Journal of Cleaner Production 549 (2026) 147859

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Where absorptive capacity resides: A locus study across firm and project boundaries in the twin transition

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HIGHLIGHTS

- This paper seeks to improve the understanding of the twin transition in construction project-based firms.
- Helps project-driven industries to develop well-structured development processes for navigating organisational change.
- Potential absorptive capacity (acquisition and assimilation of knowledge) takes place mainly in firm boundaries.
- Realised absorptive capacity (transformation and exploitation) takes place mainly in the boundaries of projects they deliver.

ARTICLE INFO

Keywords:
Dynamic capabilities
Green transformation
Knowledge absorption
Net zero
Digitalisation
Digital innovation

ABSTRACT

Absorptive capacity in construction is crucial for effectively managing change amidst the twin transition (digital and green transitions) that is significantly affecting existing practices in the sector. Concentrating on construction sector, this research examines how firms assimilate and use digital decarbonisation practices to improve their performance. Building on a multi-method qualitative dataset comprising interviews with 53 industry experts in the UK construction sector, archival data, and validation of our findings through focus group data, the study highlights the vital role of absorptive capacity in enabling firms to navigate and benefit from digitalisation and sustainability initiatives. The findings indicate that the potential absorptive capacity (acquisition and assimilation of knowledge) takes place mainly in firms whereas the realised absorptive capacity (transformation and exploitation) takes place mainly in the boundaries of projects they deliver. This offers a mutually reinforcing cycle of exploration and exploitation that can equip firms to meet contemporary challenges and institutional demands effectively to cope against the twin transition. Our study contributes with a four-phase process model for understanding the organisational change management processes required for the twin transition in project-based settings. Most existing research on absorptive capacity focuses on either organisational or industry-level dynamics, our study examines the loci of absorptive capacity (e.g., by examining firm and project boundaries) in a highly complex, project-driven industry such as construction.

1. Introduction

The Net Zero vision describes man-made decarbonisation efforts that stop adding new climate-heating emissions to the atmosphere to avert climate change. Recently, the United Kingdom (UK) became the first G7 country to legislate for Net Zero, targeting 2050 Net Zero carbon emissions (CCC, 2019). This includes efforts to decarbonise public sector buildings, reduce carbon emissions from transportation, and improve energy efficiency. Project-driven sectors such as construction have an important role in delivering this vision, given their energy-intensive operations (Fathalizadeh et al., 2021). Simultaneously, digitalisation, which is the process of making workflows and operations digital, is seen as central in monitoring and, ultimately, reducing emissions towards a more sustainable future through the power of data (Papadonikolaki et al., 2022). Especially the potential of Digital Twins (DTs) in achieving sustainable development goals has been identified before (Siedschlag et al., 2024; Xie et al., 2024), suggesting important links between digitalisation and reaching decarbonisation. For instance, DTs that are a

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https://doi.org/10.1016/j.jclepro.2026.147859
Received 14 May 2025; Received in revised form 6 February 2026; Accepted 22 February 2026
Available online 2 March 2026

cornerstone of current digitalisation efforts, update data in real time and as virtual models may compare virtual with physical assets and continuously monitor environmental behaviour to make it more sustainable (Siedschlag et al., 2024; Xie et al., 2024).

Whereas *digitisation* is a largely technical term, describing the transformation of information from analogue to binary, *digitalisation* is the process of changing businesses (Gartner, 2013; Ross, 2017) embracing 'technology in use' (Morgan, 2019) leading to eventual *digital transformation* at a system level affecting businesses, market, policy and other institutions (Marnewick and Marnewick, 2022). In this paper, the focus is on how digitalisation enables the transition to Net Zero in project-driven sectors like construction. This twin shift towards digital transformation alongside climate change mitigation is also known as the simultaneous or 'twin transition' (Siedschlag et al., 2024), hereon referred to as the *twin digital/green* transition. Specifically, understanding the processes through which firms navigate this twin transition, namely, how they adopt digital technologies, and how these processes are linked to sustainable business practices, is essential for informing policies that incentivise firms to foster these twin transitions. Motivated by this practical challenge, this paper addresses how firms in construction can adapt and innovate in response to these simultaneous pressures.

To address this challenge, our study applies the theoretical lens of dynamic capabilities to understand how firms develop, deploy, and modify internal resources, and absorptive capacity to explore how external knowledge is identified, assimilated, and utilised. Theoretically, the concept of Absorptive Capacity (ACAP) has been considered a dynamic capability that is intertwined with the systems, processes, and structures of a firm in dealing with dynamic and rapidly changing environments (Sun and Anderson, 2010). Zahra and George (2002) refer to ACAP as an organisation's dynamic capability with which they develop routines – stable patterns of behaviour – for the acquisition, assimilation, transformation, and exploitation of externally sourced knowledge. Past studies have identified the lack of and time-sensitive need for developing dynamic capabilities and ACAP to manage technology adoption in construction organisations and projects and respond to technological innovation and digital transformation (Maldonado et al., 2018; Miao et al., 2021; Papadonikolaki et al., 2022). There is a growing interest on how ACAP is manifested in project-driven sectors such as construction (Killen et al., 2012; Kraatz and Hampson, 2013; Love et al., 2024; Love et al., 2016). Studies illustrate the importance of understanding how ACAP is developed and built in construction project settings, where it is shown to have a critical role in assimilating and applying new knowledge (Love et al., 2024). However ACAP's role in construction firms, where knowledge transfer from project to organisation is a barrier to adaptation (Hobday, 2000), remains little understood, especially from a human and social capital perspective. The twin transition increases the importance of addressing this gap as it creates conditions where ACAP becomes more relevant than ever in managing complex shifts (Miao et al., 2021; Secundo et al., 2024) for instance, where firms are targeting both digital transformation and combat climate change through strategic green initiatives, such as Net Zero. Against this backdrop, the following research question (RQ) emerges:

- *How do project-driven industries such as construction develop absorptive capacity for leveraging the twin (digital and green) transition through digital twins for achieving Net Zero?*

The construction sector is a key contributor to carbon emissions (Huang et al., 2018; UN, 2022; WGBC, 2019). As a largely project-intensive industry (Morris, 2004) construction projects are unique highly inter-organisational settings where firms share resources, competences, information and knowledge continually through multi-firm consortia to deliver projects (Hobday, 1998; Sydow et al., 2004) constrained by localised activities on-site, high degree of embeddedness (Blomquist and Packendorff, 1998), and involvement of internal and external actors where knowledge is typically lost across the project lifecycle and the involvement of various firms. This highlights the critical role of ACAP in organisational learning within construction, particularly in supporting sustainable development and responses to climate change. Therefore, ACAP becomes crucial on how the construction sector can cope with external stressors such as digital transformation and the green transition.

The main contribution of this study is a theoretical process model which comprises four distinct phases that explain how construction firms develop ACAP for leveraging the twin transition. By developing this process model, our study responds to calls for connecting the twin transition (Siedschlag et al., 2024; Xie et al., 2024), through an organisational change management approach (Krystallis et al., 2023). Responding to our research question, the findings demonstrate that the potential and realised ACAP take place in different loci. Whereas potential ACAP takes place predominantly at firm boundaries, realised ACAP takes place primarily in project boundaries.

We elaborate this theoretical process model by offering four propositions to further extend the theory of dynamic capabilities and ACAP in construction projects and firms for navigating the twin transition. Subscribing to theory elaboration as an actionable research approach (G. Fisher and Aguinis, 2017), our findings contribute to the theoretical advancement of ACAP. According to Zahra and George (2002), absorptive capacity constitutes a dynamic capability that enables organisations to establish routines for acquiring, assimilating, transforming, and exploiting knowledge originating outside the firm. While this conceptualisation is well established, there remains limited empirical understanding of how absorptive capacity is developed in construction project environments, where it has been shown to be instrumental in supporting the assimilation and use of new knowledge (Love et al., 2024).

Whereas previous work distinguished between external and internal ACAP in programme alliances and their projects, our contribution refines existing theoretical ideas of ACAP in project settings by offering an elaborated four-phase processual model of ACAP and, at a more granular level, explaining how realised ACAP is placed primarily at project boundaries, whereas potential ACAP is placed predominantly at firm boundaries. In addition, we document the routines that emerged from our empirical observations in leveraging the twin transition.

The structure of the paper continues with the theoretical framing (Section 2) and the methodology (Section 3). In Section 4, the data analysis is presented, and the paper continues with a scientific discussion (Section 5) and concluding remarks (Section 6).

2. Theoretical framing and phenomenon

1.1. Twin (digital and green) transition in construction assets and processes

Throughout its lifecycle, the construction sector directly controls, and is responsible for, 43% of the global greenhouse gas emissions (UN, 2022, p. 62), including direct and indirect emissions from residential and non-residential, materials concrete, aluminium, steel, brick, glass and other emissions. Other sources calculate buildings as responsible for 39% of global energy-related carbon emissions: "28% from operational emissions, from energy needed to heat, cool and power them, and the remaining 11% from materials and construction" (WGBC, 2019). Green buildings are only a part of green construction (Luo et al., 2022), which includes the decarbonisation of project delivery-related processes but also material decisions, operations and logistics, beyond the running costs of operating built assets. The UN emphasises that for decarbonising the construction sector, all stakeholders need to take greater responsibility in understanding the environmental impact of their decisions across the life cycle, which requires having access to the right data at the right time (UN, 2022). The change towards 'green innovation' is particularly accentuated in the construction sector due to its

resource-intensive nature. However, as an organisational process, innovation is often a static and esoteric concept (Slaughter, 1998) that cannot capture the peculiarities and dynamic nature of continuous sociotechnical change processes unless approached as systematic innovation. Therefore, the concept of 'system innovation' or transition becomes more relevant and meaningful to describe such phenomena of the twin green and digitalisation industry change (Elzen et al., 2004).

Digital technologies support sustainability efforts and enable firms to meet their sustainability objectives to Net Zero through the twin transition (Muench et al., 2022; E Papadonikolaki and Anumba, 2024; Siedschlag et al., 2024); a complex, dynamic evolutionary process where digital transformation is intertwined with and drives sustainability transitions. Key digital technologies enabling the twin transition are data-intensive solutions for modelling, analysing, optimising and benchmarking scenarios that reduce carbon emissions by streamlining data and operations and building data analytics capabilities (El Hilali, El Manouar and Idrissi, 2020; Nidumolu et al., 2009). This study focuses on DTs and how they can support Net Zero.

Digital Twins are chosen as the primary digital tool in the study given its various use cases, connections with other digital construction technologies and cross-industry applications. DTs were originally defined by Grieves (2014) and paved the way to cyber-physical interaction and convergence between physical and cyber worlds of production. DTs bring together data across product lifecycle, promoting efficient synergies between different stages (Qi and Tao, 2018), laying the foundation that enables traceability and better control of sustainability objectives. DTs were created to support Product Lifecycle Management (PLM) in engineering and manufacturing sectors (Grieves, 2023) and as such, in construction sector, rely especially on good data from Building Information Models (BIM). However, as noted by Radzi et al. (2024), significant development is still needed to raise the level of granularity and usefulness from BIM data and knowledge management to fully operational digital twins.

All the above DT applications range across project delivery and operation phases of construction projects but are often disconnected and developed as post-hoc interventions after built assets are set up (Whitmore et al., 2024). The integration of digital twins across project execution and operation could enable accurate decision-making at the project start for establishing desirable future asset behaviour and sustainable processes to meet Net Zero (Dowd et al., 2018; Li et al., 2022). To successfully navigate the twin transition through digital twins, the front-end of the twin transition (Papadonikolaki, 2025), innovation capabilities (Saari et al., 2024) and new organisational structures and strategies are needed (Trevisan et al., 2024). Understanding how construction sector develops ACAP to leverage external knowledge, is essential for leading innovation and change initiatives for the twin transition, which is the focus of this study.

1.2. Firm-boundary: absorptive capacity in firms

The intersection of innovation, carbon neutrality and disruptive technologies brings a paradigm shift in how organisations, industries and societies approach sustainable practices by holistically immersing themselves at various types of innovations, which require both technical and organisational restructuring (Trevisan et al., 2024). To study this twin transition mentioned in the previous section, we engage with the concept of ACAP. ACAP, introduced by Cohen and Levinthal (1990) within the context of innovation, emphasises a firm's ability to recognise, assimilate, and apply external knowledge to drive innovation – especially technological innovation according to Maldonado et al. (2018). ACAP has since been a foundational concept in understanding how firms innovate by leveraging external knowledge and converting it into commercial success. Additionally, ACAP has significant relevance in change management, particularly in understanding how organisations adapt to external changes, especially in complex sociotechnical systems (Miao et al., 2021). In change management, ACAP is seen as a critical capability that enables organisations to not only absorb new information but also to implement it effectively during periods of transition, such as digital transformation or shifts toward sustainability (Rodríguez-González et al., 2023).

The ACAP of firms is crucial in renewing their knowledge base and competences enabling them to innovate and compete in changing markets and environments, for instance considering the pressing need of addressing climate change. The theory of ACAP originated in Cohen and Levinthal (1990) work, where they argued that a firm's prior related knowledge plays a critical role in its ability to evaluate and use external information. Earlier studies highlighted the social capital of organisations, emphasising its importance of developing close relationships to create and strengthen information flows and codify knowledge. Essentially, the more knowledge a firm has, the greater its capacity to acquire and make use of new knowledge (March, 1991). Cohen and Levinthal (1990) valued highly the importance of external relationships such as alliances and multinational collaboration in establishing absorptive capacity and used traditional econometric indicators such as Research & Development (R&D) output (Kraatz and Hampson, 2013) or number of patents at the expense of the human factors contributing to absorptive capacity (Lund Vinding, 2006).

Other studies focused more on the impact of human capital on ACAP (Mangematin and Nesta, 1999), e.g., by unpacking tacit knowledge and the competence levels of the personnel (Keller, 1996), and how new knowledge is internalised in organisations (Mowery et al., 1996). Kim (1998) argued that ACAP requires, first, a learning capability to assimilate knowledge and second, problem-solving skills to adjust and internalise to create new knowledge for innovation. Zahra and George (2002) reconceptualised the concept of ACAP to identify four components: (a) acquisition, (b) assimilation, (c) transformation and (d) exploitation. They argued that acquisition and assimilation capabilities relate to the *potential* of ACAP while transformation and exploitation relate to the *realised* ACAP that has received less attention in research (Zahra and George, 2002). Potential ACAP is crucial in renewing the knowledge base and competences in an organisation to enable it to compete in changing markets whereas the realised ACAP relates to how firms can leverage the potential ACAP.

1.3. Project-boundary: absorptive capacity in project settings

Whereas the concept of ACAP is well known in strategic management, in the field of project-based organisations that are key organisational vessels in construction – the study's context – it is less so (Killen et al., 2012). Nevertheless, the relation between absorptive capacity and inter-organisational collaboration has been studied before in traditional sectors, new product development and manufacturing. For instance (Sáiz Bárcena, Pérez Miguel, & Manzanedo del Campo, 2018), identified the impact of various forms of inter-organisational collaboration such as joint ventures, suppliers' and customers' cooperation on absorptive capacity to form their potential ACAP and improve their innovation outcomes. However, despite showing the how ACAP serves as mediating mechanism between collaboration and innovation, there is little research on the typologies of ACAP (Sáiz Bárcena et al., 2018). In cross-industry collaborations of R&D sectors, the firm-boundaries and cognitive distance are crucial antecedents for potential ACAP and the more radical the innovation, the more unrelated the knowledge domains should be (Enkel and Heil, 2014). Contrariwise, knowledge from related domains is linked to higher absorptive capacity for incremental innovations without departing from a firm's existing knowledge base (Enkel and Heil, 2014). However, Enkel and Heil (2014)warn that firms need to internalise and realise the knowledge and ACAP to prepare for crossing distant boundaries to collaborate. Also, in the R&D domain (de Jong and Freel, 2010) found evidence that a firm's absorptive capacity is positively related to the geographical distance to its innovation partners and other forms of other forms of proximity such as cognitive proximity. However, relying too much on geographical proximity and too-familiar

collaboration partners may weaken the absorptive capacity of firms (de Jong and Freel, 2010), failing to recognise new knowledge. These inter-organisational perspectives resonate with characteristics of construction as a project-based sector but with significant differentiations. However, an important caveat is as explained next, the nature of the boundaries among firms in project-based sectors.

Here we differentiate between firms whose key business is organised in projects (Winch, 2014) and projects that are temporary organisational forms of organising with a clear start and end,and have no permanent functional departments (Hobday, 2000). While each construction firm develops their own ACAP as a critical innovation capability, as firms aggregate at a project-level they can innovate and draw upon their expertise and individual ACAP. To this end, ACAP becomes important for project settings, as much-needed resource for innovation and delivering unique projects. In their meta-analysis of ACAP in technological innovation, Maldonado et al. (2018) identified both organisations and alliances (including both formal and informal collaborations) as loci and sources of ACAP. Organisational knowledge is sticky and resists transfer from where it is created because it is highly contextual and tacit (Von Hippel, 1994). In project-intensive settings such as construction, it was found that while ACAP relates to organisational change, the ability to acquire and assimilate new knowledge was more easily achieved than the ability to transform and exploit this knowledge (Killen et al., 2012).

Studies on ACAP in construction are indeed scarce, leaving out a potential for effectively dealing with change. Love et al. (2016) provided a first where construction firms organised around a project alliance used their knowledge recombination capabilities to absorb knowledge – that is ACAP – for reducing rework while improving safety. They found that the ACAP of the alliance helped the firm participating in alliance projects by shifting from single-loop, e.g. corrective actions, to double-loop learning, e.g. "correcting the underlying causes behind the problematic action" (Love et al., 2016, p. 1124:1124). However, their study focused on developing knowledge processing systems through "actively acquiring and transferring knowledge through formal and informal mediums" (Love et al., 2016, p. 1136:1136) and less on the human and social capital that this study focuses on. A. Singh et al. (2023) studied ACAP at project-level and discovered a positive mediating relation between strong social processes and project performance. They highlighted that social processes such as social integration mechanisms that cater knowledge management and support the human capital of projects can influence the potential ACAP (A. Singh et al., 2023). Building upon Love et al. (20160 and Singh et al. (2023) insights on processes, this study reveals the micro-foundations of such social processes, including leadership behaviours, new practices and talent integration, connecting back to the origins of ACAP in social and human capital. The scarcity of studies in ACAP in the construction sectors outlines a need to operationalise and conceptualise it stronger with empirical foundations.

1.4. Knowledge gap

The gap that this study addresses relates to the potential and realised ACAP of construction firms in addressing the phenomenon of twin transition. The twin transition refers to the combination of the digital transition and the green transition and in particular here the use of DTs in streamlining decarbonisation efforts (Siedschlag et al., 2024). Whereas ACAP has been traditionally considered as a quantitative metric and studied through econometric approaches (Kraatz and Hampson, 2013; Maldonado et al., 2018; Miao et al., 2021), here the focus is on ACAP's roots, around social and human capital. However, the focus of the present study is on construction firms and projects and how ACAP can support organisational change management to navigate the twin transition.

The mediated role of ACAP has been previously associated with firms' business continuity in sociotechnical systems undergoing dynamic change (Miao et al., 2021). However, there is a scarcity of studies linking ACAP directly to industries undergoing digital transformation. For instance, Siachou et al. (2021) identified that absorptive capacity and strategic interdependence are boundary conditions to how inter-organisational collaborations contribute to the digitalisation of firms. Few studies have looked at the positive mediating role of ACAP in contributing to digitalisation and firms' innovation performance (Kastelli et al., 2024). As construction is a project-based setting, these scarce models explained above are not enough to capture how the firms participating in inter-organisational projects through temporary project networks (Krystallis et al., 2025) and hence, their potential ACAP is not restricted only within their firm boundaries but extends to the projects they engage in. Table 1 summarises existing ACAP literature and how the paper addresses the gaps in knowledge.

2. Methodology

2.1. Rationale and context

This study builds upon a multi-method qualitative dataset featuring: (i) semi-structured interviews with a stakeholder sample of 53 industry experts from construction and its related ecosystems of manufacturing, technology and energy sectors; (ii) archival data from publicly available sources; and, (iii) focus group data. To ensure research rigour, several measures in (See Appendix 2) were taken in this qualitative study. Fig. 1 summarises the stages and purpose of each of the methods employed in our study.

As this study poses a 'how' question, qualitative methods and data were deployed to address it (Creswell, 1994). This study adopts a theory

Table 1
Summary of key literature and novelty of this paper.

Focus	Key findings
General ACAP literature	- Cohen and Levinthal (1990) emphasised the importance of a firm's ability to recognise, assimilate, and apply external knowledge to drive innovation. - ACAP is foundational in how firms leverage external knowledge for innovation and commercial success. - ACAP is crucial in change management, helping organisations adapt to external changes, particularly in complex sociotechnical systems (Miao et al., 2021). - ACAP is seen as a key capability for absorbing and effectively implementing new information during transitions such as digital transformation or sustainability shifts.
ACAP in Firms	- Zahra and George (2002) reconceptualised ACAP into four components: (a) Acquisition, (b) Assimilation, (c) Transformation, and (d) Exploitation. - Acquisition and assimilation are associated with potential ACAP, while transformation and exploitation relate to realised ACAP. - Maldonado et al. (2018) identified both organisations and alliances (including formal and informal collaborations) as key sources and loci of ACAP.
ACAP in Projects	- Love et al. (2016) highlighted how construction firms organised around project alliances used ACAP to reduce rework and improve safety. - In the context of organisational change, acquiring and assimilating new knowledge is easier than transforming and exploiting it. - Singh et al. (2023) reconceptualised ACAP as an organisational capability of acquiring and leveraging knowledge to improve project performance.
This paper	- Gap: Previous studies focused less on the human and social capital (organised in projects) of ACAP, emphasising primarily on traditional econometric indicators of firm and project performance e.g., (Al Halbusi, Soto-Acosta, Popa and Hassani, 2023). - Gap: Scarcity of studies explaining the relationship between ACAP and digitalisation. This is the first study explaining how the ACAP concept transforms to enable the twin transition. - This study addresses this gap by exploring mechanisms enabling construction organisations through inter-organisational projects to harness digital twins for the twin transition towards sustainability and digitalisation.

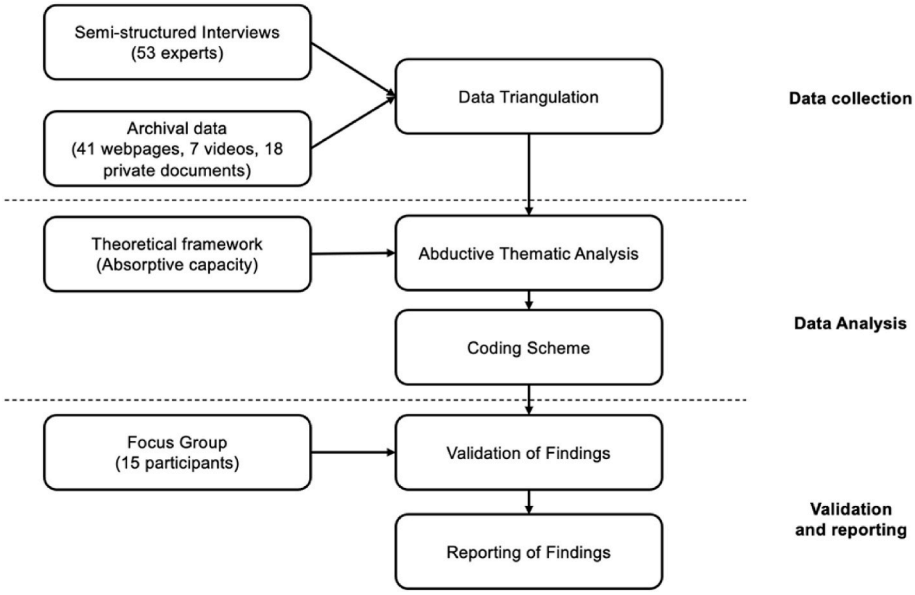

Fig. 1. Research design workflow.

elaboration approach as outlined by Ketokivi and Choi (2014). Theory elaboration involves refining and expanding on the contextual logic of an existing general theory. While it shares a similar underlying logic with theory testing, the key distinction is that the researcher's goal is not to test the theory but to further develop and elaborate on it. In studying the complex phenomenon of twin transitions and exposing new theoretical dimensions on understanding the ACAP of construction firms, the study focused on experiences from various stakeholders and firms involved in relevant infrastructure and building projects as use cases of the twin digital and green transition rather than focus on one case. This qualitative dataset complements existing studies of traditional quantitative metrics of ACAP such as firm innovative performance (S. Singh et al., 2020), R&D practices and financial returns (Maldonado et al., 2018). Experts' experiences were captured through interviews, a key qualitative data collection strategy that focused on meaning making from a dialogue between interviewer and interviewee, not just information elicitation (DiCicco-Bloom & Crabtree, 2006). By specifically focusing on semi-structured interview format, the production of qualitative data is ensured (DiCicco-Bloom & Crabtree, 2006).

To address the RQ, various DT and green initiatives were studied in the UK construction through experiences of key actors involved. The UK construction sector is ideal research setting for studying digital and green as the sector has been pushed by the government to increase digitalisation, for instance through the mandate for digital delivery in publicly-procured projects released in 2011 (GCCG, 2011). This follows an extended innovation agenda expressed through industry improvement reports that focuses on improving the performance of the sector. Apart from the digital shift of UK construction, construction is also a key contributor to carbon emissions and Net Zero attracts a lot of government and industry interest, as construction is key contributor to carbon emissions (Huang et al., 2018; UN, 2022; WGBC, 2019). This situation makes the built environment an ideal setting for the study on the twin transition.

2.2. Data collection

2.2.1. Semi-structured interviews

Data were collected through in-depth interviews with industry experts to increase data richness (Creswell, 1994) as interviews are considered appropriate means to elicit their expertise. 53 industry experts were interviewed between November 2022-February 2023. The sample size was not predetermined but was developed over the course of the investigation and eventually reached saturation, when no new information was added and repetitive ideas emerged (Bazeley, 2013). To reduce social desirability bias, the sampling criteria of the interviewees were: (a) familiarity to the topic (Nederhof, 1985) of twin transition, (b) hands-on or consulting experience with use cases (projects) of the twin transition such as buildings, infrastructure, cities etc., (c) senior position or high-flyers, (d) employed across diverse companies of the built environment ecosystem (See Appendix 1). Additionally, we made conscious steps for research balance, diversity and inclusion by including diverse firm types, such as Small-Medium Enterprises (SMEs, n = 14), large firms (n = 21) and Multi-National Corporations (MNC, n-18). Moreover, since rigour in qualitative research is not only related to sample size but also to interview length (LaDonna et al., 2021), we took extra time to perform in-depth interviews with average interview duration circa 48 min. Appendix 1 (see Supplementary material document) presents the interviewees' detailed profiles, diverse background information (as to sector and seniority) and roles across industry, policy and academia, the use case where they have experience in, and how pointers to quotations are made, e.g.: "Int-x", where "x" their ID number.

All interviews were conducted online and all interviewees were appropriately briefed about the research and the interview protocol in advance and signed consent forms allowing audio recording according to university research ethics practices. As all interviewees agreed to participate under confidentiality and anonymity only non-identifiable information is available. After the interviews were recorded, they were subsequently transcribed – only one respondent preferred to answer the questions via email (Int-53), The questions were designed to reflect the research aim and were piloted in advance of the actual interviews with three industry experts to strengthen the protocol (Castillo-Montoya, 2016). The questions were indirect so as to limit social desirability bias (R. J. Fisher, 1993). Seven semi-structured, open-ended questions (see Appendix 3) allowed for additional follow-up questions for elaboration during the interview. The initial questions were descriptive and addressed the background of interviewees, their routine and roles in relevant DTs and Net Zero innovative initiatives. Afterwards, the questions were reflective about organisational changes required for the twin transition, the role of leadership in organisations, projects and the external environment. A final measure of limiting social desirability bias in data collection (apart from clear sampling criteria and indirect questioning) was using two

debriefing sessions (Bergen and Labonté, 2020) in focus groups explained later.

2.2.2. Archival data

Due to the sampling strategy followed above, all interviewees selected to participate in the research were involved hands-on in relevant use cases of small-scale (e.g. neighbourhood energy update, housing thermal renovations) and large-scale projects (e.g. HS2, Thames Tideway, East West Rail) contributing to the twin transition. Their involvement was through different use cases of DTs and Net Zero that exemplified their familiarity and suitability for this study. Therefore, to increase the rigour of the research, contextualise it (Creswell, 1994) and achieve true and near code saturation (Squire et al., 2024), secondary data was collected about the use cases the interviewees were involved to enable 'thick descriptions' (Geertz, 1994). The archival data were first used to cross-check the expertise of the interviewees, inform and validate the sampling strategy and second to validate findings, since these sources told a consistent story and gave confidence to the conclusions.

Where publicly available, documentation from these use cases and the firms involved was used to triangulate the data provided by the interviewees by providing context and factual cross-checks for the interview insights. Whereas, detailed information about the exact projects they were involved cannot be disclosed so as not to breech the interviewee's confidentiality, the list below gives an overview of the archival data that were reviewed so as to contextualise the interviews, ensure the familiarity of the interviewees with the research, reducing impression management (Eisenhardt and Graebner, 2007) and triangulate the research findings. This secondary and archival data were analysed with qualitative content analysis and were used to triangulate the quotations used in the research. Where, quotations could not be verified from the archival data below, they were excluded from the analysis. Alternatively, the archival data was integrated with the quotations to contextualise the phenomena. In total, the following secondary data was collected and inspected from public and other sources:

- 31 webpages of interviewees' organisations;
- 10 webpages of interviewees' projects;
- 7 relevant public presentations on YouTube;
- 18 privately shared documents (videos, reports and presentation slides).

2.3. Data analysis

The transcripts from the interviews and archival documents were analysed through abductive thematic analysis (Miles and Huberman, 1994). The study used both deductive and inductive coding, consistent with qualitative abductive content analysis (Thompson, 2022). Inspired by Thompson (2022), the next eight steps of abductive qualitative analysis were adapted for this study and followed:

- Step 1: Transcription and familiarisation – reading and transcribing interviews and archival data;
- Step 2: Coding – analysing all interviews and archival data through first cycle of coding;
- Step 3: Codebook – setting definitions of codes through examples;
- Step 4: Theme development – grouping the codes through second cycle of coding;
- Step 5: Theorising – identifying relation between the themes of the deductive codes;
- Step 6: Comparison of datasets – comparing through quantification of codes;
- Step 7: Data display – connecting data through thematic network analysis;
- Step 8: Writing-up of themes – denoting relations between theory and contextualised data.

After the interview and archival data transcription (Step 1), first, for the first cycle of coding (Step 2), we applied inductive codes (data-based) derived from repetitive concepts emerging during the interviews and archival data, such as 'learning,' 'collaboration,' 'top management support,' 'commitment to twin transition' and so forth. The coding took place in the atlas. ti Qualitative Data Analysis (QDA) software. This process involved identifying routines as the lowest denominator in the data, allowing us to capture the fundamental patterns and practices within the organisations and projects studied. The inductive codes were mainly *in vivo* codes, based on words or phrases taken directly from data (Saldanā, 2009) e.g., that presented personal and unique quotations of interviewees on their views. This data was structured in the codebook (Step 3). The focus of the inductive coding was to elicit information about the relationship between ACAP and the twin transition.

Next, as there is not a definitive manner to rigorously analyse qualitative data (Robson and McCartan, 2016) the theoretical framework of ACAP was used as a sensitising concept for data analysis (Blumer, 1954). In the second cycle of coding (Step 4), constructs of the theoretical framework were used as deductive (theory-based) codes that directed the analysis of the dataset, such as the components of absorptive capacity: (a) acquisition, (b) assimilation, (c) transformation and (d) exploitation by Zahra and George (2002). In theorising from data (Step 5), the firm boundaries and project boundaries emerged and ACAP components such as knowledge assimilation and knowledge transformation related to both firm and project levels. Next, a quantification consistency check was done to compare the data across the interview sample (Step 6, see Appendix 1, right column). This check confirmed a well-balanced distribution of codes in our data that increased the validity and reliability of the process. Fig. 2 shows the coding scheme (Step 7) and the analysis write up (Step 8) is shown in the fourth section.

2.4. Research validation

For increasing research rigour (Eisenhardt and Graebner, 2007), research validation methods were deployed to help overcome the shortcomings of mono-method studies (Sarantakos, 2005). There are different types of research validation, such as internal validity (whether data analysis was accurate, involving research subjects) and external validity (involving new subjects external to the research) (Boudreau et al., 2001). Here we focused on hybrid internal and external validation to grasp the reflections of interviewees on the research results and additionally involved four new participants to facilitate the focus groups.

Validation was first supported through triangulation of multiple and different sources and investigators to corroborate evidence and shed light on the themes derived from the research (Miles and Huberman, 1994). In addition, member checking validation was undertaken (Miles and Huberman, 1994). The author team solicited 11 research participants' views on the credibility of the findings and interpretations by taking data, analyses, and interpretations back to the participants so they could judge the accuracy and credibility of the account.

The focus group attracted 11 of the original interviewee participants (Int-4,7,8,9,11,15,17,20,26,32,48) in a representative sample across industry roles. In total, there were 15 participants; as four researchers (Researcher-1,2,3,4) not previously involved in this study were invited to the focus group to increase external research relevance, protect against researcher bias, and facilitate the discussions. According to (Wutich et al., 2024), this sample size can ensure both data accuracy and interpretative validity of themes.

The focus group was conducted online in June 2023 and it was deemed more efficient for time management to break it into two representative groups where participants could have more time to reflect and voice their ideas. The composition of the two groups was balanced and they were formed by interviewees with comparable backgrounds and helped to reach saturation as repetitive ideas emerged. Because of this balanced distribution of experts among the two focus

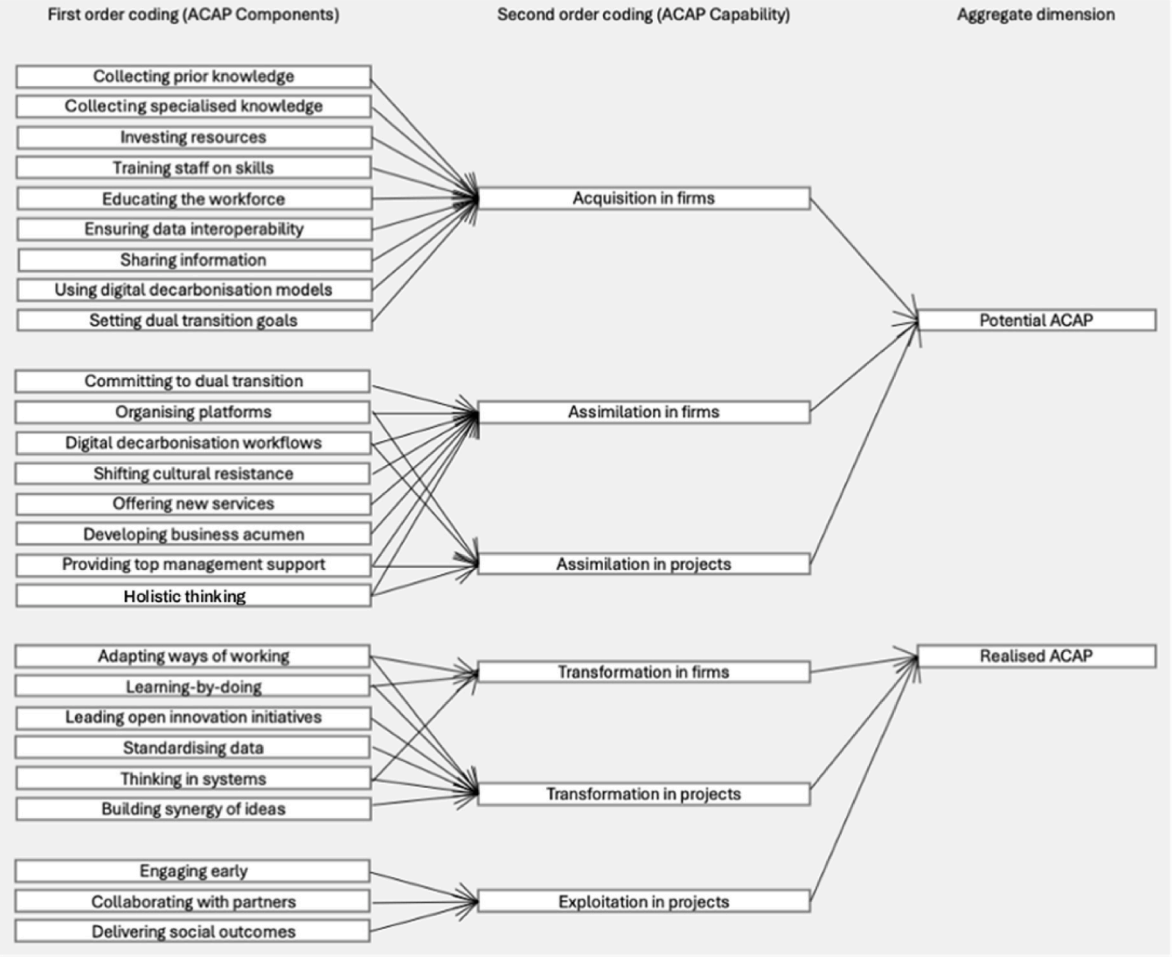

Fig. 2. Coding scheme of the data on absorptive capacity of organisations in leveraging the twin transition.

groups, there were no detrimental to research rigor to the focus groups dynamics.

The focus group was facilitated using an online whiteboard tool (Google Jamboards) and consisted of two phases: a 'presentation' phase, where the preliminary research findings were shared and, 'co-creation' phase, where participants were asked to reflect on how to support construction firms' and projects' ACAP in leveraging the twin transition by adopting DTs for reaching Net Zero. The discussions were structured around the four areas of technology, industry-level, project-level and firm-level and the aim to capture both the internal and external environment of firms' ACAP in pursuing the twin transition.

Finally, sensitivity analysis was undertaken to assess the robustness of the interpretive themes. We examined whether findings were sensitive to alternative analytical framings (in line with abductive reasoning, see Thompson (2022)), researcher perspectives, and contextual variation. Interpretations were challenged through abductive re-analysis, peer discussion (focus group), and participant reflection. While the expression of themes varied across contexts, the core experiential patterns and inferred relationships remained stable, indicating interpretive robustness.

3. Results

The data revealed distinct patterns of ACAP emerging in different loci. Specifically, it was shown that mostly acquisition and assimilation (potential ACAP) was taking place inside the organisational boundaries of firms as opposed to transformation and exploitation (realised ACAP) taking place in projects. This difference can be explained based on how the firm boundaries and the project boundaries in the construction sector relate. Table 2 contains examples of how the data was coded in the four dimensions of ACAP at corresponding firm or project level. The data will be presented next per each of the four ACAP dimensions, their associated routines and the quotations mentioned in *italicised* text.

3.1. Potential ACAP

3.1.1. Phase 1: acquisition of knowledge at firm boundary

According to Zahra and George (2002, p. 189), acquisition is a firm's *"capability to identify and acquire externally generated knowledge that is critical to its operations"*. The data analysis showed that acquisition of knowledge capability was displayed only at firm-level. Furthermore, this capability was related to both *collecting prior knowledge* and new *specialised knowledge* by *investing resources* to new systems and training. As Int-45 stated, to *"produce something [digital twin] which is faithful to the original, it does require a huge up-front investment [at firm level] to create something that is going to be faithful to a complex original."*

Equally, investment was required for *training staff on skills* according to many interviewees: *"So, there should be a lot of training and also skills that need to be introduced in the companies"* (Int-27). However, as Int-11 explained: *"because of the way we are trained on the job and in academia as well, we tend only to be reactive and learn from lessons and past experiences"* that shows that acquiring new knowledge goes beyond making investment in new systems and training people. At a more profound level, it concerns *educating the workforce*: *"I think educating people [in companies] around the power of Digital Twins, rather than just thinking it's a flashy 3D model- Actually, what it's actually designed to do will probably accelerate the*

Table 2
Dimensions of Absorptive Capacity (ACAP), corresponding level and example routines and quotations.

ACAP Dimension		ACAP level	Example of routines (see Fig. 1 for full list)	Representative quotes
Potential ACAP	Acquisition	Firm	•Collecting prior knowledge •Collecting specialised knowledge •Educating the workforce •Training staff on skills	"We need to make sure that actually, we're [at the firm level] using the people who have been educated in a time of digital effectively. (…) And that there is a real drive to be digital by default. But there is the support to allow those people who may not be digital natives to have the skills that they need to be able to use digital technologies." – Int-8 (routine: Collecting specialised knowledge)
	Assimilation	Firm	•Providing top management support •Setting digital decarbonisation workflows	"The first thing that you absolutely need is, obviously, top-level buy-in. If the company owners or investors or shareholders or directors [at the firm level] aren't bought into it then it's very, very, difficult to design a digital twin for sustainable processes because a digital twin for sustainable processes is most likely very interlinked across the whole business or across the whole ecosystem that you're looking at in that particular case." – Int-37 (routine: Providing top management support)
		Project	•Thinking strategically •Organising data platforms	"So, bring together specifically the BIM office and the project management office into a single information management office [at the project level], so that I don't get this divergence of [views 0:12:03] from the engineering [team to] the project management team [to] the current status of the project. (…) It might be a spread sheet of information, it might be a CAD model, it might be an asset [database 0:17:28]. There's a whole load of things that come together." – Int-9 (routine: Organising data platforms)
Realised ACAP	Transformation	Firm	•Working in adaptive ways •Learning by doing	"The other thing is having a very agile, light approach, to deal with the implementation of new technologies. The testing, the design testing, and appointment of new technologies. And having appetite for that as well, having appetite to use new technologies and fully integrate them [at the firm level]. I think those are the two key things." – Int-24 (routine: Working in adaptive ways)
		Project	•Leading open innovation initiatives •Standardising data Holistic thinking	"I think just to add, the delivery of Net Zero [at the project level] and, kind of, by implication, environmental protection and so on, is really, really complicated. And the more tools we can have in order to understand, "If we make this decision in this place, in this way, what happens?" and Digital Twins can give us that, kind of, insight. That's absolutely crucial to the delivery of Net Zero because it's really, really hard, and Digital Twins give us that understanding of how this really complicated system interrelates with each other." –

(continued on next page)

Table 2 (*continued*)

ACAP Dimension	ACAP level	Example of routines (see Fig. 1 for full list)	Representative quotes
Exploitation	Project	•Engaging early •Collaborating with partners •Delivering social outcomes	Int-35 (routine: Holistic thinking) "We need to be looking at the environmental and the social outcomes of those projects, in a very real way, rather than an afterthought add-on. Because actually, if we don't do that, the financial outcomes aren't going to come longer term [at the project level]. (…). So, how does that work with Digital Twins? Because Digital Twins are so good at looking at how things work, and what those consequences are. Once you've done that click from actually, I need to be thinking about the environmental social outcomes, and I need to be looking at the outcomes rather than just the next step of what I'm doing." – Int-8 (routine: Delivering social outcomes)

industry, moving forward, to a Net Zero goal" (Int-50). Similarly, Int-8 added:

> "Because most people in those very senior roles [in companies] will have been educated at a time when these technologies didn't exist. So, we, and I include myself in there, we need to catch up, we need to make sure we know what's happening."

Other important routines include *ensuring data interoperability* and *sharing information* routines in the twin transition. As Int-35 explained: *"I think it probably is in other companies as well, but that is quite a paradigm shift I think, from thinking about the assets as king and now thinking about the data as equally important."* Int-9 explained: *"there needs to be a much stronger link between the organisational information needs and the way the project manages information, so that what is given back to the organisation when it moves into operation is consistent with the information strategy for the organisation, not just the project."*. This position of organisations in recognising the power of data in information sharing using digital decarbonisation models and setting twin transition goals is an important step towards setting twin transition goals because *"there needs to be a greater understanding around how Digital Twins and digital technologies can address some of the challenges around sustainability"* (Int-40). Int-36 added on this point:

> "There needs to be a change in the culture of the organisation so that they actually value the data about their assets, for example, as much as the assets themselves so that you can actually have a credible and meaningful digital twin emerge that you can then leverage to undertake the use cases that will help you with your Net Zero goals."

3.1.2. Phase 2: assimilation of knowledge at firm boundary

At a firm level, assimilation of knowledge is another capability, and includes the firm's routines and processes to analyse, process, interpret, understand and eventually comprehend and internalise in their own unique manner the knowledge acquired from external sources (Zahra and George, 2002). However, our findings show that knowledge assimilation also occurs at the project boundaries.

Concerning the acquisition of knowledge on the twin transition at the boundaries of the firm, education plays an important role but to successfully assimilate it, *committing to twin transition* is needed, as Int-5 shared: *"I think there is a re-education, we need to go back to school."* Several interviewees emphasised on *shifting cultural resistance* needed for the twin transition withing the boundaries of organisations. Int-13 explained that: *"there's an element of needing to flatten the business, at times, to help drive those ambitions forward because good ideas come from everywhere in the organisation."*

To effectively internalise the new knowledge for the twin transition, *strategic thinking* was deemed crucial*: "the main change that's needed at the strategic level is that the organisation needs to have a clear set of objectives, a strategy and plans for building its digital capability across the board"* (Int-32). Equally, according to Int-50 *"you need to have a digital transformation strategy in place at any organisation. You need to move forward with the times and use technology, harness technology, to be able to* support *you in achieving Net Zero carbon"*. Similarly, Int-12 stressed that *"the use of Digital Twins, helps, from the strategic point of view, a lot to flatten the hierarchy inside the organisation."* Another important routine on this topic is *providing top management* support for change initiatives as construction *"is an industry that can only be changed when owners [in companies] want to change"* (Int-42). Similarly, Int-29 added:

> "And then, so, yes, I would say we've got a good basis from the top leadership down [the firm], on what we're doing. So, it's now on everybody's mind. The mindset is that, that we've got to do something, and do it now. And the Digital Twin is, just as I said before, a tool to helping us achieve and monitor, going forward."

3.1.3. Assimilation of knowledge at project boundary

At project level, for the successful interpretation of the newly acquired knowledge *setting digital decarbonisation workflows* are crucial: *"in terms of project delivery, this is (…) about making sure that you've got the right skills within the team to understand what's required and to manage this from really the design and the pre-procurement phases onwards"* (Int-32). And as the boundaries within organisations flatten, they also need to become better defined between organisations and consider how construction firms are *organising platform solutions*. According to Int-10, *"what has changed, with using a digital twin, is that there are a multitude of different companies [involved in the project], some really big and some much smaller, and they offer bits of service. The key is how they all plug into one another."*

3.2. Realised ACAP

3.2.1. Phase 3: transformation of knowledge between firm and project boundaries

At firm level, transformation of knowledge is the firm's capability to develop and update routines that focus on combining prior existing knowledge and newly acquired and assimilated knowledge from the previous steps (Zahra and George, 2002). Eventually, in knowledge transformation, firms are able to synthesise prior and newly assimilated

knowledge in order to remodify it in a different manner and facilitate the generation of new insights. The importance of routines of *adapting ways of working* was stressed for transforming knowledge. Specifically, Int-24 explained that *"a more agile (…) management approach [in companies], trying to be lean, especially when dealing with legacy. So, we need to have better business intelligence to inform delivery"*.

At a project level, peer-learning, holistic thinking, sharing learning experiences bundled as *learning-by-doing* routines across the supply chain was also deemed important in knowledge transformation as Int-29 shared: *"obviously, it's our [project] supply chain, and it's our end-users as well. So, we're trying to help them in their journey as well."* Push and pull innovation were also found important in knowledge transformation. For instance, *leading open innovation initiatives* brought transformative routines as Int-18 shared: *"open source is our remit, we try and make everything we learn available to anybody who wants it."* The tensions of push and pull innovation also emerged: *"it has to be a balance of policymakers, just like what we did with BIM, mandating specific objectives and specific requirements. And equally, the pull from communities, from supply chain, from people who are advocates and are quite keen about this to really make it happen"* (Int-28). As Int-29 added on the need of *standardisation* routines:

> "… creating standardised systems that can be used to train other people to use digital twin technology [in the project], and really, I think the standardisation of process within the construction industry is really critical".

Another key routine for the transformation of knowledge in twin transition was holistic *thinking*. As Int-41 pointed out: *"the reason you need other organisations, outside of your organisation, is to bring people together to make systemic decisions [in projects]."* Likewise, Int-39 shared: *"if you're modelling the water industry you also need to have access to the model of the energy industry because the water industry uses electricity to pump water around so there is an impact on the energy grid from the water companies pumping water about."* Recognising the importance of *holistic thinking* was a first steps towards *building synergy of ideas* and remodifying the assimilated knowledge: "*there's a whole variety of skills which are needed to put together all the multiple perspectives in order to take this digital building project lifecycle view"* (Int-42). As Int-22 shared:

> "… in terms of strategic changes, I guess we were already doing that briefing out. We were approaching companies that were doing that and getting them to engage with our [project] partners, because we could see the change coming."

3.2.2. Phase 4: exploitation of knowledge at project boundary

Exploitation of knowledge follows the transformation of knowledge. It is the capability to apply transformed knowledge through routines that allow firms to refine, extend and leverage it for creating and bringing new goods, systems, processes, knowledge or new organisational forms to the market (Zahra and George, 2002). This capability was only displayed at a project level and related to three specific routines. First, *engaging early* was crucial in knowledge exploitation as *"there's a whole range of organisations that will be involved, even at the relatively early [project] stages, who are actually delivering different components of this or taking forward work in different areas that we then need to bring together"* (Int-32). Equally, Int-42 supported that:

> "Project delivery has to be done differently. We have to get out of design, bid, build. We have to get into more integrated project delivery, progressive design-build, ideally integrated project delivery. That's a cultural change, that is not a technical change."

Second, *collaborating with partners* was a key routine for exploiting knowledge and harvesting resources. As Int-31 explained: *"there are multiple companies involved in that [project], and you need to explain that to various stakeholders. And each of them also has a role to play in the success of the solution delivery. Because they will be providing the data."* Collaborating with the project partners eventually allows firms to use their developed competences and leverage them: *"the more we can collaborate as an industry, rather than maybe holding onto great ideas that we've developed internally, will see us get to that goal faster"* (Int-50). Beyond the project boundaries, collaboration across industries is also important as Int-53 explained: *"it's a greater awareness of what other industries are doing that we could then mirror and also collaborate and be interoperable with. So, from a gas side, we're working with electricity, but we know we need to work with water a bit more."* Equally, it was shared that fostering meaningful collaboration among partners can support the exploitation of knowledge:

> "I think that, again, leadership is incredibly important for the coordination of those different projects because this is such a huge beast trying to tackle […] the digital twin and then the use cases for Net Zero. That I don't think any one project will be able to tackle the entirety of the problem or bring forward the entire solution. So, they will need to work in concert to actually allow them to kick off, and keep you moving in the right direction." (Int-36).

Third, the articulation and focus on *delivering social outcomes* was stressed by a significant number of interviewees as the cornerstone of developing ACAP for the twin transition. This is a significant part of exploiting the newly developed knowledge: *"the leadership needs to start to articulate benefits to other things other than pounds and pence"* (Int-6). Likewise, Int-13 explained that *"at the same time, doing things like carbon tracking, monitoring any social value that might be generating as a business, and thinking about the governance that needs to change in your organisation to drive the right behaviour as part of the overall ESG [Environmental, Social & Governance] agenda really."* As Int-17 stressed the social outcomes-based approach entails productivity, health, safety, among others:

> "So, the first strategic change that's needed is in the thinking of the client, or the project sponsor, in designing an outcomes framework. So, rather than thinking of acquiring a project delivery partner at the lowest cost, first figure out what is the performance or the outcomes that you're looking for. So, (…) upfront, try to take an outcomes-based approach. Is decarbonisation one of your outcomes that you're looking for? Is occupant productivity, health, safety, one of the outcomes? Is social value one of the outcomes? So, create an outcomes-based framework specific to the project and asset that you have in hand."

3.3. Research validation through focus group

During the 'presentation' part of the focus groups where the preliminary research findings were shared, the discussions revolved mainly around holistic thinking and how the nature of the twin transition requires a holistic view developing ACAP. No further codes emerged during this stage but solidified the existing codes.

The participants prioritised the routines (see Fig. 2) and created a roadmap to support construction firms' and projects' ACAP in leveraging the twin transition by adopting DTs for meeting Net Zero. The data analysis revealed that assimilation routines (12 quotations), such as *'shifting cultural resistance'* and *'thinking strategically'* along with transformation routines (8 quotations) such as *'holistic thinking* and *'standardising data'* were regarded as highly influential for raising the ACAP of construction firms. These ACAP dimensions were related to both firms and project levels as well as the realised and potential ACAP and highlighted the importance of managing the interfaces between firm and project boundaries. Additionally, and to a lesser extend the exploitation routines (7 quotations) such as *'collaborating with partners'* and *'delivering social outcomes'* were discussed vividly in enhancing ACAP. This was followed by acquisition routines (5 quotations) on training and investment that were considered basic building blocks in supporting the twin

transition.

4. Discussion

Responding to our research question, the findings demonstrate that the potential and realised ACAP take place in different loci. By organising our findings into four distinct phases, we show first that, the *potential ACAP* takes place predominantly at firm boundaries that acquire knowledge through various routines of investing resources, skills training, educating the workforce and setting twin transition goals among others (Table 2). In Phase 2, the firms, and to a lesser extend the projects, assimilate knowledge through routines of commitment to twin transition, shifting cultural resistance, top management support and strategic thinking, among others.

Contrary, in Phase 3, the *realised ACAP* takes place primarily in project boundaries that become the milieu for transforming knowledge through routines of adaptive approaches, open innovation, learning-by-doing and holistic thinking. In this context, holistic thinking routines become central by expanding project management beyond execution discipline to a learning, adaptive and context-sensitive practice, departing for the reductionist approach towards a holistic and interdependent view. Lastly in Phase 4, this newly transformed knowledge is exploited only at project-level through early engagement, collaboration with project partners and harvesting social outcomes. This knowledge is then re-acquired and internalised by the firm level after project end.

This study answers the research question by developing a theoretical process model - consisting of four phases - of how firms in construction develop absorptive capacity for the twin (digital and green) transition through digital twins for Net Zero. The process model comprises four theoretical propositions that manifest throughout the lifecycle of ACAP in construction firms and projects. These are illustrated in Fig. 3 and constitute mechanisms for enabling construction firms develop ACAP for the twin (digital and green) transition through digital twins for Net Zero.

- **P1**: Firms acquire knowledge through structured routines and strategic initiatives such as workforce training, driven by top management. This knowledge is assimilated by overcoming cultural resistance and embedding strategic thinking aligned with twin transition goals.
- **P2**: In inter-organisational projects, firms apply their internally assimilated knowledge, engaging with co-makers who bring their own knowledge bases. This interaction facilitates knowledge comparison, synthesis, and spillover effects.
- **P3**: Acquired knowledge is transformed into action using adaptive approaches and learning-by-doing in the boundaries of projects At the project boundaries, knowledge is integrated across project phases during engagement with the supply chain, and collaboration with partners to achieve practical results. This process ensures that knowledge is contextually relevant and effectively exploited to drive the success of the twin transition.
- **P4**: After project handover, the projects are disbanded yet each firm (engaged in the disbanded project) carries new knowledge back that can be evaluated strategically. Post-project reviews support cross-project learning and subsequent knowledge spill-over effects.

4.1. Theoretical contributions

This study makes several contributions. First, this study advances understanding of the twin (digital and green) transition in construction by examining how digital transformation is being repurposed to support sustainability objectives. While prior research has extensively explored digital transformation in the built environment (Papadonikolaki et al., 2022; Whyte and Hartmann, 2017), and how a digital organisational culture can enhance the firm's ability to acquire, assimilate, and utilise external knowledge and resources, thereby improving its absorptive capacity (Rodríguez-González et al., 2023), this study focused on the repurposing of digital transformation for reaching sustainability objectives (Fathalizadeh et al., 2021; Sepasgozar, 2021), in this case of meeting the Net Zero vision, supporting green innovation. In doing so, it offers a novel perspective on the interdependence between digital and environmental goals, which are often treated separately in existing literature. By investigating how construction firms and their projects integrate digital tools, such as digital twins, not just for efficiency, but

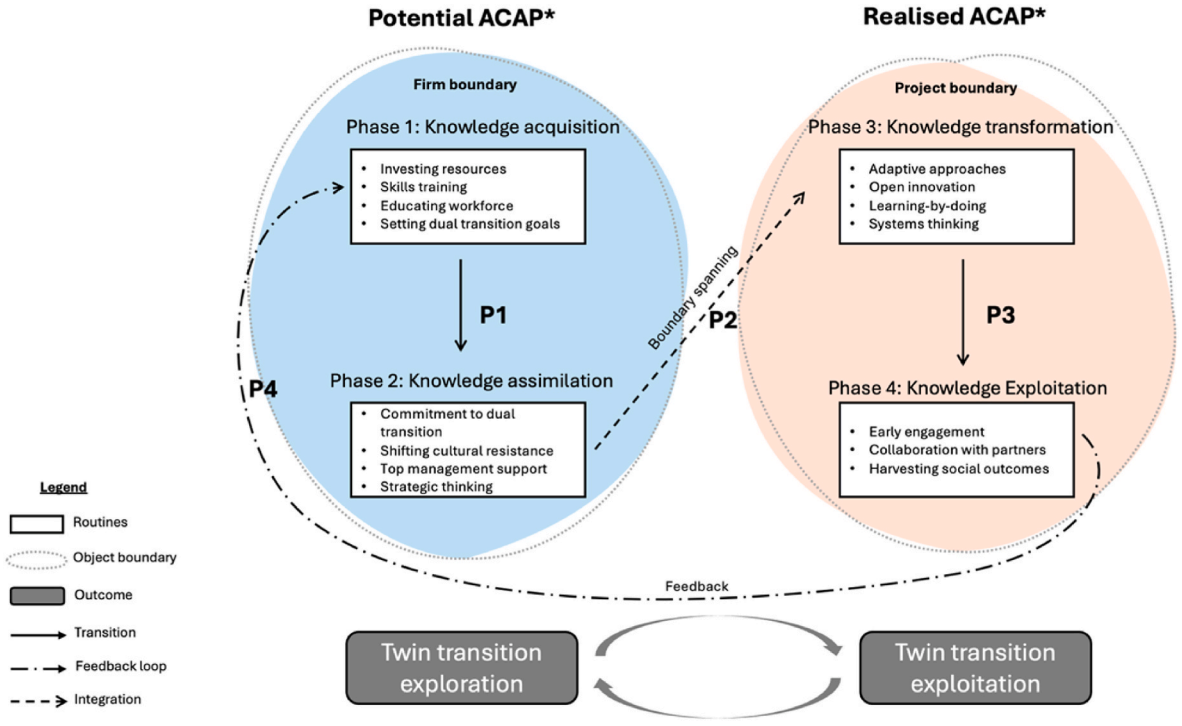

Fig. 3. Process model of ACAP development for leveraging twin transition in construction firms (*ACAP: Absorptive Capacity).

also for climate-related outcomes, this study deepens our understanding of how absorptive capacity supports the strategic alignment of digital and green innovation. Furthermore, it highlights the potential for such transitions to enhance boundary-spanning capacity and project-to-project learning, which are critical for sustainable transformation in project-based settings.

Second, the study has provided a rich empirical context that applied the ACAP model by Zahra and George (2002) to firms' dynamic capabilities where they develop routines for the acquisition, assimilation, transformation and exploitation of external knowledge, and re-acquisition, which is important in project-based settings. This study elaborated more routines to show how this model can be used to understand the organisational change management required in the twin transition. In doing this, the study focused on the impact of human and social capital aspect of ACAP theory that related to people organised in projects, their learning and their competences as opposed to ACAP related solely to firm performance (Keller, 1996; Kim, 1998; Mangematin and Nesta, 1999). This perspective reveals the micro-foundations of change in organisations.

Third, this study offered an extended perspective on ACAP and capabilities in construction organisations by examining the loci of ACAP and revealing the tensions between potential and realised ACAP within 'permanent' firms and 'temporary' projects. ACAP forms a bridge between the firm's external environmental and its innovation activities (Cohen and Levinthal, 1990; Miao et al., 2021; S. Singh et al., 2020). Table 2 and Fig. 2 showed that the potential ACAP takes place primarily in firms, since acquisition is only at a firm-level and assimilation at both firm- and project-level, and that the realised ACAP emerges primarily in projects, as transformation is on both firm- and project-level and exploitation only on project-level.

The findings extend Killen et al. (2012) findings that in project-intensive settings while ACAP relates to organisational change, the ability to acquire and assimilate new knowledge was more easily achieved than the ability to transform and exploit this knowledge and further specify that the exploitations takes place in projects. After all, despite being seemingly temporal, projects have similar learning mechanisms as organisations (Brookes et al., 2017). Such construction firms are typically service providing firms whose primary business mechanism is projects (Lindkvist, 2004) and as service firms respond to external stressors and are acquiring and internalising external knowledge. However, the transformation or remodification and exploitation of this knowledge primarily takes place in projects that are typically delivered through projects (Hobday, 1998; Sydow et al., 2004) since these multi-firm consortia are the only way to deliver projects in construction by implementing inter-organisationally acquired knowledge. This suggests some hybridisation of ACAP in project-based settings. Although there are a lot of arguments on the illusion of temporality of projects (Brookes et al., 2017; Engwall, 2003), this study showed that firms and projects synthesise a mutually-reinforcing spectrum of ACAP where knowledge is acquired, assimilated, transformed, exploited and re-acquired.

The data showed that prior knowledge is collected from project experiences, which implies a cyclical link between firms and projects. Prior research has focused primarily on how new knowledge is acquired by delivering innovative (to the business) projects (Davies and Brady, 2016; Lobo and Whyte, 2017) but this study shows also the opposite mechanism of new knowledge acquired and assimilated in firms and exploited in projects. This resonates with studies highlighting the need of project-based organisations to develop the ability to recognise new knowledge and assimilate it for competitive advantage (Bakker et al., 2011). Moreover, because the study focus was on the firm-boundary and the project-boundary emerged during data analysis, it shows a more pragmatic and holistic approach in conceptualising ACAP in construction, as it is not only present in project networks and alliances as seen in past studies (Love et al., 2016, 2024) but also at firm-boundary. Also, while strong social processes have a positive mediating relation between ACAP and project performance (A. Singh et al., 2023), there is less information on the social processes that support knowledge and human capital in projects and this study address this shortcoming by revealing specific potential and realised ACAP needed for green innovation in projects and by projects.

A final theoretical contribution is made in illuminating how routines are critical in driving strategic change in construction organisations and the sector (Rodríguez-González et al., 2023; Krystallis et al., 2023). The data presented here show how routines are developed and changed in response to the new ways of working demanded by the twin transition. By attending to routines, the micro-foundations of dynamic capabilities such as ACAP are revealed. This aligns with the practice perspective of organisational routines, where the situated actions of individuals in their performances of organisational routines (Feldman and Pentland, 2003). By viewing routines in this way, they show how processes of change occurring at micro levels and are thus sources of generative change involving multiple actors (Feldman, 2000; Feldman and Pentland, 2003).

4.2. Implications for practice

Our study has practical implications for construction firms, project managers, and clients seeking to develop absorptive capacity (ACAP) for the twin transition through digital twins for Net Zero. Rather than treating ACAP as a static organisational capability, the findings demonstrate that it develops through a four-phase process that unfolds across firm and project boundaries. Hence, managerial attention should shift from isolated digital initiatives towards supporting progression across the acquisition, assimilation, transformation, and exploitation phases of ACAP.

In *Phase 1 – Acquisition (firm level),* our findings showed strong evidence that managers should prioritise investment in workforce education, skills development, and knowledge infrastructure to support the acquisition of externally generated knowledge. Another important insight was the role of senior leadership in this phase. Senior leadership commitment is critical to legitimise investment and establish clear twin transition goals. In *Phase 2 – Assimilation (firm and project levels)*, to support assimilation, managers should focus on embedding strategic thinking, providing top management support, and addressing cultural resistance. Specifically, at the project level, aligning digital workflows and information management practices helps internalise newly acquired knowledge. *In Phase 3 – Transformation (project level)*, project managers should enable adaptive approaches, learning-by-doing, and holistic thinking to transform knowledge into contextually relevant practices. Our findings indicated that collaboration across the supply chain and openness to innovation are particularly important at this phase. Lastly, in *Phase 4 – Exploitation (project level with firm-level feedback)*, managers should support early engagement and collaboration with project partners to exploit transformed knowledge and deliver environmental and social outcomes. Following project completion, firms should deliberately re-acquire and evaluate project-level learning through post-project reviews to inform future initiatives.

Firms are encouraged to develop the routines and practices internally identified in this study that will encourage and support potential and realised ACAP. For instance, the organisational commitment to the twin transition goals (potential ACAP) is further articulated in adaptive approaches and systems thinking in projects (realised ACAP). Likewise, during inter-organisational collaboration with partners during projects, a safe space for knowledge exploitation is created (realised ACAP) that can subsequently feedback into new intra-organisational learning practices (potential ACAP). This cyclical process is crucial in taking full advantage of ACAP in practical settings. These newly-developed routines need the full support from leadership and to be embedded in wider functions, such as HR routines, project debriefs, marketing and so on, to be accessible to the firm (Morgan, 2019). Such routines institutionalise ACAP learnings and will help increase the likelihood of 'potential ACAP'

learning on projects becoming 'realised ACAP' that is institutionalised in the firm.

4.3. Boundary conditions and future research

All studies come with some inherent limitations. Qualitative methods may include biases such as impression management or retrospective sensemaking (Eisenhardt and Graebner, 2007) and social desirability bias that was managed through clear sampling criteria, indirect questioning and debriefing (Bergen and Labonté, 2020; R. J. Fisher, 1993; Nederhof, 1985). Additionally, to reduce researcher bias, the focus group ensured congruence between data obtained and researchers' interpretation of the phenomenon. In the future, to further reduce bias even more, a longitudinal case study would be a good approach to follow up and elaborate more on the findings. Since the focus of the study has been on the human and social capital view of ACAP, large-scale quantitative studies will not necessarily add much towards theory validation, since their operationalisation is at a higher level and not on micro-foundations like this study. Future research could additionally investigate whether ACAP is sufficient as a lens for understanding firm adaptation, and how/if ACAP can be enriched by other dynamic capabilities following Teece (2007) and Eisenhardt and Martin (2000) idea of dynamic capabilities as best practices.

5. Conclusion

This research highlighted the pivotal role of ACAP in facilitating construction firms' move to the digital and green transition. By examining the loci of ACAP, this study demonstrated that potential ACAP - characterised by knowledge acquisition and assimilation - occurs primarily within firm boundaries, while realised ACAP - involving knowledge transformation and exploitation - manifests within project settings. Specifically, our study demonstrated that first, the potential ACAP takes place primarily at firm level that acquire knowledge through the routines of investing resources, skills training, educating the workforce and setting twin transition goals among others (see Table 2). Second, mainly the firms assimilate that knowledge through routines such as committing to twin transition, shedding cultural resistance, providing top management support and strategic thinking. Third, the realised ACAP takes place predominantly in projects that transform the internalised knowledge through routines of adaptive approaches, open innovation, learning-by-doing and holistic thinking. Fourth, this transformed knowledge is exploited only at project-level through early engagement and collaboration with supply chain partners to harvest social outcomes.

This twin manifestation underscores the hybrid nature of ACAP across firms and projects – something unique in construction sector –, contributing to a nuanced understanding of ACAP in project-based environments. By putting forward four propositions constituting clear strategies and mechanisms for lifecycle ACAP development and exploitation for leveraging the twin digital and green transition in construction is revealed (see Fig. 2). The study also emphasised the significance of strategy, leadership and collaboration in fostering an organisational culture conducive to continuous learning and innovation. For construction firms, enhancing ACAP extends beyond technological adoption; it involves strategically leveraging these capabilities to drive sustainable and digital transformations through project delivery. These insights are crucial for policymakers and industry leaders aiming to enhance the resilience and competitiveness of the construction sector in an evolving environmental and technological landscape.

CRediT authorship contribution statement

Eleni Papadonikolaki: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Ilias Krystallis:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Bethan Morgan:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Royal Academy of Engineering (RAEng) Leverhulme Trust Research Fellowship scheme 2022-2023 in the United Kingdom (UK) (6642415).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.147859.

Data availability

The data that has been used is confidential.

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