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Navigating Circular Economy and Digitalisation: A Comparative Study of Manufacturing Strategies in the UK and Saudi Arabia

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Abstract

This study presents an integrated framework for evaluating manufacturing maturity in embracing circular economy principles and digital technologies, with a focus on comparing best practices between the UK and Saudi Arabia. The framework incorporates circular economy principles, such as waste elimination, material circulation, and nature regeneration, across product, process, and business model innovations. It also encompasses key Industry 4.0 technologies that facilitate smart and connected manufacturing. Utilising secondary data sources, the research maps the capabilities of selected manufacturers in both countries across categories including operations and technology. The findings indicate that the UK leads in most areas due to its sustained emphasis on sustainability and digitalisation over the past decade. In contrast, Saudi Arabia exhibits a lack of concrete policies and investments in these domains but demonstrates the potential for adapting UK practices to its unique context. The study proposes a staged roadmap to guide Saudi Arabia in a systematic transition towards circular and digital manufacturing, emphasising coordinated efforts in policy, infrastructure development, skills enhancement, and industry collaboration. This comparative assessment offers valuable insights into manufacturing best practices and opportunities for improvement.

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Keywords: Circular Economy; Digital Transformation; Industry 4.0; Benchmarking; Saudi Arabia; UK

1. Introduction

In the quest for sustainable manufacturing practices and enhanced competitiveness, recent years have witnessed growing interest in the intersection of circular economy (CE) principles and Industry 4.0 (I4.0) technologies [1,2]. Despite this interest, a significant gap persists in understanding how manufacturers can systematically integrate these strategies to realise their full potential [3]. This paper seeks to bridge this gap by developing a comprehensive capability maturity assessment framework tailored for manufacturers in both the United Kingdom (UK) and Saudi Arabia (SA), aiming to guide their adoption of CE principles and I4.0 technologies.

1.1. Overview of manufacturing sectors

The manufacturing sectors of the UK and Saudi Arabia, contributing nearly 8% and 14% to each nation's GDP respectively, are poised for substantial growth by 2030 [4]. These sectors encompass a wide array of industries, including petrochemicals, metals, machinery, electronics, and food production. Embracing circular practices such as renewable energy utilisation, material recycling, and product life extension, alongside the integration of digital technologies, holds promise for enhancing resource productivity and reducing environmental impacts.

Building upon this foundation, this paper has developed a structured evaluation framework to assess manufacturing

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readiness for adopting CE principles and I4.0 technologies in both the UK and Saudi Arabia. Through an analysis of current practices, the paper has identified successful strategies and approaches, serving as valuable benchmarks for stakeholders seeking to enhance sustainability and competitiveness. Leveraging insights from the UK, the paper has also proposed a high-level roadmap to guide Saudi Arabia in achieving its circular economy and digitalisation objectives, providing actionable steps for stakeholders in both countries.

2. Literature Review

This section delves into the pertinent literature on CE and I4.0, encompassing principles, visions in the UK and SA, existing frameworks, and their respective categories, pillars, and sub-pillars. A comprehensive search across scholarly databases including google scholar, scopus, science direct, and research gate was conducted, employing keywords including "circular economy," "industry 4.0," "digital transition," "manufacturing best practices," "sustainable manufacturing," "smart manufacturing," "UK manufacturing," "Saudi Arabia manufacturing," "Saudi Arabia industry 4.0 Policies," and "UK circular economy policies".

This search yielded around 150 articles, which were meticulously sorted based on publication year, framework availability, and relevance to the UK and SA. The literature review revealed a notable gap concerning the unavailability of integrated frameworks addressing both CE and Digital Transition (DT). Through this study, this gap was addressed by developing the Circular Economy and Digital Transition (CE-DT) framework.

2.1. Industry 4.0

Industry 4.0 encapsulates the utilisation of emerging digital technologies such as industrial internet-of-things (IIoT), artificial intelligence (AI), cloud computing, additive manufacturing, and advanced robotics to establish smart, interconnected manufacturing systems [5]. This paradigm shift enables advanced tracking, monitoring, and analytics, thereby optimising production efficiency while concurrently reducing costs and environmental footprints. Integrating I4.0 with CE strategies holds significant promise in maximising resource efficiency and sustainability in manufacturing. Key technological visions underpinning Industry 4.0, as identified in various studies [6,7], include autonomous robots, simulation, horizontal and vertical integration, IIoT, big data analytics, augmented reality, additive manufacturing, cybersecurity, and cloud computing. Through an extensive literature review, existing DT frameworks [8–14] were accessed to delineate categories, pillars, and sub-pillars for further analysis.

2.2. Circular economy

The circular economy offers an alternative to linear economic models, aiming to minimise resource consumption, waste generation, and emissions [15]. Through a thorough review of existing frameworks, the study identified key principles essential for the manufacturing sector, with the Ellen MacArthur Foundation's principles being the most influential [16]. An analysis comparing various frameworks, including the 10R framework [17], 5R framework [18], and strategies for resource recycling [19], with the Ellen MacArthur Foundation's principles confirmed their comprehensive coverage. "Regenerate nature," "elimination of waste and pollution," and "circulation of products and materials" emerged as foundational for the circular economy framework.

As explained by the Ellen MacArthur Foundation [20], "regenerate nature" emphasises conserving natural resources, enhancing natural capital, and minimising waste through emulation of nature's regenerative processes. "Elimination of waste and pollution" ensures materials can be reintroduced into the economy, mitigating waste and pollution. Similarly, "circulation of products and materials" advocates maintaining materials in use, prolonging their lifecycle within the economy. Aligned with these principles, the framework encompasses three categories: circular business model, circular product design, and operations. Circular business model evaluates a company's alignment with circular economy principles in its business model [21,22]. Circular product design focuses on integrating circularity into product and process design [19], emphasising new product development for environmental sustainability [23]. Operations encompass sustainable manufacturing, circular supply chain management, and organisational culture [19,24].

Pillars within each category were selected based on their prevalence in existing frameworks and studies, mentioned above. Additionally, sub-pillars were chosen to comprehensively cover factors relevant to each pillar, ensuring a holistic approach to circular economy implementation.

3. Research Methodology

3.1. Principles and values

The research methodology commenced with a comprehensive review of existing literature to identify the fundamental principles and visions of circular economy and Industry 4.0, respectively. From the circular economy perspective, principles such as regeneration of nature, elimination of waste and pollution, and circulation of products and materials were selected. In parallel, visions encompassing autonomous robots, simulation, horizontal and vertical integration, industrial internet-of-things, big data analytics, augmented reality, additive manufacturing, cybersecurity, and cloud computing were identified as core tenets of Industry 4.0.

3.2. CE-DT framework development

The development of the CE-DT framework entailed identifying categories and pillars through a comparative analysis of existing frameworks. Subsequently, sub-pillars were outlined to comprehensively cover each chosen pillar. Drawing insights from established CE and DT frameworks, the framework's hierarchical levels were defined, culminating in Level 3 to articulate best practices for each CE and DT category.

3.3. Case study implementation

To conduct a comparative analysis of the manufacturing sectors in the UK and SA, the following methodology was employed.

3.3.1. Identifying common sectors

The first step involved identifying common, well-established manufacturing industries in both countries. Sectors with a proven track record of performance and presence in both the UK and SA were sought.

3.3.2. Data collection & analysis

First, key players in both the UK and SA were identified for benchmarking purposes. Data collection encompassed various sources, including literature, reports, articles, company websites, published papers, government statistics, and relevant case studies. Subsequently, the collected data underwent analysis to benchmark manufacturing practices and identify areas for improvement in Saudi Arabia's adoption of digital transition and CE practices.

3.3.3. Strategy suggestion

To support improvement efforts in the identified areas within SA, a roadmap was proposed to guide the implementation of CE and DT practices.

4. CE-DT Framework

The proposed CE-DT framework offers a systematic approach to evaluate organisations' current state across various dimensions, enabling the identification of capability gaps and areas for improvement through comparative benchmarking.

Comprising two distinct sub-frameworks for Industry 4.0 and circular economy, the CE-DT framework is designed for universal adoption by companies, irrespective of their location. Rooted in the fundamental visions and principles of Industry 4.0 and circular economy, respectively, this framework meticulously assesses the extent to which manufacturing companies embody digital transition and circularity.

Structured with a category, pillar, and sub-pillar approach, the framework provides clarity and understanding of Industry 4.0 and circular economy's role in the manufacturing sector. Categories encompass different domains of the manufacturing sector, while pillars cover aspects within each category, and sub-pillars delineate parameters measured across three levels:

- Level 1 - Emerging: Companies at this stage are in the initial phases of implementing digital transition and circular economy practices within the specific category.
- Level 2 - Established: Companies in this tier have made significant strides and are actively integrating digital transition and circular economy principles into their operations.
- Level 3 - Leading: Representing the pinnacle of achievement, companies at this level are considered exemplary models, showcasing best practices in embracing digital transition and circularity within their specific category.

This framework offers a comprehensive assessment of manufacturing companies' circularity efforts and their adoption of Industry 4.0, facilitating a detailed evaluation of their progress and alignment with Industry 4.0 visions and circular economy principles across critical dimensions.

4.1. Digital transition sub-framework

The Digital Transition section of framework, presented in Figure 1, evaluates the adoption and integration of Industry 4.0 technologies across various dimensions of the manufacturing sector. It delineates categories, pillars, and sub-pillars, each addressing critical elements crucial for successful digital transformation.

4.1.1. Category 1: Operations

Operations encompass the entirety of production and manufacturing processes, along with resource capabilities and supply chain management practices, essential for delivering products and services [25]. In the context of Industry 4.0, operations aim to harness smart technologies for creating agile, intelligent, and efficient value chains [26]. It is structured around three pillars: process, resource capabilities, and supply chain. The process pillar concentrates on refining manufacturing processes with industrial IoT and robotics to improve efficiency and integration [27]. It encompasses sub-pillars i.e., machine integration, autonomously guided workplaces, and automation, enabling connected and autonomous manufacturing. Resource capabilities emphasise building infrastructure and competencies for smart manufacturing, addressing equipment readiness and maintenance [25]. Supply chain aims to transform linear chains into circular networks with IoT and cloud computing [28]. Its sub-pillars include inventory planning & control, visibility, flexibility, and integration, enhancing coordination across supply chain processes.

4.1.2. Category 2: Business strategies

Business strategies involve plans and initiatives aimed at leveraging Industry 4.0 technologies to achieve strategic goals [29]. It comprises two pillars: product and management & business vision. The product pillar focuses on utilising IoT, AI, and big data analytics to develop customised and smart products [26]. It includes sub-pillars like customisation and smart products, facilitating the shift towards flexible and connected offerings. Management & business vision highlights the importance of leadership and strategic planning in driving digital transformation [29]. Sub-pillars encompass strategies and investments in Industry 4.0, crucial for realising its potential through visionary leadership and strategic investments.

4.1.3. Category 3: Technology

Technology encompasses emerging digital technologies and infrastructure essential for digitising and transforming manufacturing operations. It comprises five pillars: industrial internet of things, cloud computing, big data analytics, cybersecurity, and digital modelling & simulation.

The IIoT pillar facilitates connectivity between industrial assets, creating smart manufacturing environments [30]. It includes sub-pillars such as the device layer and operational technology, supporting smart, connected manufacturing processes. Cloud computing enables access to shared computing resources and real-time monitoring and control of operations [31]. Sub-pillars like tracking and control enhance connectivity and information sharing in smart factories. Big data analytics involve utilising advanced data collection and analysis to derive actionable insights [32]. Sub-pillars include data collection and storage, data visualisation, and analytics, facilitating continuous optimisation of manufacturing operations. Cybersecurity focuses on preventing unauthorised access and ensuring information system integrity [33]. Sub-pillars encompass access control management and asset identification & risk monitoring, crucial for protecting against cyber threats. Digital modelling & simulation creates virtual representations of physical systems to optimise performance [34]. Sub-pillars include digital models and digital twins, supporting virtual prototyping and analysis for informed decision-making.

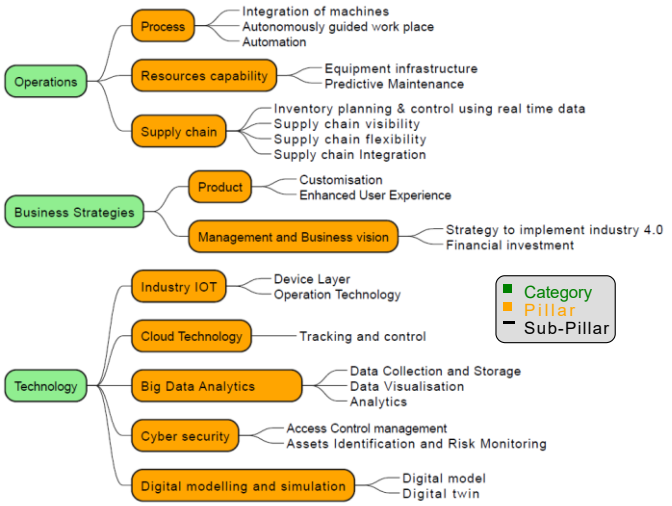


Fig. 1. Digital transition framework

4.2. Circular economy sub-framework

The Circular economy segment of the framework, presented in Figure 2, assesses companies' adoption of circularity principles across various dimensions of their operations. It consists of categories, pillars, and sub-pillars, each designed to evaluate different aspects of circularity integration.

4.2.1. Category 1: Circular business model

The circular business model (CBM) category centres on redefining the value creation process by retaining economic value in products throughout their lifecycle [35]. It comprises the business model pillar, advancing through levels from cradle to grave, focusing on sustainable production, to product life extension, extending product use, and finally, to product as a service (PaaS), emphasising access over ownership and minimising waste [36]. The CBM aims to drive economic and environmental benefits by shifting from a linear to a circular approach to value creation.

4.2.2. Category 2: Circular product design

Circular product design (CPD) evaluates how well companies integrate circularity considerations into product and process design [37]. The CPD framework encompasses five pillars including design for material sourcing, design for manufacturing, design of packaging for transport and distribution, design for use, and design for end of life. Each pillar emphasises strategies like selecting sustainable materials, optimising manufacturing processes, and facilitating end-of-life recovery, all contributing to a more circular product lifecycle [38,39].

4.2.3. Category 3: Operations

Operations focus on integrating circular economy principles into day-to-day practices, production, and supply chain activities [40]. It comprises three pillars: sustainable manufacturing, circular supply chain, and culture & organisation. The Sustainable manufacturing pillar emphasises environmentally friendly practices, such as waste and emissions reduction and renewable energy adoption. Circular supply chain aims to create restorative and regenerative cycles, including closed loop supply chain initiatives to maximise value creation and minimise waste [41]. The Culture & organisation pillar underscores the importance of embedding circularity into the organisational culture, fostering innovation, collaboration, and employee engagement to drive circular economy adoption [19].

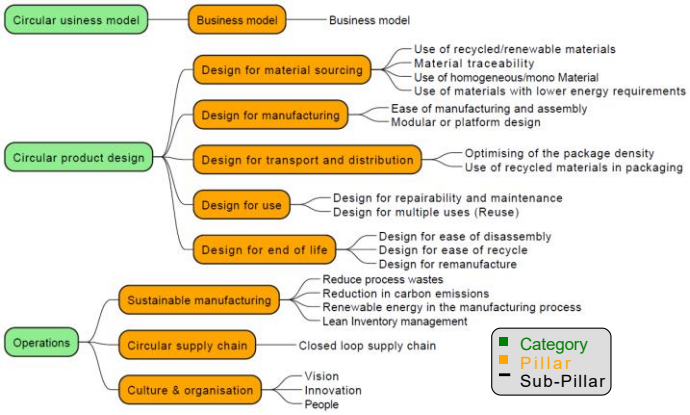


Fig. 2. Circular economy framework

5. Petrochemical Companies Case Study

In the first step of selecting a common sector, despite both nations initially targeting their robust Fast-Moving Consumer Goods (FMCG) sectors, the lack of detailed data on FMCG manufacturing practices in Saudi Arabia led to a shift in focus towards the petrochemical industries in both countries. Data collection efforts were concentrated on prominent petrochemical businesses in the UK and SA, with key players like Saudi Aramco in SA and Shell and BP in the UK being selected for benchmarking Industry 4.0/digital transformation and circular economy practices. However, challenges arose in accessing data from Saudi Arabian industrial enterprises, posing significant obstacles during the benchmarking process, attributed to factors such as time constraints and the inability to disseminate the CE-DT framework for self-evaluation by

corporations. Subsequently, benchmarking of companies was carried out for categories of the CE-DT framework where complete data was available, with Industry 4.0 focusing on "operation" and "technology," while circular economy prioritised the "operation" category for benchmarking.

5.1. Industry 4.0

Category Operations: The operational aspects of Industry 4.0 implementation were assessed based on data from Shell Global [42] and Aramco [43]. A spider graph depicting the performance in the operations category is presented in Figure 3. Aramco is in Level 2 (Established) for 70% sub-pillars of Industry 4.0 - Operations category, whereas Shell is in Level 3 (Leading) for 100% Industry 4.0 operations category. For Aramco to be at Level 3 (Leading), best automation, equipment infrastructure and supply chain practices need to be adopted.

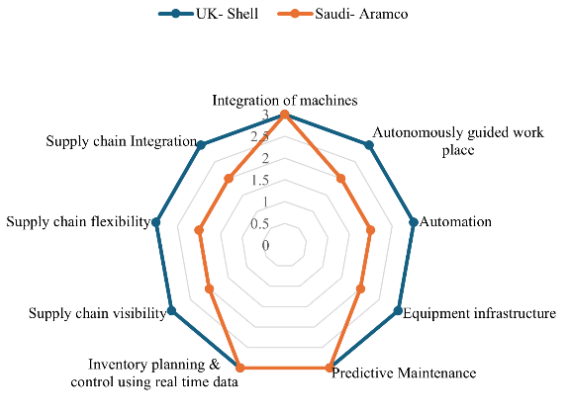


Fig. 3. Spider graph for DT framework - Operations

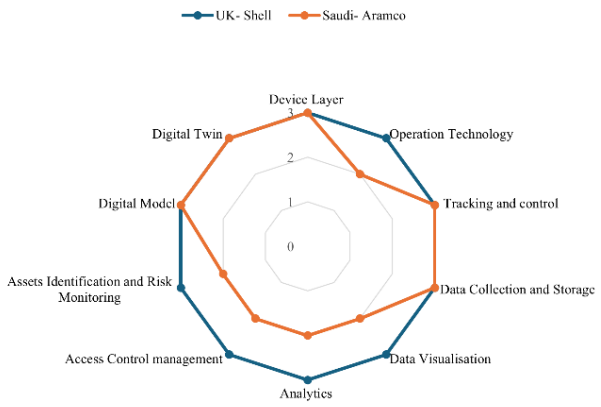


Fig. 4. Spider graph for DT framework - Technology

Category Technology: The technological capabilities and advancements in Industry 4.0 were analysed using data from Shell Global [42] and Aramco [43]. A spider graph illustrating the performance in the technology category is displayed in Figure 4. In the technology category of Industry 4.0, Aramco is in Level 2 (Established) for 60% of sub-pillars. By adopting best practices in IIOT, big data analytics and cyber security, Aramco can reach at par with Shell (UK) in Technology category.

5.2. Circular economy

Category Operations: The CE practices of the benchmarked companies were evaluated based on data from BP [44] and Aramco [43]. A spider graph demonstrating the performance in the operations category is displayed in Figure 5. From the analysis of the spider graph of the operations category of circular economy, it has been found that Aramco is in Level 1 (Emerging) for 70% of sub-pillars. For Aramco to be at Level 3 (Leading) in the operations category best sustainable manufacturing practices are to be adopted.

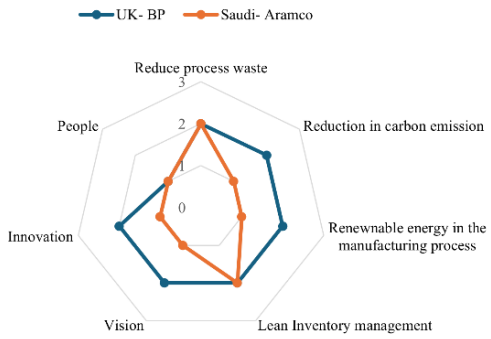


Fig. 5. Spider graph for CE framework - Operations

6. Roadmap for Advancing Circular Economy and Digitalisation in Saudi Arabia

In line with KSA vision 2030, Saudi announced its National Industrial Development and Logistics Program. The program aims to transform the Kingdom into a leading industrial powerhouse and a global logistics hub, while unlocking the full potential of local content and the 4th Industrial Revolution (4IR). Also, the government subsidises the industries though Future Factories Program to help increase factories' adoption of the best global practices of Industry 4.0 [45]. However, those programs do not embody CE and DT in sector contexts nor they lay a robust policy layer for the sector. A proposed roadmap that enclose the CE-DT in building manufacturing capabilities could include:

- Defining the Circular Economy and Digital Transition Goals:

  The roadmap begins by defining clear circular economy and digital transition goals tailored to national priorities and contexts. This provides a guiding vision and targets to work towards. Policy frameworks tailored to unique economic and social objectives have greater success [46].

- Establishing a Supportive Policy Environment:

  Creating conducive policy environments and legislative frameworks lays the foundation for achieving defined goals. Initiatives such as the EU's Circular Economy Action Plan [47] and the UK's Industrial Strategy [48] underscore a commitment to advancing circular technologies and digital infrastructure. Similarly, Saudi Arabia's Vision 2030 [45] emphasises economic diversification and sustainable resource management, signalling opportunities for the adoption of circular and digital solutions.

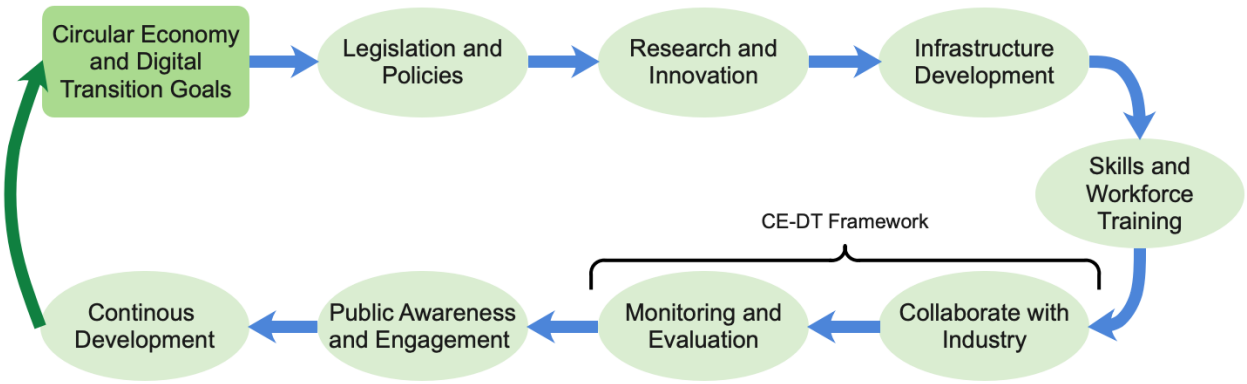


Fig. 6. Roadmap for advancing CE and DT

- Investing in Research and Innovation:
  Governments play a pivotal role in fostering innovation by investing in academic and industry research. This investment uncovers new technologies, materials, processes, and business models essential for accelerating circular and digital transitions [49].

- Developing Supportive Infrastructure:
  This includes building supportive infrastructure, including recycling facilities, digital networks, renewable energy systems, and sustainable transportation links that are vital for underpinning circular and digital transitions [50].

- Enhancing Workforce Skills:
  Training programs aimed at enhancing digital literacy and equipping workforces with circular economy skills are imperative to maximise human capital and drive successful transitions [51].

- Fostering Collaboration with Industries:
  Collaborating with industries and businesses to align commercial activities with national goals is essential. Voluntary initiatives can complement policy mandates, fostering synergy between public and private sectors [52].

- Implementing Robust Monitoring and Evaluation:
  Continuous monitoring and evaluation frameworks are essential for collecting data on key circular economy and digital adoption metrics. This data enables stakeholders to assess progress, identify improvement areas, and inform adaptive policymaking [53].

- Engaging in Public Awareness Campaigns:
  Garnering community and stakeholder buy-in and participation through public awareness campaigns is crucial for fostering an inclusive transition [54].

- Ensuring Continuous Development:
  The cyclical nature of the roadmap allows for continuous enhancement based on insights gained from evaluation and monitoring. Adaptive policymaking enables agile responses to emerging opportunities and challenges.

In summary, this staged roadmap offers a holistic blueprint for Saudi Arabian stakeholders to systematically transition towards a circular economy and digital technologies. Through strategic milestones spanning policy development, infrastructure enhancement, innovation, skills building, stakeholder collaboration, monitoring, and public engagement, Saudi Arabia can navigate its transition with precision and flexibility. Leveraging frameworks such as the CE-DT framework enables targeted interventions and facilitates progress across the roadmap's milestones.

7. Conclusion

The comparative analysis between the UK and Saudi Arabia underscores significant disparities in manufacturing practices concerning circular economy principles and digital transition. While the UK demonstrates advanced progress in adopting these models, Saudi Arabia exhibits promising steps towards their implementation. Leveraging the developed CE-DT framework can offer substantial benefits, facilitating a structured approach to integrating digitalisation and circularity in manufacturing.

The UK's leadership in circular economy and digital manufacturing maturity can be attributed to sustained efforts in prioritising sustainability and digitalisation within manufacturing, supported by long-standing national policies and industry strategies. In contrast, Saudi Arabia's emphasis on these areas is still evolving, although within the framework of Vision 2030. The CE-DT framework provides a systematic guide for Saudi Arabia to navigate these complexities, offering a roadmap for aligning national priorities with industry practices.

Moreover, the UK benefits from more developed digital infrastructure, a critical component for smart manufacturing, highlighting areas where Saudi Arabia could focus its investments to bridge the gap. By embracing the CE-DT framework, Saudi Arabia can strategically allocate resources towards developing robust digital infrastructure, essential for driving innovation and efficiency in manufacturing processes.

Additionally, workforce skills play a pivotal role in the successful implementation of circular economy and digital

transition initiatives. The proposed roadmap emphasises the importance of workforce development, providing guidelines for training programs that build digital literacy and equip workers with circular economy skills. This holistic approach ensures that human capital remains a driving force behind Saudi Arabia's manufacturing transformation.

While this study offers valuable insights, it is constrained by reliance on secondary data sources and a limited sample size from specific industries in both countries. Future research will involve further analysis by incorporating primary data collection methods and expanding the scope to include more countries. Moreover, some case studies will be performed to assess the maturity of manufacturing organisations utilising the CE-DT framework. Overall, the research underscores Saudi Arabia's potential to embrace sustainable and technologically advanced manufacturing practices similar to the UK. Achieving this will necessitate coordinated efforts from government and business leaders, with targeted interventions in policy, infrastructure, and workforce development. This study serves as a foundational step towards guiding Saudi Arabia's journey towards a more sustainable and technologically driven manufacturing sector, enabled by the CE-DT framework.

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