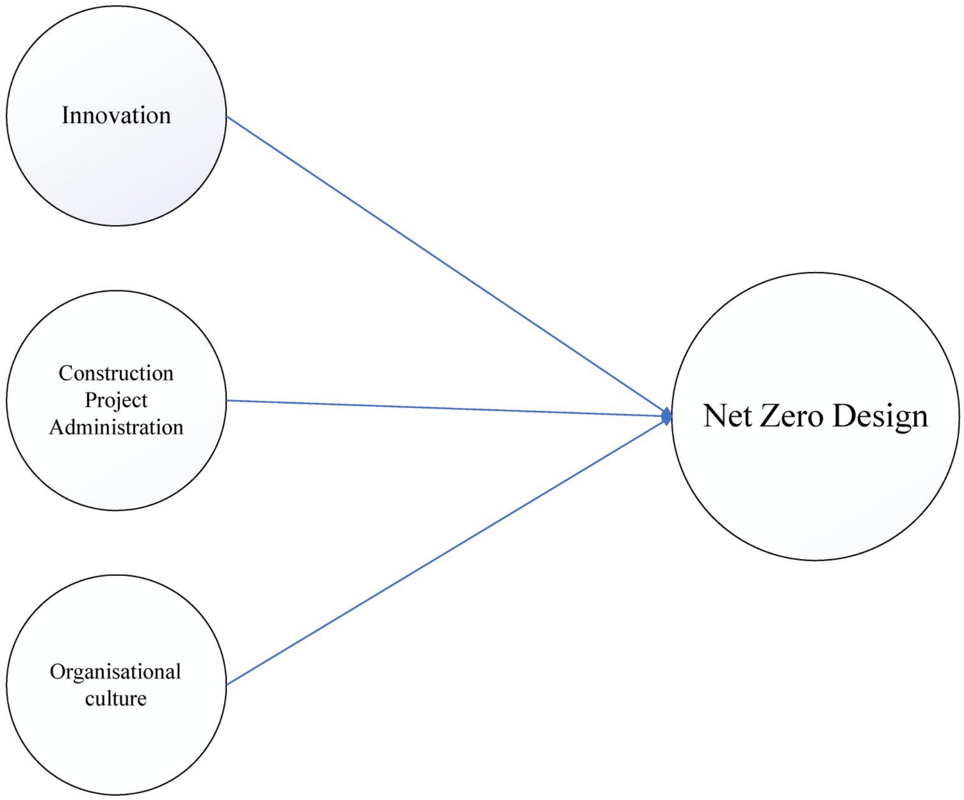

Figure 4. Framework for transitioning the construction industry to net zero.

experts in agreement, and when two-thirds agree it is referred to as common consent. This study aimed to ensure that each attribute should have a consensus although a common consensus was also accepted.

Table 3 presents the sub-attributes that were used to measure the three (innovation, construction project administration, and organizational culture) variables that were used in measuring the transition to net zero design. Regarding innovation, the experts considered renewable energy and low-carbon concrete as a very high impact (VHI: 9-10) on the transition of building to net zero design. The findings from this Delphi coincide with (Karlsson et al. 2020a; Su et al. 2022; Tirelli and Besana 2023) studies. Su et al. (2022) discovered that the rise of the fourth industrial revolution gave rise to innovations that support renewable energy technologies which provide feasible paths for reducing carbon dioxide (CO_2) emissions. Zhang et al. (2017) affirmed that the adoption of low-carbon materials contributes to eliminating carbon emanating from buildings. Other significant forms of innovation responsible for net zero building design are alternative fuels, building simulations, building optimization technology, and carbon pricing tools. It can be deduced from the findings that innovations responsible for transition to Net Zero can be divided into technological and building materials innovation.

Regarding construction project administration Table 3 revealed there was a consensus for all the variables with an IQD between 0.00 and 1.00. However, from the expert's response only two variables were considered to have a very high impact (VHI: 9-10) in ensuring net zero building design. The two variables have a very high impact ($\bar{x}$) of 8.53 to 8.67. The variable with the highest mean score ($\bar{x}$) is cost management followed by decarbonization methods. Leach et al. (2014) discovered that effective cost management is needed for net zero energy buildings to become the norm in the commercial development of buildings. Likewise, Torcellini et al. (2015) affirmed that cost management is needed for net zero buildings to gain market relevance and global adoption. The cost management technique should ensure that merging zero-energy building technologies with existing building technologies will not lead to an increase in the cost of construction. Other factors with high importance are waste management, risk management strategies, energy auditing, continuous monitoring, and life cycle analysis. Towards ensuring net zero Chuenwong et al. (2022) identified waste management as a crucial practice that can be achieved through onsite waste sorting.

Concerning organizational culture, Table 3 revealed that consensus was reached for all the variables. The experts rated some variables as having a higher impact than others with a commitment to sustainability having the highest impact (VHI: $M = 10$, $\bar{x}$ =9.73. $\sigma X = 0.62$ and IQD = 0.50). The experts strongly believed that a culture that creates an environment or supports the commitment to sustainability has the potential for transitioning the construction industry to net zero design. The findings from this study are similar to Zaman (2023). This implies that commitment to sustainability practices has the potential to achieve net zero energy, carbon, and water. Other organizational culture variables with high impact are communication, leadership, collaboration, and stakeholders' involvement with net zero design. Ko et al. (2022) and Obobisa (2022) asserted that leadership is a major factor in transitioning to Net Zero design in the construction industry. Ko et al. (2022) indicated that the Paris Agreement which agreed to limit temperature increases below 2 C preferably to 1.5 C was made possible through effective leadership.

Structural equation modelling

The second objective was focused on validating the impact of variables (innovation, organizational culture, construction project administration) extracted from the Delphi study in ensuring net-zero design in the construction industry. The validation will confirm the hypothesis that a holistic approach of combining innovation, organizational culture, and construction project management will ensure net zero carbon, energy, and water simultaneously. This was achieved using structural equation modelling and a framework was proposed as shown in Figure 4. Prior to conducting the structural equation modeling (SEM) Oke and Ogunsemi (2016) and Hair et al. (2013) recommended that confirmatory factor analysis (CFA) should be the first step in conducting SEM. The CFA would ensure that the measurement items fit effectively into the model and are achieved through several iterations.

Confirmatory factor analysis

This study employed the AMOS software to conduct a Confirmatory Factor Analysis (CFA) to assess the alignment of the measurement items with their respective constructs. AMOS was chosen for this purpose due to its ability to evaluate the degree of correspondence between the collected data and the proposed theoretical models, known as the goodness of fit (Osunsanmi et al. 2023). Shek and Yu (2014), Oke and Ogunsemi (2016) and Mustafa et al. (2020) recommended that the first step in performing CFA is to check the factor loadings for each measurement variable. Oke and Ogunsemi (2016) recommend that the factor loadings for each variable should be above 0.6 and the average variance explained above 0.5. The results of the confirmatory analysis are presented in Table 4, which displays the loadings of each variable comprising the constructs, as well as the composite reliability (CR) and average variance extracted (AVE). To obtain the optimal model fit, the analysis was performed three times, during which certain variables contributing to each construct were removed.

Innovation

Innovation was the first construct in the CFA as shown in Table 4 used for developing the model that supports the transition to net zero in the construction industry. This study describes innovation as the implementation of new methods and technologies that support the transition to net zero in the construction industry. A critical look at Table 4 revealed that the CFA confirmed that four variables are suitable for measuring innovation. The variables are INO_7 = Renewable energy technology, INO_8 = Building optimization, INO_5 = Low carbon materials, and INO_6 = Building automation. All the variables have a loading of above 0.6 with building optimisation technology and renewable energy technology having the highest loadings. Ohene et al. (2022b) also discovered that since the emergence of net zero researchers and practitioners have explored numerous renewable energy technologies (RET). Alirezaei et al. (2016) and Hughes et al. (2011) revealed that the adoption of RET for net zero design is classified into two broad categories. The first category focused on providing electrical energy and technologies. The second category is technologies that support building optimization and management. The CFA also revealed low-carbon material as a significant measurement variable for innovation. Zhang et al. (2017) also discovered that the alteration of building materials supports the construction industry transition to net zero. Thus, it can be implied that the innovation responsible for transitioning to net zero consists of technology adoption and building materials alteration.

Construction project administration

Table 4 revealed that construction project administration was the second construct used in developing the model for the transitioning of the construction industry. This study describes construction project administration as a group of specific activities involved in planning, organizing, and controlling projects to achieve a net zero design. Figure 5 depicts that five variables are suitable for measuring construction project administration. The variables are CPA_7 = Decarbonisation methods, CPA_2 = Cost management, CPA_6 = Energy auditing, CPA_8 = Waste management, CPA_3 = Risk management. The composite reliability also gave a value of 0.918 which according to Hair et al. (2019) reflects a better reliability of the variables used to measure the constructs. All the measurement variables have a loading of above 0.6 with cost management and decarbonization methods having the highest loadings at 0.85 and 0.83 respectively. Leach et al. (2014) and Torcellini et al. (2015) emphasized the need for stringent cost management practices focused on achieving net zero energy buildings. The CFA also confirms energy auditing as a crucial construction project administration technique for achieving net zero. This finding was also in tandem with Chisale and Mangani (2021) and Balaras (2022) who discovered that achieving net zero energy cannot be possible without proper auditing. Balaras (2022) proclaimed that energy audits provide

Table 4. Confirmatory factor analysis and convergent analysis of the model.

Construct	SEM Coding	Measurement variables	Outer Loadings	Composite Reliability	AVE
Innovation	INO_7	Renewable energy technology	0.72	0.838	0.565
	INO_8	Building optimization technology	0.81		
	INO_5	Low carbon materials	0.80		
	INO_6	Building automation	0.67		
Construction Project Administration	CPA_7	Decarbonisation methods	0.83	0.918	0.691
	CPA_2	Cost management	0.85		
	CPA_6	Energy auditing	0.84		
	CPA_8	Waste management	0.81		
	CPA_3	Risk Management	0.83		
Organisational culture	OGC_1	Leadership	0.83	0.942	0.729
	OGC_10	Visibility	0.78		
	OGC_7	Collaboration	0.88		
	OGC_6	Research and Development	0.87		
	OGC_5	Commitment to Sustainability	0.87		
	OGC_4	Communication	0.88		
Net Zero Design	NZD_1	Net Zero Energy	0.92	0.931	0.818
	NZD_2	Net Zero Carbon	0.94		
	NZD_3	Net Zero Water	0.86		

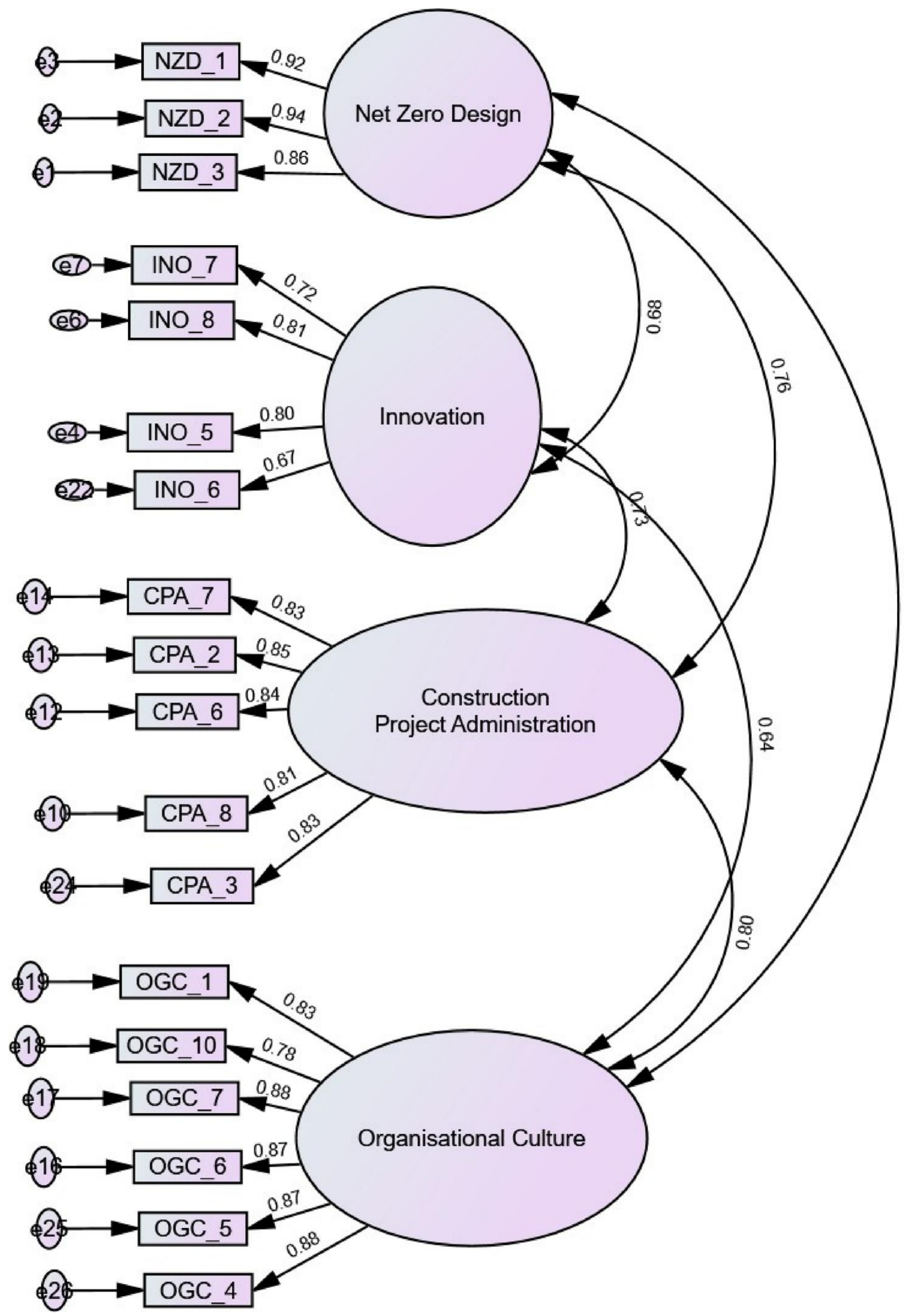

Figure 5. Confirmatory factor analysis.

valuable data for quantifying and providing solutions for the transition to net zero energy buildings.

Organizational culture

Organizational culture was the third construct that was used in developing the model that supports the transition of the construction industry to net zero design. This study describes organizational culture as the shared values and collective mindset within which construction professionals and stakeholders interact and work. Figure 5 shows that six measurement variables were used to quantify organizational culture. The variables are leadership = 0.83, visibility = 0.78, collaboration = 0.88, research and development = 0.87, commitment to sustainability = 0.87 and communication = 0.88. Past research like Christiansen et al. (2023), Ko et al. (2022) and Song et al. (2014) have identified collaboration, leadership, and commitment to sustainability as crucial variables for achieving net zero. Thus, it can be implied that construction stakeholders adopting a culture of collaboration and commitment to sustainability have a better chance of achieving net zero. Visibility was another crucial measurement variable confirmed by the CFA. Osunsanmi et al. (2022) also discovered that visibility supports collaboration and communication.

Net zero design

Net zero design in this study was described as the zero emission of carbon, energy, and water. Table 4 revealed that all the

Table 5. Discriminant validity analysis.

	Organisationalculture	NetZeroDesign	Innovation	Construction ProjectAdministration
Organisational culture	0.854			
NetZero Design	0.808	0.904		
Innovation	0.638	0.685	0.752	
Construction Project Administration	0.803	0.763	0.727	0.832

measurement variables for net zero design achieve a loading of above 0.6. However, net zero carbon (NZD_2) has the highest loading of 0.94, followed by net zero energy (NZD_1) with a loading of 0.92. The high loadings attributed to net zero energy and carbon are related to the enormous research conducted in the field (Song et al. 2014; Torcellini et al. 2015; Balaras 2022). Valiulahi et al. (2023) discovered that numerous advancements have been made in the field of net zero energy. Amongst this advancement is the creation of vehicle-to-home (V2H) technologies for net zero energy buildings that support the adoption of renewable energy technologies (Hughes et al. 2011; Ohene et al. 2022b). V2H technology can enhance energy efficiency, stabilize the grid, and facilitate the integration of renewable energy sources (Rehman et al. 2021). Numerous advancements in the area of net zero water include real- time water quality monitoring and seamless water management Olmos and Loge (2013) and Englehardt et al. (2016).

Structural model assessment

The structural model was assessed by checking the discriminant validity of the model and the fit indices. The model was assessed following the recommendation of Byrne (2001), Hair et al. (2019), and Aliu and Aigbavboa (2020). The discriminant validity analysis of the constructs is presented in Table 5. The discriminant validity test is aimed at determining if the measurement variables are consistent with the nature of the constructs. The fornell-Larcker criterion was employed to conduct the discriminant validity test. According to Hair et al. (2019), the validity of the discriminant test is established when all other correlations in the table are smaller compared to the highest correlation on each diagonal. Conversely, Hair et al. (2010) stated that the discriminant test is valid if the square root of the average variance extracted (AVE) for each construct exceeds the inter-construct correlations. The bolded topmost correlation in Table 5 was determined by calculating the square root of the AVE for each construct. A thorough examination of Table 5 indicates that the bolded topmost correlation is higher than the other correlations. Therefore, it can be inferred that the variables utilized to measure the four constructs in this study are adequate and possess discriminant validity.

To further confirm the structural model assessment the fit indices were examined following the recommendations of Oke and Ogunsemi (2016), Ong and Puteh (2017), and Aliu and Aigbavboa (2020). These indices include the standardized root mean square (SRMR), comparative fit index (CFI), Tucker Lewis index (TLI), and other indices, which are presented in Table 6. The recommended threshold was also presented in the table and was used to determine the model validity. Upon initial examination of Table 6, it was observed that all the fit indices fall within the recommended threshold. Hair et al. (2010) and Rosenbaum and Spears (2009), stipulated that the SRMR should range from 0.05 to 0.07. Table 6 shows that the SRMR is within the recommended threshold. Other fit indices such as TLI, CFI, RMSEA, NFI, and IFI were also within the threshold. Thus, it can be inferred that the values obtained from these indices affirm the validity of the model's structural component.

Table 6. Model fit indices assessment.

Fitindices	Recommendedthreshold	Finalmodel
SRMR	0.05 to 0.07	0.062
TLI	0.95 to 1.00	0.952
CFI	0.93 to 1.00	0.960
RMSEA	0.05 to 0.08	0.069
NFI	0.60 to 1.00	0.947
IFI	0.93 to 1.00	0.960

Structural relationships among the constructs

The structural relationships among the constructs were tested in this section to validate the hypothesis that was postulated in this study. This study postulated that there is a significant impact of innovation in transitioning the construction industry toward a net zero design. The same hypothesis was postulated for organizational culture and construction project management. The graphical representation of the hypothesis was presented in Figure 6 and was generated from AMOS. Mustafa et al. (2020) recommended that in AMOS the path coefficients between the constructs are depicted with the arrows. The construct with the arrows pointing toward them is called the dependent or endogenous variables. Thus, it can be inferred from Figure 6 that the dependent variable is net zero design and the independent variables are innovation, organizational culture, and construction project administration.

Figure 6 presents the standardized value for the path coefficient for each construct. The value alongside their estimates is further shown in Table 7. The estimate in Table 7 for innovation reveals that it is greater than 1.96 which confirms that there is a positive significant impact of innovation in transitioning the construction industry to net zero design. The CFA confirms that innovation was measured using variables that relate to technology and the altering of building materials. Studies like Hughes et al. (2011), Alirezaei et al. (2016) and Su et al. (2022) have emphasized the need for technological innovation in transitioning to net zero. On the other hand, Zhang et al. (2017) and Patrizio et al. (2021) recommended that altering building materials like adopting biomass and low- carbon construction materials will assist in transitioning towards net zero.

Table 7 also revealed that there is a positive significant effect of construction project administration in the transition to net zero design. The standardized estimate gave a value of 26% which implies that an increase in the construction project administration would speed the transition rate to net zero design by 26%. Amongst the variables that were used to measure construction project cost management, energy auditing, and decarbonization methods have the highest loading. Activities that support the decarbonization of activities are an emerging field within the construction industry. The activities include the adoption of low-carbon materials, energy auditing, life cycle analysis, and renewable energy. (Karlsson et al. 2020a; Chisale and Mangani 2021). The experts from the Delphi study indicated

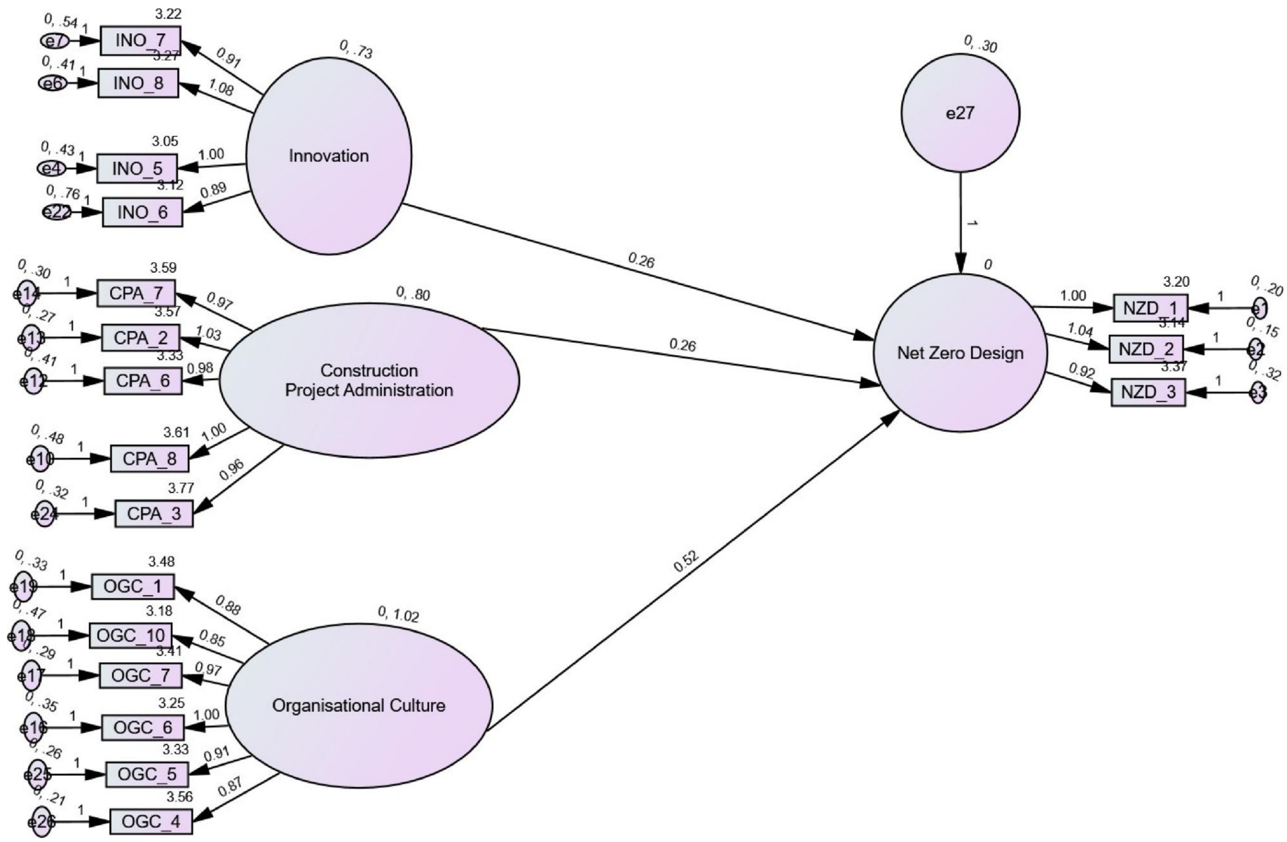

Figure 6. Model for transitioning to net zero design in the construction industry.

Table 7. Structural model assessment and hypothesis testing.

Impacts	Estimate	S.E.	C.R.	P	Remark
NetZero Design <— Innovation	0.258	0.035	7.466	0.000	Significant effect
NetZero Design <— Construction Project Administration	0.262	0.032	8.246	0.000	Significant effect
NetZero Design <— Organisational Culture	0.524	0.031	16.928	0.000	Significant effect

that cost management is needed to achieve decarbonization activities.

The third hypothesis formulated in this study was assessing the impact of organizational culture on transitioning to net zero. Table 7 revealed that the estimates attributed to organizational culture are greater than 1.96 and therefore confirm a significant effect for transitioning the construction industry to net zero design. The standardised estimate yielded a value of 52% which implies that more than half of the activities responsible for the construction industry transitioning to net zero are related to stakeholders' behaviour. Marteau et al. (2021) and Dixon et al. (2022) emphasized that behavior change by individuals, commercial entities, and policymakers is needed to achieve net zero in all domains. Furthermore, Nelson and Allwood (2021) discovered that the transition to net zero would be faster in the presence of behavior change. Valiulahi et al. (2023) and Ko et al. (2022) recommended collaboration, leadership, and communication as crucial behavioral change.

Conclusions and recommendations

The transition to net zero design for the construction industry can be likened to a poisonous three-headed hydra of the Greek mythology with each head representing energy, water, and carbon emission. Eliminating the hydra has been a daunting task for construction stakeholders because a reductionist approach has been adopted that focuses on eliminating the head individually. The review of the literature revealed that the heads (carbon, energy, and water) are related, and like Greek mythology, eliminating one head will lead to the growth of another. Thus, this study proposed a holistic approach that supports the transitioning of the construction to a net zero design by eliminating all the heads at once.

Net zero design in this study was described as the integration of different sustainability concepts, including net-zero energy, water, and carbon. These concepts work together to reduce the environmental impact of infrastructure provided by the construction industry and create a sustainable built environment. This study hypothesizes that the approach toward achieving net zero design must include a combination of innovation, organizational culture, and construction project management. The effective implementation of the variables or practice would foster the transition of the construction industry to net zero design. The hypothesis was tested and validated by developing a model using a combination of the Delphi study and structural equation modeling (SEM).

The model developed using SEM validated the opinion of construction stakeholders that organizational culture, construction project management, and innovation will ensure the transition to net zero design. This implies that the combination of these practices would guarantee that infrastructure developed within the construction industry achieves net zero energy, carbon, and water. Innovation as a practice involves the implementation of new methods and technologies that support the transition to net zero in the construction industry. The technologies supporting the transition are divided into two categories with the first category focused on providing electrical energy and technologies. The second category is technologies that support building optimization and management. The technologies in the second category rose from the application of the fourth industrial revolution. These technologies utilize artificial intelligence to monitor and control the energy, water, and carbon emitted in buildings.

Construction project administration was also another practice capable of achieving net zero design in the construction industry. It was described as a group of specific activities involved in planning, organizing, and controlling projects to achieve a net zero design. Cost management was discovered as a crucial project administration strategy in ensuring net zero design. It was discovered that for net zero design to be a standard the cost of incorporating innovative technologies into existing infrastructures must be at its barest minimum. For instance, decarbonization a construction project administration technique that involves the adoption of low-carbon materials, energy auditing, life cycle analysis, and renewable energy should not increase the overall cost of developing the infrastructure.

This study found that the ability to ensure cost management of decarbonization methods is related to the organizational culture adopted by the stakeholders. Organizational culture was described in this study as the shared values and collective mindset within which construction professionals and stakeholders interact and work. A culture that creates an environment or supports the commitment to sustainability has the potential to transition the construction industry to net zero design. The culture thrives in the face of effective leadership, collaboration, communication, and visibility. The absence of effective leadership has been the bane for the construction industry in transitioning to net zero design.

This study contributes to practice and research as it provides a holistic solution that supports the transitioning of the construction industry to net zero carbon, energy, and water simultaneously. The study contributed to providing practices and behavior that enable stakeholders in the construction industry to achieve net zero design. The findings from this research will contribute to ensuring that the construction industry contributes to promoting environmental conservation. The findings from this study will contribute to the UK construction industry achieving net zero in line with the 2050 target. The study recommended that stakeholders in the construction industry should embrace a culture that supports the commitment to sustainability. The culture should be channeled towards creating environmental awareness of construction activities which should be implemented through collaboration with employees and leadership commitment. It is also recommended that stakeholders within the construction industry adopt project management techniques capable of reducing the extra cost of innovative technologies that support net zero design.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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