Digital Twin for Smart Farming – The case of sustainability in Beef Farming Supply Chains

1 Introduction

The beef industry is gaining prominence among households across Europe and the rest of the world. In 2021, Europe alone produced 6.8 million tonnes of beef carcass weight (Eurostat, 2021)[1]. Though essential to people's daily life, the beef industry has been under critique for its detrimental effects on sustainability. According to the United Nations Food and Agriculture Organization, 14.5% of all GHG emissions are caused by livestock, amongst which cattle represent approximately 65% of the emissions, with beef cattle contributing 41% and dairy cattle 20%. The emission intensities of beef are double or triple that of other forms of meat protein (Cheng et al., 2022). At the production end, organic beef produces 22.3kg of CO_2[2] equivalent GHG emission while certain other types (koge) of beef produce approximately 36.4kg of CO_2 (Avery and Avery, 2008). Furthermore, the social and economic side of the beef industry has also been critiqued. Due to the lack of communication, formal policies and transparency in the beef farming supply chain (Amicarelli et al., 2021; Malafaia et al., 2021), the stakeholders have their own concerns. The chemical composition and quality of feed (Brown et al., 2002), beef traceability (Feng et al., 2013), cattle health, trading decisions, GHG emissions (Zeidan et al., 2020), food waste (Magalhaes et al., 2020), prices (Susila et al., 2021), and nonuniform policies (Malafaia et al., 2021) are a few prominent issues.

Studies have been vocal about resolving these issues through the modernisation of Beef Farming Supply Chain (BFSC) using advanced technologies (Maples et al., 2019; Waldron et al., 2010). Digital twins (DT) in particular, can cater to the prevailing BFSC issues and address the inefficient management of the beef supply chain and have positive implications for the triple bottom line (Malafaia et al., 2021; Alves et al., 2023). DTs have been well known for creating a virtual replica of the business, making it easy to identify loopholes, streamline processes, enhance capabilities and make data-driven decisions for better performance (Gotz et al., 2020; Bhandal et al., 2022; Fukawa, 2022). More studies are required to advance DT innovation and to address a research gap that lacks connection or a fit of DT with BFSC (Cenamor et al., 2017; Fukawa et al., 2022; Gotz et al., 2020; Nguyen et al., 2022).

This study aims to develop a conceptual framework that shows how the DT transforms the different supply chain processes and reconfigures the stakeholders' role for sustainability[3] in DT– BFSC. The framework is proposed by critically reviewing and synthesising the literature complemented by modelling emerging industry practices, thus answering the following research questions.

RQ1 – How can DTs create economic, social and environmental sustainability in BFSC?

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[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=427096#Veal_and_beef

[2] Carbon dioxide

[3] "The integration of environmental health, social equity and economic vitality in order to create thriving, healthy, diverse and resilient communities for this generation and generations to come' (UCLA Sustainability Committee).

RQ2 – How is the BFSC reconfigured with the use of digital twins?

The contribution of this study is threefold. The study (i) proposes a holistic framework that devises DT as a means to address the pressing issue of sustainability of the BFSC, (ii) unearths the underlying value creation mechanisms and processes that enhance the efficiency and sustainability of the BFSC, and (iii) explores the reconfigurability of BFSC partners and restructuring of resources and facilities in the SC for enhanced performance. At the practitioner's end, the study is valuable for the agricultural industry that is continuously looking for ways to enhance sustainability and competitiveness simultaneously.

2 Literature Review for the Proposed Framework

2.1 DT Technology and Digital Capabilities

A DT is defined as the virtual duplication of the physical system enabled through digital technologies and the consistent exchange of data being generated by them (Dhar et al., 2022; Grieves and Vickers, 2017). Embedded with IoTs, data storages, virtual reality, augmented reality, machine learning and artificial intelligence (AI), digital twin (DT) helps create visibility and decision support capabilities (Bhandal et al., 2022). Owing to the synonymous terminologies[4] used, the DT literature has blurred concepts and boundaries in terms of the '*process'* of value creation in supply chains (Bhandal et al., 2022; Fukawa, 2022; Nguyen et al., 2022). Studies have emphasised the need to explore the *'how'* aspect and broadly direct new research to gain an in-depth understanding of (i) how DT can be leveraged to enhance sustainability, (ii) how its adoption changes information-sharing practices among SC partners, (iii) how is resource utilisation impacted, (iv) how DT facilitated knowledge exchange can help with firms innovation performance, and (v) how manufacturing and SC operations are optimised due to DT (Bhandal et al., 2022; Fukawa, 2022; Gotz et al., 2020; Nguyen et al., 2022).

The continuous synchronization of data between the virtual and the physical layer is the core capability of the DT that, in essence, realizes performance outcomes. The DT allows *real-time monitoring* of the processes, updates on the condition and working of equipment and assets, availability of resources, process execution, and taking preventive measures to avoid interruptions (Grieves and Vickers, 2017; Wang et al., 2021). The real time information is supported by the *interoperability* between the IoTs, smart machines, data storage, dashboards and other technologies that allow standardization of data and processes. This *standardization* plays a critical role in eliminating waste throughout the production process, improve processes and make effective use of resources (Chirumalla et al., 2023; Gotz et al., 2020; Kalaboukas et al., 2023; Kamble et al., 2022).). DT in SC have the potential to enhance collaboration collective decision making, resource sharing, designing optimal processes and enhancing

[4] Cyber physical systems, virtual copy, digitalization, digital transformation, hyper connectivity

responsiveness to market changes (Boyes and Watson, 2022; Jabbour et al., 2020, Santos et al., 2021; Wang et al., 2022; Zhou et al., 2017).

2.2 Digital Capabilities and Supply Chain Capabilities

The visibility, integration and real-time information exchange developed by the DT bring changes in the organizational processes, routines and structure (Belhadi et al., 2022; Fukawa and Rinfleisch, 2022). These changes arise primarily due to the increased information made available by the use of DT. Grieves and Vickers (2017) posit that the tasks and processes of a firm can be measured and quantitatively monitored in terms of the cumulative sum of the tangible and intangible resources associated with them. They state that information from the DT can be used to replace the waste of these resources[5] and optimize process efficiency and effectiveness. The realization of waste reduction from information is enabled by the ability of organizations to utilize this information to (re)organize and (re)design and (re)modify organizational elements. This ability of organizations is termed the reconfiguration capability that, in realm of DT, is developed as a result of data and information synchronization.

Although use of technology in supply chains for sustainability is not a new concept, firms still struggle to identify the required capabilities that lead to sustainable performance outcomes. A firm’s sustainable success depends on the efficiency, responsiveness and adaptability of its supply chain, which DT-enabled integration and connectivity can help with. However, many firms struggle to use these technologies effectively and often fail to leverage their full potential (Cenamor et al., 2017). Though studies on DT in supply chains identify supply chain risk management, supply chain resilience, decision support capabilities, supply chain sustainability, supply chain analytics and servitisation as potential outcomes (Dhar et al., 2022; Kamble et al., 2022; Lv et al.; 2023) yet it is imperative to understand the contingency factors that enable their development and effective utilization. Process optimisation, predictive maintenance, enhanced quality, improved efficiency, waste reduction, cost reduction, and product and process innovation as some of the most common enabling mechanisms (Bhandal et al., 2022, Gotz et al., 2020) however, the way they are leveraged remains a context-specific element that needs to be understood.

2.3 Digital twin in Beef Farming Supply Chain (DT-BFSC)

The integration of digital twins (DT) in BFSC provides a novel arrangement that can bring significant improvements in sustainability, transparency, and efficiency to the beef industry. The use of DT can enable resource orchestration, SC reconfiguration and data management in a way that minimizes the sustainability concerns of stakeholders. In the context of the BFSC, the DT will be equipped with IoTs (sensors), thermal imaging drones, data management systems (DMS) and AI. These technologies shall transmit and receive real-time biometric and environmental data of the cattle at different stages of their lifecycle and maintain digitised records making farm asset management more transparent and efficient (Feng et al., 2013). In

[5] Resources here depict time, energy and materials

the upstream supply chain, DT with accurate information on the cattle breed, the feed, health and immunisation records, growth patterns and trading history shall be available to all stakeholders. In the downstream supply chain, interconnected sensors can improve food traceability, meat quality & grading, and special requirement from niche demand.

Existing DT developments are often limited to dairy farming where cows return to the milking station on a regular basis for the sensors to capture data. However, beef cattle are often out in the wild for most of the year, making farm-centric tracking systems “blind”. Airborne imagery and AI capabilities have demonstrated possibilities to compensate for the deprivation of data in a wild setting (Neethirajan et al., 2021, Paul et al., 2022). In addition, whilst dairy cattle are predominantly Holstein, beef cattle could be any of the over 200 breeds recognised by the UK Government. Solutions working on one breed will need further validation against other breeds.

The thermal imaging drones can hover safely above the cattle and can detect and capture methane emissions from the cows and with required development can provide weight, height, and muscle mass information as well. This data helps stakeholders make decisions on trading and product type, benefitting their decision-making. While DMS stores and standardises data on the cattle, the AI can help in predictive and prescriptive analytics that determine the type of feed a certain cow/breed need, new feed mix that can help reduce GHG emission from cows, medication and immunisation specifications, the best time for trading a cow, growth patterns and preventive care for the cattle.

2.4 Sustainability in DT - BFSC

Sustainability of the BFSC has been criticised owing to its excessive use and waste of resources and being a major contributor to GHG emissions (Feng et al., 2013, Maples et al., 2019, Singh et al., 2015). Using the theoretical lens of resource orchestration theory, we propose that the use of DT can eliminate if not all, most of the inefficiencies of the BFSC through unique resource fit and the modification or extension of existing capabilities.

The use of DT in the BFSC allows for transparency and visibility to all stakeholders. This facilitates bidirectional information, knowledge exchange and data-driven decision-making. The upstream partners through the use of DT make optimised decisions on breeding, feeding, health checks, trading timing and production of appropriate products from the cattle. The digitised records on the cattle lifecycle along with possible tracking of methane emissions, benefit the stakeholder’s knowledge base and increase profitable decision-making. Similarly, in downstream BFSC, the customers will benefit from farm-to-fork traceability, which would make them willing to pay more for premium beef and other relevant products. The concerned customers can also benefit from DT as they will be getting information on the feed, health and emissions of the cattle, making their purchase decisions easy and informed. Hence, the use of DT, the integration of the BFSC and the end-to-end visibility created will help the BFSC become more economically, ecologically and socially sustainable.

3 Proposed Conceptual Framework

The Resource Orchestration Theory (ROT) brings together the concepts of resource management and asset orchestration and shows how their integration can enhance firm performance (Sirmon et al., 2011). The theory posits that the possession of resources alone is not sufficient for performance, rather the orchestration and exploitation of resources helps by (i) structuring the resources by acquiring, accumulating and divesting, (ii) bundling the resources to modify, extend and create existing and new capabilities respectively, and (iii) leveraging the resources by coordinating and deploying different configurations. The ROT helps in realising the actual process of creating a competitive advantage through the effective management of resources and capabilities.

Underpinned by the ROT, the proposed conceptual framework (Figure 1) shows how the structuring, bundling, and leveraging of farm resources and technologies in a certain manner can create an economically, ecologically and socially sustainable beef supply chain. The DT in BFSC makes the farm equipped with visibility, interoperability, knowledge exchange, real-time process and asset monitoring and analytics (Francis et al., 2008, Malafaia et al., 2021). These capabilities facilitate efficient processes, optimal use of resources (cows, machines, feed, immunisations, supplements, transport, production etc.) and bidirectional flow of real-time information to all stakeholders. This consequently alters the traditional BFSC configuration maximising stakeholders' benefit and sustainability in the BFSC.

4 Conclusion

This study advances the existing knowledge base on BFSC and DT by clubbing them together to address a pressing concern of sustainability in the beef industry. The authors propose a framework that explores the relationship between DT, BFSC and sustainability and identifies the different contingencies that play a role in effectively utilising the DT. DT governance is an essential requisite for the appropriate use of data, technologies, analytics and decision support systems. At the same time, the SC capabilities act as a mediating factor between DT and BFSC and play a pivotal role in the value-creation mechanism. The outcome of the framework is classified into social, economic, and ecological sustainability of the BFSC and their interdependency. The framework uses resource orchestration theory as an explanatory mechanism that shows the bundling of different farm resources and actors with technology restructures and modifies the BFSC actors' roles and processes. The restructuring, along with the DT is leveraged to create sustainability of the BFSC. The study contributes to the net zero agenda in the beef farming context.

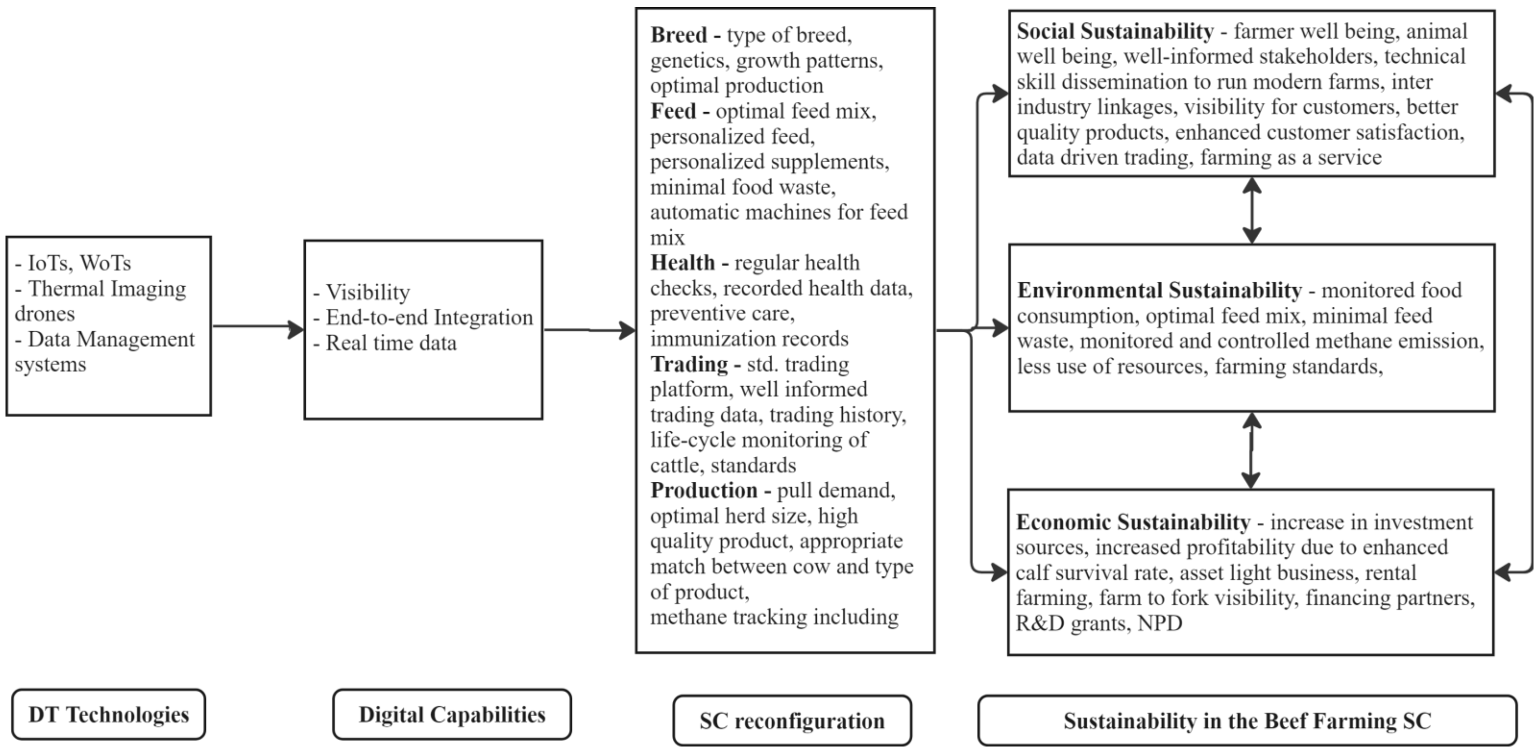

Figure 1 Proposed Conceptual Framework for the DT-BFSC

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