Digital Transformation and the Circular Economy: Creating a competitive advantage from the transition towards Net Zero Manufacturing.

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Abstract (250 words)

Manufacturers are exploring the extent to which digital technology applications can support their sustainability efforts by helping to convert abstract sustainability goals, such as those of net-zero emissions and circular economy (CE), into feasible and practical actions, achievements, and ultimately, a sustainable competitive edge. This work adopts a resource-based view (RBV) to explore the potential role that digital technologies play in the cultivation of a manufacturing firm's competitive advantage, and the deployment of existing internal resources and core competencies to achieve net-zero manufacturing emissions and CE. Two questions are addressed (1) What competitive advantage(s) may be derived from the integration of digital technologies to achieve net-zero manufacturing emissions, and (2) does adopting an RBV facilitate the development of meaningful competitive advantage? Engaged scholarship is used to analyse and apply theory to an empirical, real-world dataset documenting the perspectives and experiences of 13 manufacturing firms. Applying the VRIO framework, 21 identified digital technology-based core competencies are categorised as forms of competitive advantage that may be possible for manufacturing firms pursuing net-zero emissions. Four scenarios of digital technology adoption pathways are proposed, differentiated by the degree of radical vs. incremental interests and options available to the firm. This study highlights the critical need for firms to incorporate intangible asset management and development, including the labour and supply chain relationships, as part of their digital transformation strategies. Further, we demonstrate the potential of RBV as a lens for evaluating the competitive advantage potential of corporate sustainability initiatives, and facilitating the development of related strategies.

Key words: Digital Transformation, Resource-Based View, Net-Zero Manufacturing, Circular Economy, Sustainable Competitive Advantage.

1.0 Introduction

When the international community established a policy priority to limit global warming to the critical threshold of 1.5°C (IPCC, 2018), it led to the launch of diverse national and corporate initiatives to reduce greenhouse gas (GHG) emissions, such as the United Kingdom's (UK) Net Zero 2050 Target, and the Science Based Targets initiative (Committee on Climate Change, 2019; Science Based Targets, 2022). The importance of the Paris Agreement target of net-zero carbon emissions is emphasized in the UK through government's policies such as the Industrial Decarbonisation Strategy, which states how industry can decarbonise in line with net zero. Furthermore, while the energy crisis caused by the Russian invasion of Ukraine has led to the UK (Department for Business Energy Industrial Strategy, 2022a) and the European

Union (EU) (Rosenow, 2022) to review their net zero approaches, with a greater emphasis placed on achieving energy and economic security, both, currently, remain committed to meeting their net zero targets. Net zero is expressed as, “reducing net CO2 emissions from energy and industrial processes, after accounting for carbon capture and sequestration, to zero” (Rogelj, J., *et. al.* 2015). In 2020, the transport sector was estimated to be the highest GHGs emitting sector at 24%. The rest include, 21% from energy supply, 18% from business, 16% from residential sector, 11% from agriculture and 9% from residual sectors (including waste management, industrial processes, land use, etc), according to the Department for Business, Energy and Industrial Strategy, 2022b.

Due to this UK policy emphasis, an unprecedented pace and scale of decarbonisation is required for the UK industrial sector which constitute 21% of the UK’s GHG emissions in 2017 (Committee on Climate Change, 2019). Alongside increasing consumer demands, the manufacturing sector is being called upon to take responsibility for the 45% of global emissions associated with production of materials and goods and the management of land (Ellen MacArthur Foundation, 2019). This does not include fuel extraction, refining, processing, and transportation. Within such complex, dynamic, and ever-changing market, economic, and policy conditions, it is not surprising that many manufacturing firms find it increasingly difficult to achieve and sustain competitive advantage in the short to medium term (D’Aveni, *et al*., 2010; Elia *et al.*, 2021; Lindskov *et al*., 2021).

Manufacturing firms often possess highly-complex supply chains that are increasingly vulnerable to rising costs, risks and disruption affecting stakeholders across the supply chain (Choi, *et. al.*, 2001; Ghadge *et al*., 2019 ; Hendricks and Singhal, 2005; Woetzel *et al*., 2020). Manufacturing firms’ efforts to manage supply chains have led to increasing complexity and, often, helplessness, as managers struggle with the dynamic and complex nature of supply chain networks and the inevitability of ambiguity in prediction and control (Choi, *et. al.*, 2001). This situation is compounded by other related uncertainties including hyper-competition, globalisation, rising customer expectations (Dominguez, *et. al.,* 2021) as well as new risks tied to climate change and COVID-19 disruption (Bier, *et. al.,* 2020; Durán-Romero *et al.*, 2020; Tseng *et al*., 2021). In 2020 alone, COVID-19, geopolitical tensions, and other disruptions caused more than $4 trillion of unanticipated costs to global firms and their suppliers (Economist, 2020). The advancement and availability of digital technology, and the ensuing digital transformation, have presented new opportunities for manufacturing firms to mitigate supply chain risk and increase coordination that is needed to optimise operations, including the meaningful response to the climate crisis. Given the diverse range of opportunities for firms to engage with digitisation and digital technologies, including internet-of-things (IoT), additive manufacturing, artificial intelligence (AI), big data, and cloud-computing, manufacturing firms have recognized the joint challenge-opportunity that may be derived from embracing technological advancement and the ongoing ‘digital’ industrial revolution (Elia *et al.*, 2021; Frank *et al*., 2019; Shakor *et al*., 2022). This is especially true for manufacturers who, although potentially not ‘born’ digital or global, are willing to pursue digital transformation and internationalisation as core competitive strategies (Elia *et al*., 2021; Hennart, 2014).

The common response to many of these external pressures, complexities and forces tends to be technocentric, with firms looking to *external* technologies, competitors and markets to reduce supply chain risk, and increase overall firm resilience. However, the Resource-Based View (RBV) of the firm posits that, by focusing on *internal* resources and core competencies that the firm *already* possesses, a more effective competitive advantage may be sustained (Barney, 1991; Harts, 1995; Barney *et al*., 2001; McDougall, *et al.,* 2019). RBV thus provides a viable lens for exploring the potential roles that digital technologies, CE, and net-zero ambitions internal to the manufacturing firm, may play in the development of a firm’s competitive advantage through configuration and deployment of existing internal resources and core competencies. In this context, we utilise the term “resources” to refer to two different forms of resources available to the firm: tangible resources, referring to physical assets of the firm including land, equipment, buildings, machinery, and capital; and intangible resources, referring to non-physical assets that can still be owned by a firm, such as brand reputation, trademarks, intellectual property, systems, and processes.

As shown in Figure 1, an RBV approach is used to delineate how some manufacturing firms are strategically leveraging diverse digital technologies to engage in CE and pursue net-zero emissions targets.

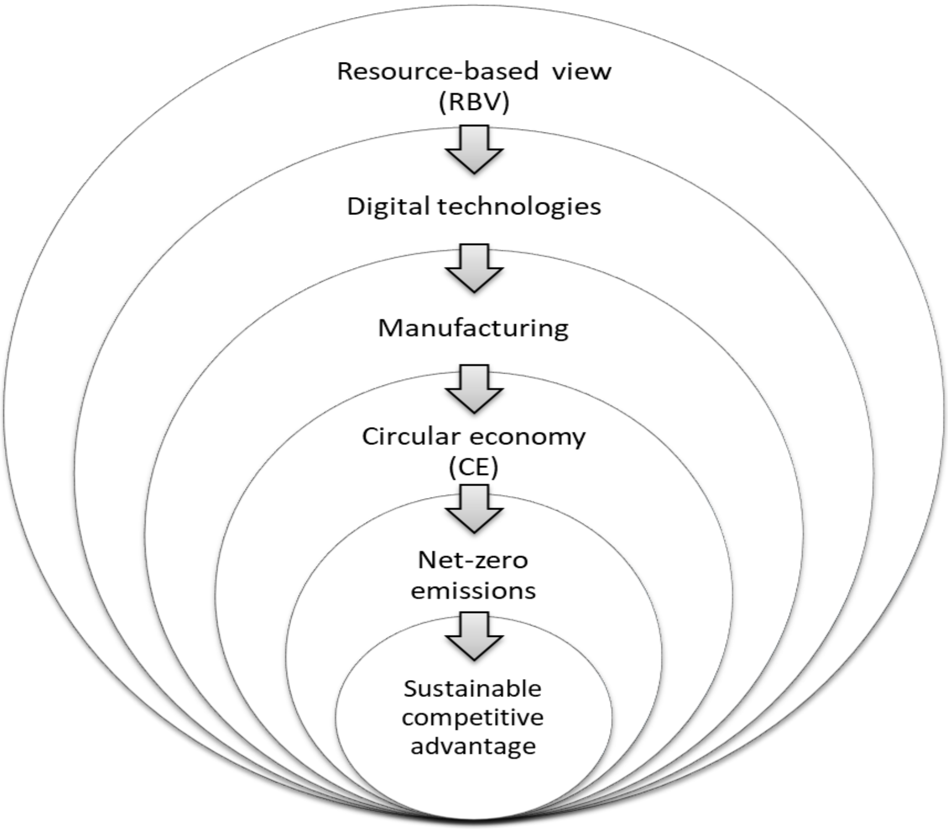


Figure 1: Visual representation of the framework for exploring our core research themes, their connections, and specific applications, applying a resource-based view of the (manufacturing) firm.

This work specifically explores the following research questions: (1) What competitive advantage(s) may be derived from the integration of digital technologies to achieve net-zero manufacturing emissions; and (2) For manufacturing firms pursuing a digital transformation, does adopting RBV facilitate the development of sustainable competitive advantage?

Researchers following the RBV are often criticised for ignoring the impact of institutions by the principal argument that distinct combinations of resources and capabilities contribute to the competitive advantages of firms (Patnaik *et al*., 2022). Our work contributes to this gap within the context of a manufacturing firm. Applying an RBV approach, we identify various competitive advantages and value that can be derived when the studied manufacturing firms are simultaneously engaged in digital transformation and the pursuit of net-zero emissions. Furthermore, our findings demonstrate the essential role of human capital in the achievement of incremental and radical digital transformation, and the ultimate achievement of sustainable competitive advantage.

Resource-based theories about competitive advantage have been broadly applied to digital technologies and transformation, manufacturing strategy, and the pursuit of environmental sustainability (Wiengarten *et al.*, 2013; Elia *et al.*, 2021; Tseng *et al*., 2021). Within these contexts, RBV theory suggests that firms can achieve lasting competitive advantage by bundling and coordinating the resources and capabilities they have on-hand into core competencies (Barney, 1991; Grant, 1991; Baker and Sinkula, 2005). According to Paiva *et al*. (2008), a firm's "*know-what*" (i.e., where to find necessary cross-functional information) and "*know-how*" (i.e., how to operate specialised technologies and processes, smoothly) are essential core competencies for strong manufacturing performance. This includes complex, tacit resources, such as knowledge gained through practice, internal methodologies, specialised knowledge – invisible resources gained through learning and practice (Harts, 1995). Further, competitive advantage can be derived from the combination of a) access to resources for expanding and enhancing operational capabilities, b) access to and use of predictive analytics from big data, and c) access to a skilled labour force that facilitates improved cost and operational performance (Dubey *et al.*, 2019). In many cases, manufacturing firms' core resources come in the guise of digital technology, data and firm capabilities (Davenport and Redman, 2020), skillset (Tolstoy *et al.*, 2021) and other intangible and human resources (Verhoef *et al.*, 2021), rather than the physical equipment and assets they possess.

RBV literature has shown that internal firm investments, i.e., into cross-functional orientation, training, and information-sharing, can lead to increased internal capabilities and organisational knowledge, and better firm performance as a result (e.g., versus firm investment into generic technology and employees with generic skills (Schroeder *et al*., 2002; Paiva *et al*., 2008). Thus, despite a long-standing emphasis on technology as the key to progress, RBV insights reassert the invaluable contribution of skilled workers, connected and communicating decision-makers, and implementation of human networks and systems to ensure timely access to relevant information.

Core competencies enabled by digital transformation are defined in terms of the manner by which the firm is able to create and capture value via meeting customer wants and needs, through the strategic and coordinated use of a portfolio of digital technologies (Chaffey *et al*., 2019; Elia *et al.*, 2021). The dimensions of digital transformation, and thus the mechanisms by which firms can seek competitive advantage through digital asset adoption and coordination include: strategic vision, culture of innovation, know-how and intellectual property, digital capability (firm-level internet capability), strategic alignment, and technological assets (Glavas and Mathews, 2014)

This alludes to a logical and strategic opportunity for the integration of digital technologies (as advanced technologies and skills) in the pursuit of broader firm objectives, such as sustainability, circularity and net-zero emissions. Within a CE, core competencies that are commonly supported by digital technologies may potentially be leveraged in pursuit of net-zero emissions, such as: digitised reverse-logistics systems that monitor location of products ("cores") (Bag *et al*., 2019); procurement practices and sourcing systems designed to streamline recovery, assessment, and reintegration (Kalverkamp, 2018); and specialised diagnostic competencies and workforce training to extend "core" product service-lives (Bag and Gupta, 2020). Firm investments to "servitise" the resources and competencies of the firm may also create additional benefits for consumer-users and producer-owners alike (Opresnik and Taisch, 2015). The implementation of such complementary, core competencies into established business models requires investment in developing a strong and skilled workforce and a culture that can coordinate and exploit synergies (Nasr *et al.*, 2017; Dubey *et al.*, 2019; Bag and Gupta, 2020).

The paper is structured as follows. Following the introduction, Section 2 presents the study methodology and explains our two-prong approach: First, a literature review is conducted to explore the research coverage of key themes regarding digital technologies, net-zero, circular economy, and sustainable manufacturing, whilst at the same time, clarifying the key themes in the study and further exploring the gap that this work addresses. Second, an engaged scholarship approach is detailed, documenting the data used within this study and how the analysis was performed. In Section 3, the results of both methods are presented and briefly described. Our extended analysis is discussed in Section 4, in which we present synthesis and strategies regarding the pathways and considerations affecting the potential for digital technologies to contribute to competitive advantage within net-zero manufacturing strategies. Four scenarios of digital technology adoption pathways are proposed, differentiated by the degree of radical vs. incremental interests and options available to the firm. This work is concluded, with reflection on limitations, in Section 5.

2.0 Methodology

Our approach utilizes two key methods as part of a framework for analysis: (1) a literature review to clarify the existing overlap between key concepts and themes; and (2) an engaged scholarship approach that applies insights from the literature review to real-world, practical challenges of understanding how RBV theory can contribute to net-zero strategy and achievement within the UK manufacturing sector. A flow chart representing the data, method and framework of this analysis is further described in Figure 2.

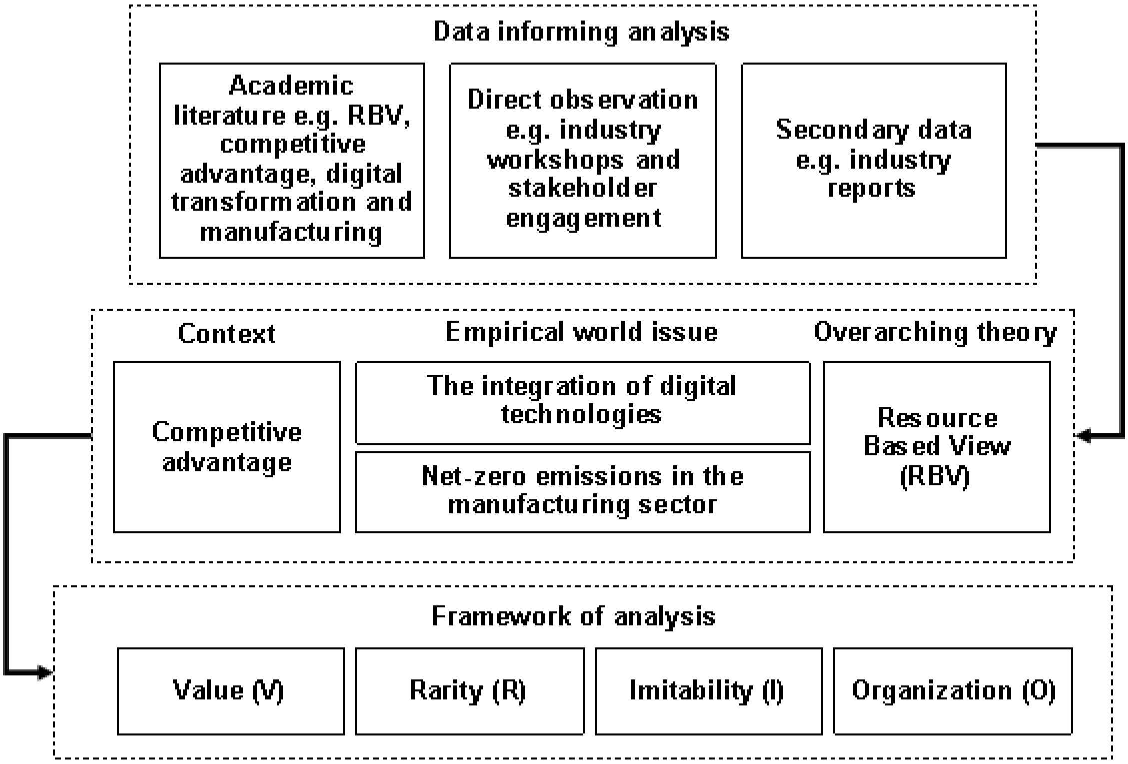


Figure 2: Flow chart representing the data, method and framework of this analysis

2.1 Review of extant literature

To address the research questions outlined in the introduction, previous research from the academic literature was studied to understand the theoretical background (Tranfield *et al*., 2003), establish a solid platform for increasing knowledge and enabling theory development (Dubois and Gadde, 2002). Key words such as “resource-based view”, “RBV”, “competitive advantage”, “digital transformation”, “sustainability”, and “manufacturing” were used to understand the extent to which referenced topics have been covered. A combination of SCOPUS, EBSCOhost, ScienceDirect, and Web of Science were used to obtain the core of the articles.

2.2 Engaged scholarship and systematic combining

This stage of our research methodology integrates elements of engaged scholarship (Bansal and Corley, 2011) and systematic combining approaches (Dubois and Gadde, 2002). Engaged scholarship is a participative form of research for obtaining the advice and perspectives of key stakeholders (in this context manufacturing leaders) to understand and solve a real-world problem. Easter, *et. al.,* (2021) argue that engaged scholarship is well suited to highly complex and interdisciplinary research such as sustainability challenges. This work was inspired by industry interaction and the real-world problems they face, despite previous criticisms of engaged scholarship that argues the method has tended to be one-sided and centre on the relevance of academic research for practise (Van de Ven, 2007).

Our research employs the concept of ‘the evolving case’ to address the requirement for contextualization (Ragin and Becker, 1992). This concept suggests that case researchers must continuously switch between theory and evidence in order to guide their methodological decisions during the project rather of basing them too much on pre-established norms (Buchanan and Bryman, 2007). This involves close consideration of the aim of the study, the unit of analysis, and therefore the study boundaries that emerge from the context.

The flow chart in Figure 2 illustrates how the case is linked to the context and overarching theory. The case under observation is the empirical world issue of achieving ‘net-zero emissions in the manufacturing sector’ through the context of ‘the integration of digital technologies’. This case is viewed through the specific aspect of understanding what ‘competitive advantage’ may be derived as a result. The over-arching theory is applied to further understand whether adopting an RBV facilitates the development of meaningful competitive advantage. The main objective of using this approach is to ‘provoke thought and new ideas’ rather than finding flaws in pre-existing theory (Siggelkow, 2007).

While it has been argued that case-based empirical investigations are insufficiently generalizable because they are too situation-specific (Miles, 1979; Yin, 2018), this can be overcome by using appropriate theory to improve the explanatory power of the study (Dubois and Gadde, 2002; Dubois and Gadde, 2014). To achieve this, we integrated and organised data collected from the industry workshops, with secondary data including that available in the literature, industry reports, and publicly-available documents.

A systematic combining approach was used to blend the primary and secondary data sets for additional analysis and consideration. Systematic combining provides an argument for a stronger reliance on theoretical (vs. empirical) foundation, and allows for constant consideration of the crossover between the empirical world and the theoretical, which is essential for effective case research (Dubois and Gadde, 2002). As with much of the qualitative literature, including case study methods, there are concerns that such an approach can blur and confuse valuable concepts of validity and generalizability (Easton, 1995; Miles 1979). However, there is general agreement that these concerns can be addressed via descriptive and appropriate methodology disclosure (Dubois and Gadde, 2014; Eisenhardt, 1991). Thus, to be consistent with the systematic combining approach, the research questions and analytical framework were constantly evaluated to consider the empirical reality, and our methodology is shared in detail. Combining approaches often results in an effective process where theoretical framework, empirical fieldwork, and context analysis all develop at the same time and therefore these methods were considered the most suitable for this research.

Between 2018 and 2021 the UK had a renewed focus on tackling the climate change emergency through its “Net Zero 2050” strategy, which included the UK government’s Industrial Decarbonisation Strategy (HM Government, 2021a) and the Net Zero Strategy (HM Government, 2021b), published in March 2021 and October 2021 respectively. Within the engaged scholarship approach, we sought to capture and understand the implications and effects of this renewed national focus, collecting data from both primary and secondary sources. Empirical data was collected via stakeholder engagement and discussions at industry workshops. The workshops were held at two distinct points in time, and documented the perspectives and experience of 13 manufacturing firms operating in the UK. Manufacturing firms which had Scope 3 emissions reduction as its sustainability objectives were chosen. (Scope 3 emissions include indirect emissions that happen in the upstream and downstream of a firm’s supply chain, Mahapatra, *et. al.,* 2021). In addition, the selected firms reflect a broad and diverse sectoral classification. These include aerospace, automotive, IT and FMCG sectors. The importance to manufacturing of the net-zero target is very high at 92% (MAKE UK, 2020), as such no outlier were expected from the data collected. Finally, Circular Economy awareness amongst these firms are high, as they formed part of the respondents captured in prior publication from same authors (Okorie *et al*., 2020). The first workshop (Workshop #1), held in July 2018, focused on manufacturing firms who were in the process of implementing digital technologies as part of the CE adoption strategies; a second (Workshop #2) was then held three years later in May 2021, anticipating that those digital technologies had been fully implemented.

The methodology of the selection is further explained in this paragraph. The participating manufacturing companies were chosen in a purposeful and sequential manner, using theoretical sampling principles and multiple selection criteria (Eisenhardt, 1989). They were selected from across the manufacturing sector, including businesses who offered different distinctive qualities (e.g., their nature of work) (**Table 1**). For example, a large firm that manufactures steel will likely experience different challenges than a smaller business operating in the food industry, however, both have data-driven improvements which digital processes can support, and both have a shared responsibility to the local community. To ensure that our findings reflect the broad spectrum of business, we chose situations where key principles of reducing GHG emissions are followed and supported by digital technology. For instance, workshop participants indicated that some firms have developed sophisticated tools to track emissions in supply chains, whereas others are using data to extend life of materials/components and reduce consumption. We selected firms of various sizes and dates of establishment, because we expected these characteristics to reveal contrasting patterns (Eisenhardt and Graebner, 2007) and variety in how firms experienced benefits of digital transformation in the context of reducing emissions. The most established business has been operating since 1962 and the most recent was incorporated in 2009.

Table 1: Overview of basic descriptive data of workshop participants (nature of business, incorporation year, turnover, and job role)

	Nature of business	Incorporation year	Turnover for 2020	Participant’s role
Company A	Manufacture of motor vehicles Other research and experimental development	2001	Not available	Managing Director

Company B	Manufacture of engines and turbines	1971	£11.82 billion	Global Sustainability Manager
Company C	Manufacture of aerospace products	1989	£915.63 million	Industrial Environment Programme Manager
Company D	Other information technology and computed service activities	2005	£35.78 million	Sustainability Lead
Company E	Other information technology service activities	2008	£9.66 billion	Head of Manufacturing Practice Digital Transformation Group
Company F	Other research and experimental development on engineering	2009	£83.0 million	Senior Director Strategy
Company G	Management consultancy activities	1994	Not available	Director
Company H	Manufacture of other transport equipment	1881	£913 million	Head of Sustainability
Company I	Intergovernmental organisation	1975	£913 million	Research Specialist
Company J	Manufacture of fluid power equipment Manufacture of pumps	1997	Not available	Commercial Director
Company K	Recovery of sorted materials	2002	Not available	Executive Chairman
Company L	Manufacture of basic iron and steel and of ferro-alloys	2006	£6.20 billion	Digital Enablement Lead
Company M	Computer Hardware	1962	£3.52 billion	Technical Leader

As engaged scholarship allows the researcher to blend the perspectives of those who produce knowledge and those who use knowledge as part of the research process (McIsaac *et. al..*, 2020), findings from Method (1) were used to inform the identification of the sector and companies that were ultimately explored further using Method (2) as follows: Workshop #1 focused on the broader question of circular manufacturing in the digital age. We asked; *What are the short term, medium term, long term opportunities, challenges and research questions for circular manufacturing in the digital age?* After the discussions, the participant comments and notes were captured and synthesised into a tabular format. Data from Workshop #1 (July 2018) was used to develop, refine, and clarify a series of focused questions for Workshop #2 (May 2021). Accordingly, Workshop #2 intentionally focused on the resulting questions and discussion, as outlined below:

- How is digitisation (technology and data) being used to overcome the barriers to achieving ‘net zero’ emissions?
- What existing policies / initiatives / support have been useful in helping manufacturers start their journey towards ‘net zero’ emissions and what additional policies / support is required to achieve ‘net zero’ emissions by 2050?
- What does a ‘net zero’ emission manufacturing sector look like in 2050? What technologies will be commonplace?
- What future challenges will we need to address to get there?

2.3 Theory-based analysis

To understand whether and how conventional competitive advantage, and achievement of net-zero performance are derived from these digital technologies, data from the workshops was evaluated and organised (across manufacturing, CE, digital transformation, and net zero). Tangible and intangible assets were distinguished, as well as the value (V), rarity (R), imitability (I), and organisation (O) of these resources in accordance with the VRIO framework (Barney, 1991, 2001; Lopes *et al*., 2018). VRIO analysis permits differentiation of advantage achieved. A resource that yields two (2) VRIO characteristics enables competitive parity for a firm relative to its competitors; having three (3) of the VRIO characteristics results in temporary competitive advantage for a firm; and having four (4) of the VRIO characteristics can lead to a sustained competitive advantage (Barney, 1991; Barney, 2001). The VRIO model was originally designed for the context of firms (Barney, 1991; Lopez *et al*., 2019) and has been adapted with RBV for the identification of competitive strategies and public policies in firms (Mudambi and Puck, 2016). Conventionally, organisational attributes are evaluated to distinguish the extent to which *a firm* has the internal organisational systems and structures necessary to fully exploit a potential competitive advantage. However, in this case we evaluate the extent to which *the digital technology* (not the firm) can contribute to and facilitate internal cross-functional information sharing and coordination that is often needed to exploit a competitive advantage. We then extended the evaluation to consider whether the digital technology resource would also be able to facilitate or enable achievement of net-zero performance as a corollary to conventional competitive advantage (**See Table 2**).

3.0 Results & Analysis

Focusing on the future of net-zero emissions manufacturing, we explore the role of digital transformation as it contributes to the advancement of manufacturing capability and capacity, the establishment of competitive advantage, and the enabling of sustainability strategies including climate target achievement and CE.

3.1 Findings from the literature review

Figure 3 organizes and reflects the key themes that were deductively applied to the literature review: (a) Strategic management themes, including RBV and competitive advantage (Figure 3(a)); (b) Sustainable manufacturing themes, including circular economy (CE), sustainability, climate targets, and net-zero (Figure 3(b)); (c) Digital transformation themes related to manufacturing within CE (Figure 3(c)); and (d) Digital resources and competencies necessary for net-zero emissions (Figure 3(d)); and (e) Emergent issues and themes connected to digital transformation are also presented.

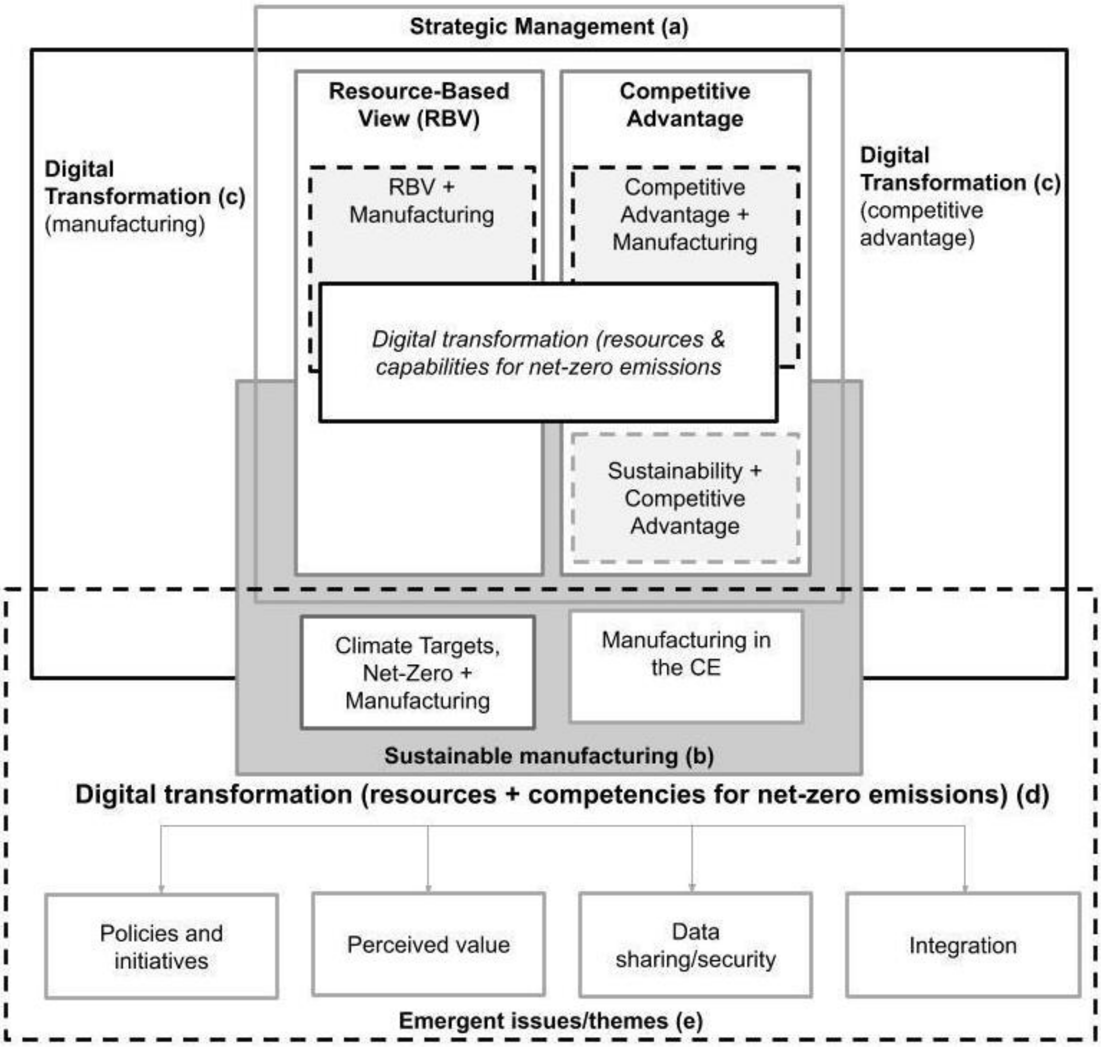


Figure 3: Diagram of the reviewed literature, compiled and organised by key thematic area: (a) Strategic management; (b) Sustainable manufacturing; (c) Digital transformation for manufacturing and competitive advantage; (d) Digital transformation resources and competencies for net-zero emissions; and emergent themes (e). Adapted from (Hegde and Tumlinson, 2021)

3.1.1 Digitally-enabled circular economy: Core competency for achieving net-zero?

Digital transformation is holistically described by Mergel *et al*. (2019, pg. 12) as:

> "…a holistic effort to revise core processes and services of an [organisation] beyond traditional digitization efforts. It evolves along a continuum of transition from analog to digital to a full stack review of policies, processes, and user needs and results in a complete revision of the existing and the creation of new digital services. The outcome of digital transformation efforts focuses among others on the satisfaction of user needs, new forms of service delivery, and the expansion of the user base."

Manufacturers spend 4-10% of annual turnover on the management of their waste materials, while the current "make-use-dispose" economic model continues to rely on endless consumption of raw materials and contributes to rapid depletion of finite resources. This is particularly problematic for the manufacturing industry, with rising concerns behind the volatility and security of supply chains (Lowe, 2021). Catalysts of CE transformation, digital technology adoption, and digital transformation create and capture value by targeting the systemic efficiency of resource flows – whether slowing these flows (extending product life), closing these flows (eliminating waste in the system), narrowing flows (reducing material volumes) or creating new flows (manufacturing new products from waste feedstocks) (Ranta *et al*., 2021).

CE transition research has suggested that manufacturers who successfully transition to CE business models will likely experience significant economic benefits, reduced manufacturing costs through sustainable supply chain and end-of-life managements, lower input prices, and minimise environmental penalties and waste generation (Park *et al*., 2010; Zhu and Tian, 2016). For example, an annual material cost-saving opportunity of between $520 billion and $630 billion USD is estimated for the EU alone (Ellen MacArthur Foundation, 2013). By avoiding the requirement and consumption of primary materials through the use of sustainable manufacturing strategies (i.e., circular design, remanufacture, cleaner production, servitization-based business models (Acerbi and Taisch, 2020; IRP, 2018)), there is an implicit opportunity for reduced life-cycle emissions associated with components, parts, and products. However, while a CE transition may be on the horizon, no coherent CE adoption plan for manufacturers and their supply chains currently exists. Further, CE methods are not universally appropriate for all manufacturing activities, and CE-transitions can and should vary widely across products, sectors, and geographies (IRP, 2018).

The adoption of digital technologies has helped to facilitate advancements in CE business performance and innovation (Opresnik and Taisch, 2015; Bag and Gupta, 2020). These are predominantly applied to enhance CE business model strategies, patterns, and components, support implementation of managerial practices during CE transition, and enable the implementation of product-service systems and other servitization models (Bempong *et al*., 2019). To-date, examples of applied digital technologies for CE include but are not limited to: Data collection and integration; Internet of Things (IoT); Cloud-based technologies to track asset status and analyse performance; Enterprise Resource Planning (ERP) systems; online ordering systems; and artificial intelligence (AI) based forecasting (Ranta *et al*., 2021). While digital transformation can also increase a firm’s manufacturing and process capabilities, Blichfeldt and Faullant (2021) argue that it may not be enough to achieve a sustainable competitive advantage over competing firms. A critical task in the resource-based approach to strategy is to continuously develop existing capabilities, and create new ones (Leonard-barton, 1992). To achieve these new capabilities as competitive advantage, there is the need to build core competency around achieving net-zero emissions (new capabilities) by leveraging existing capabilities (digitally-enabled CE). We believe the RBV can help unlock this (Leonard-Barton, 1992).

3.1.2 Sustainable manufacturing: Circularity and opportunity for carbon reduction

The triple-bottom line perspective of sustainability (economic, social and environmental advantages) (Azevedo and Barros, 2017; Okorie *et al*., 2021) considers sustainability to be a form of competitive advantage (Wagner, 2005; Pacheco-de-Almeida and Zemsky, 2007; York, 2009).

In many industries, firms’ ability to sustain their competitive advantage depends on their ability to adopt sustainability in their businesses. A growing body of work within sustainability and management literature has explored ways in which firms place sustainability at the centre of their pursuit and attainment of competitive advantage (York, 2009; Cantele and Zardini, 2018; Ioannou and Serafeim, 2019). As an example of this challenge, the UK Government has committed to reaching net zero GHG emissions by 2050 (Committee on Climate Change, 2019). Firms have begun to implement energy efficiency measures, and although additional development and research is needed, many are reporting increased profit margins and increased competitiveness as a result (MAKE UK, 2020; Rydge *et al*., 2018; Stern and Valero, 2021).

Accordingly, climate change targets (e.g., net-zero emissions) can also be examined as a competitive advantage opportunity through the lens of sustainability. The link between a firm's sustainability targets, net-zero (emissions reductions), and sustainable development goals has been established in literature (Gil *et al*., 2019; Hasan *et al*., 2020). Further, there is an increasing awareness that the mitigation and reduction of GHG emissions associated with manufacturing value-chains is essential for the achievement of a sustained competitive advantage (Morioka *et al*., 2017; Olatunji *et al*., 2019).

The global manufacturing sector is among the largest contributors to GHG emissions, accounting for approximately 24.2% of global annual GHG emissions (Ritchie and Roser, 2021). However, this figure only reflects direct emissions, such as consumption of fossil fuels, transportation, and electricity usage. The inclusion of indirect emissions, such as those associated with supply chain and waste management, would more than triple the manufacturing sector's contribution to global GHG emissions (Hertwich and Wood, 2018).

A range of factors have resulted in GHG emissions reduction becoming a meaningful manufacturing performance indicator for both linear and circular business models, including but not limited to: reputation risk; cost; pre-emption of expected legislation and compliance requirements; increased supply chain transparency; risk associated with changing market conditions tangential to manufacturing-based emissions (e.g., reduced budgets for related infrastructure); public-facing environmental responsibility commitments; and others (Olatunji *et al*., 2019). Depending on their specific context, these factors can lead manufacturing firms to focus on carbon emissions as both a measure of performance, and as a strategy for competitive advantage. The alignment of sustainability investment and risk mitigation objectives in the case of GHG emissions reduction is also apparent when it comes to the CE transition.

3.2 Workshops

3.2.1 Integrating real-world and literature review insights: Systematic combining

A primary objective of this research is to explore what competitive advantage(s) may be derived from the integration of digital technologies to achieve net-zero manufacturing emissions. Developed using a systematic combining approach, **Table 2** summarises the main findings and insights from across primary and secondary data sources, and organises these into the digital technology categories derived from the same sources. **Table 2** (columns 1 and 2) reflect data and perspectives collected from workshop participants regarding types of digital technologies perceived to be most influential, and the associated value that can be derived from them, respectively. These are complemented by additional synthesis and analysis of the literature. The potential contribution of digital technologies to achievement of CE and net-zero is clarified (Table 2, column 3), as well as associated external policies and initiatives required for competitive advantage to be derived to achieve net-zero manufacturing emissions (Table 2, column 4).

The workshop data presented in Table 2 shows that five (5) of eight (8) digital technology-enabled forms of value identified by participants refer to tangible value (Table 2, column 2). Intangible value, derived from worker skills, interconnectedness of data for forecasting, and market responsiveness, were also identified (Table 2, column 2), however these were still framed in terms of how they could contribute to tangible value (monetary); None of the intangible value items were identified as directly contributing to a net-zero emissions objective.

Table 2: Summary of identified digital technologies and the perceived competitive advantage that can be derived to achieve net-zero manufacturing emissions, per workshop participant data. Adapted from (Ranta *et al*., 2021) and (Wee *et al.*, 2016)

Identified digital resources and capabilities	What value can be derived	How this contributes to achievement of CE and net-zero (Examples from the literature)	Policies and initiatives required
Machine health and use data are collected via IoT technology	Reduction of maintenance costs Reduction of machine downtime	Regular maintenance will improve efficiency of equipment (Ding et al., 2021)	Policies are required that encourage the growth of internet infrastructure, effective use of wireless transmission and data centre expansion Privacy and data security policies that reflect its possible implications on users should be examined
Large amounts of data are stored, integrated, and analysed using cloud technology	Productivity increase	Virtualization is a popular means to consolidate servers and results in lower power and cooling requirements (Sigwele, Hu, & Susanto, 2020)	Proposing heightened regulations on carbon emissions for operators to use renewable energy
Automated machines, autonomous robots and production equipment	Productivity increase	Smart factories are able to manage dynamic requirements of energy supply and feedback (Stock & Seliger, 2016)	Policies to ensure that the automation is operating in a secure environment free of hacking, malware, and/or other network disruptions
Electronic data labels for products and shelves with IoT technology	Allow autonomous and real-time price adjustments.	Digital passport can be embedded to provide information on how to handle materials (Atta, Bakhoum, & Marzouk, 2021)	Electronic labels represent how comfortable people are with digital information access. The global benefit will not be realised until the majority of countries agree to their use (Cory, 2021).
Customers can order inventory directly using an online ordering system	Costs for inventory holding decreased	There is no waste inventory since products are only manufactured when required. Emissions avoided from unnecessary transit. Enables reverse supply chain through established relationships (Ellsworth-Krebs, Rampen, Rogers, Dudley, & Wishart, 2022)	Regulation to reduce the impact of deliveries in relation to 'last mile' emissions could be considered (World Economic Forum, 2020)
Forecasting abilities are provided by AI technology	Accuracy forecasting increased	AI and machine learning software can detect parameters that need to be changed in order to reduce emissions.	Concerns about algorithmic bias, privacy, and security have highlighted ethical arguments; governments are focusing on how to regulate AI.
Data for product development operations is integrated via a resource planning system.	Reduction in time to market	Can be combined with life cycle assessment as a valuable tool for evaluation and monitoring of product impacts (Ferrari, Volpi, Settembre-Blundo, & García-Muiña, 2021)	
Intangible skills, attitudes, and capabilities	Comprehension and optimal use of operations, data and equipment	Employee participation and buy-in are crucial in organisational change.	Initiatives to train existing (and new) staff to provide skills and knowledge required

3.3 VRIO framework analysis

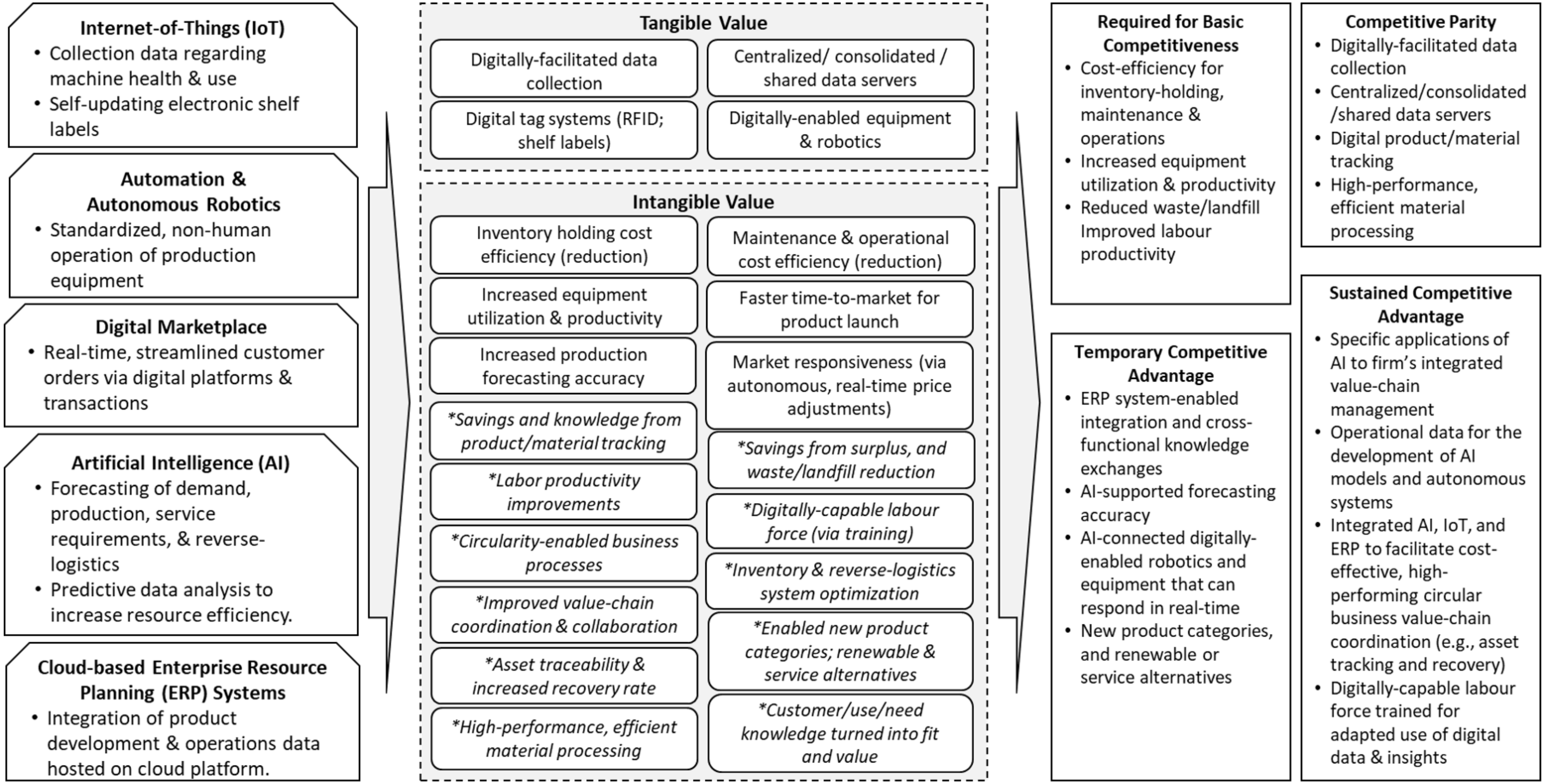
VRIO analysis permits differentiation of the advantage achieved (if any): A resource that leads to two (2) of VRIO characteristics enables *competitive parity* for a firm relative to its competitors; having three (3) of the VRIO characteristics results in *temporary competitive advantage* for a firm; and having four (4) of the VRIO characteristics can lead to a *sustained competitive* advantage (Barney, 1991; Barney *et al*., 2001). As described in **Table 3**, there are only a few digital transformation resources that lead to a sustained competitive advantage, achieving all four VRIO requirements. Applying the conventional view (VRIO) to the dataset, the digital technologies that, in combination can lead to a sustained competitive advantage include:

- Application of digital technologies specific to the firm's operations (e.g., digital passports; RFID, digital tags) (tangible);
- Faster time-to-market for product launch (intangible);
- Market responsiveness via autonomous, real-time price adjustment (intangible);
- Digitally-capable labour force (intangible);
- Circularity-enabled business model (intangible);
- Inventory and reverse-logistics system optimization (where applicable)(intangible);
- Asset traceability and increased recovery rate (intangible);
- Improved value-chain coordination and collaboration (intangible); and
- Enabled new product categories, including renewable and service alternatives (intangible).

Table 3: Assessment of digitally-derived resource/value using VRIO framework, distinguishing achievement of competitive advantage vs. net-zero performance. (* denotes adapted insights from Ranta *et al*. 2021).

Resource/ Value Derived from Digital Transformation for CE and Net-Zero		**Extent to which Digital Technology Resources:**				
		Lead to value for customers (V)	Are rare (R)	Are costly/ difficult to Imitate (I)	Help to organize operations to exploit advantage (O)	Help to organize operations to achieve net-zero
Tangible	Digitally-facilitated data collection & management via ERP	X	--	--	X	--
	Centralized/consolidated/shared data servers	X	--	--	X	✱
	Digital applications specific to firm (e.g. tags; RFID; digital passports)	X	X	X	X	--
	Digitally-enabled robotics and equipment	X	--	X	X	--
Intangible	Inventory holding cost efficiency	X	--	--	--	--
	Maintenance and operating cost efficiency	X	--	--	--	✱
	Increased equipment utilization and productivity	X	--	--	--	✱
	Faster time-to-market for product launch	X	X	X	X	--
	Increased production forecasting and accuracy	X	--	X	X	✱
	Market responsiveness (via autonomous, real-time price adjustment)	X	X	X	X	--
	*Savings and knowledge from product/material tracking	X	--	--	X	--
	*Savings from surplus and waste/landfill reduction	X	--	--	--	✱
	*Labour productivity improvements	X	--	--	--	--
	*Digitally-capable labour force (via training)	X	X	X	X	✱
	*Circularity-enabled business processes	X	X	X	X	✱
	*Inventory and reverse-logistics system optimization	X	X	X	X	✱
	*Asset traceability and increased recovery rate	X	X	X	X	✱
	*Improved value-chain coordination and collaboration	X	X	X	X	✱
	*Enabled new product categories; renewable & service alternatives	X	X	X	X	✱
	*High-performance, efficient material processing	X	--	--	X	✱
	*Customer/use/need knowledge turned into fit and value	X	X	--	X	✱

Figure 4 synthesises and combines the insights and patterns assessed from **Tables 2** and **3** into a clear pathway for considering the role and potential for digital technologies within net-zero strategies as a form of competitive advantage. The five primary forms of digital technologies for net-zero manufacturing were identified by workshop participants: (1) Internet of Things (IoT); (2) automation and autonomous robotics; (3) digital marketplace; (4) artificial intelligence (AI); and (5) cloud-based enterprise resource planning (ERP) (**Figure 4(a)**). Using RBV, the specific digital resources/value, and/or their benefits as identified in **Tables 2** and **3** were classified into tangible vs. intangible asset categories (**Figure 4(b)**). Finally, the varied degrees of competitive advantage that may be derived from adoption and appropriate application of digital technologies, are presented based upon the findings of the VRIO analysis (**Figure 4(c)**).



(a) CE Manufacturing-Relevant Digital Technologies & Applications for Achieving Net-Zero

(b) RBV of Organizational Resources that can be leveraged through digitization for CE (adapted from Ranta et al., 2021)*

(c) Assessment of Potential Competitive Advantage (via VRIO) in pursuit of Net Zero

Figure 4: Synthesis of the pathways and considerations necessary for relevant digital technologies to contribute to competitive advantage outcomes (via VRIO) in the pursuit of net-zero manufacturing. (* denotes adapted insights from Ranta *et al*. 2021).

4.0 Discussion

4.1 Valuing tangible and intangible assets

Workshops discussions revealed that tangible competitive advantages associated with digitization for net-zero emissions were more readily identified by participants (vs. intangible), such as quantifiable cost reductions and acquisition of equipment and software.

Further, these contributions (Table 3) indicate that the primary advantage of adopting digital technologies is perceived to be largely associated with anticipated or realised efficiency improvements, productivity increases, and cost reductions enabled by general digitization, and were not associated with net-zero manufacturing emissions.

However, when contrasted with the literature, the benefits of digitization to achievement of net-zero emissions may be more predominantly intangible in nature. That is, in many cases digital technologies enable optimization and improvement of manufacturing processes and other activities across the value-chain which cannot be quantified or monetized. Instead, competitive advantage is derived from firm-specific, and/or product-specific data sets, transfer and sharing of data and information, and effective organisation of human capital (intangible assets/value).

Two additional key insights are noted from **Table 3**: First, the mere adoption of digital technologies does not lead directly to *sustained competitive advantage (having four VRIO characteristics)* - at best, digital technologies can enable a *temporary competitive advantage (having three VRIO characteristics)*, or *competitive parity (having two VRIO characteristics)* (Barney, 1991; Barney *et al*., 2001). Second, where digital technologies do enable sustained competitive advantage, that advantage is derived from both the appropriate and optimised application of the digital technology (e.g., firm-specific digital tools, such as digital passports), and from the associated intangible benefits (e.g., trusting relationships with suppliers, advanced labour force capabilities) that extend beyond digital technology itself.

Accordingly, it is critical to note that the digital technologies that may lead to net-zero emissions performance are not necessarily those that lead to sustained competitive advantage, particularly those targeting tangible assets and outcomes. According to workshop participants, some firms are already exploring how the use of cloud-based computing and shared server resources can be optimised to reduce their overall GHG emissions and material-use footprints. However, while the use of shared data servers (tangible) for in-house applications may help firms to avoid being in a non-competitive position, this is neither rare nor difficult to imitate, and will not enable sustained competitive advantage.

Further, the importance of possessing a digitally-capable labour force able to interpret data and innovate its adaptive uses to advance firm efficiency (e.g., fully trained, able and innovative) is also apparent. Through innovative intangible (e.g., human capital) resources, digital technologies can be integrated with one another to further enhance the firm-specific application and achievement of competitive advantage.

As demonstrated in **Figure 4**, firms that utilise digital technologies in concert with intangible assets that include a digitally-capable labour force, and relationship- and trust-building across the value chain, will ultimately achieve more meaningful data-sharing and mutual benefit that can lead to large-scale net-zero performance optimization. Accordingly, firms investing in labour force training, and having established relationships and trust with their suppliers may achieve a more sustainable competitive advantage by leveraging such relationships within their net-zero strategy, especially relative to newer and/or less-connected firms.

CE’s 4R framework argue a value retention hierarchy, where the ‘R’s’ order reflects the priority in terms of environmental sustainability, aiming at retaining the maximum resource value at all time (Reike, *et. al.,* 2017) . Thus the CE presupposes a completely different understanding of the relationship between supply and demand. For instance, the implementation likelihood of CE practices, as investigated by Gebhardt *et al*, (2021), is not congruent with the value retention hierarchy advocated by the 4R framework. This may become a threat to the transition towards a CE. For manufacturing firms, the identification of tangible and intangible assets can enable the understanding the relation between supply and demand in a CE context.

4.2 Strategic use of digital transformation to achieve net-zero manufacturing

Despite ‘digital transformation’ being discussed as a potentially optional, or future-based transition, our workshop data clarifies the inherent urgency from the perspective of the firm: simple adoption of digital technologies to acquire basic operational data and improve cost-efficiency will yield only basic levels of competitiveness, due to the fact that adoption of these technologies provides some degree of value to customers. However, these resources are neither rare nor non-substitutable, suggesting that, at the very least, basic application of digital technologies will be necessary if firms are to avoid a *non-competitive* position.

More advanced digital technology applications can be used to improve production planning, integrate cross-functional data-based decision-making, and bring transparency to complex value chains. These activities are critical for pursuing *competitive parity*, given the easily accessible nature of these technologies for a wide range of firms and industries. For example, cloud-based ERP systems have increased their market share from 23% to 51% between 2015 and 2019 (Salih *et al*., 2021).

Firms may achieve *temporary competitive advantage* from the use of digital technologies to create firm-specific efficiencies, insights, and knowledge, and/or to enable advanced uses of digital technologies, such as for increased forecasting accuracy. However, it is also clear that the path to sustained competitive advantage for CE and net-zero via digital transformation is only possible through integration of multiple digital technologies, and achievement of a digitally-capable labour force. Such integration of human and physical capital aligns with RBV theory: integration of digital technologies facilitates sharing of knowledge and information across functions and decision-making centres of the firm; achievement of a digitally-capable labour force ensures that such knowledge and data can be used to strategically advance operational efficiency of the firm (e.g., in pursuit of net-zero), as well as securing and defending a sustained competitive advantage. Alone, digital technologies are neither rare nor non-substitutable; when integrated, appropriately applied, and utilised by a skilled workforce, the results can be qualified as both rare and difficult to imitate.

Our findings from this study suggest a connection between the degree of digitalisation (effective adoption of both tangible and intangible aspects of digital technologies) of a manufacturing business and the extent of competitive advantage (via progress towards net-zero) that may be possible. Building on the work of Ranta *et al.* (2021) we propose four scenarios of digital technology adoption and business model innovation for net-zero, catalysed by digital technologies (**Figure 5**).

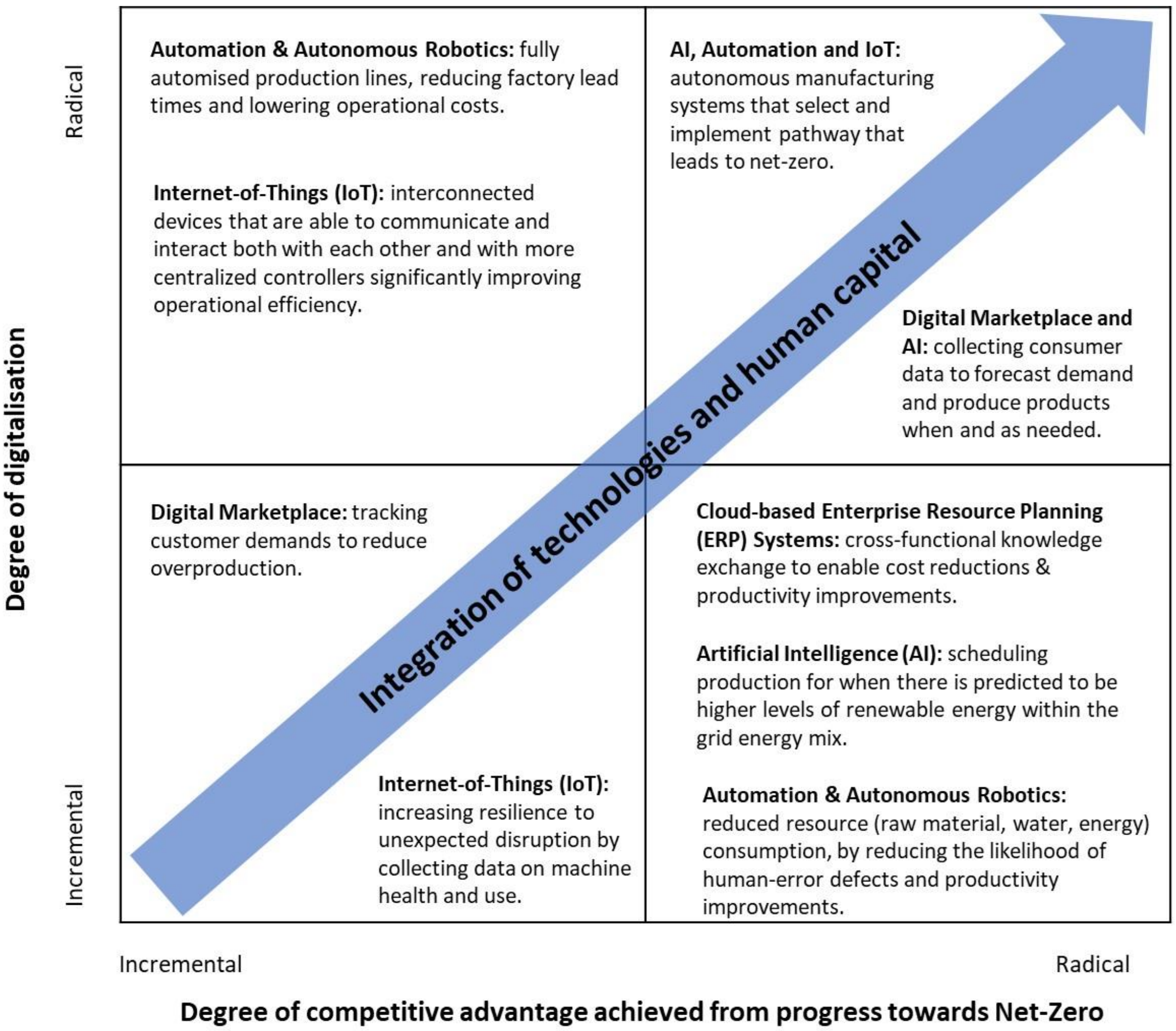


Figure 5: Model of four scenarios of digital technology adoption for net-zero. Presented as a 2x2 matrix reflecting combinations of incremental vs. radical degrees of digitalisation (y-axis) and of competitive advantage achieved from progress towards net-zero manufacturing (x-axis).

Within the model, per **Figure 5**, we identify four scenarios differentiated by the level of digitalisation achieved by the firm, and the application of these technologies to reduce emissions.

1) **Incremental digitalisation of the business and incremental net zero gains**: In this scenario the manufacturer has taken their first steps on the digitalisation journey with a limited adoption of digital technology. There is a small competitive advantage achieved from reduction of emissions, for example using digital marketplaces to reduce overproduction, but these remain small and net zero is not the priority of business.
2) **Radical digitalisation of business but incremental net zero gains**: Digital technologies have achieved a high level of adoption and novel use throughout business, but their full potential to deliver net zero gains has yet to be realised. Instead, competitive advantage from digital technologies is primarily economic with small environmental gains. For example, using IoT to decentralise analytics and decision-making to improve overall operational efficiency and economic productivity (Lampropoulos *et al*., 2019).

3) **Incremental digitalisation of business, but radical net zero gain**: Digital technologies use within business is limited but are being effectively utilised to deliver a competitive advantage from significant reductions of emissions. For example, use of AI forecasting to schedule production for when there is predicted to be higher levels of renewable energy within the grid energy mix.
4) **Radical digitalisation of business and radical net zero gains:** Digital technologies are prevalent throughout business and are used together, and/or integrated for novel applications that reduce emissions throughout the manufacturing value chain.

Thus, the conceptual model developed by Ranta *et al.* (2021) is extended with this work. In order to strategically optimise use of digital transformation to achieve net-zero manufacturing emissions there needs to be an integration between different digital technologies and, also, digital technologies and human capital (**Figure 5**, upper-right scenario). The radical adoption of digital technologies has potential to account for up to 50% of the emission reduction required by 2030 (Bitkom and Accenture, 2022), representing an estimated 2.07GT carbon emissions reduction in Europe only (Digital Europe, 2020). However, it should also be noted that digital technologies may, themselves, pose sustainability concerns including: possessing large carbon footprint (Patsavellas and Salonitis, 2019); being short-lived products; being difficult to recycle; and/or leaching toxic chemicals into the environment (de Vries and Stoll, 2021; Kottmeyer, 2021). To avoid jeopardising the potentially valuable and helpful role of digital innovations, future research should seek to reveal and improve understanding regarding the complex interactions between digital technologies, net zero and CE systems in order to avoid rebound effects and other unforeseen sustainability consequences.

5.0 Conclusions

The importance and complexity of ensuring operational continuity, particularly on a global scale, has been highlighted in recent years, and in parallel, the shift toward digital capabilities and technologies has become a strategic priority for many companies seeking to maintain and increase their competitive positions. Insights from the literature suggest that companies can achieve long-term competitive advantage by bundling resources and capabilities into core competencies, and the more complex the bundle, the more difficult it is for competitors to replicate or find substitutes for it. This study emphasises the importance of intangible assets (non-physical assets owned by a business that aid in its ongoing performance) and suggests that additional investment and development are required. It has also been argued that sustainability and CE have become primary drivers of innovation, and that implementing circular business models to mitigate risks associated with climate change can provide a competitive advantage. Within CE, where product-as-a-service, product life extension, and resource recovery business models are more likely to be adopted, businesses must ensure they have the right set of skills and resources to adapt.

In almost all cases, capturing value from digital technology will entail significant operational challenges that manufacturers must overcome. Participant firms expressed concerns surrounding the challenges associated with data collection, use, analysis and storage; Concerns about privacy, and security have also revealed that many firms are still hesitant to share their data. While RBV takes a firm-specific view, it is clear that there is opportunity for greater coordination and optimisation across the value-chain if policy-based support is provided. As identified throughout interactions with participating firms, policy measures that emphasise emissions reduction can help to encourage the shift to digital options that may support achievement of CE and net-zero ambitions, and a more universal approach. Additional policy guidance regarding appropriate use, applications and management of data collected and utilised within the digital transformation will be important for creating greater firm comfort in engaging in digitally-enabled supply-chains.

This study has several limitations, but also provided interesting opportunities for future research. Collection of more data to see how transferrable or reproducible a firm's digital skills are, would help to further understand sustained competitive advantage. We gathered data from individuals who were directly involved in commercial application of digitization in relation to CE. As a result, there may be some perception bias in terms of the extent to which digital technologies can provide a competitive advantage. Despite these limitations, our study is one of the first theoretical contributions that discusses intersection of RBV and CE to help understand how firms' digital resources and capabilities contribute to development of a competitive advantage based on digital transformation.

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