Shaping the dual transition: Stakeholder dynamics in digital twin-using net-zero projects

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ABSTRACT

Digital Twins are becoming increasingly important in Net Zero projects, fostering a dual sustainability and digitalisation transition. Project stakeholders are key in this dual transition as they interact and co-create within the socio-technical system. Stakeholder dynamics are especially critical in construction sector, a major contributor to global carbon emissions. This study uses a multi-method approach to examine how stakeholder dynamics emerge to enable joint digitalisation and decarbonisation efforts. The study moves beyond stakeholder analysis and integrates theories from the multi-level perspective of transitions. The findings highlight the prominent role of key stakeholders such as clients/owners, government and regulators in supporting the dual transition through competitive, hybridised and symbiotic dynamics with variable disruption potential. Theoretically, the study bridges project and transitions studies by illustrating how digital twins can be strategically deployed to drive decarbonisation and support sustainability by projects. Apart from deepening the understanding of stakeholder dynamics in the dual transition the study also provides actionable insights for practitioners and policymakers in navigating emerging stakeholder constellations to enable socio-technical system change.

1. Introduction

Countries such as the United Kingdom (UK) legislate for Net Zero (henceforth: net-zero), targeting 2050 net-zero carbon emissions (CCC, 2019). Net-zero describes man-made decarbonisation efforts to stop adding new climate-heating emissions to the atmosphere. This study focuses on how projects in construction – an energy-intensive sector – can deliver the net-zero vision. Construction is responsible for 43 % of global greenhouse emissions (UN, 2022, p. 62). Digitalisation through cloud computing, internet-of-things, robotics and artificial intelligence, shows the potential to monitor and, ultimately, reduce these emissions facilitating more sustainable futures. For instance, smart devices can reduce energy use in buildings around 10 % (IEA, 2017). UN (2022) emphasise that for decarbonising construction, all stakeholders should take greater responsibility in understanding the environmental impact of their decisions, which motivated this study.

As a carbon-intensive (UN, 2022; WGBC, 2019) and project-intensive industry (Morris, 2004), construction has a high degree of embeddedness (Blomquist & Packendorff, 1998) through numerous internal and external stakeholders. Additionally, projects play a significant role towards sustainability and achieving global net-zero carbon emissions

(Terenzi et al., 2024; Winch et al., 2023). Alongside the emergence of net-zero projects (Geels & Locatelli, 2024; Terenzi et al., 2024), a strong link between net-zero projects and digitalisation appears. Digitalisation through Digital Twins (DTs) supports decarbonisation (Tzachor et al., 2022). DTs are virtual replicas of real-world products or systems, e.g. building or infrastructure assets, using massive data to model and simulate various operational scenarios (Grieves, 2014) and support decision-makers (Leonardi & Leavell, 2024). The UK 'Gemini' principles argue that DTs improve societal outcomes and sustainable value creation through effective information management (Bolton et al., 2018).

Digital transformation is a system-wide change affecting how businesses and economies operate (Marnewick & Marnewick, 2022). Digital transformation through technologies such as DTs paves a parallel transition to the sustainability transition, creating long-term structural changes in the economy. Muench et al. (2022) argue that this simultaneous or 'twin green and digital transition' could enable carbon-neutral Europe by 2050. Heretoforth, we refer to *dual digitalisation/sustainability* transition instead of 'twin transition', so as to not confuse with 'digital twins'. This dual transition involves sustainability and digitalisation evolving simultaneously but through distinct, interdependent paths. Digitalisation can reduce overall emissions and energy use, if managed

carefully (Creutzig et al., 2022), highlighting the need aligning the front-end of dual transition.

Since construction projects are inter-organisational (Sydow & Braun, 2018), stakeholders become increasingly important and understanding their interactions is strategic for the dual transition. This study sheds light on how DT-using net-zero projects enable the dual transition strategically by focusing on stakeholder dynamics, of interactions, influences and power plays that happen between stakeholders at project front-end. We adopt the sociotechnical systems (STS) lens, focusing on the interplay of technological, economic, institutional, and cultural elements (Geels, 2011). We respond to calls for connecting transitions and project studies (Sovacool & Geels, 2021) furthering the inter-organisational perspective of projects as milieus of sociotechnical transitions (Miterev & Engwall, 2024; Papadonikolaki et al., 2023). This work is anchored on multiple-level perspective (MLP) unpacking change at a systems-level, focusing on stakeholders by exploring expert perceptions of how construction as a resource/carbon-intensive and project-based sector addresses the dual transition. It poses the research question (RQ): *How do stakeholders interact in net-zero projects' front-end deploying digital twins to shape the dual transition?*

After framing the theory around transitions and project studies' focus on agency, we then present the rationale and set-up of our multi-method approach. Next, we present the data and discuss them, alongside theoretical contributions to different theoretical points of departure, explain the practical implications and end with a concluding summary.

2. Theoretical framing

2.1. From sustainability transitions to dual (digitalisation and sustainability) transition

Projects are important for articulating and participating in grand challenges such as climate change, resource depletion and energy crisis (Winch et al., 2023) through project shaping. Whereas projects are essential for net-zero, there is little focus on projects pursuing net-zero due to insufficient emphasis on how projects relate to their institutional context (Terenzi et al., 2024). Sustainability transitions affect and are affected by practices of both 'sustainability of the project' and 'sustainability by the project' (Huemann & Silvius, 2017). Sustainability of projects has been studied intensely (Sabini et al., 2019), with less emphasis on *sustainability by projects*. Sustainability as the 'triple bottom line' (3BL) of people, planet and profit (or societal, environmental and economic sustainability) focuses less on eco-social benefits according to Elkington (2018), who developed the 3BL concept. Silvius (2017) notes that a holistic understanding of sustainability is needed by integrating the three 3BL strands and economic with eco-social perspectives. Hence, sustainability and net-zero transitions go beyond business propositions and cost-cutting, engaging several project stakeholders.

Digital technologies support sustainability efforts and enable organisations to meet sustainability objectives reaching net-zero through the *dual digitalisation/sustainability* transition (Muench et al., 2022), since digitalisation reduces energy use (IEA, 2017). Creutzig et al. (2022) warn that widespread digitalisation may result into increased electricity use, which needs to be monitored and managed via policy, underscoring the intertwined nature of the dual transition (Muench et al., 2022) necessitating proactive and integrative management. Transitions increasingly appear entangled and interweaved. Dual transitions have been studied before in political sciences, e.g., Spain's simultaneous transition to democracy and open economy (Bermeo, 1994) or simultaneous labour transition and green transition in Latin America (Durán & Balestro, 2024), requiring rigorous strategic considerations and reform.

This study focuses on a subset of dual transitions via DT-using net-zero projects. DTs were originally defined by Grieves (2014) and paved the way to cyber-physical interaction and convergence between physical and cyber worlds of production. Through their performativity, any changes in the model showcase the impact on the real-world that the model represents (Leonardi & Leavell, 2024), making them indispensable for decision-makers. DTs can update data in real time, as models undergoing continuous improvement by comparing virtual with physical assets (Tuegel et al., 2011). DTs bring together data across the lifecycle, promoting efficient synergies (Qi & Tao, 2018), enabling traceability and better control of sustainability.

The affordances of DTs include numerous applications from smart manufacturing, health, smart cities, energy, transportation, public emergency and agriculture (Papadonikolaki & Anumba, 2022), and their adoption and diffusion is continuously growing (Li et al., 2022). In construction, DTs have several applications including simulation of construction site logistics (Greif et al., 2020; Zhang et al., 2022), workforce safety (Hou et al., 2020), building performance (Terreno et al., 2020), energy efficiency (Schmidt & Åhlund, 2018), facility management/preventive maintenance (Xie et al., 2020), temporary structures monitoring, and financial management in public projects (Lynch et al., 2023). The UK Gemini Principles argue for aggregating data and activities to monitor sustainability objectives at smart-cities scale (Bolton et al., 2018), through 'Connected DTs', using a System-of-Systems view. Such DT applications range execution and operation phases of construction projects but are often disconnected and developed as post-hoc interventions after assets are set-up (Whitmore et al., 2024). The strategic integration of DTs across execution and operation supports accurate decision-making early at the asset lifecycle establishing desirable future asset behaviour for net-zero. This strategic integration requires alignment of sustainability and digitalisation transition requirements and stakeholders at the front-end, which is the focus of this study.

2.2. Stakeholder management and analysis

Stakeholders are actors who have a 'stake/interest in the project or 'can affect and be affected by' it (Littau et al., 2010). Stakeholders are central to strategic management (Freeman, 2010). In the 1990s the concept of stakeholders was extended and adjusted to projects (Xue et al., 2020). Stakeholders include not only key project members, e.g. client, contractor, consultants and suppliers, but also other project environment members, e.g. local community, regulatory authorities and government, among others (Aaltonen et al., 2008). Stakeholders are crucial for projects that become increasingly inter-organisational, societal, community-affecting and transition-inducing. Project scholars seek new ways to further study stakeholders more inclusively (Derakhshan et al., 2019). As stakeholder theory was transplanted to project management, its main goal is to enable project managers understand and manage stakeholders strategically. Stakeholders are internal or external (Freeman, 2010). Internal stakeholders are formal members of the project and usually support it (Winch, 2002), typically through a contractual relationship (Lehtinen & Aaltonen, 2020). External project stakeholders are not formally associated with it but may affect or be affected by it (Freeman, 2010).

To manage stakeholder complexity, project stakeholder management includes stakeholder analysis and interacting with stakeholders meaningfully (Eskerod & Jepsen, 2016). Stakeholder analysis includes (a) identifying project stakeholders, (b) assessing how they contribute to projects, (c) prioritising their relative power and (d) engaging (Eskerod & Huemann, 2016). These steps typically focus on managing individual stakeholders independently (Neville & Menguc, 2006) consecutively and bilaterally. However, the dyadic approach does not tell the full story and institutional views such as project stakeholder landscape model (Aaltonen & Kujala, 2016) provide a more holistic view.

There are different ways of stakeholder analysis depending on theoretical bases upon which stakeholder analysis is used and breadth of stakeholder definition (Reed et al., 2009). A well-known way to analyse stakeholders is by mapping their values, beliefs, power, cooperative potential and interests (Brugha & Varvasovszky, 2000). Understanding

their relative power or influence to their interest in the organisation or project (Brugha & Varvasovszky, 2000; Reed et al., 2009), typically represented in a matrix. Social Network Analysis (SNA) is another established tool for analysing stakeholder relationships (Mok et al., 2015; Prell et al., 2009). Such stakeholder analysis and classification approaches focusing on morphology only offer a static view and do not include their dynamic nature (Mok et al., 2015; Reed et al., 2009) that may vary over time in projects (Yang et al., 2009). Missonier and Loufrani-Fedida (2014) suggest that stakeholder decision-making is more than their network structure and relate to their evolving interactions and influences within and on the project network. Here, we consider stakeholders' dynamics not only on their network morphology but also on interactions, influences and power plays that happen among stakeholders at the front-end.

2.3. From stakeholders in projects to actors of socio-technical systems

Agency holds formative power in sociotechnical systems. Sociotechnical systems (STS) consist of techno-economic parts, institutions, socio-cultural elements and relevant actors within a wider landscape of macro influences that affect niche and regime dynamics (Geels, 2011). From a neoinstitutional and STS view, Geels (2004, 2017) provided a multiple-level perspective (MLP) for innovation as a STS where actors and institutions interact through different rules and induce transitions in the innovation landscape. This macro-level view of innovation features: (1) actors and social groups, (2) rules and institutions, (3) technologies and STS interacting dynamically (Geels, 2004). The actors and social groups embedded in the STS use the rules of the institutions to introduce new technologies, make investment decisions about technology or develop new regulations and standards using different resources (e.g. money, knowledge, tools) to realise their decisions and influence social rules (Geels et al., 2016).

The MLP in sociotechnical transitions is a well-known approach to investigate transitions in sustainability issues, e.g. energy, smart grids, green buildings (Hiteva & Watson, 2019; Nykamp, 2017; Papachristos et al., 2013; Tongur & Engwall, 2017), providing a strong support to the importance of actors (Geels et al., 2016). From interactions among actors and social groups with rules and institutions, various events can be mapped that eventually shape the transition of the innovation landscape through pathways of substitution, transformation and reconfiguration (Geels et al., 2016). Such interactions between niche and regime could be strategic alliances, intermediary projects and transformative niche events (Berry et al., 2013) where niches and regimes confront one another and learn. These pathways show important roles that project stakeholders could play in shaping STSs. Lately, projects are also conceptualised as integral parts of STS (Geels & Locatelli, 2024).

The recent research agenda of sustainability transitions recognises the profound role that multi-actor considerations play (Köhler et al., 2019). While stakeholders are not explicitly associated with that agenda, stakeholder engagement is increasingly mentioned in recent sustainability transitions narratives (Gudek et al., 2024). Mottee et al. (2024) underscore that net-zero projects require investment in system-level innovation and long term commitment that involves the values, interactions and influences of key stakeholders, aligning with recent policy advice (Muench et al., 2022; UN, 2022). The concept of stakeholder bears similarities and differences to the core pillar of MLP: actors (Geels, 2004, 2011). We argue that the difference between stakeholders and actors is not a semantic but an essential one. In transitions, actors are independent, e.g. as incumbents or new entrants, but also groups/networks/constellations of actors forming regimes exerting rules and causing system inertia and change (Geels et al., 2016; Geels & Schot, 2007). Regime actors focus on maintaining existing STSs (Raven, 2007; Smith & Raven, 2012) whereas niche actors who articulate new visions, participate in knowledge sharing processes (Schot & Geels, 2008). Sociotechnical niches develop progressively and transform existing STSs, i.e. legacy technologies, incumbent actors and core regime rules

(Geels, 2011). Simultaneously, intermediary actors perform knowledge activities to create, standardise and distribute knowledge (Kivimaa et al., 2019; Schmidt & Werle, 1998). Actors and STSs interact in different patterns in sustainability transitions, across a spectrum of competition and symbiosis with different disruption potential (Raven & Verbong, 2007; Rosenbloom, 2019) and their interactions vary from resistance to alliances.

2.4. Research gap around the front-end of dual transition projects

As the study investigates the novel phenomenon of the dual transition, following the logic from 'periphery to the core' (Dencker et al., 2023), Table 1 explains how the study contributes to the existing state-of-the-art, summarising the gaps.

Using the concepts of stakeholders and actors, we bridge projects and transitions studies by focusing on the role of projects in long-term sociotechnical transitions through an inter-organisational perspective (Miterev & Engwall, 2024). This follows previous studies highlighting the importance of the inter-organisational dimension in STS transitions (Miterev & Engwall, 2024) by untangling the dynamics among stakeholders who are leading project initiatives towards the dual transition of sustainability and digitalisation. For instance, in megaprojects, governed by innovative processes, technologies and ideas of varying actors coming together unexpectedly also act as niches challenging the regime (Papadonikolaki et al., 2023). Projects due to their innovative nature, challenge existing experiences of megaprojects incumbents acting as regimes by instead having positive action catalysing innovation and change in niche-to-regime activities (Papachristos et al., 2024; Papadonikolaki et al., 2023). Some STS actors may also be stakeholders with an acute interest/stake on project outcomes, hence being strategic. However, existing studies in project stakeholder management do not examine stakeholders' impact on large-scale STS transitions beyond project boundaries or how they interact and influence one another. Here, using MLP conceptualisations of actors and STS interactions (Raven & Verbong, 2007; Rosenbloom, 2019) we explain stakeholder dynamics in the complex phenomenon of dual transition.

Projecting for the dual transition to net-zero through DTs constitutes an STS inside which projects deliver transitions as vessels of innovation and change, e.g., exploratory, deployment incremental, reorientation or decommissioning projects (Geels & Locatelli, 2024). In STSs, the interacting societal and technical elements are equally important (Geels, 2004). As temporary organisations mobilising people and resources to build or modify specific artefacts (Winch, 2022), projects rely on numerous stakeholders who can affect and be affected by project outcomes. Equally, STS transitions address grand challenges through the dominant human and social capital view of MLP. This link of project

Table 1

Summary of state-of-the-art and paper contributions.

Category	State-of-the-art	Contribution
Phenomenon	Existing work focuses on sustainability by projects (Huemann & Silvius, 2017; Sabini et al., 2019) or net-zero transition and projects (Terenzi et al., 2024)	Focusing on complex and intertwined dual (digitalisation and sustainability) transition (twin transition)
Theory	Project stakeholder theory is increasingly expanded from static to include dynamic and holistic of stakeholder landscape (Aaltonen & Kujala, 2016; Aaltonen et al., 2015)	Adding evidence on how the interactions, influence, interplay and power relations of stakeholders contribute to their stance
Domain	There is little research on positioning projects as integral parts of STS, (Geels & Locatelli, 2024; Papachristos et al., 2013; Terenzi et al., 2024)	Enabling cross-domain exchange from transitions to projects through stakeholders

studies and STSs suggests that stakeholders and actors respectively are key in the dual transition. We focus on the front-end of projecting (Winch & Sergeeva, 2022) in dual transition and particularly stakeholder dynamics of interactions, influence and power plays. Stakeholders are formative not only in systemic technology deployment but also in addressing environmental and social sustainability requirements.

3. Methodology

3.1. Rationale, research stages and context

As this study poses a 'how' RQ, multi-methods and data types were deployed to enhance research accuracy (Creswell, 1994) by combining them. Gorard and Taylor (2004) challenged monothematic research methods and argued for synthesising findings through triangulation. The RQ was addressed by synthesising data collection and analysis methods from three stages inducing communicative validity (Sarantakos, 2005) by involving participants to check data accuracy and enrich interpretations. The study features participatory research, where the two spheres of action – science and practice – meet, interact and develop an understanding for each other (Bergold & Thomas, 2012). In participatory research, the emphasis is "bottom-up" as opposed to conventional research methods (Cornwall & Jewkes, 1995). The value of it lies in including research participants as research partners of knowledge production with mutual benefits (Bergold & Thomas, 2012). Participatory research benefits by enhanced practical relevance and improved data quality since industry experts co-created data with the authors while validating and reflecting on it (Cornwall & Jewkes, 1995). The participatory/co-creation approach was followed in two of the total three stages (Stages 1 and 3) and increased the commitment of experts offering them a 'safe space' (Bergold & Thomas, 2012) empowering them to consider new ideas and develop long-term interests across all three research stages.

This study builds upon two simultaneous stages (1–2) and a subsequent validation stage (3):

1. Stage 1: *Card-sorting activity* with 32 construction experts on stakeholder analysis
2. Stage 2: *Semi-structured interviews* with a multi-stakeholder sample of 53 experts consisting of the above construction experts plus additional interviewees from manufacturing, technology and energy sectors comprising the STS
3. Stage 3: *Focus group* with 15 experts from interview participants ($n = 11$) and academic researchers ($n = 4$) to validate the findings and co-create insights.

The quantitative results from Stage 1 and qualitative results from Stages 2–3 were synthesised for RQ. Table 2 relates the stages to stakeholder analysis approaches (descriptive, normative or instrumental).

The context was UK construction that offers various DT-using net-zero projects and initiatives to study through experiences of key project actors. Construction is key contributor to carbon emissions (UN, 2022) with buildings being responsible for 39 % of global energy-related carbon emissions: 28 % from operations and energy needed to heat, cool and power them and 11 % from materials and construction (WGBC, 2019). Hence, net-zero construction projects attract a lot of government and industry interest. Simultaneously, UK government pushed construction to increase its digitalisation through the 2011 (GCCG) mandate for digital delivery via Building Information Modelling (BIM) in publicly-procured projects. Following an extensive innovation agenda expressed through industry improvement reports such as 'Rethinking construction' (Egan, 1998), 'Constructing the team' (Latham, 1994), 'Construction 2025' (HMG, 2013) and 'Modernize or die' (Farmer, 2016), the digitalisation of UK construction has followed transition pathways of reconfiguration, transformation and substitution (Papadonikolaki et al., 2023). This makes UK construction ideal setting for researching DTs in net-zero projects. By focusing on project front-end, the study researched different stakeholders, projects and firms rather a single entity. The scope includes the entirety of construction including infrastructure and buildings.

3.2. Stage 1 – stakeholder analysis through card sorting

Card-sorting is a creative, participatory method that also incorporates gamification. Card-sorting is used primarily in user experience design to evaluate information structures (Conrad & Tucker, 2019) successfully also used in stakeholder analysis (Hare & Pahl-Wostl, 2002). As card-sorting has its roots in psychology (Puff, 2013) and knowledge management (Wood & Wood, 2008), it provides insights into how users structure information into logical groups revealing their mental models. During card-sorting, participants organise topics into categories that make sense to them, revealing how they perceive and categorise information. There are two main types of card sorting: open card-sorting, where participants define own categories, and closed card-sorting, where they sort items into predefined categories. Here, closed card-sorting was used to gain insights into participants' user mental models with the benefits of clarity, structure, speed, simplicity, comparability due to standardised results and easy identification of divergent opinions.

Card-sorting in research typically takes place on-site but currently there are various online solutions. The main difference between on-site and online card-sorting is that participants perform the online card-sorting activity on their own and cannot discuss with other participants (Greifeneder & Bressel, 2022). However, online card-sorting allows for participants from different locations to participate, is less time-consuming, allowing more time for briefing and reflection and more possibilities for quantitative analysis. Here, card-sorting was used to elicit participants' knowledge on categorising stakeholders according to Power-Interest grid. The influential Power-Interest grid builds on the work of Eden and Ackermann (2013) book on stakeholder analysis and strategic management using cognitive and causal mapping techniques. The stakeholder analysis through Power-Interest grid using card-sorting took place through:

- Card-sorting activity using the open-source Kardsort[1] online tool.
- Data collected by 32 construction experts involved in strategy, development and/or exploitation of DT-using net-zero projects. These experts came from Stage 2 interviewees (see Appendix-Table A1) excluding experts from manufacturing, technology and energy sectors.

Table 2
Summary of stakeholder dynamics analysis stages.

	Stakeholder dynamics analysis		
	Descriptive (Stage 1)	**Normative (Stage 1)**	**Instrumental (Stages 2 and 3)**
What?	Identification of key stakeholders	Power-Interest grid	Stakeholder dynamics
How?	Card-sorting activity	Card-sorting activity	Semi-structured interviews and focus group
Who?	Researcher and experts (through hybrid card-sorting)	Experts	Experts and academic researchers

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[1] Kardsort is a platform is specialised in collecting data by hat allowing the participants to organize labeled digital cards by dragging and dropping cards into piles. It was developed at the University of Paderborn and is maintained by Kailaash Balachandran, further information retrieved from https://kardsort.com

- Closed card-sorting technique featuring:
  - Four pre-defined categories of Power-Interest grid stakeholder mapping: low/high power and low-high interest.
  - 20 cards with stakeholders for DTs for net-zero projects, raised to 28 stakeholders/cards by the participants, sorted in the four categories above
- Data analysis via algorithms run on Casolysis 2.0 (Szwillus et al., 2015):
  - Cluster analysis: statistical method to cluster cards based on how frequently they are grouped together to identify the most natural groupings:
  - Multidimensional Scaling (MDS): statistical technique plotting the cards in a spatial arrangement to visualise their relationships.

The goal of card-sorting analysis is to extract meaningful patterns and insights that align with informants' mental models. The detailed implementation of the algorithms is elaborated in the data and results section.

3.3. Stage 2 – semi-structured interviews

In Stage 2, data was collected through interviews with industry experts to increase data richness (Creswell, 1994) as interviews are considered appropriate to elicit their expertise. 53 industry experts were interviewed between November 2022-February 2023. The 32 of them who were experts from construction were the card-sorting informants of Stage 1, while the other 21 were experts from the manufacturing, technology and energy. The selection criteria were: (a) expertise in net-zero projects (Terenzi et al., 2024), (b) development or management role in DT deployment, (c) project experience of over 15 years on average and (d) involvement in DT use cases/projects of micro- (e.g. neighborhood energy update, housing thermal renovations) and megaprojects (e.g. HS2, Thames Tideway, East West Rail) shaping the dual transition. The sample size evolved during the study and eventually reached saturation, when no new information was added and repetitive ideas emerged (Bazeley, 2013). Rigour in qualitative research is not only related to sample size but also to interview length (LaDonna et al., 2021), hence we took extra time for in-depth interviews of average duration 48 min. Appendix-Table A1 shows their detailed profiles, the DT-using net-zero use cases they were involved, and how the pointers to interviewees' 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 interview protocol in advance, having signed consent forms allowing audio recording. The questions were designed to reflect the research aim and question. Seven semi-structured, indirect and open-ended questions (Appendix-Table B1) allowed for additional follow-up and elaboration during interviews, reducing social desirability bias (Fisher, 1993). The first questions were descriptive and addressed the background of interviewees, their roles in relevant DTs and net-zero initiatives in micro- and megaprojects. The last questions were reflective about the STS developing around DT-using net-zero projects for the dual transition.

The transcripts were analysed through 'coding' (Miles & Huberman, 1994), using both deductive and inductive coding, consistent with qualitative content analysis. As there is not a definitive manner to rigorously analyse qualitative data (Robson & McCartan, 2016), the theoretical framework was used as a sensitising lens for analysis (Blumer, 1954). Constructs of the theoretical framework were used as deductive (theory-based) codes that directed the analysis of the dataset, such as 'net-zero, 'stakeholders, 'system'. Next, inductive codes (data--based) from repetitive concepts emerging during the interviews, such as 'collaboration', 'investment', 'incentives' and so forth. The inductive codes were mainly in vivo codes, based on words or phrases directly from data (Saldaña, 2009). The focus of the inductive coding was to elicit information about the relationships and the dynamics among

stakeholders. The coding took place in atlas.ti data analysis software.

3.4. Stage 3 – focus groups

In Stage 3, to strengthen the research rigor and evaluate the relevance and accuracy of findings, we employed research validation triangulating the results and addressing limitations of mono-method studies (Sarantakos, 2005). Data collection strategies such as debriefing, member checking and triangulation ensured data dependability and credibility (Carter et al., 2014). Here, we focused on internal validation to grasp the reflections of interviewees on the findings and external validation by involving four new participants (Boudreau et al., 2001). According to Straub et al. (2004) such expert panels are key to research validation.

The focus group attracted 11 interviewees and card-sorting participants (Int-4,7,8,9,11,15,17,20,26,32,48,) in a representative sample. Eventually there were 15 participants with by adding four academic researchers (Researcher-1,2,3,4) to facilitate the discussions and contribute to external validation (Carter et al., 2014). Due to the large number of focus group participants, since typically four to ten is optimum (Morgan & Spanish, 1984), it was broken into two representative sessions in June 2023. The two focus groups were conducted a week apart, lasted 2 h each and helped reaching saturation as repetitive ideas emerged. The composition of the two focus groups was balanced and they were formed by interviewees with comparable backgrounds. Each focus group was facilitated using an online interactive whiteboard tool (Google Jamboards) to structure the discussion about DT-using net-zero projects. The focus groups had two parts: 'presentation' where the author presented the preliminary findings, followed by discussion and 'co-creation' where the findings on stakeholder dynamics were challenged in an interactive session using digital 'post-its' aiming to them. The focus group outline is shown in Appendix-Table C1.

4. Data and results

4.1. Stage 1 – mapping key project stakeholders in the dual transition

Understanding the key stakeholders involved in the dual transition through Power-Interest stakeholder analysis followed Eden and Ackermann (2013) and was conducted through card-sorting designed such that informants could first identify key stakeholders in the dual transition and afterwards categorise them in a matrix. A list of 20 stakeholders was identified in advance and the informants added eight new stakeholders to that list. Then, the card-sorting data was analysed statistically. Two main approaches were used: clustering and Multidimensional Scaling (MDS).

First, clustering showed how frequently cards about various stakeholders were grouped together, revealing their position in the power-interest matrix showing the most natural groupings by the informants. Two different clustering methods were used (DBSCAN and SLA, discussed next). DBSCAN (Density-Based Spatial Clustering of Applications with Noise) was used to group data points (cards on various stakeholders) based on how many times they were categorised in a specific power-interest category. This identified clusters based on density of how many points/cards within a specified radius. A minimum number of points/cards was included in each category. Simultaneously, noise was added to handle the outliers. The combination of density and minimum points provided a threshold for DBSCAN (Ester et al., 1996). Here, threshold of 18 % was selected to sort all cards across the power-interest categories: (a) high power/high interest, (b) high power/low interest, (c) low power/high interest and (d) low power/low interest. Choosing the right threshold is crucial and significantly affects the results (Ester et al., 1996) as a smaller threshold could not include all stakeholders in the four power-interest categories and a very large threshold could leave some categories empty. The results of DBSCAN showed how informants grouped various key stakeholders of DT-using net-zero projects. Fig. 1(i)
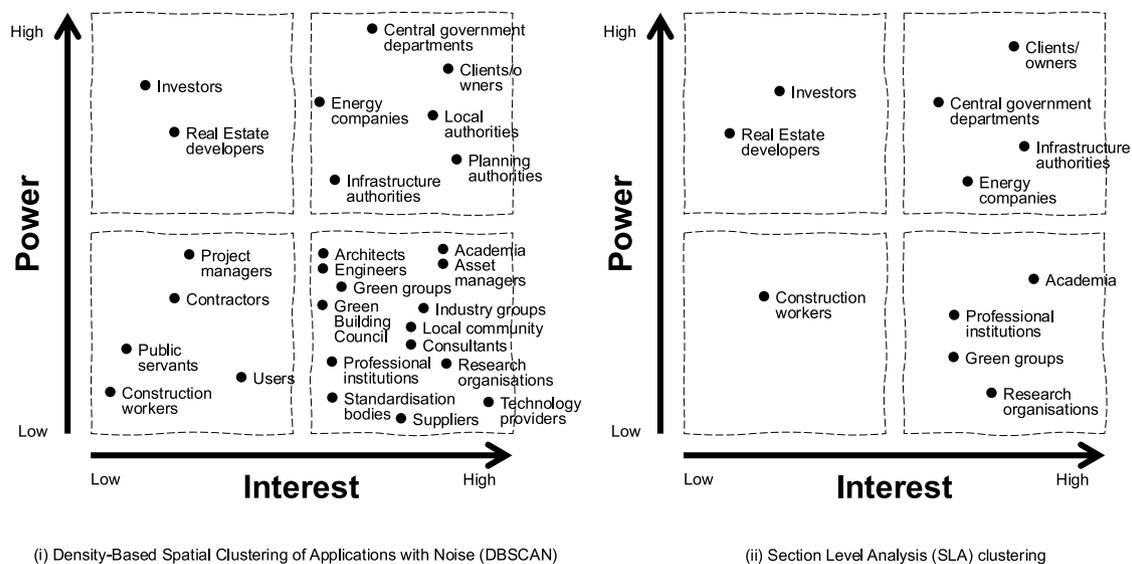
Fig. 1. Results of Density-Based Spatial Clustering of Applications with Noise (DBSCAN) using threshold 18 % and of Section Level Analysis (SLA) algorithm with threshold 51 % plotted in a Power-Grid matrix categorising the key stakeholders of the dual transition.

presents these results.

The next clustering algorithm applied was Section Level Analysis (SLA), used to analyse the card sorting at a more granular level than categories. The SLA focuses on identifying the 'threshold' for a consensus that limits the data points and card groupings and helps in deciding the most important stakeholders. The SLA threshold depends on the number of informants (Nawaz, 2012) determining what level of agreement or commonality among informants' responses is needed to consider a card grouping as meaningful category. Setting an appropriate threshold ensures reliability of the analysis as too low a threshold might include irrelevant or weak groupings, while too high a threshold might miss out on meaningful but less obvious patterns. Here, SLA threshold 51 % is used showing agreement of 51 % of informants in determining the Power-Interest matrix groupings. This was selected by not leaving any of the four categories empty without cards. Fig. 1(ii) illustrates this.

Next, Multidimensional Scaling (MDS), a "statistical analogue of the card-sorting technique" (Whaley & Longoria, 2009, p. 106) was used to analyse stakeholder cards and visually represent similarities or dissimilarities among them. MDS is a statistical technique used for analysing card-sorting data (Whaley & Longoria, 2009). MDS visualises similarity or dissimilarity among items in a low-dimensional space, as opposed to clustering algorithms such as DBSCAN and SLA shown before that categorise based only on similarity. MDS creates a spatial representation where the distance between any two items reflects their perceived similarity as closely as possible and unobstructed by informants' pre-conceptions as the groupings created are emergent and objective (Rosenberg & Park Kim, 1975). MDS helps in visualising how informants perceive relationships between the different stakeholder cards by creating a map where similar items are placed closer together, and dissimilar items further apart. The spatial map shows new clusters of cards that represent potential categories or themes (irrespective of the Power-Interest matrix) and offer insights into how informants perceive and organise information, key in participatory research (Whaley & Longoria, 2009).

The benefit of MDS is that its visual nature makes it easier to interpret complex relationships and uncover new underlying structures. A key metric of MDS is stress, a measure of how well the MDS configuration visualises similarity or dissimilarity. It quantifies the difference between the distances in the MDS plot and the actual similarities/dissimilarities. Lower stress values indicate a better fit, meaning the MDS plot more accurately reflects the original data. High stress suggests a poor fit, implying the MDS representation may be distorting or over-simplifying relationships in the data. This visual helps understanding the informants' mental models, identifying potential meaningful cluster or themes for further research. In Fig. 2 below, the results of MDS for the stakeholder card-sorting for stress level 0.16788 are presented. The algorithm was run a few times and it created very similar groupings that allow for further interpretation.

Giguère (2006) argues that MDS is used to confirm hypotheses about social-psychological structures hidden in data. The concept of 'actor constellations' was used in our interpretation. Wittmayer et al. (2017) distinguish two units of analysis in actors' roles in sustainable transitions: single role and role constellation. Role constellation refers to "webs of roles, which interact, interrelate and co-evolve with one another" (Wittmayer et al., 2017, p. 52) and the benefits of considering this level of analysis is on highlighting relations among different roles. Four distinct groupings of stakeholders were observed in the MDS output in Fig. 2, and were categorised as intermediaries (A), regime actors (B), niche actors (C) and collective actors (D).

4.2. Stage 2 – relations of key project stakeholders in the dual transition

4.2.1. Mapping stakeholders' relations and patterns of interactions

The stakeholder mapping presented above follows a normative approach to study key stakeholders involved in the dual transition. Stage 2 is based on qualitative content analysis of interviews, combining the card-sorting with instrumental stakeholder management. Combining various collection methods in stakeholder analysis serves different purposes (Reed et al., 2009). Our pragmatic approach focused not only on identifying and categorising stakeholders but also on delving deeper into their relations. Here, it should be noted that the labels/names of stakeholders of Stage 2 (interviews) are not the same as those of Stage 1 (card-sorting) because the analysis of Stage 2 was based on in-vivo coding whereas the stakeholder identification of Stage 1 took place through the collaboration of authors and informants in a participatory approach.

The first order codes unpack the interactions among stakeholders. Table 3 illustrates these interactions in the first two columns from the left-hand side as stakeholder influencing (source) and influenced (target) in the relation. The next column to the right shows frequency (strength) that this interaction appears in the data. The second order coding in Table 3 contains inductive coding about relation type. The
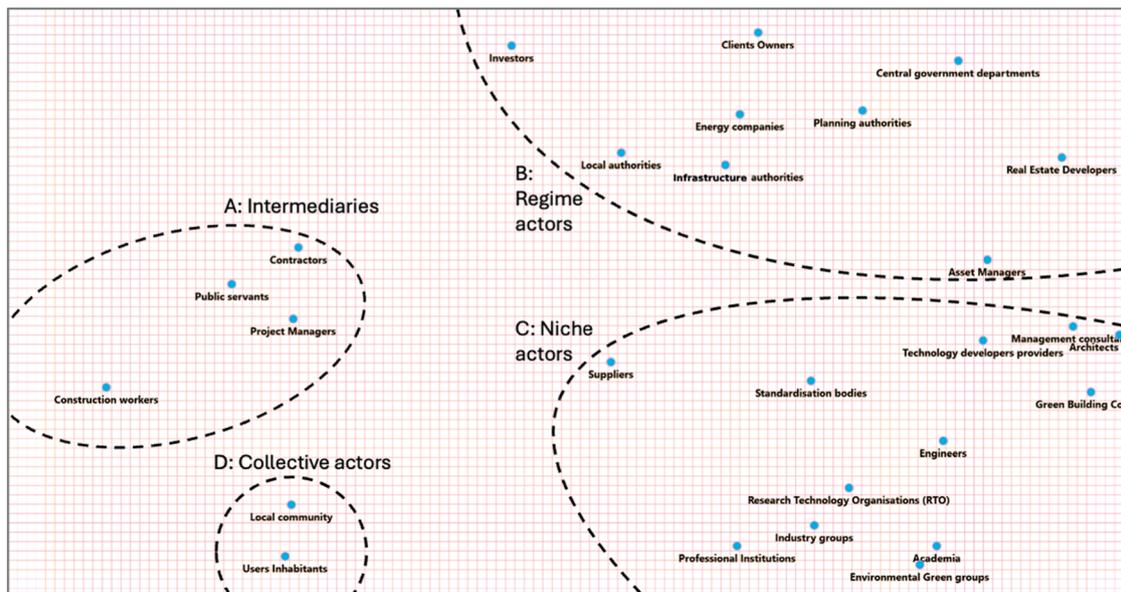
Fig. 2. Results of the Multidimensional Scaling (MDS) algorithm applied to the data showing three clusters of the key stakeholders of the dual transition (A: intermediaries, B: regime actors, C: niche actors, D: collective actors).

Table 3
Summary of the coding process.

First order coding (Stakeholder relations)			Second order coding (type of relation)	Aggregate dimension (pattern of interaction)
Stakeholder influencing (source)	Stakeholder influenced (target)	Frequency of code (strength)		
Policy-makers	Contractors	29	Standardisation, Collaboration	Hybridised
	Clients/Owners	4	Mandate	Competitive
Government	Contractors	24	Incentives, Investment, Control	Competitive
	Clients/Owners	8	Mandate, Legislation, Silos	Competitive
	Policy-makers	7	Communication, Collaboration	Symbiotic
	Community	4	Mandate, Communication	Hybridised
Community	Clients/Owners	18	Grassroots, Communication	Symbiotic
	Government	3	Grassroots	Symbiotic
Suppliers	Contractors	16	Control, Contracts	Competitive
Tech companies	Clients/Owners	16	Collaboration, Silos, Monopoly	Hybridised
	Consultants	5	Communication	Symbiotic
	Policy-makers	5	Collaboration, Pressure	Hybridised
	Government	4	Collaboration	Symbiotic
Clients/Owners	Contractors	15	Contracts, Investment, Silos	Competitive
Industry groups	Government	13	Grassroots	Symbiotic
	Clients/Owners	9	Communication, Collaboration	Symbiotic
Academia	Industry groups	9	Communication	Symbiotic
	Policy-makers	5	Communication, Collaboration	Symbiotic
Contractors	Clients/Owners	9	Resistance, Contracts, Investment	Competitive
Consultants	Clients/Owners	7	Communication, Collaboration	Symbiotic
	Community	5	Communication	Symbiotic
NGOs	Clients/Owners	6	Grassroots	Symbiotic
Manufacturers	Suppliers	5	Collaboration, Investment	Hybridised
	Contractors	2	Communication	Symbiotic
Professional Institutions	Industry groups	5	Collaboration	Symbiotic
SMEs	Manufacturers	5	Collaboration	Symbiotic
Energy companies	Clients/Owners	4	Control, Collaboration	Hybridised
Facility managers	Clients/Owners	1	Resistance	Competitive

aggregate dimension relates to deductive coding and shows patterns of interactions as to competitive versus symbiotic relations drawing upon Rosenbloom (2019) adding emerging hybridised interactions to show actors displaying a mixture of competitive and symbiotic relations simultaneously.

4.2.2. Competitive, symbiotic and hybridised patterns of actors' interactions
The relations among the key stakeholders of the dual transition were of various types and oftentimes more than one relation was discussed between a dyad of stakeholders, even from the same interviewee

(Table 3). These varying and multiple relations were categorised as competitive or symbiotic but for some pairs of stakeholders the relations were hybridised featuring simultaneously competitive and symbiotic interaction patterns.

4.2.2.1. Competitive interaction patterns. In the competitive interaction patterns, the relations between government and industry are profound, especially in how market is controlled through taxation and rules shaping new digitalisation and decarbonisation initiatives. As Int-42 explained: *"The UK is all top-down, driven by government standards and*

compliance and understanding the rules. If the rules will not get you there then you can follow the rules but you're just like a lemming going off the edge of the cliff." For Int-5, the government also influences the industry through economic incentives to facilitate the net-zero transition: "*Any policy, governmental incentive, to fund the tools that will enable the know-how of energy reduction and efficiency, I welcome. […] Government and institutions have a role, to play to guide manufacturing and construction, in that journey.*"

The power of real estate investors as incumbent actors influencing the landscape of dual transition was acknowledged clearly in the card-sorting described in sub-Section 4.2.1. Through the interviews, real estate investors were important actors greatly influencing the direction and decisions of client/owners as Int-42 elaborated: "*I think the only group that's going to put pressure on the owners is the stock market and the investors. So, to me, I would start with the key driver, which is going to be a financial driver.*" Another key competitive pattern was initiated by clients/owners who are influencing the industry and its culture using contractual means to protect against the risk of new investment and requirements for the dual transition. As Int-19 shared: "*The contracts are a killer because of the way that they're set up and people will only do exactly what's written. So then there comes the maturity of the client to explain very clearly and succinctly what they need.*" The clients/owners are considered dominant in sustaining the contractual culture that characterises the built environment and makes it ripe for disruption.

4.2.2.2. Symbiotic interaction patterns. Symbiotic interaction patterns of project stakeholders involved in the dual transition were typically initiated by non-regime actors, such as niche actors or intermediaries. Key front-runners in this are consultants who are influencing the industry through communication and collaborative relations, as Int-51 elaborated: "*The thing is they can see how we can help them through our technology to get a digital twin they can actually use to help them plot and plan the decarbonisation over the next 20–30 years.*" Additionally, the role of Small-Medium Enterprises (SMEs) in pulling the change and influencing incumbents such as manufacturers through collaboration was profound. As Int-11 shared: "*In the digital era, […] the relationship between big corporation and small and medium enterprises is totally changed and it is a much more productive, much more effective.*"

Other symbiotic interaction patterns were influencing the government initiated by niche actors such as community players pulling change in the STS through grassroots initiatives. As Int-28 shared communities are initiating niches and shaping the creation of digitalisation and sustainability transitions: "*So it has to be a balance of policymakers […] 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.*" Similarly, technology companies influence the government by communicating about new possibilities of the digital transition to support sustainability transitions: "*We've actually been into government to talk about a more collaborative model that actually uses Digital Twins as a way to share information and insight so that, when a policy decision is made, policy-makers are able to test and analyse the impact of making that change but also give industry a way to test and validate the policy changes.*" (Int-13).

4.2.2.3. Hybridised interaction patterns. The hybridised interaction patterns of stakeholders involved in the dual transition were actors influencing other actors or constellations developing both competitive and symbiotic interactions. Int-39 explained how energy companies collaborate with other parts of the industry such as water companies: "*If you're (digitally) 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.*" Simultaneously, energy companies exert control to the industry by being overly competitive and closed (Int-35):

So we've already alluded that water companies are in not quite so much of a commercial tension, but the idea of energy companies playing nicely, telecoms companies playing nicely, understanding it's for the greater good that they maybe risk some of their commercial advantage in pulling together of these things to then move stuff forward will be interesting.

Fig. 3 summarises the first, second coding and aggregate dimensions of Table 3 data.

4.3. Stage 3 – complexity of stakeholder dynamics in the dual transition

4.3.1. Validation and reflection on mapping the stakeholders

The focus group aim was to validate the previous two stages' findings. Regarding the mapping of key stakeholders in the dual transition in Stage 1, the authors presented and explained the visualisations of the DBSCAN, SLA and MDS algorithms. The participants agreed that the roles of central government departments and clients/owners as regime actors are highly powerful and important. This finding was further elaborated by Int-9 who clarified that the government is acting as an enabling system of the dual transition. Int-24 added:

"I don't think I can highlight one single, highest-power entity there. I think it's an aggregate. […] possibly a collection of consortia, or an aggregate that has some other structure. They all need to work – they will have to work – together, because they will all be using the system, or system of systems, or systems of systems, in different ways."

Int-26 further added to this idea: "*If you are trying to establish one governing body for the governors, basically, who is checking the checker, then yes, it's probably government legislation that would drive this forward, but I don't think it would be a single entity that would look after it.*" Furthermore, Int-7 shared: "*…the kind of systems of systems we've just been talking about, I think it's important to recognise that they are complex systems and cannot be controlled in the engineering sense. It can't be controlled.*". Especially concerning the results of MDS (Fig. 2), Int-8 stressed the important role of user-inhabitants and local communities:

"One that I'd like to say is citizens. Citizens kept coming up in all our bits of conversations as a stakeholder. We tend to think about investors or regulators, or government, but actually, it's about people."

4.3.2. Validation and reflection on stakeholders' interaction patterns

Regarding the interactions of key stakeholders in the dual transition from Stage 2, the focus group reflected on all competitive, symbiotic and hybridised interaction patterns. First, regarding competitive interactions, the discussions revolved around financial incentives for supporting the STS tackle external pressures of climate change by meeting the net-zero vision while navigating niche innovations of digital twins. Since construction is created and maintained through projects, the discussion stressed the role of financiers. Int-8 reflected on this: "*Does the current economic model drive net-zero, and how do we get it to do that?*", highlighting that market competition is key disruptor.

In discussing hybridised interactions, the importance of government in indicating guidelines for developing and governing federated DTs to reach net-zero was stressed. However, it was emphasised that flexible regulations that cater for collaboration and innovation and needed to enable the dual transition as the current regulatory regime may slow down the adoption of innovation. As Int-11 explained:

"There has been a discussion (…) around regulations, how flexible regulations are, and also how much informed they are. […] In many cases it hinders innovation or slows down innovation, so there is definitely something there in the regulatory regime that needs auctioning."

There is an urge for government and local authorities to participate actively, indicating a need for clear governance mechanisms, perhaps a roadmap for adopting DTs. The necessity of outcomes-based regulation and new legislation adapting furthering the objectives of dual transition
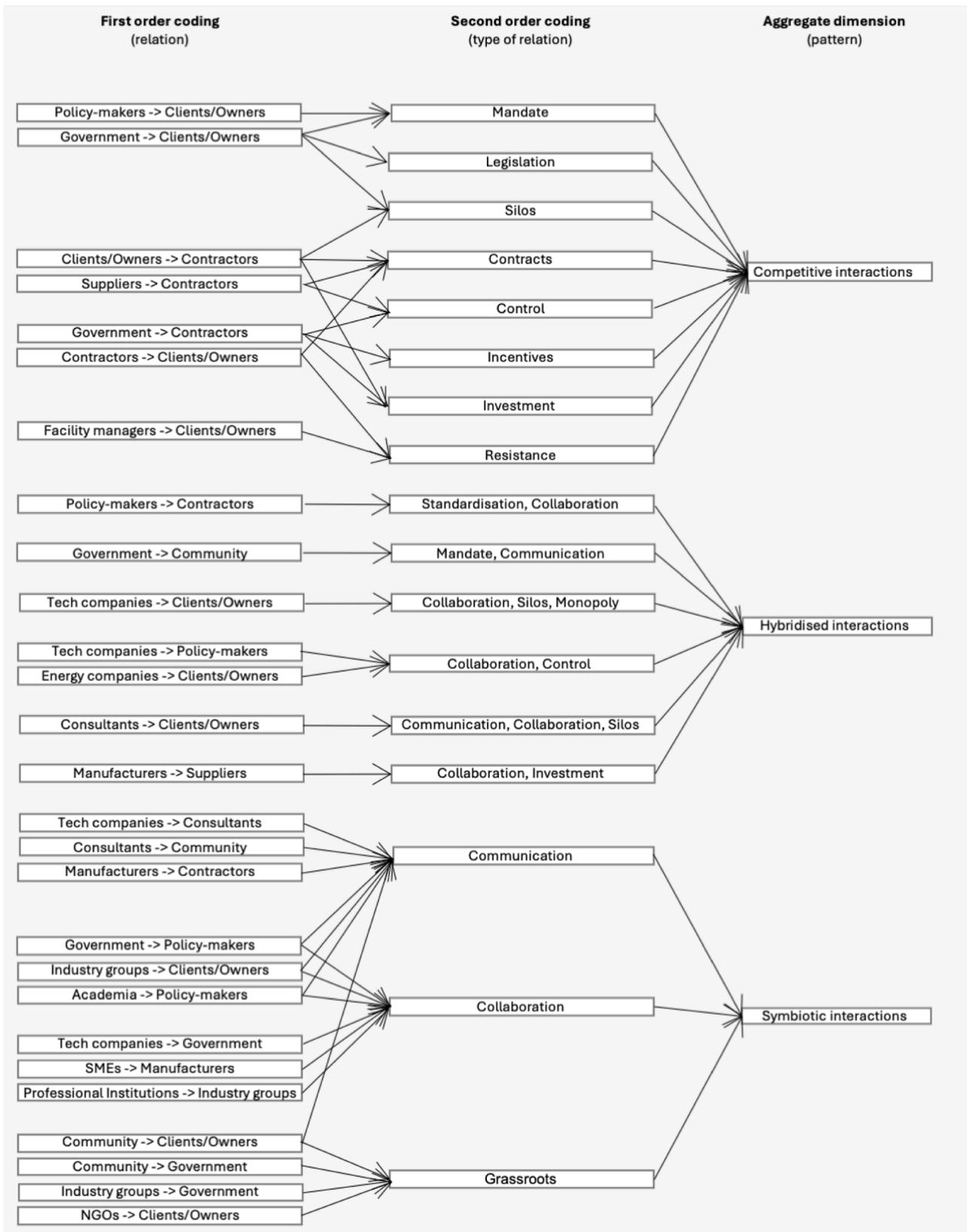
Fig. 3. Summary of coding process from first order to second order coding and aggregate dimensions.

was stressed. As Int-8 stressed: *"we need a regulator and a regulatory model that focuses on outcomes, so, [...] the water industry [...] as an industry that's regulated by what are the outcomes for the customer, rather than what is their profit-per-unit effort, for example. So, we need a regulator that's looking at that."*

Regarding symbiotic interaction patterns, the focus group emphasised the importance of collaboration among various stakeholders such as technology companies, industry groups, government and others as Int-

17 explained: *"So, skilled in competencies and then establishing collaborative platforms and public-private partnerships. Software providers can play a good role, […] but let's not have a hammer searching for a nail."* This supports the low disruption potential of symbiotic patterns.

5. Discussion

5.1. Stakeholder dynamics in the dual transition

In answering the RQ about stakeholders' interactions, the three research stages showed that stakeholders such as the policy-makers, government, clients/owners, industry groups (all regime actors, see Fig. 2), community (collective actors), suppliers and technology companies (niche actors) as crucial in enabling the dual transition and shaping the conditions around projects leveraging DTs to support the net-zero vision. Through a Power-Interest analysis, it was found that the government, clients/owners, energy companies and local, planning and infrastructure authorities were highly powerful and highly interested stakeholders in the dual transition (Fig. 1). This normative approach to stakeholders and comparison in Fig. 1(i) and (ii) revealed the multiplicity of Power-Interest dynamics shaped by our multi-expert pool of informants.

Various patterns of interactions emerge in activating stakeholders for the dual transition. First, a variety of competitive tensions such as legislation, contracts, silos, control, incentives and resistance (Fig. 3) dominant relations according to their frequence (Table 3) emerge, primarily initiated by regime and incumbent actors (Fig. 2). Second, a variety of symbiotic tensions arises such as communication, collaboration and grassroots initiatives (Fig. 3), mainly initiated by niche and intermediary actors (Fig. 2). Third, these extremes are mediated by hybridised patterns where interactions between stakeholders are simultaneously of competitive and symbiotic nature and hence more fluid and harder to unpack and understand.

The hybridised patterns are typically initiated by niche and intermediary actors (see Fig. 2) and are less predictable than competitive and symbiotic patterns making their disruptive potential elusive. They are typically initiated by technology companies, energy companies and consultants who are brokering change to aid the dual transition. The nuances of the hybridised interaction patterns reveal the importance of the niche and intermediary actors whose practices are central in shaping the dual transition. The moderate tensions in the hybridised interaction patterns have the potential to reshape the boundaries of actor constellations and shift the STS towards increased competition that can bring greater disruption. Competitive agendas emerged, for instance, technology companies were pushing DT solutions for reaching net-zero and energy companies prioritised data transparency for decarbonisation. Nevertheless, together, in these symbiotic patterns, they recognised the need for collective action. The entanglement of the niche, regime, intermediary and collective actors, throughout these competitive, symbiotic or hybridised interaction patterns brings an alternative layer of stakeholder analysis focusing on their pre-existing relations, individual agendas in the dual transition, power and institutional roles and not only on their individual stance.

5.2. Theoretical contribution

At micro-level, this study revealed new cross-overs of project studies and transitions research regarding stakeholders (project studies) and actors (transitions). In business and project studies, stakeholders are approached through management of stakeholders and management for stakeholders (Eskerod & Huemann, 2016) that may also include both actors and non-actors. Contrariwise, in transitions actors are seen as intelligent agents interacting bottom-up across the STS and through their resisting or enabling actions shaping pathways for disruption from new technologies (Rosenbloom, 2019). In facing the dual transition, this study assigns some additional autonomy to project stakeholders as

rational entities by revealing interactions, influence and power play with their immediate competitors or collaborators. While recognising the significant differences of 'stakeholder' and 'actor' concepts, we argue for extending the notion of stakeholder in navigating transitions.

At meso-level, we contribute theoretically to project stakeholder management literature and especially external stakeholders by furthering stakeholder analysis approaches by not only looking at their past and future (Aaltonen et al., 2017) or supportiveness and salience (Aaltonen et al., 2015) instead broadening our understanding of their embeddedness in net-zero projects through their interactions. Following the concept of 'shadows of the context' by Eskerod and Larsen (2018), we provide rich descriptions of how stakeholder behavior can be understood through stakeholders' interactions and the dynamics of how they influence one another. Drawing upon transitions research, we emphasised on constellations of actors from Wittmayer et al. (2017) recognising the entanglement of their interactions. Additionally, by qualifying these interactions and dynamics as competitive or symbiotic inspired by MLP in transitions (Raven & Verbong, 2007; Rosenbloom, 2019), we revealed to what extend stakeholders' interactions are conducive of disruption in project environments as too many competitive interactions can create displacements and too symbiotic can create new couplings with less perceived challenges and opportunities. It is also important to establish how emerging regime and niche clusters/constellations of stakeholders in Fig. 2, correspond to initiators of competitive and symbiotic interaction patterns respectively in Table 3.

At macro-level, this study focused on both STS and projects promoting change and transitions at a systems level. Thus, it furthered the conceptualisation of projects as integral parts of STSs (Geels & Locatelli, 2024), an acknowledgement that can bring increased theoretical richness in understanding project environments, departing from the idea of projects as 'islands' (Engwall, 2003). This is contrary to the dominant view of projects as separate units of analysis that miss the inter-organisational dimension in their analysis (Sydow & Braun, 2018). We extended the important inter-organisational dimension of STS transitions (Geels & Locatelli, 2024; Miterev & Engwall, 2024) by untangling stakeholder dynamics in leading project initiatives furthering the dual transition of sustainability and digitalisation. Stakeholder dynamics reinforce the importance of projects in delivering net-zero and addressing climate change (Winch et al., Terenzi et al., 2024; 2023). This sociotechnical view creates a deeper conceptualisation of project embeddedness in their socioeconomic and historical context (Blomquist & Packendorff, 1998).

5.3. Methodological contribution and limitations

Methodologically, this study contributes with a pluralistic data collection strategy that supports the bridging of project and transitions studies as the two typically follow different research methodologies – that is often qualitative case studies in the former and quantitative empirical analyses in the latter. Additionally, our multi-methods approach combines normative and instrumental stakeholder analysis approaches, echoing voices for increasing and supporting the collaboration and knowledge spillovers between them (Reed et al., 2009). Another contribution of the multi-method approach is capturing the interactions of multiple actors from various data sources that could have been otherwise not included in a single-method approach, e.g., only from interviews or only from card-sorting. By deploying card-sorting in stakeholder analysis, this worked as a "structured interview method supported by the use of cards to remind stakeholders which stakeholders they should talk about in their answers" (Hare & Pahl-Wostl, 2002, p. 60). By focusing on understanding the constellations or 'webs of actors' (Wittmayer et al., 2017), Social Network Analysis (SNA) terminology (source, target and strength, Table 3) was used that are popular in both project studies in understanding project and actor dependences respectively (Killen & Kjaer, 2012; Sedita & Apa, 2015) and transitions research, for instance in understanding interactions among regime

networks (Ertelt & Kask, 2024). Such analytical methods can help uncover the dynamics among stakeholders and actors in projects and transitions respectively.

Finally, all studies come with some inherent limitations, especially in data collection. First, it was observed that despite the long-term nature of sustainability, only one financier was involved (Table A), whereas many more were approached to – even though they are key stakeholders in the Power-Interest matrix, revealing a limitation in the data. Second, the interviews may still include biases, e.g. social desirability bias, that was managed through preemptive measures such as clear sampling criteria, indirect questioning and debriefing (Bergen & Labonté, 2020; Fisher, 1993; Nederhof, 1985). Third, to reduce impression management or retrospective sensemaking (Eisenhardt & Graebner, 2007) the multi-method approach including triangulation via focus group provided communicative research validation (Sarantakos, 2005) by involving internal and external experts to check data accuracy and enrich the interpretations.

5.4. Practical implications

Institutions shape regulations and provide frameworks for successful implementation of DTs in enabling the net-zero transition (CCC, 2019; IET, 2022). The study shed new light on the role of regime and incumbent actors in developing competitive and hybridised interactions pushing disruption. Contrariwise, niche and intermediary actors were initiators of mostly symbiotic and hybridised interaction patterns. While theoretically, we know more about the disruption potential of competitive dynamics, the hybridised relations emerged strong and pronounced, typically initiated by technology companies and energy companies. These actors become prominent in the dual transition but they each carry their individual agendas; the former relating to higher technological determinism and the latter relating to social outcomes and long-term vision. As a whole, these niche actors reinforced one another in the dual transition, despite their incongruent individual agendas. Across the analysis, collaboration was found as a key emerging theme (Table 3), whether it is across industry and government or public-private partnerships, highlighting the multi-faceted approach required in dual transition (Muench et al., 2022). This collaborative approach echoes recent recommendations by the Institution of Engineering and Technology (IET)'s 'Apollo Protocol' report on breaking silos not only inside construction and across infrastructure assets (Papadonikolaki & Anumba, 2024) but also across manufacturing and construction (IET, 2022).

As the complexity of the STS is complemented by a complex System-of-Systems of DTs needed to support the net-zero vision explicated in the 'Gemini Principles' report (Bolton et al., 2018), the dual transition is characterised by lack of control in the traditional sense, underscored by Int-24,26 in the focus group (Section 4.3.1). Throughout the data and analysis, an emerging need for a government-led orchestrator (Int-26, Section 4.3.1) emerged. The government-led orchestrator will be able to convene, connect, and bring stakeholders to work together, following the vision of Construction Innovation Hub (CIH, 2021). The emerging idea of an industry ecosystem orchestrator stresses the importance of a long-term perspective and the need to legislate for social outcomes, not just business outcomes, to further the objectives of dual transition.

The role of government is important in understanding the context of not only net-zero projects but also micro-projects and megaprojects that will be delivering associated visions related to the dual/twin transition. From a technological perspective, there is a clear call for integration and better use of existing technologies rather than creating new solutions. By governing data, this emerging orchestrator/conductor role could prioritise the different digitalisation and sustainability strands of the dual transition (Int-13, Section 4.2.2). In could be a first step in overcoming the socio-cultural barriers for successful technology adoption.

6. Conclusion

Sociotechnical systems involve complex, persistent and entangled interdependences with stakeholders' dynamics, technological interplay, incongruent agendas, institutional influences and socio-cultural factors, all contributing to the ambitious goal of dual transition through DT-using net-zero projects. This study contributes to research on sustainability by projects through stakeholder dynamics, illuminating the dual transition's reliance on a coalition of policymakers, client/owners and technology innovators. Their interplay is marked by competitive, symbiotic and hybridised interaction patterns (answer to RQ) eventually shaping diverse disruption pathways. The theoretical contribution is bridging project studies and transitions through the lens of agency: stakeholders and actors respectively. Theoretically, the study also adds the concept of staheholders' interaction patterns to enrich the toolbox of stakeholder studies. Technologically, the dual transition calls for strategic integration of existing tools and standards rather than technology development and the primacy of data governance, pinpointing these as socio-culturally essential. Institutionally, dual transition ecosystem orchestration, outcomes-based regulation and a legislative environment responsive to the dual transition's needs are needed. The study demonstrates a societal shift towards a more techno-collaborative and sustainability-conscious approach to projects, enabled by orchestrated stakeholder dynamics towards the dual transition.

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CRediT authorship contribution statement

Eleni Papadonikolaki: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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Appendix

Tables A1, B1, C1

Table A1

Detailed expert profiles participating in the three research stages: Stage 1: card-sorting activity, Stage 2: Interviews and Stage 3: Focus groups.

ID	Role	Company	Background	Use case	Experience	Stage 1	Stage 2	Stage 3
1	Founder/CEO[1]	Architecture	Architecture	Buildings	20y	x	x	
2	Sales	Technology	Business	Buildings	25y	x	x	
3	Founder/CEO	Consultancy	Engineering	Infrastructure	15y	x	x	
4	Technologist	Technology	Architecture	Buildings	15y	x	x	x
5	Founder/CEO	Manufacturing	Engineering	Manufacturing	15y		x	
6	Researcher	Research Inst[2]	Engineering	Manufacturing	10y		x	
7	Executive	Contractor	Engineering	Infrastructure	25y	x	x	x
8	Consultant	Finance	Finance	Cities	20y	x	x	x
9	Project Mgr[3]	Consultancy	Engineering	Infrastructure	25y	x	x	x
10	Strategy	Contractor	Law	Infrastructure	15y	x	x	
11	Researcher	Academia	Engineering	Infrastructure	15y	x	x	x
12	Manufacturer	Manufacturing	Engineering	Manufacturing	25y		x	
13	Consultant	Technology	Engineering	Manufacturing	15y		x	
14	Consultant	Asset Mgmt[4]	Architecture	Buildings	10y	x	x	
15	Researcher	Consultancy	Engineering	Infrastructure	10y	x	x	x
16	Consultant	Technology	Engineering	Buildings	10y	x	x	
17	Executive	Professional Inst	Project Mgr	Buildings	25y	x	x	x
18	Programme Mgr	Policy Group	Business	Manufacturing	15y		x	
19	Executive	Technology	Engineering	Buildings	20y	x	x	
20	Researcher	Professional Inst	Finance	Buildings	30y	x	x	x
21	Researcher	Policy Group	Finance	Infrastructure	15y	x	x	
22	Programme Mgr	Industry Group	Engineering	Manufacturing	15y		x	
23	Project Mgr	Consultancy	Engineering	Manufacturing	15y		x	
24	Engineer	Client/Operator	Architecture	Infrastructure	20y	x	x	
25	Engineer	Architecture	Architecture	Buildings	5y	x	x	
26	Engineer	Architecture	Architecture	Buildings	10y	x	x	x
27	Head of Digital	Contractor	Engineering	Buildings	15y	x	x	
28	CTO[5]	Client/Operator	Engineering	Infrastructure	15y	x	x	
29	Executive	Technology	Engineering	Manufacturing	20y		x	
30	Executive	Professional Inst	Engineering	Manufacturing	35y		x	
31	Engineer	Engineering	Engineering	Cities	15y	x	x	
32	Director	Government	Business	Infrastructure	20y	x	x	x
33	Researcher	Academia	Engineering	Manufacturing	10y		x	
34	Head of Digital	Energy	Engineering	Buildings	20y	x	x	
35	Head of Digital	Client/Operator	Engineering	Infrastructure	20y	x	x	
36	Asset Mgr	Client/Operator	Engineering	Infrastructure	20y	x	x	
37	Founder/CEO	Manufacturing	Engineering	Manufacturing	15y		x	
38	Consultant	Technology	Engineering	Manufacturing	20y		x	
39	Executive	Technology	Business	Manufacturing	20y		x	
40	Researcher	Consultancy	Engineering	Manufacturing	15y		x	
41	Executive	Professional Inst	Business	Infrastructure	20y	x	x	
42	Head of Digital	Technology	Engineering	Buildings	30y	x	x	
43	Professor	Academia	Engineering	Manufacturing	30y		x	
44	Executive	Professional Inst	Engineering	Buildings	25y	x	x	
45	Engineer	Manufacturing	Engineering	Manufacturing	15y		x	
46	Consultant	Technology	Engineering	Manufacturing	15y		x	
47	Project Eng[6]	Research Inst	Engineering	Manufacturing	15y		x	
48	Consultant	Consultancy	Architecture	Manufacturing	15y		x	x
49	Founder/CEO	Manufacturing	Business	Manufacturing	25y		x	
50	Head of Digital	Contractor	Engineering	Buildings	15y	x	x	
51	Founder/CEO	Energy	Engineering	Infrastructure	30y	x	x	
52	Project Eng	Manufacturing	Engineering	Manufacturing	25y		x	
53	Innovation Mgr	Energy	Business	Cities	20y	x	x	
54	Researcher	Academia	Business	N/A	25y			x
55	Researcher	Academia	Engineering	N/A	15y			x
56	Researcher	Academia	Engineering	N/A	15y			x
57	Researcher	Academia	Business	N/A	15y			x
	Totals					32	53	15

1: Chief Executive Officer, 2: Institution, 3: Manager, 4: Management, 5: Chief Technology Officer, 6: Engineer.

Table B1

Semi-structured interview questions.

Research summary
This research project focuses on digital twins for addressing environmental and social sustainability responding to the global visions of Net-zero. Your responses to this interview, which will last approximately 35–50 min, will be kept strictly confidential and used only for the above research. The focus of this interview is to elicit your experiences and perspectives on practices, pathways and engagements needed so that Digital Twins can support meeting Net-zero. Through a system thinking approach, the findings will be synthesised to propose solutions to untangle stakeholder complexity in Digital Twins projects for Net-zero. The responses will be anonymized, combined, analyzed and the findings reported only in their aggregate form and you will not be identifiable through your responses. Thank you for your participation!

No.	Description	Interview question
1	Personal background	Briefly describe your educational background, work experience in the built environment/manufacturing/technology industry and your current role in your company.

(continued on next page)

Table B1 (*continued*)

	Research summary	
2	Set the scene	In 2019, the United Kingdom (UK) became the first G7 country to legislate for Net-zero, targeting 2050 Net-zero carbon emissions. What do you see as key practices, use cases and pathways that Digital Twins can help in this transition?
3	Stakeholder analysis	How does the stakeholder landscape of Digital Twin projects for Net-zero look like?
4	Leadership	When designing a Digital Twin project for Net-zero, what strategic changes in (a) your organisation and (b) project delivery should take place?
5	External support	Describe how other organisations/partners/institutions/policy-makers/communities external to your organisation can help with the twin digital and green transition?
6	Case Studies	Do you have any projects that could be used as a case study for this research?
7	Other	Do you have any additional the information or views on the role of digital twins in achieving Net-Zero?

Table C1

Focus group discussion guide.

Purpose	Description	Duration
Welcome	Brief welcome, followed by introductions by its participants.	15 min
Presentation	Brief presentation of the findings from the initial research Stage 1 (card-sorting) and Stage 2 (interviews).	5 min
Discussion (Q&A)	Reflection on the initial findings with the focus group participants, aiming test, enrich and validate the findings and strengthen them.	25 min
Co-creation (using online whiteboard collaboration tool)	Facilitated discussion on how to co-design interventions to enable sustainability transitions to meet the Net Zero by better harnessing the potential of digital twins in micro- and megaprojects. These interventions/strategies will consider the wider socio-technical system, consisting of techno-economic elements, the institutional regime, socio-cultural elements, and relevant actors (from industry, policy, academia and professional institutions among others).	60 min
Close	Summary of the discussions and closing of the focus group with thanks.	5 min

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