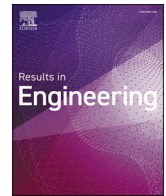


Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

A cooperative governance framework for sustainable digital transformation in construction: The role of digital enablement and digital strategy

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ARTICLE INFO

Keywords:

Sustainable digital transformation
Cooperative governance framework
Institutionalism
Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL)
Digital enablement
Digital strategy

ABSTRACT

Sustainable digital transformation is not just a technological shift but a comprehensive cultural and operational change for more efficient, effective, and sustainable processes. Existing studies neglect the importance of stakeholder collaboration in achieving these goals. This study addresses this gap by developing a Cooperative Governance Framework designed to align technological advancements with environmental and social objectives. Drawing on institutionalism and political systems theory, the study identifies five aspects and 36 criteria, using a hybrid approach of the Fuzzy Delphi Method and Fuzzy Decision Making Trial and Evaluation Laboratory. The study aims to identify and validate critical drivers of sustainable digital transformation in the construction industry, explore their interrelationships, and propose a comprehensive governance framework. The results validated 26 criteria and highlighted core drivers as digital enablement and digital strategy. Key practical findings emphasize the importance of digital infrastructure, competence, quality control, and business strategy integration for effective transformation.

1. Introduction

Digital transformation has potential to support progress towards sustainability however the current state encourages unsustainable practices that undermine the environment and social wellbeing [1–3]. According to the Coalition for Digital Environmental Sustainability [4], the current state contributes to a substantial share in global electricity consumption, reaching 7 %. The demand for digital technologies is also driving increasing demand on critical minerals globally and the rise of annual global e-waste production, which now stands at 54 million metric tons [5–7]. Moreover, an estimated one billion workers worldwide will lose a job to digital automation and other technologies by 2030 with potentially disastrous consequences for sustainable developments [1,4,8]. This points to the urgent need for Sustainable Digital Transformation (SDT) capabilities and potential solutions to decreasing negative environmental consequences, enhancing resource efficiency, and more generally fostering human well-being [3,9,10]. SDT is more than a shift in technology and operational and cultural change could benefit from advances to create better processes. However, the

prior studies provide limited insight into the importance of harmonious collaboration among SDT stakeholders [2,11]. Alghamdi et al. [12] found that lack of coordination among stakeholders led to isolated initiatives that fail to align with sustainability objectives. Moreover, prior studies highlighted that poor collaboration is key problem bringing misallocation of funds and poor use of resources which hinders the effectiveness of SDT efforts [13–15]. To ensure that technological advancements are in fact aligned with economic, environmental, and social goals, a cooperative governance framework (CGF) is necessary [9,16,17]. Therefore, this study generates new knowledge by bridging the fragmentation in existing literature, consolidating isolated insights on policy development, technology integration, and cultural change into a holistic and actionable governance framework.

In prior studies, different key drivers have been noted as significant for determining the successful implementation of digital initiatives while promoting sustainability [5,6,16]. For example, strategies have enabled actions to factor digital technologies into a coherent whole, supporting operational efficiency, innovation, and stakeholder engagement [3,5,18]. In turn, improved alignment underlies the necessity to

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<https://doi.org/10.1016/j.rineng.2025.104139>

Received 26 October 2024; Received in revised form 3 January 2025; Accepted 21 January 2025

Available online 23 January 2025

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ensure that the organizational structure, policies, and both technology-related and change processes are in place and coherent. Similarly, without resources, capabilities, and training, the ability to harness digital technologies and achieve positive results is limited [13, 19,20]. Technical performance is imperative to guarantee that the tools under consideration are adequate for the construction industry's demands and compatible with the facilities in place, thus measurably contributing to sustainability [9,21,22]. Another critical driver is organizational culture with its emphasis on the actual commitment to fostering digital literacy at all organizational levels [23–25,26]. However, while these aspects are critical, the existing literature often lacks fuller studies that encompass these dimensions into a single, unified framework [8,19,10]. Instead, relatively many works focus rather narrowly on individual drivers [16,17,24]. For these reasons, this study aims to develop a CGF based on the Institutionalism and Political Systems Theory to build a more all encompassing model that can inform the governance of SDT in construction [27,28].

This study uses Fuzzy Delphi Method and Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL). The construction industry comprises many stakeholders with varying expertise, perspectives, and interests [10]. The use of FDM is most suitable for synthesizing expert opinions and enhances the accuracy and generality of results; particularly when responses are highly uncertain and subjective, fuzzy logic can be used to well consider the context of uncertainty and vagueness of expert judgments [10,29]. Moreover, SDT contains complex interrelated drivers, such as technology, organizational culture, policies, and stakeholder dynamics. Therefore, FDEMATEL is the best method for analyzing and visualizing such complex interlinkages [30, 31]. The FDEMATEL is employed to identify the influence and dependence of the drivers for formulating a fuzzy cognitive framework influencing the development of SDT in the construction industry. The main objectives of this study are to:

- Identify and validate the SDT critical drivers in the construction industry using expert consensus
- Investigate the relationships and existence of the validated drivers cause-and-effect relationships
- Propose a CGF that provides practical and theoretical implications for aligning digitization with construction sustainability.

This study makes contributions to the field of SDT in the construction industry. Firstly, the study validates different drivers that influence SDT, and thus, offer a refined understanding of the criticality of these drivers and to what extent they serve as ultimate determinants ensuring positive outcomes. Secondly, the study uncovers the complex intricacies and insightful causal relationships, and hence, offers a clearer glimpse of these drivers and the way these factor triggers different outcomes. Finally, from a practical point of view, the construction of a CGF presented in this study has given rise to certain implications and will direct stakeholders to resort to more efficient and smart means in achieving more appealing results. The rest of the chapter is organized as follows: chapter 2 provides a literature review, chapter 3 covers the description of the methodology adopted in this study, chapter 4 provides the result and findings, the implications are provided in chapter 5 and, finally, chapter 6 concludes and provides recommendations for further research at the end.

2. Literature review

2.1. Conceptual framework

The study draws from Institutionalism and Political Systems Theory, thereby providing insights that are particularly valuable for comprehending the complex nature of the developing CGF [27,32–34]. Schiavi et al. [27] highlights institutionalism centers on the impacts of both formal and informal rules, norms, and other structures on the manner of

conduct of people within organizations and between industries. In the context of SDT, Burton-Jones et al. [32] defines institutions as all the relevant frameworks that offer guidance on how the digital strategies are to be organized, designed, and maintained. These encompass both regulatory standards and industry guidelines, and even the policies in individual organizations matched by informal norms of practice [28,26]. Since Institutionalism focuses on both the formal and informal structures, it is important both for understanding how different institutions facilitate or inhibit the adoption of digital technology and play a role in facilitating the alignment of organizational forms and processes to the digital objectives. Particularly in the SDT perspective, the theory explains the ways in which the norms and rules of different institutions are put in place to prescribe and constitute the digital technologies. For example, institutional norms and rules provide the criteria which technical performance are measured to ensure that digital solutions comply with industry standards and support SDT [10,34,35]. Even though limited, there are numerous perspectives offered by Institutionalism in relation to the structures and norms that are in place and how they facilitate the SDT process within the construction context.

Political systems theory, in turn, is related to the actions of the selection of a system's relevant interacting units or elements and the outputs from the system as public policy [36,37]. The theory looks at the way competing interests from government, business, and labor, among other groups, play out in producing the systems' social policy outcomes. In a construction context, digital transformation is an additional set of political systems, with a range of actors with competing interests and differential power and influence [3,18,10]. They include both government bodies and relevant industry associations to private corporate interest and labor unions. Applying Political systems theory to digital construction practices can enable better context understanding and lens via which to examine ongoing activities of SDT by recognizing how particular stakeholders are competing and negotiating among themselves, with other stakeholders, and the overall construction industry [33,38]. This theory is particularly useful for analyzing how providing the necessary resources, capabilities, and infrastructure for SDT is shaped by the political dynamics in the industry [19,20]. The theory also related on the role of political and social forces in the development of a digital culture in organizations including the advocacy of influential stakeholders and the push for regulatory reforms.

In combining Institutionalism and Political Systems Theory, this study anticipates the development of a CGF which presents the complex view of SDT in construction. Grounded in Institutionalism, this model will showcase the structural and normative constraints that shape the phenomenon, while Political Systems Theory can provide valuable insights into the political plays and resource dynamics that underpin the CGF.

2.2. Sustainable digital transformation

Extensive studies have been conducted on SDT in the construction industry, showing the concept's potential to change old techniques and improve sustainability [39–41]. Studies have demonstrated that technologies such as Building Information Modeling, Internet of Things, and Artificial Intelligence are advantageous to enhancing efficiency, decreasing waste, and assuring better resource management [9,13,42]. For example, Stojanovska-Georgievska et al. [42] showed how BIM enables better project coordination and visualization, which results in considerable time and cost savings. The significance of IoT in real-time monitoring and data collecting, which improves operational efficiency and decision-making processes, was highlighted by Maqbool et al. [43] and Moshood et al. [19]. Furthermore, Oloruye et al. [7] exploration of AI applications in predictive maintenance and construction site management has produced encouraging outcomes in terms of reducing downtime and maximizing resource utilization. Significant environmental benefits have also been associated with the integration of these technologies. Research shows that by maximizing material use and

enhancing energy efficiency, digital technologies may dramatically lower the carbon footprint of building projects [39,44,45]. These studies demonstrate how digital technologies can revolutionize sustainable building methods. Studies also highlight the difficulties in using digital technology, such as high implementation costs, a lack of technical know-how, and industrial opposition to change [46–48].

Despite these developments, the literature frequently offers a limited perspective by concentrating on SDT features or individual technologies [41,49,50]. Prebanić and Vukomanović [23], for example, emphasized the fragmented character of digital transformation initiatives, in which different stakeholders apply discrete solutions devoid of a cohesive plan. This fragmentation can lead to inefficiencies and reduced overall effectiveness. Furthermore, as Hassan et al. [10] point out, there is a notable regulatory lag in the construction sector because of which current rules are unable to keep up with the quick improvements in technology, resulting in a discrepancy between the potential and real benefits of digital transformation. Data security and privacy have been noted as important issues in earlier research. The privacy and security of data are becoming more and more important as building projects depend more and more on digital technologies for data management and collection. Previous studies [8,16,40] highlighted the weaknesses in the data governance processes that are in place and the importance of implementing strong cybersecurity measures to safeguard sensitive data. Studies that have already been conducted tend to concentrate on new developments in technology and their immediate effects rather than on the larger governance frameworks that are required to facilitate and maintain these developments [3,11]. Naji et al. [9] highlighted the need for additional study into how digital technologies can be integrated into current regulatory frameworks, but they did not offer specific suggestions for how to do so. To close this gap and guarantee that the advantages of digitalization are shared fairly among all parties involved, this research offers a thorough CGF that incorporates SDT techniques.

2.3. SDT aspects

Based on institutionalism and political systems theory, this study examines five critical driver aspects identified from existing literature that influence SDT in the construction. These drivers include Digital Strategy, Institutional Alignment, Digital Enablement, Technical Performance, and Digital Culture.

2.3.1. Digital strategy

Digital Strategy (AS1) represents an overarching plan that puts to work integrating digital technologies with organizations and industries [40,51]. The function of the digital strategy has changed from the end-to-end technologic process to aligning digital means with business requirements, scope, and sustainability [9,30,52]. Digital strategies in construction so far have centered around increasing efficiency, lowering costs, and implementing effective project management [18,41,53]. The latter, however, are not seen as sustainable digital strategies, but they undoubtedly have an impact on the environment and the use of resources. Hence, in recent years there has been a paradigm shift towards looking at using digital strategies sustainably. In other words, digital strategist prescribes a straightforward sequence on integrating technology with the sustainability goals and highly promotes a collaborative effort among stakeholders [17,54]. Moreover, to lead the construction sector through the challenges of SDT by managing the tradeoff and synergy between sustainability targets, collaboration, and overall project performance [40,55]. Therefore, digital strategy is an important part to consider for the formation of a CGF which can enhance the SDT success in construction sector.

2.3.2. Institutional alignment

Institutional Alignment (AS2) is a combination of policies, standards, and guidelines that are used across an organization or across multiple organizations towards achieving the same objectives [56–58]. This key

in making sure all stakeholder are working towards common goals on both sustainability and digital transformations [34,59,60]. Institutional alignment is about getting regulations, standards and governance structures compatible with stakeholder interest and SDT goals. This kind of alignment is crucial in construction, where projects are generally large-scale and include input from multiple stakeholders, not to mention the complex regulatory environment. Here, prior studies showed that the misalignment of institutions significantly affects the problem in adapting digital technologies and sustainability measures [25,42,61]. Varying regulations or standards might provide barriers to the implementation of new technologies or a lack of coordination among stakeholders might bring about inefficiencies and project delays [60,62,63]. Thus, institutional alignment is necessary to navigate these headwinds and enable SDT success. Adopting policies and practices that align the business creates an environment in which stakeholders can more effectively work together, share knowledge, and drive innovation. This is critical for developing CGF, merging the different skills and perspectives needed to understand complex challenges from an SDT perspective.

2.3.3. Digital enablement

Digital Enablement (AS3) encompasses the processes to empower organizations and individuals with tools, skills, and resources to effectively leverage digital technologies. The emphasis on transformation in the face of digital disruption has drawn attention to the importance of deploying digital technologies to achieve greater efficiency, lower costs, and better project-based results [25,64,64]. However, access to the tools is not alone enough, successful implementation of these technologies needs preparation in the stakeholders—with skills and competencies to use them as well [19,35,41]. Realizing the effort to BIM and other digital tools can be successful, provided the project team has been using these tools effectively. This in turn requires continuous training and support to ensure stakeholders have the right capabilities and knowledge [20,56,65]. Digital enablement facilitates innovation by providing stakeholders with the tools and resources to experiment with new technologies and approaches, leading to the creation of novel solutions for sustainability challenges [17,10]. Therefore, the study sets out to enrich this perspective by viewing digital enablement through the prism of capability ideal-type and its role in not only enhancing stakeholders' capabilities but also promoting innovation and thus aiding in sustainable outcomes for the successful implementation of CGFs.

2.3.4. Technical performance

Technical Performance (AS4) is related to the efficiency, reliability, and effectiveness of digital tools and technologies in achieving the desired impact and performance. Digital solutions must be sustainable and not only conform to the functional demands of construction projects but also help further sustainability targets at all aspects, from energy efficiency to waste, as well as resource management optimization [21, 23,30]. The effective BIM application is directly dependent on the provision of quality software and hardware solutions to enhance the appropriate exchange of data between stakeholders timely and accurate. Technical performance stands related to the functional and stable behavior of digital tools, but also includes how well these tools can integrate with other systems and processes in place. For the majority of construction projects, several digital solutions are used, however, their combined operation must be flawless in order to achieve the intended results [22,25]. This requires careful planning and coordination to make sure none of these systems become incompatible with the other parts. As such, technical performance is a crucial driver for the development of CGF and helps to fulfil SDT objectives.

2.3.5. Digital culture

Digital Culture (AS5) involves the appropriate use, attitudes and values towards digital technologies in the organization or industry. Prior studies in SDT suggest that in the digital era where technology is invading our ideas and thoughts, building and sustaining a digital

culture will significantly affect the success of transition [13,23,24]. Such organizations that possess a robust digital culture are more willing to adopt new tools and methods, experiment with novel solutions, and keep on refining their processes [3,19,66]. Which ultimately results in improved project results through greater efficiency, lower costs and improved sustainability. Equally vital is the potential of digital culture to promote collaboration as well as knowledge-sharing among a variety of stakeholders [9,20,67]. On construction projects we typically see a range of different parties with diverse skill sets and culture plays an important role in ensuring that all these groups can work together to solve the problems they face. This is particularly relevant for SDT since digital technologies must be adopted and adapted throughout the complete project life cycle with sustainability principles [17,13,34].

2.4. Proposed methods

The application of multiple-criteria decision-making (MCDM) techniques to evaluate and facilitate SDT is well-established, with various methods tailored to specific domains and decision environments. For instance, Tanveer et al. [68] employed a fuzzy TOPSIS model for selecting digital technologies in circular supply chains, effectively ranking alternatives based on their proximity to ideal solutions. Yüksel and Dinçe [69] adopted Quantum Spherical Fuzzy DEMATEL to assess criteria for cyclical production and digital transformation, further extending their analysis with ELECTRE for performance evaluation. Shahidpoorfalah et al. [70] prioritized risks associated with digital transformation using a Fuzzy-VIKOR approach, emphasizing its capability to handle trade-offs in compromise solutions. Similarly, Saraji et al. [71] developed a Fermatean fuzzy CRITIC—COPRAS framework to rank challenges in Industry 4.0 adoption within fintech companies, highlighting the importance of precise weighting methods. Chen [29] used DEMATEL combined with ANP to visualize and weight digital transformation criteria, followed by fuzzy comprehensive evaluation for assessing digital maturity in small enterprises. Finally, Li et al. [30] explored digital transformation pathways in the construction sector using DEMATEL-ANP, contributing to a systematic evaluation framework for Industry 4.0 adoption.

Despite these advancements, FDM and FDEMATEL offer distinct advantages that address critical gaps in SDT research [10,30,29]. FDM refines expert input iteratively, achieving consensus and filtering irrelevant factors — essential for developing a focused and reliable evaluation framework [9,10]. Furthermore, FDEMATEL excels in capturing and visualizing the causal relationships and interdependencies between SDT drivers, a capability that other MCDM techniques often lack [30, 29]. The integration of FDM and FDEMATEL thus provides a robust methodological foundation for this research, enabling a comprehensive and actionable understanding of SDT.

3. Methods

3.1. Case study

Somaliland is facing a growing need for housing due to population growth and rural displacement caused by droughts, is experiencing a surge in construction activities. These activities also bear negative impacts on the environment, further exacerbated by the urgency of climate change in Somaliland [72,73,31]. The shift has fuelled increasing competition for land and natural resources, in a situation where climate change is already Somaliland's pressing vulnerabilities. However, this has since woken the idea of green building initiatives due to these environmental concerns. Energy efficiency, waste reduction and use of eco-friendly materials have been the focus of many projects. With these ambitious sustainability pushes also comes the digitalisation of Somaliland construction, with various smart products being used to make processes faster and improve overall productive efficiency. WhatsApp is a popular for reporting from sites, to aid in instant on-time

communication and collaboration among the project teams. Through accounting and management software, they can provide secure financial tracking and project management and through structural analysis software we make sure that our building is safe. Additionally, leading telecommunications company Telesom has created the Xoogsade app that will provide contractors access to construction workers to solve labor shortages and streamline workforce management. Still, you cannot secure the ground of digitalization in a sustainable way without a complete governance model. This framework should set out the practices, standards and regulations which would regulate digitally based information sources in the construction industry [10]. This must also create training and capacity building programs to ensure a digitally adept workforce. By setting up a robust governance framework, Somaliland can not only improve the present digital efforts but also secure them for future success and consequences, in the end laying the foundation for an enhanced efficient, profitable, and durable construction sector.

3.2. Proposed measures

Based on the literature reviewed in this study, 36 criteria are proposed and re-classified into five main aspects. These dimensions are rooted in the theories of institutionalism and political systems theory which provide a strong framework for analyzing the drivers (Table 1).

3.3. Data collection

The research data for this study is obtained through expert surveys and online interviews to acquire the understanding of experienced stakeholders. To ensure that a minimum depth of experience is available and that only experts with at least 5 years of practice / experience in the field (building construction and renovation, technology sector, sustainability domain) are contacted an approach of purposive sampling was followed for expert selection. The process includes two types of questionnaires in the data collection. First is FDM questionnaire which uses a 5-point Likert scale, experts will rate the weightage/importance of SDT criteria, where 1 represents "Not Important" and 5 means "Extremely Important". The experts will then receive the FDEMATEL questionnaire following the FDM questionnaire. This questionnaire is based on a pairwise comparison method for valuing the influence and interrelations of the factor. The experts will rate the drivers on a five-point Likert scale (1 = No Influence; 5 = Strong Influence). Using these two questionnaires, the research is trying to record the experts view regarding the validated factors and the interrelationship among the SDT drivers. The research framework of this study is presented in Fig. 1.

The Table 2. Below summarizes the expert's profile.

3.4. Data analysis

The data collected from expert surveys and interviews is analyzed using FDM and FDEMATEL techniques discussed below to validate factors, assess interrelationships, and provide theoretical and practical implications.

3.4.1. FDM method

1. *Converting linguistic terms:* Expert evaluations expressed in linguistic terms are converted into corresponding Triangular Fuzzy Numbers (TFNs) using Table 3.

2. *Experts Consensus:* To consolidate expert opinions, the geometric mean of the fuzzy weight (w_j) of each criterion is calculated using Eq. (1).

$$w_j = \left\{ a_j = \min(a_{ij}), b_j = \left(\sum_{i=1}^n (b_{ij}) \right)^{1/n}, c_j = \max(c_{ij}) \right\} \quad (1)$$

where j indicates criterion j 's level of significance, i stands for the expert

Table 1
SDT drivers.

| Aspects | Criteria | Description | Supporting Reference |
|-------------------------------------|----------|----------------------------------|--|
| AS1: Digital Strategy | IC1 | Value proposition | The value offered by SDT such as efficiency, cost savings, etc. [17] |
| | IC2 | ICT procurement | Practices for acquiring and integrating information and technology systems. [53] |
| | IC3 | Digital service delivery | Methods for delivering digital services effectively [52] |
| | IC4 | Monitoring | Techniques for continuous assessment and evaluation of SDT initiatives. [9] |
| | IC5 | Customer centricity | Ensuring SDT efforts meeting the customer needs and expectations [9] |
| | IC6 | Research and development | Supporting R&D activities to drive innovation in SDT [30] |
| | IC7 | Digital startup incubation | Supporting the growth of startups focused on SDT [50] |
| | IC8 | Digital roadmap | A strategic plan outlining the steps and milestones for implementing SDT [54] |
| AS2: Institutional Alignment | IC9 | Policy levers | Government and organizational policies that can drive SDT [58] |
| | IC10 | Funding mechanisms | Financial strategies and sources to fund SDT ensuring sustainable investment. [42] |
| | IC11 | Financial scrutiny and oversight | Mechanisms for ensuring the effective uses of funds allocated for SDT [61] |
| | IC12 | Accountability and Transparency | Ensuring clear responsibilities and transparent processes in the management of SDT. [57] |
| | IC13 | Public trust | Building and maintaining trust among stakeholders [63] |
| AS3: Digital Enablement | IC14 | Promotion opportunities | Strategies for promoting the advantages of SDT to various stakeholders. [25] |
| | IC15 | Co-ordination mechanisms | Processes and structures to ensure effective coordination among different stakeholders. [17] |
| | IC16 | Stakeholder involvement | Engaging all relevant stakeholders in the SDT [10] |
| | IC17 | Organizational climate | Creating a supportive and innovative organizational culture [25] |
| | IC18 | Digital infrastructure | Developing and maintaining the necessary technological infrastructure [56] |
| | IC19 | Digital competence | Ensuring that employees and stakeholders have the necessary skills and knowledge [41] |
| | IC20 | Digital thinking | Encouraging a mindset that embraces digital innovation and continuous improvement. [57] |
| | IC21 | Digitalization of SMEs | Supporting small and medium-sized enterprises to adopt digital technologies. [66] |
| AS4: Technical Performance | IC22 | Data management | Implementing data management to ensure data accuracy, security, and accessibility. [23] |
| | IC23 | System reliability | Ensuring that digital systems are reliable and function as intended. [9] |
| | IC24 | Easy maintenance | Designing digital systems that are easy to maintain and update. [67] |
| | IC25 | System efficiency | Optimizing digital systems to maximize efficiency and performance. [30] |
| | IC26 | Cybersecurity measures | Implementing security measures to protect digital assets and data from cyber threats. [21] |
| | IC27 | Technological methodologies | Utilizing advanced technological methods and tools to enhance SDT. [9] |
| | IC28 | Cloud services | Leveraging cloud computing to enhance scalability, flexibility, and collaboration [25] |
| | IC29 | Business strategy | Aligning digital transformation efforts with the overall business strategy to ensure coherence and effectiveness. [30] |
| AS5: Digital Culture | IC30 | Change management | Managing the human and organizational aspects of SDT to ensure smooth transitions. [13] |
| | IC31 | Leadership commitment | Ensuring strong leadership support and commitment to drive digital transformation initiatives. [67] |
| | IC32 | Communication | Maintaining clear and effective communication throughout the SDT [23] |
| | IC33 | Digital quality control | Ensuring that SDT solutions meet quality standards and deliver consistent performance. [9] |
| | IC34 | Collaborative platforms | Implementing platforms that enable collaboration among stakeholders [17] |
| | IC35 | Consumer preferences | Considering the preferences and needs of consumers in the design and implementation [67] |
| | IC36 | Ethical considerations | Ensuring that SDT efforts adhere to ethical standards and practices [3] |

that rated the criterion, n refers to the number of interviewed experts, and a , b , and c indicate the values of the TFNs.

3. Defuzzification: The aggregated fuzzy weights are defuzzified using Eq. (2).

$$S_j = \frac{a_j + b_j + c_j}{3} \quad j = 1, 2, 3, \dots, m \quad (2)$$

where m is the total number of criteria considered.

4. Validating drivers: A threshold value (α) is used to determine which criteria are significant. If $S_j \geq \alpha$, the criterion is considered valid, while if $S_j < \alpha$, it is deemed insignificant and excluded from further analysis.

3.4.2. Fuzzy dematel

5. Converting linguistic terms: The expert pairwise comparison from the FDEMATEL questionnaire are converted into TFNs using Table 3.

6. Normalization: TFNs are normalized using Eq.3 to ensure comparability across criteria.

$$S = \left(s_{lij}^f, s_{mij}^f, s_{uij}^f \right) \\ = \left[\frac{\left(z_{lij}^f - \min z_{lij}^f \right)}{\left(\max z_{uij}^f - \min z_{lij}^f \right)}, \frac{\left(z_{mij}^f - \min z_{mij}^f \right)}{\left(\max z_{uij}^f - \min z_{lij}^f \right)}, \frac{\left(z_{uij}^f - \min z_{mij}^f \right)}{\left(\max z_{uij}^f - \min z_{lij}^f \right)} \right] \quad (3)$$

where $\left(s_{lij}^f, s_{mij}^f, s_{uij}^f \right)$ represents the normalized values of a TFN.

7. Computing normalized crisp values: Left (S_{lij}^f) and right (S_{rij}^f) normalized values, total normalized crisp values, and crisp values were calculated using Eq. (4), Eq. (5), and Eq. (6), respectively.

$$\left(S_{lij}^f, S_{rij}^f \right) = \left[\frac{s_{mij}^f}{\left(1 + s_{mij}^f - s_{lij}^f \right)}, \frac{s_{uij}^f}{\left(1 + s_{uij}^f - s_{mij}^f \right)} \right] \quad (4)$$

$$S_{ij}^f = \left[\frac{S_{lij}^f \left(1 - S_{lij}^f \right) + \left(S_{rij}^f \right)^2}{\left(1 - S_{lij}^f + S_{rij}^f \right)} \right] \quad (5)$$

$$\tilde{w}_{ij}^f = \min z_{lij}^f + S_{ij}^f \left(\max z_{uij}^f - \min z_{lij}^f \right) \quad (6)$$

8. Calculating synthetic value: Eq. (7) is used to calculate synthetic value by defining an initial direct relation matrix (IDRM) that sums the opinions of n experts.

$$w_{ij}^f = \frac{1}{n} \left(\tilde{w}_{ij}^1 + \tilde{w}_{ij}^2 + \tilde{w}_{ij}^3 + \dots + \tilde{w}_{ij}^f \right) \quad (7)$$

where w_{ij} denotes the degree to which criterion i affects criterion j .

9. Normalized direct relationship matrix (U): U value is obtained by standardizing the IDRM and applying Eq. (8).

$$U = w \otimes IDMR \quad (8)$$

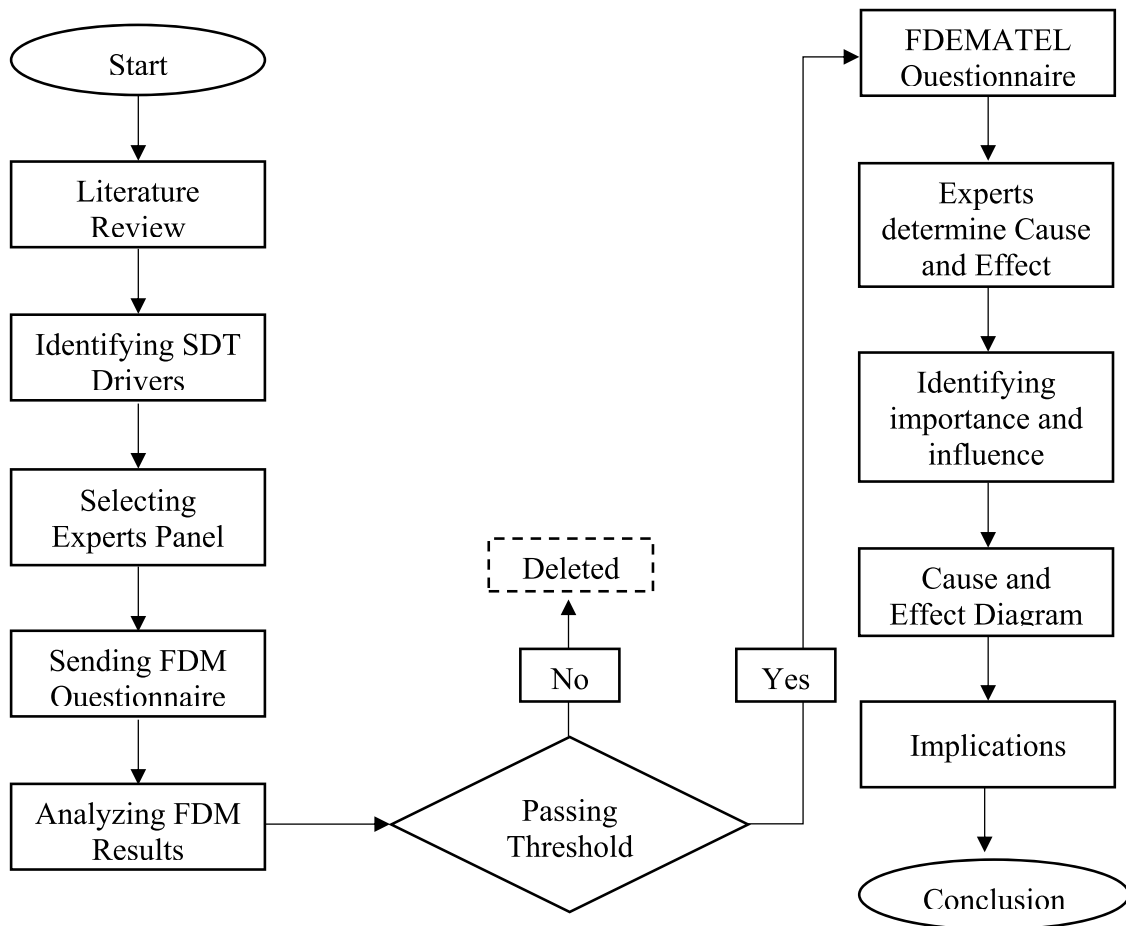


Fig. 1. Research framework.

Table 2
Expert profile.

| Expert # | Educational Background | Experience | Profession |
|-----------|------------------------|------------|------------|
| Expert 1 | Master | 8 | Industry |
| Expert 2 | PhD(c) | 5 | Academia |
| Expert 3 | Bachelor | 6 | Industry |
| Expert 4 | Master | 9 | Industry |
| Expert 5 | Bachelor | 8 | Industry |
| Expert 6 | PhD | 13 | Academia |
| Expert 7 | Master | 13 | Industry |
| Expert 8 | PhD | 5 | Industry |
| Expert 9 | Bachelor | 6 | Government |
| Expert 10 | Master | 5 | Industry |
| Expert 11 | Master | 12 | Industry |
| Expert 12 | Master | 10 | Academia |
| Expert 13 | Bachelor | 12 | Industry |
| Expert 14 | Master | 6 | Government |
| Expert 15 | Bachelor | 9 | Industry |
| Expert 16 | Bachelor | 6 | Industry |
| Expert 17 | PhD(c) | 9 | Industry |
| Expert 18 | PhD | 6 | Academia |
| Expert 19 | Bachelor | 8 | Government |
| Expert 20 | Bachelor | 10 | Industry |
| Expert 21 | Master | 7 | Industry |
| Expert 22 | Master | 5 | Industry |
| Expert 23 | Bachelor | 11 | Government |
| Expert 24 | Master | 7 | Industry |
| Expert 25 | Bachelor | 6 | Academia |
| Expert 26 | Bachelor | 10 | Industry |
| Expert 27 | Bachelor | 12 | Industry |
| Expert 28 | Master | 11 | Industry |
| Expert 29 | Bachelor | 6 | Government |
| Expert 30 | Master | 6 | Industry |

Table 3
TFNs for FDM and FDEMATEL assessment.

| Linguistic Terms | Corresponding TFNs | | |
|------------------|--------------------|------|------|
| Extreme | 0.75 | 1.00 | 1.00 |
| Demonstrated | 0.50 | 0.75 | 1.00 |
| Strong | 0.25 | 0.50 | 0.75 |
| Moderate | 0.00 | 0.25 | 0.50 |
| Equal | 0.00 | 0.00 | 0.25 |

where $w = \max(\sum_{j=1}^n w_{ij}^f)$ for all i from 1 to n .

10. Total interrelationship matrix Y : Eq. (9) is used to calculate Y value by utilizing the matrix U obtained in the previous step.

$$Y = U(I - U)^{-1} \tag{9}$$

where I represent an identity matrix of size n .

11. Establishing causal relationship: Lastly, the strength of the cause-and-effect relationship is determined by utilizing Eq. (10) and Eq. (11)

$$D = \sum_{j=1}^n U_{ij} \text{ for all } j \text{ from } 1 \text{ to } n \tag{10}$$

$$R = \sum_{i=1}^n U_{ij} \text{ for all } i \text{ from } 1 \text{ to } n \tag{11}$$

Vector D represents the cumulative values of the rows, whereas vector R represents the summation of the columns. The horizontal axis, referred to as the "prominence" axis, is formed by the sum of D and R . On

the other hand, the vertical axis, known as the "relation" axis, is determined by the difference between D and R. A positive value of (D-R) indicates membership in the causal group, highlighting the presence of causal attributes. Conversely, a negative value of (D-R) indicates recognition of the enabler as part of the effect group.

4. Results and findings

4.1. FDM results

The goal of the FDM analysis was to validate the criteria identified from the literature. The results indicate that 26 criteria were accepted, while 10 were rejected, based on their relevance and importance in the context of SDT in the construction industry in Somaliland. These accepted criteria met the threshold weight of 0.636 and will be utilized in the subsequent FDEMATEL analysis to further classify and prioritize these factors, ultimately aiding in the development of a robust governance framework for digital transformation. The results are shown in Table 4, while Table 5 displays the renumbered validated criteria.

4.2. FDEMATEL results

The expert committee used the validated drivers from the FDM results to assess the interrelationships among the attributes, employing the linguistic scales shown in Table 3. The initial direction matrix, created by averaging the crisp values from all experts, is presented in Table 6. The total interrelationship matrix for aspects is displayed in Table 7. Causal interrelationships among aspects and drivers were identified by computing the total interrelationship matrix, as shown in Table 8. Fig. 2 reveals the cause-and-effect map through the x and y axes. Core aspects

Table 4
FDM results.

| Criteria | Weight | Decision | |
|-----------|----------------------------------|--------------|----------|
| IC1 | Value proposition | 0.767 | Accepted |
| IC2 | ICT procurement | 0.454 | Rejected |
| IC3 | Digital service delivery | 0.765 | Accepted |
| IC4 | Monitoring | 0.417 | Rejected |
| IC5 | Customer centricity | 0.750 | Rejected |
| IC6 | Research and development | 0.651 | Accepted |
| IC7 | Digital startup incubation | 0.408 | Rejected |
| IC8 | Digital roadmap | 0.655 | Rejected |
| IC9 | Policy levers | 0.681 | Rejected |
| IC10 | Funding mechanisms | 0.767 | Accepted |
| IC11 | Financial scrutiny and oversight | 0.770 | Accepted |
| IC12 | Accountability and Transparency | 0.658 | Rejected |
| IC13 | Public trust | 0.430 | Rejected |
| IC14 | Promotion opportunities | 0.765 | Accepted |
| IC15 | Co-ordination mechanisms | 0.660 | Accepted |
| IC16 | Stakeholder involvement | 0.651 | Accepted |
| IC17 | Organizational climate | 0.522 | Accepted |
| IC18 | Digital infrastructure | 0.761 | Rejected |
| IC19 | Digital competence | 0.772 | Accepted |
| IC20 | Digital thinking | 0.649 | Accepted |
| IC21 | Digitalization of SMEs | 0.765 | Rejected |
| IC22 | Data management | 0.667 | Accepted |
| IC23 | System reliability | 0.759 | Rejected |
| IC24 | Easy maintenance | 0.410 | Rejected |
| IC25 | System efficiency | 0.655 | Accepted |
| IC26 | Cybersecurity measures | 0.774 | Rejected |
| IC27 | Technological methodologies | 0.426 | Rejected |
| IC28 | Cloud services | 0.452 | Accepted |
| IC29 | Business strategy | 0.651 | Accepted |
| IC30 | Change management | 0.668 | Accepted |
| IC31 | Leadership commitment | 0.786 | Rejected |
| IC32 | Communication | 0.532 | Accepted |
| IC33 | Digital quality control | 0.664 | Rejected |
| IC34 | Collaborative platforms | 0.654 | Rejected |
| IC35 | Consumer preferences | 0.408 | Rejected |
| IC36 | Ethical considerations | 0.653 | Accepted |
| Threshold | | 0.636 | |

Table 5
Validated criteria.

| Aspect | Criteria | |
|------------------------------|----------|----------------------------------|
| AS1: Digital Strategy | C1 | Value proposition |
| | C2 | Digital service delivery |
| | C3 | Customer centricity |
| | C4 | Research and development |
| | C5 | Digital roadmap |
| AS2: Institutional Alignment | C6 | Policy levers |
| | C7 | Funding mechanisms |
| | C8 | Financial scrutiny and oversight |
| | C9 | Accountability and Transparency |
| | C10 | Promotion opportunities |
| AS3: Digital Enablement | C11 | Co-ordination mechanisms |
| | C12 | Stakeholder involvement |
| | C13 | Digital infrastructure |
| | C14 | Digital competence |
| | C15 | Digital thinking |
| AS4: Technical Performance | C16 | Digitalization of SMEs |
| | C17 | Data management |
| | C18 | System reliability |
| | C19 | System efficiency |
| | C20 | Cybersecurity measures |
| AS5: Digital Culture | C21 | Business strategy |
| | C22 | Change management |
| | C23 | Leadership commitment |
| | C24 | Digital quality control |
| | C25 | Collaborative platforms |
| | C26 | Ethical considerations |

Table 6
Initial direction matrix for aspects.

| | A1 | A2 | A3 | A4 | A5 |
|----|-------|-------|-------|-------|-------|
| A1 | 0.808 | 0.800 | 0.767 | 0.583 | 0.748 |
| A2 | 0.441 | 0.595 | 0.441 | 0.264 | 0.305 |
| A3 | 0.699 | 0.728 | 0.743 | 0.402 | 0.741 |
| A4 | 0.654 | 0.685 | 0.646 | 0.568 | 0.417 |
| A5 | 0.207 | 0.221 | 0.208 | 0.193 | 0.470 |

Table 7
Total interrelationship matrix for aspects.

| | A1 | A2 | A3 | A4 | A5 |
|----|-------|-------|-------|-------|-------|
| A1 | 0.746 | 0.788 | 0.735 | 0.528 | 0.714 |
| A2 | 0.413 | 0.481 | 0.413 | 0.277 | 0.365 |
| A3 | 0.652 | 0.699 | 0.664 | 0.433 | 0.653 |
| A4 | 0.617 | 0.663 | 0.615 | 0.463 | 0.534 |
| A5 | 0.219 | 0.236 | 0.219 | 0.168 | 0.290 |

Table 8
Cause-and-effect group among aspects.

| Aspect | R | D | D + R | D-R | |
|--------|-------------------------|-------|-------|-------|---------|
| A1 | Digital Strategy | 2.648 | 3.512 | 6.159 | 0.864 |
| A2 | Institutional Alignment | 2.867 | 1.950 | 4.818 | (0.917) |
| A3 | Digital Enablement | 2.646 | 3.101 | 5.747 | 0.455 |
| A4 | Technical Performance | 1.869 | 2.892 | 4.761 | 1.023 |
| A5 | Digital Culture | 2.557 | 1.131 | 3.689 | (1.426) |

identified are AS3: Digital Enablement and AS1: Digital Strategy, while AS2: Institutional Alignment and AS4: Technical Performance are driving factors. AS5: Digital Culture is the influenced aspect. In Appendix A, Table A1. provides the criteria's initial direct relation matrix, Table A2. shows the total interrelationship matrix for criteria, and Table 9 details the criteria's cause-and-effect relationships, which are then used to create the cause-and-effect map depicted in Fig. 3. Criteria above the horizontal line are considered causal, while those below are considered effects. The most significant criteria are C13: Digital

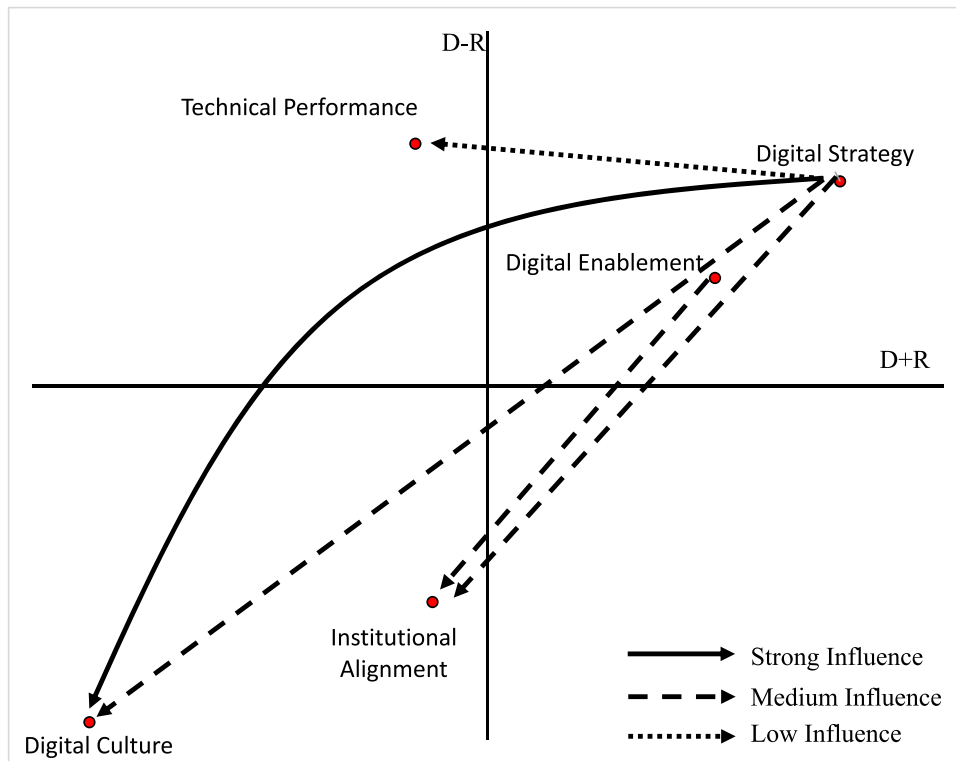


Fig. 2. Aspect causal-effect diagram.

Table 9 Cause-and-effect group among criteria.

| Criteria | R | D | D + R | D-R |
|-------------------------------------|-------|-------|-------|---------|
| C1 Value proposition | 1.478 | 2.575 | 4.052 | (1.097) |
| C2 Digital service delivery | 1.472 | 2.168 | 3.640 | (0.695) |
| C3 Customer centricity | 1.585 | 2.599 | 4.184 | (1.013) |
| C4 Research and development | 2.085 | 1.739 | 3.824 | 0.347 |
| C5 Digital roadmap | 2.107 | 1.796 | 3.903 | 0.311 |
| C6 Policy levers | 2.105 | 1.712 | 3.818 | 0.393 |
| C7 Funding mechanisms | 2.107 | 1.506 | 3.613 | 0.601 |
| C8 Financial scrutiny and oversight | 1.614 | 2.000 | 3.614 | (0.386) |
| C9 Accountability and Transparency | 1.633 | 1.882 | 3.515 | (0.249) |
| C10 Promotion opportunities | 1.769 | 2.260 | 4.029 | (0.491) |
| C11 Co-ordination mechanisms | 1.564 | 1.947 | 3.511 | (0.383) |
| C12 Stakeholder involvement | 1.346 | 1.968 | 3.314 | (0.623) |
| C13 Digital infrastructure | 2.898 | 1.252 | 4.150 | 1.000 |
| C14 Digital competence | 2.839 | 1.255 | 4.094 | 0.900 |
| C15 Digital thinking | 1.799 | 1.840 | 3.639 | (0.041) |
| C16 Digitalization of SMEs | 1.746 | 2.061 | 3.807 | (0.314) |
| C17 Data management | 1.619 | 1.980 | 3.599 | (0.360) |
| C18 System reliability | 1.629 | 1.853 | 3.482 | (0.225) |
| C19 System efficiency | 1.849 | 2.346 | 4.195 | (0.497) |
| C20 Cybersecurity measures | 2.235 | 1.347 | 3.582 | 0.889 |
| C21 Business strategy | 2.063 | 1.880 | 3.943 | 0.183 |
| C22 Change management | 1.608 | 1.844 | 3.451 | (0.236) |
| C23 Leadership commitment | 2.097 | 1.671 | 3.767 | 0.426 |
| C24 Digital quality control | 2.247 | 1.860 | 4.107 | 0.387 |
| C25 Collaborative platforms | 1.543 | 1.968 | 3.511 | (0.425) |
| C26 Ethical considerations | 1.802 | 1.531 | 3.333 | 0.271 |

infrastructure, C14: Digital competence, C24: Digital quality control, C5: Digital roadmap, and C21: Business strategy.

5. Implications

5.1. Theoretical implications

The theoretical implications from this study are based on the top core

aspects and the driving aspects from FDEMATEL graph.

Digital enablement is a significant factor in the CGF of digital transformation for sustainable development, providing substantial theoretical contributions. While existing studies highlight the critical role of digital infrastructure and tools in industry-wide changes [19,25, 10], this study goes further by demonstrating that digital enablement must be integrated not only at the operational level but also at the governance level. In contrast to prior research that primarily focused on technological adoption in developed economies, our findings emphasize the importance of digital enablement in emerging economies, where the challenges of digital adoption differ significantly. Thus, our study extends the existing literature by framing digital enablement as a governance tool essential for achieving sustainable development goals in resource-constrained environments.

Digital strategy also emerges as a critical factor, underscoring the importance of aligning technological initiatives with broader business and governance objectives. Existing theories recommend incorporating digital strategy into corporate strategies [9,54]; however, the findings from this study stress that in CGF, a multi-stakeholder digital strategy is essential to ensure cohesion and purposefulness across different sectors. This contribution is particularly relevant in contexts where diverse actors—governments, private firms, and civil society—must work together toward common sustainable development goals. By focusing on the role of governance in digital strategy formulation, our study refines existing theories that primarily focus on the firm-level strategy.

5.2. Practical implications

The theoretical implications from this study are based on the top core aspects and the driving aspects from FDEMATEL graph.

Existing studies on SDT highlight that a well-developed digital infrastructure is fundamental to enabling collaboration among stakeholders [11,56]. For instance, according to Chen et al. [41], digital infrastructure facilitates data-driven decision-making and real-time monitoring, significantly improving operational efficiency in

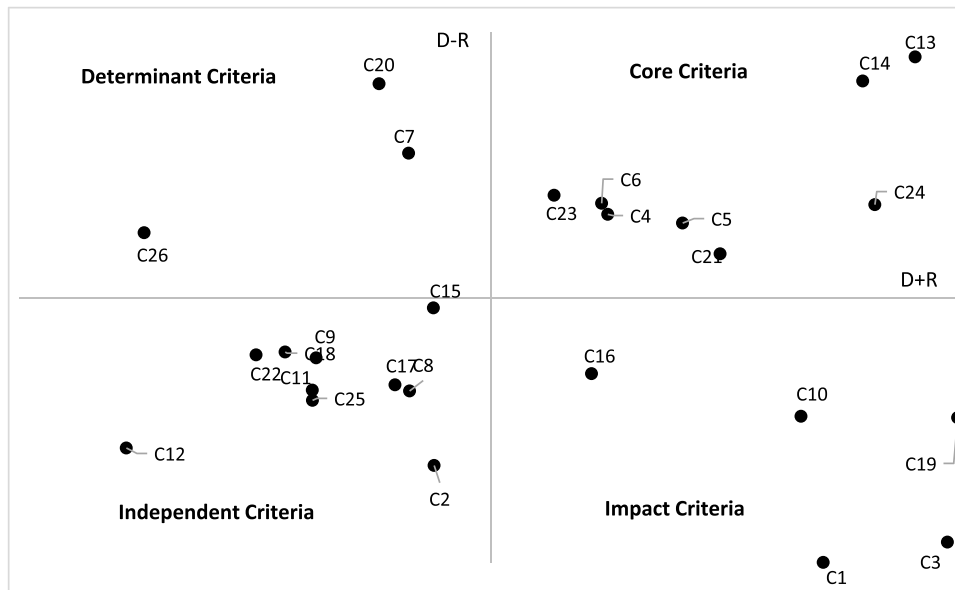


Fig. 3. Criteria causal-effect diagram.

construction projects. In alignment with this, our findings underscore the importance of robust digital infrastructure (C13) is needed to achieve cooperative governance. A well-embedded digital infrastructure enables communication, data sharing, and integration across government bodies, construction firms, and overseeing and regulatory authorities, enhancing oversight of these key stakeholders and making it easy to monitor project progress in real time. Additionally, digital infrastructure enables contractors to manage construction projects better and make timely decisions at every stage of the construction process. By allowing timely and early decision-making, the construction process in Somaliland will be made easier and cheaper, thus making the client more likely to adopt more modern methods and have the required tools to do so, which is targeted in digital transformation. The high usage of new innovative methods by contractors will improve the construction process, cut costs, and thus make cooperative governance easier to implement.

Digital competence (C14) of the workforce is required to ensure that strategies are effectively put into place and to increase digital capability. While prior studies have acknowledged the importance of equipping individuals with necessary skills and knowledge to utilize digital tools and technologies [1,34,41], our study emphasizes the role of digital competence as a core enabler of CGF in SDT. Unlike existing literature that focuses on individual or firm-level skill development, this study highlights the need for capacity-building programs that foster a collective, cross-sector culture of continuous learning and adaptability. This ensures that diverse stakeholders are proficient and aligned in their digital efforts, which is crucial in SDT in emerging economies. Enhancing digital competence enables construction professionals to adopt innovative practices, which in turn improve productivity, and ensure the effective execution of digital strategies. Thus, this competence is essential for achieving CGF by ensuring all stakeholders are proficient and aligned in their digital efforts.

The study also found that the implementation of effective digital quality control measures (C24) helps the construction industry to achieve success in SDT. This is consistent with the findings of prior studies [5,9,57], who argue that digital quality assurance is vital for ensuring compliance. On contrary, while prior work has focused on quality control at the operational level, our study emphasize that digital quality control measures ensure compliance with governance standards and foster stakeholder confidence. This contribution is especially relevant in contexts where regulatory compliance and risk mitigation are necessary

to SDT success. Digital quality control procedures guarantee regular assessment, auditing and validation of digital processes, tools, and results in accordance with specific standards and goals. With digital quality control mechanisms being in place, it will be easier to ensure that the implementation of high-quality digital processes and tools also facilitates compliance with existing regulations and standards, greater reliability, and greater accuracy of digital procedures overall. Furthermore, this would help build stakeholder confidence in the digital solutions, as they will have an assurance of their quality and effectiveness.

Digital roadmap (C5) is imperative for building a proper foundation for the construction industry. Existing literature discusses the importance of roadmaps in SDT [1,54]; however, our findings stress that roadmaps in CGF serve a dual purpose: (i) aligning diverse stakeholders toward a common strategic vision and (ii) ensuring proper synchronization of digital processes with governance requirements. This structured, systematic approach to digital implementation fosters prioritization, resource allocation, and milestone tracking, which are essential for sustaining progress in SDT initiatives. Practically, this means that policymakers and industry leaders should develop strategic roadmaps with clear milestones and allocate resources accordingly to ensure coordinated efforts across all stakeholders.

Integrating digital transformation into business strategy (C21) constructs a cooperate governance factor that anchors digital initiatives with the overall vision and goals of construction firms. Studies by Li et al. [30] and Rupeika-Apoga et al. [2] suggest that firms that integrate digital strategies in their overall business models report higher innovation rates and competitive advantage. While these prior studies emphasize the benefits of integration of digital business strategies, our study highlights how this integration serves as a governance mechanism that anchors SDT in the broader goals of sustainability. This integration will ensure that digital efforts are coherent and relevant to the company and, thus, sustainable. Firms integrated SDT with business strategy will embrace innovation, increase competitiveness, and, consequently, increase firm growth.

6. Conclusion

Digital transformation presents a significant opportunity in advancing the effectiveness and efficiency of building projects, but the current practice has negative environmental and social consequences. The existing SDT studies in the construction industry disregard the

importance of collaborative action and the need for cooperative governance approaches designed to align stakeholder interests with SDT goals. A CGF ensures that advancement in technology is in line with the construction industry's sustainability goals. The identified research gap in this study involves underdevelopment of a framework that integrates the critical drivers of collaborative governance towards SDT. This study aims to develop a CGF that ensures effective digitalization by addressing the SDT drivers from the perspective of governance. Research objective will be developing a CGF tool by identifying and validating the key factors through expert consensus. The tools for data analysis in this study are FDM and FDEMATEL, which prioritizes the identified factors.

Based on Institutionalism and Political Systems Theory, the study identified and validated 26 criteria out of the proposed 36 criteria based on their relevance and importance in the context of SDT in the construction industry. Subsequently, the FDEMATEL analysis indicated digital enablement and digital strategy are the core driving factors which influence the institutional alignment, technical performance, and digital culture. The findings also highlight that digital infrastructure, digital competence, quality control, a clear digital roadmap, and integration into business strategy are crucial for effective SDT. Theoretically, these results underscore the importance of aligning digital initiatives with broader business and sustainability goals, while practically, suggest that enhancing digital infrastructure and competence, implementing quality controls, and integrating digital strategies into overall business plans are essential for achieving cooperative governance for successful SDT.

This study faces several limitations. The attributes analyzed were derived from existing literature, which may not encompass all relevant aspects of SDT. Future research should incorporate attributes from practical and operational contexts to provide a more comprehensive evaluation. Additionally, expert opinions on these attributes might be influenced by individual differences in knowledge, experience, and perspectives. While no biases were detected in this study, expanding the sample size could help mitigate such issues in future work. Furthermore, the study's findings are based exclusively on insights from experts in Somaliland. Including data from other countries or regions could improve the generalizability of the results and lead to a more robust CGF.

Funding

This research was partially funded by University of Hargeisa, Somaliland.

CRediT authorship contribution statement

Ahmed Mohammed Shirwa: Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Abdiqani Muse Hassan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Abdiqani Qorane Hassan:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Muslum Kilinc:** Supervision.

Declaration of competing interest

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

Supplementary material

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.rineng.2025.104139](https://doi.org/10.1016/j.rineng.2025.104139).

Data availability

Data will be made available on request.

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