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Mapping the complexity of Net Zero transition through a System of Digital Twin Systems

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***Abstract*— The upsurge of digitalisation in many sectors has been associated with better environmental outcomes. Recent policy change and international convergence has shown Net Zero vision as a means of controlling global greenhouse gas emissions. This study focuses on construction sector and the complex transition to Net Zero through Digital Twins. It does so via a system thinking approach, 53 interviews and two focus groups with digital twin experts. The key factors of this dual 'digital and green' transition are breaking down silos, collaborating across the supply chain and the need for a data-oriented approach in analysing input, processing and output of the digital twins. Apart from unravelling the factors on how individual (asset) digital twins can support Net Zero, their aggregates in a Connected Digital Twin System of Systems are also crucial to addressing the complexity of this transition at a larger scale. The study also offers new insights on the orchestrators of such system of digital twin systems and their governance mechanisms in meeting Net Zero. Additionally, one emergent finding relates to the evolution of associated concepts and terminologies. By identifying the complexity factors, this study also contributes to the management of increased risk that accompanies growing complexity.**

***Index Terms*— Digital twins, Management, Net zero, Systems thinking, System of systems, Sustainable development.**

I. Introduction

VARIOUS sectors have been witnessing the effects of digital transformation in improving their business processes and creating new value towards more sustainable economies. Especially in the construction sector, digital technologies such as Building Information Modelling (BIM), digital twins and Augmented Reality (AR), Virtual Reality (VR), big data analytics and Artificial Intelligence (AI) applications for data-driven decision-making have dominated the landscape of innovation, improvement and change. In this changing landscape of digital transformation in construction, there is a clear trend of connected digital technologies [1]. The value added by these digital technologies can support improved decision-making in construction projects.

This study focuses on Digital Twins (DTs) and how they can support the decarbonisation transition of global economies towards Net Zero. It builds on digital twins being data-rich environments that can ensure convergence between physical and cyber worlds through cyber-physical interaction [2]. As DTs can update data in real time, virtual models undergo continuous improvement by comparing virtual with physical assets [3] and can continuously monitor environmental behaviour and enable a more sustainable construction sector. DTs can also be aggregated in connected ecosystems of DTs to monitor sustainability objectives at a larger scale, such as smart-cities [4]. As such, DTs are data-rich environments that can support complex decision-making accompanying environmental behaviors in the sector.

The potential of digital twins in achieving sustainable development goals has been identified [5]; however, the United Nations' (UN) Sustainable Development Goals (SDGs) are often too broad, given the far-reaching implications of sustainability [6] and difficult to operationalise. By narrowing down to the environmental sustainability and in particular decarbonisation as a step towards reaching the Net Zero vision, this study explores how DTs can deliver on the promise of sustainability. The construction sector directly controls, and is responsible for, 43% of the global greenhouse gas emissions [7, p.62], including directs and indirect 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" [8]. The UN emphasises that for decarbonising the building materials 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 [7]. This suggests important links between data from DTs and reaching decarbonisation goals.

Also, this revived 'green' transition around Net Zero seen across sectors follows the parallel recent transition towards digitalisation. This creates a dual transition, that the EU calls: "twin green and digital" transition [9]. For instance, the recent UK government's introduction of Net Zero strategy [10], is preceded by their 2011 mandate of digitally-enabled delivery in public procurement [11]. This intertwined dual transition to

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digitalisation and Net Zero suggests increased complexity in capturing data involved and understanding the roles of key system actors responsible for relevant decision-making.

Complexity in social systems can be described as "elements" and their disproportionately increased "relations" [12]. Complex behaviors and dynamic interactions between stakeholders, project systems, and environmental factors call for investigating how digital solutions such as DT may address such challenges and lay the basis for sustainable futures by managing complexity of sustainability efforts. DTs through the power of data have the potential to monitor and, ultimately, reduce carbon emissions, facilitate a more sustainable future and pave the way to Net Zero – a complex goal on its own. Despite their promising potential, DTs carry inherent complexity in aligning data, asset performance, stakeholder requirements and system design. This complexity is coupled with the complexity of Net Zero, which also relies on data, operations, stakeholder requirements and systems thinking. Therefore, both DTs and Net Zero vision are complex on their own, and capturing the complexity of their integration is important for achieving more sustainable futures. The study uses systems thinking that is key to addressing complexity [12].

This study reveals how the idea of connected DTs can manage the complexity of Net Zero transition and deliver the dual "twin green and digital" goal [9]. It does so by focusing on a System of Systems (SoS) approach to model, analyse and manage the complexity. It sheds new light on the pathway to meeting the vision of Net Zero by focusing on how DTs can support the management of complexity in this transition. Focusing on human decision-making processes, per Simon [13], to manage complexity, the study investigates social interactions in relevant informal groupings of structure emerging through this transition. It does so by focusing on two Research Questions (RQs):

- RQ1: How can digital twins and systems thinking facilitate the understanding of complexity of transitioning to Net Zero?
- RQ2: How do individual digital twins aggregate in a connected digital twins System of Systems (SoS) to support the transition to Net Zero?

This paper is organised as follows: after this introduction to the problem, the next section presents the theoretical basis. Section 3 presents the methodology while Section 4 presents data and findings. Section 5 is the discussion reflecting on answers to the RQs and the last section concludes and summarises the study.

II. THEORETICAL BACKGROUND

A. Managing complexity in the dual "twin green and digital" transition

1) Systems theory and complexity

According to Mitchell [14], there are many definitions of complexity stemming from various leading scholars such as Warren Weaver, Herbert Simon, John Holland and Stephen Wolfram in this multi-disciplinary field that encompasses a range of theories and approaches across various disciplines, including physics, biology, social sciences, computer science, and philosophy. Complexity relates to the existence of numerous or infinite components and inter-relations that compose a system [14]. From those, Simon [13] introduced the concept of bounded rationality, linking to how decision-makers with limited information and cognitive resources make decisions in organisational settings. His work centred on human decision-making processes and organisational theory as distinct from the mathematical and algorithmic focus of other complexity theorists. He frequently discussed complexity in the social sciences through a formal or informal organisational lens such as business firms and governments, but also informal groupings of structure with clusters of dense social interactions, beyond a well-defined hierarchic structure [13].

Overall, complexity relates to systems theory [13, 15]. Thinking in terms of systems originated from the need to respond to multi-dimensional problems beyond black-box approaches. Systems thinking emerged soon after World War II and offered a constructivist approach to the positivism of operations research that emerged in the interwar period [16]. INCOSE defines a system as an "arrangement of parts or elements that together exhibit behaviour or meaning that the individual constituents do not" [17]. Accordingly, they state that the system's properties as a whole emerge from its elements and their relationships and interactions amongst themselves and their environment (Ibid), which is called by Klir [16] a set of things, thing-hood and a set of relations among these things, system-hood. According to the System Dynamics society, systems thinking is a "causality-driven, holistic approach to describing the interactive relationships between components inside a system as well as influences from outside the system" and approach of thinking and learning [18] with background from various fields such as philosophy, sociology, organizational theory, and feedback thought.

2) Complexity in construction projects

Complexity is a ubiquitous phenomenon in the construction sector. Winch [19] identifies high inter-connectedness, unpredictability and high user involvement in the innovation process as traits of a complex product system, such as construction. Complexity is a multi-faceted phenomenon and could refer to various aspects of the industry such as (1) technical product complexity, due to the inherently complex design and construction processes, (2) operational or processual complexity, from the rigidities that develop along the various operations and (3) organisational complexity, which relates to the vast amount of the involved multi-disciplinary organisations [20]. In delivering innovation initiatives such as sustainability objectives of the Net Zero transition and the dual "twin green and digital" transition, projects are the main delivery mechanisms, because projects are *de facto* vessels of delivering innovation [21]. Undoubtedly, sustainability objectives such as reaching Net Zero, relate to the whole lifecycle and are materialised especially in operations. However, although the impact of Net Zero can be realised in operations, this study focuses on the front-end of projects as that sets the basis and requirements for reaching such objectives. Afterall, starting with the end in mind is crucial in managing change initiatives in complex projects [22].

Major projects such as infrastructure assets are conceptualised as complex systems with various interacting parts [22, 23]. Although a project system with few components is easy to manage and organise through traditional project management approaches and tools, more complex product systems (COPS), such as railways, airports, aircrafts, require a network of collaborators coordinated by a large organisation reliant on formal, elaborate and bureaucratic processes of reporting and control [24]. Large and complex systems lead to complexity of managing systems [25]. Apart from a large number of components, in a complex project, these components must be mutually adjusted to each other, creating the need for their dynamic adjustment and interactions [26]. To this end, the more complex the system, the higher the likelihood of information uncertainty, making task coordination and project management more difficult [27]. Consequently, in such complex projects to manage change initiatives such as delivering sustainability objectives, asset information and data become key deliverables set early on by key social actors [23].

This study focuses on human decision-making processes and complexity following informal groupings of structure with clusters of dense social interactions, beyond a well-defined hierarchic structure following Simon [13]. Boisot and Child [28] synthesised various definitions of complexity and identified two complementary views of complexity: cognitive and relational. *Cognitive complexity* focuses on the content of information flows among social actors and *relational complexity* on the structure of the social interactions that such flows allow among social actors. These informal structures that Simon [13] describes are the pre-conditions emerging in the front-end of efforts for delivering the dual "twin green and digital" transition and are becoming increasingly important in both the transition to Net Zero and the development of Connected DTs as explained in the next sub-sections.

B. From sustainability to the Net Zero transition

The concept of Net Zero has been discussed a lot recently in conjunction with other sustainability efforts to fight climate change. Sustainability is the 'triple bottom line' (3BL) of people, planet and profit (or societal, environmental and economic sustainability). Elkington [29], who developed the 3BL term, notes that business leaders predominantly focus on economic sustainability for business profit, however, success or failure on sustainability objectives cannot be measured only as profit, but instead as wellbeing of people and planetary health. This implies that sustainability is not only a business proposition and cost-cutting exercise but needs to be considered as part of a socio-technical system (STS).

The landmark Paris Agreement of 2015 set the requirements for a transition to a low-carbon economy that has increasingly adopted globally, to restrict post-industrialisation global warming to below 2°C. Following this, various countries are issuing widespread governmental green growth policies. In 2019, the United Kingdom (UK) became the first G7 country to legislate for Net Zero, targeting 2050 Net Zero carbon emissions [30]. The Net Zero vision describes man-made decarbonisation efforts that stop adding new climate-heating gases/emissions to the atmosphere. Green House Gas (GHG) emissions are categorised into scope 1, 2 and 3, showing different kinds of GHG a company creates in its own operations and across its wider value chain. While Scope 1 covers direct emissions from owned or controlled sources and Scope 2 indirect emissions from the purchase and use of energy, Scope 3 includes all other indirect emissions that occur in the upstream and downstream activities of an organisation, e.g., from its supply chain. Due to its large size, Scope 3 are very important to be measured. Since buildings are responsible for 28% of global energy related carbon [8], they contribute significantly to the complexity of the Net Zero vision and have a massive role to play in reaching it [31]. Additionally, in mapping the upstream and downstream activities of an organisation, a large number of stakeholders are involved regarding legislation, awareness and engagement [32], which contributes even further to the complexity of Net Zero.

According to the Oxford Net Zero initiative, it is important to differentiate between Net Zero (NZ) and Carbon Neutrality (CN) [33]. These two initiatives, despite sharing some similarities, have different outlooks with regard to (a) timing, (b) emission reduction goals and (c) offset strategy. CN relates to the need for organisation in reducing carbon emissions and buying offsets for the rest, whereas NZ focuses on the need to reduce emissions as much as possible, and only then use removal-based offsets for the rest. Thus, Carbon Neutrality is short-term whereas Net Zero is long-term. CN is a tool focusing on short-term and immediate emissions reductions, and can be thought of as an important intermediate step to achieving NZ [33]. The long-term vision of reaching Net Zero requires an understanding of the innate complexity of built assets and stakeholders, which this study focuses on.

C. Digital transformation and Connected Digital Twins

1) Origins of Digital Twins

Digital technologies could support sustainability efforts and enable corporations to meet their sustainability objectives reaching Net Zero. This study focuses on DTs that due to their properties can support modelling and analysis of a wide range of behaviours, including sustainability. DTs are models of an object or system, a related evolving set of data and a dynamic update or adjustment of the model in accordance to data (simulation) [34]. DTs were originally defined by Grieves [2] paving the way to cyber-physical interaction and convergence between physical and cyber worlds of production. DTs were created to support Product Lifecycle Management (PLM) in the engineering and manufacturing sectors [35]. DTs of today are still based on the same components to the original models developed more than two decades ago consisting of "mirrored spaces" and their connection in a tri-partite form: (a) physical space and products, (b) virtual or digital space and products, and (c) the connection between the two spaces [35].

DTs are based on embeddedness of information into physical objects that can be stripped and repackaged as an entity [35]. To this end, DTs are closely interrelated with information and therefore also the raw data that, after contextualization, result in pieces of information [36]. Therefore, DTs are very data-heavy and throughout their conceptual evolution they have been relying on an increased level of complexity of information. Grieves [35] identifies five phases from Traditional (Phase 0), Transitional (Phase 1), Conceptual (Phase 2), Replicative (Phase 3) and Front-running (Phase 4) that are analogous to the complexity of information and maturity of virtuality. In theory, digital twins can update data in real time, so that virtual models undergo continuous improvement by comparing virtual with physical assets [3]. DTs bring together data across product lifecycle, promoting efficient synergies between different stages [37], laying the foundation that enables traceability and better control of sustainability objectives.

2) Applications and scope of Digital Twins

DTs have numerous applications across many industries from smart manufacturing, health, smart cities, energy, transportation, public emergency and agriculture [38], and their adoption and diffusion is continuously growing, thus recognising their potential [39]. Applications range from manufacturing supply chains for elasticity and resilient recovery in disruption effects [40] by optimizing the supply chain to support emergency decision-making. Another application concerns automation and reduction of manual processes in plants, that can eventually outperform human operators in their judgement and decision-making [41]. Such interventions can also have implications for reducing emission levels in plant operations. Through a systematic literature review, it was identified that among other trends, sustainable DTs have the potential to become dominant in technology development [39].

In the built environment, DTs have several use cases that focus on the construction and buildings sector. DTs have applications to simulation of construction site logistics [42, 43], workforce and safety [44], building performance [45], energy efficiency [46], facility management and preventive maintenance [47], temporary structures monitoring [48], healthcare facilities management [49], financial management in public sector projects [50] and a variety of other applications [51]. These applications range across execution and operation phases of construction projects but are often disconnected and developed as post-hoc interventions after assets are set up. The integration of such applications across execution and operation could enable accurate decision-making at the start of the asset lifecycle for establishing desirable future asset behaviour and meeting Net Zero. These interventions require alignment of DT systems requirements and stakeholders at the front-end, which is the focus of this study.

The scope and scale of DTs has rapidly increased recently [35]. The Gemini Principles argue for aggregating data and activities to monitor large-scale sustainability objectives in smart-cities [4], via ‘Connected DTs’ or ‘ecosystems of DTs’. Therefore, DTs need to be considered beyond boundaries of isolated systems but from a System of Systems (SoS) view. The system-level view (previously discussed in managing complexity) only tells part of the story as DTs are not isolated but connected across various systems. SoS require a holistic approach beyond engineering systems including socio-technical and socio-economic views [52]. SoS are sets of systems or system elements that interact to provide a unique capability that none of the constituent systems can accomplish on its own [53]. Other definitions of SoS also exist dependent on particular application area [54] leading some to claim that there is no formal definition of SoS [55]. Here, an SoS is the integration of various pre-existing, independent complex systems called Constituent Systems (CS) [56]. In a SoS the various CSs may retain their operational and managerial independence [57], but as a distributed system they show emergent behaviour that makes their structure, relationships and interactions complex [56].

III. Methodology

A. Rationale for a Systems thinking approach

A system is defined as a complex set of interacting elements, and a system is said to be complex due to the multiplicity of its elements and their interactions, as well as the diversity of behaviours and properties it can exhibit [58]. Systems thinking assists with the decision-making of managers in making more informed decisions. Systems thinking is a methodological approach that relates to thinking and learning about interrelationships between variables of a system [18] often involving the use of formal or simulation models to analyze a complex system and to favor its understanding. It is based on the concept that "the whole is greater than the sum of parts" and everything is connected to everything else [59] with an emphasis on the interactions and feedback loops within a system. It includes a set of qualitative (such as Causal Loop Diagrams) and quantitative (such as System Dynamics) modelling principles that can be used to conceptualise the underlying feedback loop structure, and to simulate the repercussions of potential decisions over time. Systems thinking is especially useful in model testing, policy design and organisational learning [59]. At this point, it is important to differentiate systems thinking from System Dynamics (SD), the former being an approach to using, understanding and learning from systems and the latter a quantitative modelling tool [18]. In this study, we align with the Richmond [18] definition of systems thinking as an overarching concept that encompasses SD, in contrast with Forrester [60] who views systems thinking as a small and negligible sub-set of SD [18].

A system thinking methodological approach can help understand complexity in research by providing a structured way to analyze the interactions and feedback loops within a system. It allows for a better understanding of the behavioral dynamics of a system, supporting the decision-making processes that should lead to the improvement of the system. Moreover, it helps to mitigate the cognitive limits of decision-makers by providing a more comprehensive understanding of the system's dynamics. Sterman [59] defines complexity in terms of the number of, or links among, the elements of a system, or the dimensionality of a search space and argues that systems thinking, as SD, is a valuable quantitative tool to understanding and managing complexity. Especially in a complex system involving many diverse stakeholders, there is a need for appropriate methodological support in order to engage these diverse participants to take part during the model design process [58].

Main systems thinking methodological tools are influence diagrams, level-rate diagrams, and simulations. Influence diagrams highlight both variables of a system and links between these variables, indicating the polarity associated with causal links to distinguish between positive feedback loops and negative loops. Causal Loop Diagrams (CLD) are similar to influence diagrams and used to understand complex systems, such as immunization, that are hard to grasp and counterintuitive with traditional methods [61]. CLDs were was first discussed in the 60s by [60] and further elaborated by Sterman [59]. CLDs emerged as first step of the SD modelling processes, but are a self-standing systems mapping method now that may also be used as a stepping-stone to developing SD models [62, 63]. SD is quantitative modelling that represents a system with stocks and flows. Simulation models are a decision-support system, testing and comparing different scenarios of "fictive" actions to predict future behaviours of the system under consideration. Bérard [58] emphasises using various techniques such as the Delphi method, nominal group technique, system archetypes, and influence diagrams as methodological tools in systems thinking. The benefit of systems thinking is its ability to capture complex dynamics and create an environment for learning and policy design, allowing for better understanding and improvement of the behavioral dynamics of a system.

B. *Research context of UK construction*

There is a wealth of relevant applications of systems thinking, which is particularly useful in complex systems and especially sustainable systems [64]. Built and infrastructure systems that are characterised by complexity, such as transportation infrastructure of inland waterways, can benefit from the systems thinking approach to optimize the essentiality of constituent parts for modernisation and maintenance decisions [65]. As the construction sector is a key contributor to carbon emissions [7, 8, 66], Net Zero attracts a lot of government and industry interest. This situation makes construction an ideal study setting, and its STS nature warrants a system thinking approach. The study scope is the entirety of construction including infrastructure and buildings that have relevant ‘dual transition’ use cases.

C. *Methodology and research stages*

Systems thinking relates to system philosophy, established by Laszlo [67] based on the premise that it is "organismic" rather than "mechanistic" in nature. Recent efforts attempt to connect systems thinking with critical realism [68]. As per the background, complex STS are largely influenced by humans and organisational cultures [12]. It is thus necessary to use methodological pluralism to understand them [69]. First, the study accepts critical realism to understand how the complexity of Net Zero transition can be managed though Connected Digital Twins initiatives. Because this study poses ‘how’ RQs, multi-methods and data types were deployed. Creswell [70] claimed that combining and triangulating different data sources enhances research accuracy. Gorard and Taylor [71] challenged the dominance of monothematic research methods and supported the synthesis of findings from triangulation. The two RQs were each addressed by combining two data collection and analysis methods in Stage 1 and Stage 2, respectively. These multi-methods were complemented by Stage 3 focus groups to induce communicative validity [72] by involving participants to check data accuracy and enrich interpretations. This exploratory research had three stages:

- Stage 1: Interviews with a multi-stakeholder sample of 53 experts from the construction sector and its related ecosystem of manufacturing and energy sectors;
- Stage 2: Modelling using Causal Loop Diagram (CLD);
- Stage 3: Focus group with 15 participants recruited from the interviews (n=11) and the academic community (n=4) to validate the CLD and reflect on the complexity.

D. *Data collection and analysis methods*

1) *Interviews: Problem definition*

In Stage 1, data was collected through interviews with industry experts to increase data richness [70] as interviews are considered appropriate means to capture their input. In total, 53 industry experts were interviewed online between November 2022-February 2023 and the average interview duration was 48 minutes 36 seconds (see Appendix-Table A). The sample provided saturation, when no new information was added [73]. Table I presents their basic profiles diverse background information (in terms of sector) and roles across industry, policy and a few from academia. Appendix-Table B presents their detailed profiles and the use case where they have experience in both DTs and Net Zero, and how the pointers to interviewees are made, e.g.: “Int-x”, where “x” their ID number.

TABLE I

SUMMARY OF INTERVIEWEE PROFILES

Role	#	Company	#	Background	#	Experience	#
CEO/ CTO	7	Architecture/ Engineering	4	Architecture	7	Senior	46
Sales/ Strategy	2	Consultancy	6	Business	8	Junior	7
Technologists	3	Technology	10	Engineering	34		
Researchers	8	Manufacturing	6	Finance	3		
Executives	8	Academia/ Research	5	Law	1		
Consultants	5	Contractor	4				
Managers	6	Finance	1				
Manufacturer	1	Asset Management/ Client	5				
Director	1	Professional/ Industry Inst	6				
Head of Digital	5	Government/ Policy	3				
Engineer	7	Energy	3				
Totals	53						

All interviews were conducted via teleconference and all interviewees had been appropriately briefed about the research contents and the interview protocol beforehand and signed consent forms allowing the recording of the interviews. The questions were designed to reflect the research aim and question. Seven semi-structured, open-ended questions 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 initiatives. Afterwards, the questions were reflective about the Net Zero transition, the STS developing around DTs and how key stakeholders such as industry, market, government, policy can support this dual transition.

The transcripts were analysed through 'coding' [74]. The study used both deductive and inductive coding, consistent with qualitative content analysis. As there is not a definitive manner to rigorously analyse qualitative data [75] the theoretical framework was used as a sensitising concept for data analysis [76]. Constructs of the theoretical framework were used as deductive (theory-based) codes that directed the analysis of the dataset. Next, inductive codes (data-based) from repetitive ideas emerged from the data. The deductive codes were terms such as 'net zero, 'digital twins, 'system' and so forth. The inductive codes were in vivo codes, based on words or phrases directly from data [77] that presented personal and unique quotations of interviewees. The coding took place in the atlas.ti Qualitative Data Analysis (QDA) software.

2) CLD: Developing mental models

In Stage 2, CLDs were used to facilitate the understanding of a system, enabling agreement on different policies and priorities. CLPs are the basis for developing SD models [63], an approach to studying world phenomena was introduced by [60] in the 1960s, originally as a modelling methodology to support decision making for long-term goals and for solving dynamic industrial management problems by mapping system causal factor interactions [59]. Therefore, while SD models are about quantitatively simulating and analysing those relationships over time a CLD is more about identifying and understanding the relationships and feedback loops in a system in a qualitative manner. As self-standing models CLDs allow to understand how complex systems change through internal feedback loops in their structure that influence the entire system's behaviour. A relationship between two variables in a CLD is represented by an arrow showing the direction of influence. A positive sign on a link implies that a change in one variable results in a change in the same direction, whereas a negative sign denotes a change in the opposite direction. A feedback loop occurs when arrows connect a variable to itself through a series of other variables [61]. A feedback loop may be reinforcing (R) or balancing (B). A reinforcing loop is defined as a positive feedback system that represents a growing or declining action, while a balancing loop is a negative feedback system that is self-regulating.

Examining CLDs enables decision-makers to focus on the root causes of shortcomings and not the symptoms alone [61]. A CLD is a circular chain diagram of cause and effect used to

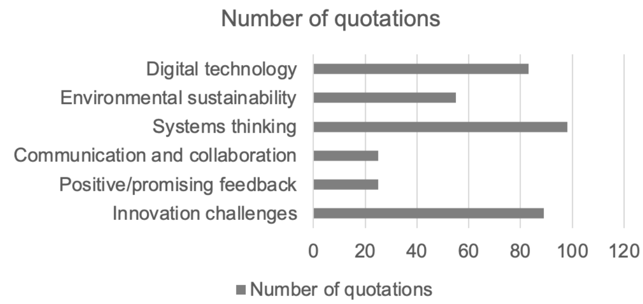

Fig. 1. Frequency of quotations on inductive topics of the interview data.

represent relationships between variables that are often difficult to describe [61]. Bérard [58] discusses the use of such diagrams to conceptualise complex systems, exchange mental models between individuals and groups, and communicate assumed important feedback loops. The CLD was created and tested in an interactive team exercise that forced the team to consider the elements of a DT for reaching NZ system and how they interact with each other [78]. The CLDs map out the structure and the feedback loops of a system to understand how behaviors and their feedback mechanisms are manifesting in a system so we can develop strategies to support or counteract them. CLDs also show to what extent and how the problem is connected with other "systems" [79] making them ideal tools for mapping SoS and different scales of systems. For instance, in studying complex innovation ecosystems, SD was used for macro- and micro-level analysis of the phenomenon [80]. To this end, CLDs can capture and analyse complex interactions between behavioral, technical, policy and cultural issues, providing a broad integrated view of the system. In this study, the CLD modeling was performed with the freeware 'Vensim PLE' software, a user-friendly modeling environment.

3) Focus group: Model testing and learning

Finally, in Stage 3, to strengthen the rigor of the research and evaluate the relevance and accuracy of the conclusions, we employed research validation methods to triangulate the results [72]. There are different types of research validation, such as construct validity (whether the study explores what it claims to be explore), internal validity (whether the data analysis was accurate, involving the research subjects) and external validity (involving new subjects external to the research) [81].

Here we focused on internal validation aimed at grasping the reflections of interviewees on the results and less on external validation involving four new participants to facilitate the focus group discussions. In systems thinking, Bérard [58] stresses the importance of involving many participants in the modelling process, aiming to increasing the relevance and usefulness of the model. This approach improves the mental models of participants and allows the alignment of their mental models to achieve consensus on how things work and make decisions by involving the group in these decisions. The focus group stage attracted 11 of the interviewee participants (Int-4,7,8,9,11,15,17,20,26,32,48,) in a representative sample. Eventually there were 15 participants with the addition of four academics and researchers as focus group participants to provide more research relevance. Since the focus group was

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online, it was deemed more efficient to break it into two sessions in June 2023 where participants could have more time to reflect and share their ideas. The two focus groups were conducted a week apart and reached saturation. The composition of the two focus groups was balanced and they were formed by interviewees with comparable backgrounds. The findings on the pathway (section 4.2.1), aggregation (section 4.2.2) and orchestrators (section 4.2.3) were synthesised from common themes that emerged independently in the two focus groups. Additionally, three other researchers familiar with the research (Researcher-1,2,3) were also included to help the first author in facilitating the discussions across the focus groups.

IV. Data and Findings

A. Stage 1: Emerging concepts and relations from interviews

Through an initial analysis of the data and in responding to RQ1 on how to understand the complexity of transitioning to Net Zero through DTs, the analysis focused on inductive coding to identify emerging themes and relations. In the inductive coding stage the emphasis was on vivo coding of words or phrases directly from data [77]. The full coding structure is shown in Appendix Figure A. Some representative quotations are presented next. Surprisingly, it was identified that although the interview protocol (Appendix-Table B) was explicitly on DTs and Net Zero, these codes did not emerge in adequate frequencies. Instead, the concepts of "digital tech*" and "data" emerged as proxies for DTs and (environmental) "sustainability" as a proxy for Net Zero initiatives. Additionally, there were other emerging in vivo codes such as "system", "communication", "collaboration", (innovation or transition) "challenges" that abounded. Notably, with regards to the transition, more challenges than positive reinforcements were discussed. Table II shows the frequency of these.

Next, through a co-occurrence analysis, the emerging topics identified above were cross-checked to identify how they emerged and if any strong relations were present in the interviews. The co-occurrence analysis of the inductive themes is shown in Table II and it is also colour-coded for ease of reading it. Despite the proxies explained above, it was found that digital technologies were not very strongly linked to (environmental) sustainability. There were only few mentions, for example, Int-5 stated: *"We live, increasingly, in a world where we think data is free and data is invisible. […]. However, the data is stored somewhere and needs energy to be generated, to be transmitted, to be stored, to be retransmitted, and to be retransmitted."* However, system approaches such as system thinking was linked strongly and equally to both the DT and Net Zero proxies. Systems thinking was also linked strongly to innovation and change challenges emerging as a solution in addressing the phenomenon.

TABLE II

CO-OCCURRENCE ANALYSIS OF KEY INDUCTIVE TOPICS OF THE INTERVIEW DATA

	Digital technology	Environmental sustainability	Systems thinking	Communication and collaboration	Positive feedback	Innovation challenges
Digital technology	N/A	13	25	0	6	25
Environmental sustainability	13	N/A	25	0	0	20
Systems thinking	25	25	N/A	2	3	30
Communication & collaboration	0	0	2	N/A	6	8
Positive feedback	6	0	3	6	N/A	0
Innovation challenges	25	20	30	8	0	N/A

Finally, apart from the emerging relations, there were associations of DTs and Net Zero, with other concepts too, that formed the basis for the CLD modelling presented in the next section. To organise these findings, the 3BL has been used across environmental, societal and economic sustainability. First, regarding environmental sustainability, interesting points were raised about the need to clarify the differences between Net Zero and decarbonisation, clearly defining scopes 1/2/3 (Int-35,36). Other emerging themes were: *"It's not just about Net Zero. It's also circular economy."* (Int-7) and importance of DTs *"Digital Twins can enable transparency and smart solutions. So, they can create a level playing field, for all companies, that kind of prevents greenwashing."* (Int-5).

Second, regarding economic sustainability, the importance of market and finance in enabling transitions was stressed (Int-8,21). The cost and impact of increased data requirements for DTs was highlighted as non-negligible aspect as firms *"invest quite a lot of time in engaging with individual organisations about data requirements"* (Int-32). However, the focus on long-term outcomes was stronger than economic benefits: *"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."* (Int-8).

Third, regarding social sustainability, important themes were how social actors affect and are affected by the NZ transition. According to Int-5: *"90% of that journey being cultural and information management and data flows",* showing that digital relies on cultural transformation. Equally, it was stressed that apart from the skills gap identified at the data handling level (Int-15), another skills gap was identified at the leadership or C-suite level (Int-5). All the above relations around the 3BL play a role in understanding the complexity of transitioning to NZ through DTs and forming building blocks of the CLD.

B. Stages 2-3: DTs for Net Zero from synthesis of CLD and focus group discussion

In presenting the data and findings from Stage 2 (CLD) it was deemed important for clarity and brevity of communication to present them together with the findings from the focus groups. This Stage 2 and Stage 3 data will be synthesised and presented together in an integrated format since the purpose of focus groups for internal validation is to validate and calibrate the findings. In the Stage 1 data presented above, some relations among key concepts were identified. In this step, the CLDs as circular chain diagrams of cause and effect are used to represent relationships between variables which are often difficult to describe.

1) Pathway of DTs for meeting the Net Zero vision

In responding to RQ1 about how to understand the complexity of Net Zero transition through digital twins, a qualitative CLD was created drawing upon Stage 1 data. Figure 2 shows the CLD of how the data-heavy concept of DTs connects to NZ as it was finetuned by the focus group. It shows the complexity of reaching NZ and untangles it by offering a decarbonisation route of continuously informed DTs by the physical asset and feeding carbon modelling data to it. In Figure 2 from left to right, DTs are unpacked into 'data input', 'data processing' and 'data output'. 'Data input' relates to data demand from various sources. 'Data processing' relates to carbon modelling and the provision of decarbonisation. 'Data output' relates to decarbonisation efforts and feedback mechanisms informing the 'data input' part anew.

In further analysing the CLD, it is important to discuss the reinforcing and balancing loops. The reinforcing loop R1 shows the relation between human actors and physical assets and how they are each informed by respected behaviors. R2 shows the relation between asset data from BIM systems and how they are influencing and influenced by 'data input' of DTs. R3 shows the reinforcing loop between individual DTs and Connected DTs via increased use of spatial data. R4 shows how DTs are organised from the relation between 'data input', 'data processing' and 'data output'. R5 illustrates the path from dashboards that communicate 'data output' to data sense-making, decision-making and human acceptance. R6 shows a feedback loop from policy resulting from 'data output' to data sense-making, decision-making and interventions/actions. Finally, the balancing loop B shows the self-regulating system from 'data output' to dashboards/mixed realities/policy through organisational capabilities and sharing culture to supply chain and contractual/benchmark/market data that give declining action relations to 'data input' and thus are regulating the system.

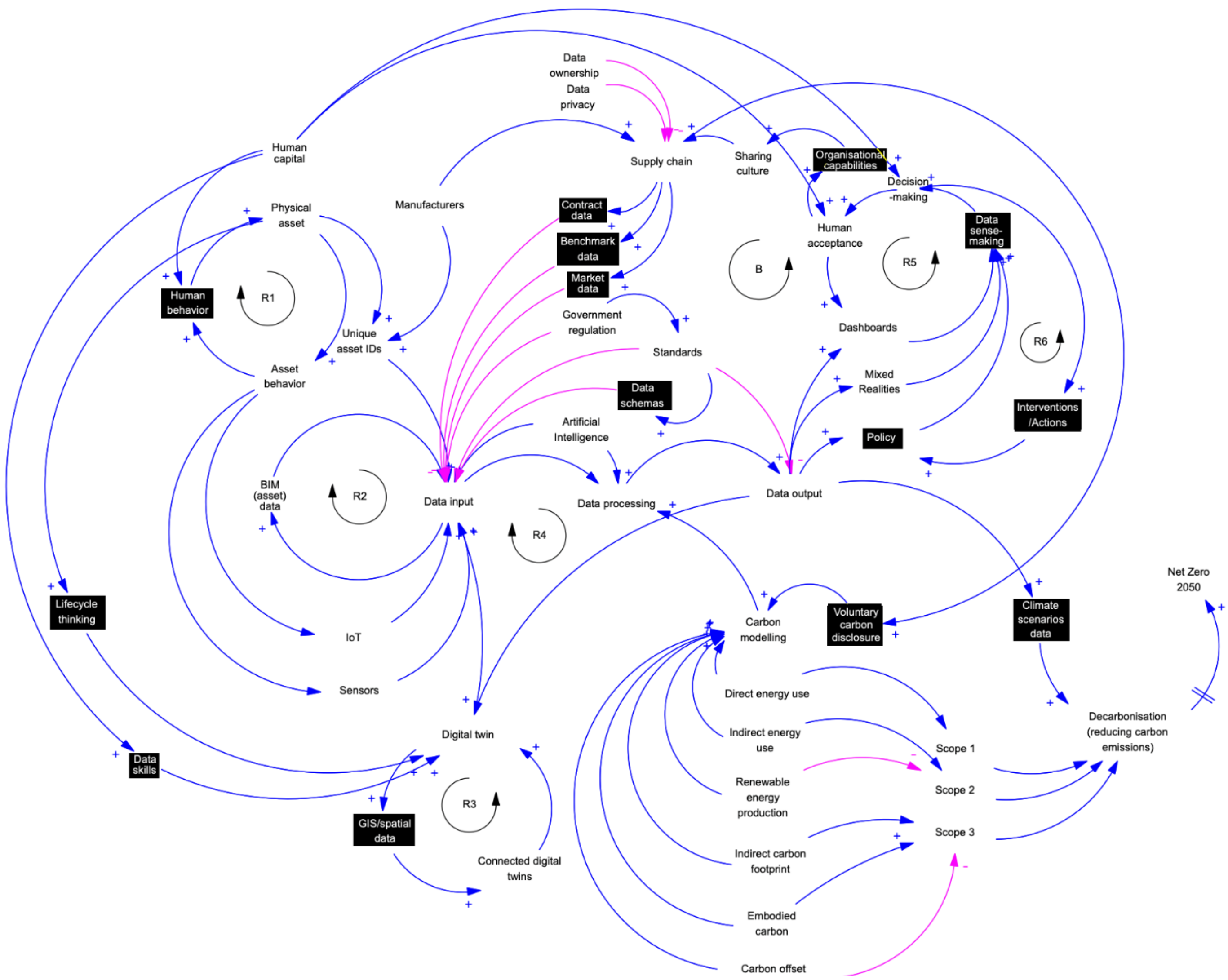

Fig. 2. Causal Loop Diagram (CLD) demonstrating the pathway from DTs to Net Zero (the blue arrows show 'growing' actions and the magenta arrows show 'declining actions). The black bounding boxes indicate factors that were added after the focus group.

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In delving deeper to understand the pathway from DTs to Net Zero, the influence of the focus group to the finetuning of the CLD is important, given that new relations emerged especially at the interfaces of 'data input', 'data processing' and 'data output'. These new relations are shown further in italics in Table III below. The focus group discussions validated the CLD and added new relationships among key concepts and strengthened or clarified other relationships in diverse ways based on the participants' expertise. The focus group did not remove any relationships but only added and consolidated existing ones in the CLD.

TABLE III
KEY RELATIONSHIPS (BLACK FONT) IN FIGURE 3 CLD AND NEW ADJUSTED (ADDED OR STRENGTHENED) RELATIONSHIPS (GREY ITALICISED FONT) AFTER THE FOCUS GROUP

Data input	Data processing	Data output

• (Data output)
• Physical asset
• Asset behaviour
• *User data*
• Asset IDs
• BIM (asset) data
• *GIS and spatial data*
• IoT data
• Sensor data
• Supply chain data
• Reference/benchmark data
• Government requirements
• *Contractual data*
• *Market/financial data*
• Standards, e.g., carbon declarations
• *Data schemas and dictionaries*
• Connected digital twins
	• (Data input)
	• Lifecycle thinking
	• *Lifecycle Assessment (LCA)*
	• Artificial Intelligence
	• Connected digital twins
	• Standards
	• *Voluntary carbon disclosure*
	• Carbon modelling:
	  • (Scope 1)
	  • (Scope 2)
	  • Scope 3
	• *Data on future climate scenarios*
	• *Skills for data processing*
		• (Data processing)
		• *Optimisation trade-offs*
		• Decarbonisation output
		• Artificial Intelligence
		• Standards
		• *Policy*
		• Dashboards
		• Mixed realities
		• Decision-making
		• *Actions & interventions*
		• *Organisational capabilities*
		• *Data sense-making*
		• Human acceptance
		• (Data input)

There were three main categories where the CLD was adjusted. First, with a focus on 'data input' the focus group participants stressed the importance of additional sources of data including user, spatial, benchmark, contractual and market data as well as links to schemas for interoperability and links to connected DTs. Second, in the 'data processing' area, the focus group discussed the need to integrate Lifecycle Assessment (LCA) and future climate scenarios data as well as align with necessary skills for data processing. Third, in the 'data output' area, the focus group stressed the importance of policy, actions and interventions stemming from the DT for Net Zero system and the need for organisational capabilities to support the system and data sense-making to support people making decisions based on it.

2) Aggregation of individual DTs in a Connected SoS to support Net Zero vision

After defining the pathway of DTs for meeting the Net Zero vision at an individual DT level, it is important to observe the phenomenon at a larger scale based on the idea of Connected DTs through a SoS view. In RQ2 on how individual DTs aggregate in a Connected DT SoS to support the transition to Net Zero, it is important to identify the relations between systems and how they can collectively contribute to the Net Zero objective. To support the readability of the SoS that is semi-hierarchical, it is presented in a tabular form in Table IV. The focus group validated the SoS and added new components to it without removing any. The focus group discussants emphasised that all the systems below, such as the Transportation SoS are of a socio-technical nature and stressed the relevance of the concept of 'doughnut economics' [82]. The focus group also differentiated between 'system of interest', that is the system whose life cycle is of interest to the project and 'enabling systems', such as finance or innovation as systems that contribute to the 'system of interest' during its lifecycle but not directly to its operation [83]; the latter are not illustrated in Table IV.

The implication of this SoS of DTs to address the Net Zero challenge is that key stakeholders such as asset owners, operators or policymakers could use it to identify interdependencies between individual DTs and strategise their pathways for achieving Net Zero. As SoS often span multiple organisational and jurisdictional boundaries this raises issues related to policy, regulation, and standards. Equally, the policy and regulatory implication is that collaborative and cross-jurisdictional approaches are needed for Net Zero. This SoS mapping also showed socio-technical considerations as the focus group emphasised on SoS being not just technical; but also involving social, organisational, and human factors. Finally, given this mapping has implications for resource allocation and economics given that efficient allocation of resources such as energy, materials and funds across the component systems are a complex task in SoS.

3) Orchestrators of the SoS

According to DeLaurentis, Moolchandani [56], systems thinking applied to a SoS needs to forgo any reliance on "total control" of the process. An emerging finding from the focus group was the idea of various levels of control on how the Connected DT SoS for Net Zero would operate. As a SoS is based on the independence of stakeholders of the constituent systems, meaning that information is compartmentalised and participation in the SoS needs to be incentivised especially if stakeholders have competing interests. Thus, questions emerged about who controls the data (see Table III), or how

TABLE IV
SYSTEM OF SYSTEMS (SOS) OF CONNECTED DIGITAL TWINS (DTS) FOR NET ZERO.(The existing constituent systems before the focus group are with black font and added or adjusted systems after the focus group are shown in grey italicised font)

	Constituent Systems (CSs) (or other SoS)		Interdependences	
			Supply	Demand
Net-Zero Digital Twins (DTs) System of Systems (SoS)	(i) Energy SoS	Energy systems	(ii)-(vi)	(vi), (vii)
		Renewable energy sources	(ii)-(vi)	(vi), (vii)
		Nuclear energy	*(ii)-(vi)*	*(vi), (vii)*
	(ii) Water System	-	(i), (v), (vi)	(vi), (vii)
	(iii) Transportation SoS	Road transport systems	(vi)	(i), (iv), (vi), (vii)
		Rail transport systems	(vi)	(i), (iv), (vi), (vii)
		Electric Vehicles (EV) system	(vi)	(i), (iv), (vi), (vii)
		Mobility-as-a-Service (MaaS) systems	*(vi)*	*(i)*
		Pedestrian system	*(vii)*	*(i)*
		Cycling system	*(vi)*	*(i), (vii)*
		Maritime system	*(vi)*	*(i), (vii)*
		Air transport system	*(vi)*	*(i)*
	(iv) Digital communication technologies	-	(i), (vi)	(i)-(vi)
	(v) Waste treatment SoS, incl. recycling	Wastewater	(iii), (vi)	(i)
		Solid waste	(vii)	(i)
	(vi) Built facilities	Buildings	(i)-(vi)	(i)-(iv)
		Industrial estates	(i)-(vi)	(i)-(iv)
	(vii) Nature, incl. climate	*-*	*-*	*(i)-(vi)*

competing issues among stakeholders with varying local goals and agendas are addressed.

Maier [57] categorised four types of SoS based on their decision-making authority: (a) directed SoS where a central authority exists, e.g.: urban transportation system, (b) acknowledged SoS where a designated manager is appointed, e.g.: global air transportation system, (c) collaborative SoS without any central objectives, management, authority, or funding, e.g.: internet, and (d) virtual SoS that is loosely connected since there is no centrally agreed-upon purpose for their assembly, e.g.: world-wide web. Based on the above categorisation, the first focus group reflected that the Connected DT SoS for Net Zero should be collaborative as *"part of the advantage of this approach of orchestration is that it can bring people together, rather than it just being one body. (…) So, we have to break the silos"* (Int-10). Additionally, Int-10 reflected:

> *"It kind of makes sense to have some local orchestrators. So, if you're having a number of connections, let's just say, in the energy area, it's good to orchestrate it to convene and connect, and to make it work together, but not control."*

The idea of 'local orchestrators' was supported in the second focus group too. Int-24 reflected that *"I wouldn't even go that far to say it's a consortium or collection of... 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."* Equally, apart from the idea of local, the idea of dynamic emerged. Researcher-2 *"mentioned a keyword, which was around 'dynamic', that we do have to anticipate change in this"*. In the same vein, Researcher-1 added that *"the orchestration of this federated system will evolve, depending on the power relationship, the interest relationships, etc., and also maybe the role of regulators on that, trying to set some limits or some regulations to the system."*

V. Discussion

A. Transitioning to Net Zero via Connected Digital Twins

1) Unpacking the complexity of transitioning to Net Zero through digital twins

In addressing the RQs, a combination of qualitative data from interviews, modelling of CLD and validation through focus groups was followed. This systems thinking approach was useful in unpacking the complexity of the pathway from DTs to Net Zero and especially testing the CLD for further policy development [59]. In unpacking this pathway, the link to data became particularly central, especially in input, processing and output. This showed a relationship between DTs and data that departed from the visualisation-focused approaches that have dominated the literature in construction [38] and instead focused on data science and pluralistic data sources. Also, Table III showed that the complexity of DTs for meeting Net Zero also relies on human and social factors apart from technical. With this approach, it was possible to describe the relationship between human decision-making and the transition complexity through relations of human and social capital, beyond hierarchic definitions [13]. Finally, the complexity of transitioning to Net Zero through DTs was apart from data- and human-centric, related to climate policy, e.g. around carbon benchmarking data, voluntary disclosure and future climate scenarios, all of which are factors in their infancy and deeply connected with emerging government policy.

2) Aggregation of DTs into Connected DTs System of Systems for Net Zero transition

To address RQ2, the focus was on how individual DTs in construction can be aggregated to a Connected DTs SoS. Modelling this system showed that it was more hierarchical than that of the individual DTs, highly interdependent (see Table IV) and of socio-technical nature. It was important to define its boundaries as a 'system of interest' without including 'enabling systems' that are also more likely to change and be affected by different contexts. A key emerging finding in the aggregation of DTs into a Connected DTs SoS for Net Zero transition was governance. This echoed extant research about independence of SoSs from "total control" [56] and instead related to orchestration of local actors federated in a dynamic structure. This implies a preference towards an open, consensus-based approach to network orchestration by connecting, facilitating and governing the SoS [84] as opposed to contractually enforced orchestration.

B. Theoretical contribution

This study has made contributions in strongly connecting the realms of digital technologies and environmental sustainability that have only sporadically been linked in research [85], despite been strongly linked in industry and policy papers [9, 86]. First, the study shed light on the complexity of both the domains of DTs and Net Zero and their joint complexity in using DTs as a vessel for addressing the Net Zero challenge. To this end, the study showed that their joint complexity was of technical (including both data requirements and software systems), social (including both human and organisational factors) and policy-related nature.

Second, the data showed the using digitalisation is key to meet sustainability objectives (see Int-5,7). This gave new support to the idea of how DTs can support SDGs [5]. Third, the co-occurrence analysis of the interview data (Table II) showed that whereas digital technologies and environmental sustainability are not very strongly linked directly, they were linked indirectly through system thinking. This reinforced the methodological approach of the study in deploying system thinking approaches as Del Vecchio, Mele [87] have highlighted the emerging applicability of CLD in strategic planning, prior to starting complex endeavors where lack of information and insufficient benchmarking data exist.

Finally, an important observation relates to how the emerging codes of the study, such as 'digital technologies' and 'environmental sustainability' worked as proxies of 'DTs' and 'Net Zero' respectively. This shows that these concepts and their relations are under development and support for these theoretical relations is developing. This is a phenomenon previously identified around digital transformation where digital technologies were vaguely defined [1]. To address the shortcoming of vagueness in describing technological artefacts, we unpacked under what conditions DTs support NZ by mapping and organising key features of DTs such as types of technological solutions, data and processing steps. Thus, this observation does not weaken the argument, but instead connects and contextualises it within extant information systems research.

C. Practical implications

The study has several implications at three main levels: (a) technical, (b) social and (c) policy-related. Regarding the data and technical implications, the study showed how asset data from various BIM systems and spatial data inform DTs and connected DTs (Figure 2,R2-R3) and how DTs are organised through 'data input', 'data processing' and 'data output' (R4). Regarding social implications, the pathway of DTs for Net Zero revealed the interdependence of humans and assets in DTs (Figure 2,R1) and a gap in data skills necessary for the development, operation, data sense-making and decision-making of DTs (see Table III and Figure 2,R5). These organisational implications also relate to leadership that is concerned with strategic directions for the attraction, development and retention of data-savvy talent [88]. Additionally, at an organisational level, business leaders and asset owners and operators need to integrate carbon modelling processes in their operations requiring alignment with various stakeholders across the supply chain.

In further support of the socio-technical nature of the DTs for Net Zero SoS, the third set of implications are on policy that is an enabler of the system. The 'data output' relates to data sense-making, decision-making and interventions/actions that are informing policy-makers (Figure2,R6). The study showed factors of 'government regulation', 'benchmarking data', 'market data' and 'voluntary carbon disclosure' strongly related to the context. As the data came from UK construction, the study was affected by its institutional context and local practices and directives. Other national contexts might have different regulations and standards. Finally, the emerging ideas of orchestration of federated Connected DTs for meeting Net Zero imply stakeholder dynamics that need to be aligned with SoS operation.

D. Limitations and future research

As with every research study, limitations can be identified from the beginning of the research design or be revealed when conducting it. The deployed systems thinking approach drew on involving many participants in the modelling process to increase research relevance [58]. Although additional measures were taken to minimise bias and increase validity such as internal and external validity [81], there are still limitations to consider. Using proxies of 'digital technologies' and 'environmental sustainability' for 'DTs' and 'Net Zero' respectively (Table II), could indicate sampling issues, although this phenomenon of using technology as proxy for its benefits is not new [89].

In the future, an SD model will follow the CLD with operationalisation and parameterisation of core variables of the proposed model to validate it further. As SD modelling is an approach to understanding the behavior of complex systems over time [60], this is crucial in the present pathway of DTs for Net Zero, given that data about the evolving nature of policy and system orchestration has been reported in the study already (see section IV). Future directions include that after completing this initial qualitative model, which explains the cause-effect relationships between the various phenomena through CLDs, it is necessary to move on to a quantitative mathematical modelling that will need to be further validated.

VI. Conclusions

This study set out to explore the dual transition, which the EU calls: 'twin green and digital' transition, and provide new evidence on how digital transformation can support environmental sustainability and in particular Net Zero objectives through DTs. To research the complexity of this transition, the study drew on a systems thinking approach featuring expert interviews, CLD modelling and focus group. The standpoint of the study was, from the front-end, aiming to reveal how relevant initiatives to meet these sustainability objectives can be set-up for successful outcomes. In addressing the first RQ, the pathway from DTs to Net Zero was shown as passing through the triad of 'data input', 'data processing' and 'data output' with input of 'carbon modelling' to 'data processing' and feedback loops from the 'data output' to 'data input' ensuring continuous updates from the digital asset to the physical asset. Additionally, in addressing the second RQ, the study developed a SoS logic aggregating relevant constituent socio-technical systems of interest. In developing the Connected DTs SoS for reaching Net Zero, emerging findings showed the need to define if and how the SoS will be controlled. The study showed clear directions towards a collaborative Connected DTs SoS for reaching Net Zero without the existence of central objectives, management, authority or funding. In managing the complexity of DTs to Net Zero, this study identified the relations of the key components of this dual transition and conditions for laying out the pathway to achieve it. Finally, it is worth noting that with growing complexity comes increased risk. This study has sought to clarify the critical elements of the complexity associated with the "twin green and digital" transformation, as a means of reducing this potential risk.

Appendix

TABLE A
Interview protocol: Semi-structured interview questions

Research summary

This research project focuses on digital twins for addressing environmental sustainability addressing global visions of Net Zero. Your responses to this interview, which will last circa 35-50 mins, 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 Net Zero. The findings will be synthesised to propose solutions to untangle 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.
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 B
DETAILED INTERVIEWEE PROFILES

ID	Role	Company	Background	Use case	Date
1	Founder/CEO	Architecture	Architecture	Buildings	2022-11-07
2	Sales	Technology	Business	Buildings	2022-11-18
3	Founder/CEO	Consultancy	Engineering	Infrastructure	2022-11-21
4	Technologist	Technology	Architecture	Buildings	2022-11-22
5	Founder/CEO	Manufacturing	Engineering	Manufacturing	2022-11-25
6	Researcher	Research Inst*	Engineering	Manufacturing	2022-11-25
7	Executive	Contractor	Engineering	Infrastructure	2022-12-01
8	Consultant	Finance	Finance	Cities	2022-12-02
9	Project Mgr**	Consultancy	Engineering	Infrastructure	2022-12-05
10	Strategy	Contractor	Law	Infrastructure	2022-12-07
11	Researcher	Academia	Engineering	Infrastructure	2022-12-08
12	Manufacturer	Manufacturing	Engineering	Manufacturing	2022-12-08
13	Consultant	Technology	Engineering	Buildings	2022-12-08
14	Consultant	Asset Mgmt***	Architecture	Buildings	2022-12-09
15	Researcher	Consultancy	Engineering	Infrastructure	2022-12-09
16	Consultant	Technology	Engineering	Buildings	2022-12-09
17	Executive	Professional Inst	Project Mgr	Buildings	2022-12-14
18	Programme Mgr	Policy Group	Business	Manufacturing	2022-12-15
19	Executive	Technology	Engineering	Buildings	2022-12-15
20	Researcher	Professional Inst	Finance	Buildings	2022-12-19
21	Researcher	Policy Group	Finance	Infrastructure	2022-12-19
22	Programme Mgr	Industry Group	Engineering	Manufacturing	2022-12-20
23	Project Mgr	Consultancy	Engineering	Buildings	2022-12-20
24	Engineer	Client/Operator	Architecture	Infrastructure	2022-12-21
25	Engineer	Architecture	Architecture	Buildings	2022-12-21
26	Engineer	Architecture	Architecture	Buildings	2022-12-21
27	Head of Digital	Contractor	Engineering	Buildings	2023-01-04
28	CTO****	Client/Operator	Engineering	Infrastructure	2023-01-04
29	Executive	Technology	Engineering	Manufacturing	2023-01-05
30	Executive	Professional Inst	Engineering	Infrastructure	2023-01-05
31	Engineer	Engineering	Engineering	Cities	2023-01-05
32	Director	Government	Business	Infrastructure	2023-01-06
33	Researcher	Academia	Engineering	Manufacturing	2023-01-05
34	Head of Digital	Energy	Engineering	Buildings	2023-01-09
35	Head of Digital	Client/Operator	Engineering	Infrastructure	2023-01-09
36	Asset Mgr	Client/Operator	Engineering	Infrastructure	2023-01-09
37	Founder/CEO	Manufacturing	Engineering	Manufacturing	2023-01-09
38	Consultant	Technology	Engineering	Manufacturing	2023-01-11
39	Executive	Technology	Business	Manufacturing	2023-01-11
40	Researcher	Consultancy	Engineering	Infrastructure	2023-01-11
41	Executive	Professional Inst	Business	Infrastructure	2023-01-11
42	Head of Digital	Technology	Engineering	Buildings	2023-01-11
43	Professor	Academia	Engineering	Manufacturing	2023-01-13
44	Executive	Professional Inst	Engineering	Buildings	2023-01-13

45	Engineer	Manufacturing	Engineering	Manufacturing	2023-01-16
46	Consultant	Technology	Engineering	Manufacturing	2023-01-19
47	Project Eng*****	Research Inst	Engineering	Manufacturing	2023-01-19
48	Consultant	Consultancy	Architecture	Manufacturing	2023-01-24
49	Founder/CEO	Manufacturing	Business	Manufacturing	2023-01-24
50	Head of Digital	Contractor	Engineering	Buildings	2023-01-25
51	Founder/CEO	Energy	Engineering	Infrastructure	2023-01-30
52	Project Eng	Manufacturing	Engineering	Manufacturing	2023-01-31
53	Innovation Mgr	Energy	Business	Cities	2023-01-31

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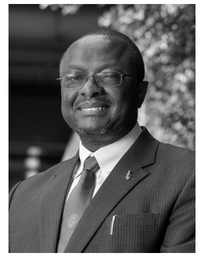

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