Digital investment for manufacturers: A literature review of challenges and good practices

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Executive summary

Although the importance of digitalisation as a critical source of innovation and competitiveness among manufacturers is widely accepted, manufacturers struggle to make the necessary investments to capture these opportunities. To support manufacturers with their digitalisation journey, it is critical to develop a detailed understanding of the digital investment challenges manufacturers are facing and how they can be overcome. This report provides the findings of a systematic review of the academic and grey literature carried out to establish the state of the art on what is known on the diverse organisational, technical and process challenges manufacturers are facing with their investment into digitalisation and the good practices that are available to address them. It also evaluates the current theoretical contributions and gaps in the existing literature to develop a research agenda to help researchers target and accelerate their future investigations on the digitalisation of the manufacturing industry.

INTERACT

The full report and other resources to support manufacturers with their digitalisation journey can be found at **interact-hub.org**

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Introduction

The future success of manufacturing is dependent on its digitalisation. On the one hand, digitalisation helps manufacturers improve their operational efficiency (Gillani et al. 2020), develop innovative products (Stornelli, Ozcan, and Simms 2021) and create new customer value propositions (Schroeder et al. 2020). On the other hand, digitalisation has altered the competitive context for manufacturers. It provides a pathway for digital-native companies to reshape the manufacturing industry by threatening to capture more of the value that is being created. Without redeveloping their own business models to embrace digitalisation, manufacturers limit their future growth opportunities (Culot, Orzes, and Sartor 2019).

Despite the range of opportunities and threats digitalisation creates, the UK manufacturing industry lags in its digital investments (MakeUK 2020). A recent survey reveals that 94% of UK manufacturers believe their industry lacks digital investment, and 56% believe that UK manufacturers have already lost sales as a result (The Manufacturer 2022). 90% of the survey respondents consider underinvestment into digitalisation to be the industry's biggest productivity blocker. Even for digitally savvy companies, only 56% develop formal business cases to scrutinize their digital investment and 34% use comparative formal indicators to make their assessment, which is a lot lower among the remaining companies (6% and 2% respectively) (Colas et al. 2014). Another survey shows that 80% to 90% of business leaders can't accurately measure ROIs of their digitalisation initiatives (Louis, Geisert, and Blessing 2020) and companies reportedly direct funds to the latest digital trend to mimic their competitors, or for publicity reasons, but not because of effective business considerations (Campagna 2018).

Although the gap in investment into digitalisation among manufacturers is widely recognised, there is less clarity on the root causes of it. As individual studies point to different organisational or technical root-causes, it becomes increasingly clear that the gap is the result of multiple factors. In fact, focusing on individual factors in isolation may limit the understanding of the complexity of the situation manufacturers are facing and can limit the effectiveness of any initiatives for solving these. The ability of researchers and advisory services to support manufacturers with their critical digitalization journey depends on the development of a comprehensive understanding of the barriers they face.

To contribute to the development of such a comprehensive understanding, the present investigation sets out to review and consolidate the current insights on the digitalisation investment challenges among manufacturers and develop a research agenda that stimulate and guides research on it.

A systematic literature review was conducted to map out and consolidate the diverse range of challenges and good practices for digital investments among manufacturers. The review covers both the academic and grey literature to ensure that the understanding captures the range of challenges of digital investments. It also extends beyond the English language domain and includes the Chinese and German language literature, which are both very active in the digital manufacturing domain.

The systematic literature review generates a number of important insights which are highlighted in the report. In particular, it identifies

- a wide range of core challenges that affect the manufacturers' effective investment into digitalization. These include the aspects of the process/procedures, people, technology, infrastructure/network, goals, and culture that create the complexity in the decision-making of digital investment.
- a range of good practices individual manufacturers have employed to overcome some of the specific challenges manufacturers face in making effective digitalisation investments.
- the range of theories and theoretical perspectives that current research apply to guide investigations into effective digital investment decisions.
- a research agenda to theoretically ground future studies, which supports manufacturers with their investments into their digitalisation journey.

InterAct Network

The investigation and the report are funded by the InterAct Network which aims to understand the human issues resulting from the diffusion of new technologies in industry and works towards the creation of a digital innovation ecosystem to accelerate the innovation and diffusion of industrial digital technologies.

Method

The systematic review took several steps to identify, analyse and synthesise a diverse range of academic and business publications to ensure the breadth and depth of the available insights feeding into the review.

Academic literature

First, the research team identified the most suitable academic database, EBSCOHost, in the English language domain. Second, the research team developed, refined, and validated the search terms. We started by using the search terms of "digital" and "business case", which intended to capture the extensive and broad discussions in this area. Thousands of articles (12,722) appeared from the search, though with quickly diminishing relevance. The phrase "business case" was used in a wide

range of topics that lacks consistency. Where definitions of business cases were aligned, most academic articles did not discuss them in terms of investment. Thus, we replaced "business case" by "investment" in the search terms. The search terms returned more articles still (14,942). While some articles cover the broader digital narrative and context, the main concern was the lack of sector-specific relevance, which led us to include "manufacturing" in the search terms to define the industry setting. Thus, the initial search and screening of articles enabled us to decide the final search terms as:

- 'manufactur*' (to include manufacture, manufacturer, manufacturers and manufacturing)
- AND "invest" (to include investment. In quotation marks to avoid capturing "investigate", which was an issue noted in this search)
- AND 'digital*' OR 'technolog *' (as it became apparent from this search that many recent articles implicitly discuss digital when discussing manufacturing technology investments)

538 papers resulted from the search using these terms.

The third step was to select the most relevant and quality outputs for the review. We created a sample of 46 Journal articles. The three members in the research team read and labelled the articles by the perceived relevance as 'low', 'medium', or 'high' independently. Low ranking outputs were due to their technical or topic specificity (e.g. software or hardware innovation, or digital finance) or time of publication being more than 5 years ago. Medium ranking outputs were due to their breadth of scope or lack of depth (e.g. general commentary on sector trends). High ranking outputs met the agreed criteria of sector relevance and scope (the manufacturing firm), subject or topic (digital investment) and themes (discussing potential or existing issues, enablers or inhibitors associated with different aspects of the organisation). Based on the analysis of the sample articles, we developed the exclusion criteria:

- Non-firm level investment (e.g. foreign investment and trade balances)
- Non-digital technology (e.g. R&D in general and green technology only)
- Less relevant research topics (e.g. digital sourcing and finance, technology outcomes, and development of new product features)
- Book reviews (book reviews often provide less empirical evidence and discussions of the most up-to-date business practices)
- Published before 2017 (earlier outputs discuss future or emerging trends with lack of insight)

Moreover, as the focus of the review is business research, the Chartered Association of Business Schools (CABS) Academic Journal Guide (AJG) (CABS 2021) was used to sort and select the quality

outputs. The selection of papers focused on leading journals in the 4- and 3-star range. Eventually, we created a final catalogue of 37 English academic papers.

To create the Chinese academic catalogue, the research team identified the most appropriate outlets by using the Chinese Social Sciences Citation Index (CSSCI). Applying the same keywords in Chinese in Baidu Academic 百度学术 (one of the largest academic search engines in China) identified 146 articles. One of the team members, as a native speaker in Chinese, screened the articles by applying the same exclusion criteria, which created a final catalogue of 27 Chinese academic papers.

To create the German academic catalogue, the research team sought to identify the most appropriate outlets by using the German Business Scholar Citation Index (Schrader n.d.). The review of the journal list showed that very few of the recognized academic journals were German language based and none of the ones that were high ranking. In fact, the German Business Scholar Citation Index largely focused on the same English language journals that were represented and already captured in the Chartered Association of Business Schools (CABS) Academic Journal Guide (AJG) (CABS 2021).

Business literature

Unlike the academic literature which is catalogued in recognized databases, the business ("grey") literature lacks a central repository and format. Also, the outlets are not formally ranked as it is the done by the Chartered Association of Business Schools (CABS) Academic Journal Guide (AJG). This lack of central repository and formal ranking is widely recognized as a critical challenge for integrating grey literature into literature review (Adams, Smart, and Huff 2017; Soldani, Tamburri, and Van Den Heuvel 2018). Instead of being able to follow a formal process the consideration of the grey literature in a literature review requires the researchers to apply judgement to apply outlet control and source expertise (Adams, Smart, and Huff 2017).

The team started with searching and identifying the English language grey literature by using the Google web-search, with the use and combinations of keywords, scope limitations, consideration of the outlets and contribution. The keywords included 'manufacturer', 'digital', 'investment', 'business case' and 'financing'. To limit the findings to substantial publications the search was limited to PDF documents and limited to hits that are not older than five years. The search results were reviewed for relevance on the basis of the short preview Google provides, the title and the nature of the outlet. The search also focused on specific outlets to identify possible contributions. These included OECD, Worldbank, US and UK government publications. The search for the English language grey

literature led to an initial corpus of 32 publications. The initial corpus was then reviewed in detail based on the criteria applied for the academic publications. Following the application of these criteria 18 publications were used in the full analysis.

The team followed the same process to search for the Chinese language grey literature. The initial search used the Baidu web-search with the combinations of keywords including 'manufacturer' 制造, 'digital' 数字, 'investment' 投资/投入, 'business case' 商业案例/实例 and 'financing' 融资. The search results were reviewed for relevance by using the excluding criteria. The search also focused on specific outlets like Alibaba Damo Academy 阿里巴巴达摩院, AliResearch 阿里研究院, China Academy of Industrial Internet 中国工业互联网研究院, iResearch 艾瑞咨询. The search for the Chinese language grey literature led to an initial corpus of 15 publications. The initial corpus was then reviewed in detail, which produced a final number of 8 publications used in the full analysis.

The search for the German language grey literature followed the process applied for the English. It focused on the use of the Google web-search with the use and combinations of keywords, scope limitations and the selected focus on individual outlets. The focus on the German speaking grey literature focused on combinations of the keywords 'Produzent', 'Hersteller', 'Invest*', 'Finanzierung', 'Digital*' and 'Industry 4.0'. To limit the findings to substantial publications the search was limited to PDF documents and limited to hits that are not older than 5 years. The search results were reviewed for relevance on the basis of the short preview Google provides in, the title and the nature of the outlet. The search also involved a focus on specific outlets to see their contributions. These included German, Swiss and Austrian governments. The search for the German language publications led to an initial corpus of 23 publications. The initial corpus was then reviewed in detail based on the same criteria applied above. Following the application of these a final number of 9 publications were used in the full analysis.

Sources of literature

Following the process of searching and identifying academic and grey literature across three centuries, a final catalogue consists of 99 articles (Table 1).

Table 1. Summary of the academic and grey literature articles

	English	Chinese	German	Sub-total
Academic	37	27	0	64
Grey	18	8	9	35
Sub-total	55	35	9	**TOTAL 99**

Themes

Challenges for digital investment

The review examined a wide range of academic and grey literature to identify the factors that are put forward to explain manufacturers' lack of digital investment and the challenges manufacturers face in making effective business cases for digital investment. The in-depth analysis of the diverse challenges that affect digital investment of manufacturers reveals that these challenges can be mapped against a socio-technical systems framework. The framework provides a structure to group the challenges into process/procedure, people, culture, goals, technology, and network themes. We explain each of the themes in the following section.

Processes/procedures

The process/procedure-category focuses on the challenges related to the actions or steps taken to make digital investment decisions. Specific challenges that fall into this category include:

Challenges related to measurement. A core challenge underlying the investment decisions were related to the measures that would guide the investment decision, in particular related to the two aspects of development or choice of measure as well as the application of the measures.

The right measures should be used to capture the wide range of implications of digital investment. While the traditional measures such as return on investments and profitability can hardly be applied to justify the digital implications, systematic digital investment measures have not been identified yet. Moreover, the manufacturing industry is moving to embrace digital technologies that make economic, social, and environmental impacts, whereas the integrated measures of these investment performances are yet to be discovered. Thus, the question of how to measure the outcome and wide implications of digital manufacturing remains challenging, which results in uncertainty.

The uncertainty continues with the use of these measures. In particular, the regular timeline for assessing the return of investment has been challenged in the digital context. Thus, the question is what measures should be used to reflect the long-term time frame that is often associated with digital investments.

Challenges related to investment process. The challenge of measurement is closely related to the challenges in the process of making investments. Digital investments are often part of an architecture, which requires a staged investment process that builds up the digital architecture and fully unfolds the digital implications. This results in a challenge for manufacturers that are thinking in discrete investments. Identifying the right timing of the investment brings the challenge to a higher level, because the puzzle pieces, as the outcomes of the staged investment process, might come

together at different times. Thus, it requires manufacturers to not only consider what portfolio of digital technologies to invest in, how to invest in the technologies, but also when to invest in each of these technologies and how to put the puzzle pieces together.

Challenges related to existing business process. Investing in digital technologies often triggers the reconfiguration of business processes, in which manufacturers face two important challenges including the lack of critical processes, disrupting the existing process, and standardising the new processes. Specifically, traditional manufacturers might follow a linear process of going from R&D, product development, to product selling, which lacks the experimentation approach. Digital investment requires an agile business process that allows manufacturers to carry out trials and make quick adjustments according to the period outcomes. This might destroy the established business process and routines, which amplifies the complexities at the operational level.

Challenges related to existing business model. Another key challenge relates to the link between digital investment and business models because technological innovations and business model changes often go hand in hand. The realisation of technological value, and thus the value of the digital investment, depends on the business model that explains how the focal firm and its transaction partners create, deliver, and capture value through digital technologies. In particular, a few studies discussed the challenges related to servitization that are triggered by digital investments, which highlighted the critical and urgent need to understand how manufactures can extract value from shifting from product-centric business model to service-led or hybrid business models.

Challenges related to existing organisational structure. Digital transformation does not end simply with implementing new technologies and letting them run. Rather, true digital transformation typically has profound implications for an organization—affecting the way the company is organised and structured. Small and medium sized manufactures might not have a clear organisational structure that can enable the implementation of digital technologies. In contrast, large manufactures might have legacy systems and structures that are not easy to adapt, which creates barriers to the effective use of digital technologies.

Table 2. Challenges related to the actions or steps taken to make digital investment decisions

Process/procedure themes	References
Challenges related to existing measurement • **Measure development** (KPI development, lifecycle costs of developing/adopting a digital technology, level of digitalisation, exporting performance,	AliResearch (2022a)*, Bai and Sarkis (2017), Belvedere and Grando (2017), Bokrantz et al. (2020), Chen and Wang (2022)*, Cheng et al. (2018),

internationalisation performance, develop economic, social, and environmental performance measures) • **Measure application** (Traditional investment metrics and processes are not applicable to digital investment, the timing of ROI assessment, estimation of the long-term value)	Chi et al. (2020)*, Colas et al. (2014), Felsberger et al. (2022), Gawankar et al. (2020), Grosch et al. (2021), Huawei (2017), IBM (2021), Kamble et al. (2020), Kromann and Sørensen (2019), Liu (2020)*, Ogbeibu et al. (2021), Qi and Cai (2020)*, Rose and Jones (2020), Siemens AG (2019), Strother and Ravens (2019), Wang (2021)*, Warwick Manufacturing Group (2021), Westerweel et al. (2018), Wischmann et al. (n.d.), Xie and Wang (2022)* Zhang et al. (2022a)*, Zhu et al. (2021)*
Challenges related to the investment processes • **Staged investment process** • **Struggle to find the right timing to adopt new technology**	Campagna (2018), Falkenberg et al. (2020), Fraunhofer Institute (2022), Rose and Jones (2020), Tang et al. (2022),
Challenges related to existing business process • **Lack of critical processes (**lack of experimentation approach, inconsistent process) • **Redesign and standardisation business processes** (digital investment amplify the complexity in the business processes and operations)	Belvedere and Grando (2017), Campagna (2018), Kwak et al. (2018), Rose and Jones (2020), Vedantam and Iyer (2021),
Challenges related to the existing business model • **Reconfiguration of the business model to accommodate new technologies** • **Extracting value from digital enabled servitization**	Chen et al. (2021)*, Dong et al. (2021)*, iResearch (2019b)* Ricci et al.(2021), Song (2022), Song et al. (2022b)*, v. Wangenheim et al. (2017)
Challenges related to organisational structure • **Organisational structure that facilitates the effective use of digital technologies** • **Small size** (SMEs face greater opportunity cost, the failure of digital	Bokrantz et al. (2020), iResearch (2019b)*, Kalaitzi and Tsolakis (2022), Wu & Song (2020)*

experimentation may cause the death of SMEs)	

* The Chinese references are provided separately in the Appendix

People

The people-category focuses on the challenges related to the individuals involved in making digital investment decisions. Specific challenges identified that fall into this category include:

Lack of decision-making structure. Digital investment is naturally associated with decision-making, in which manufactures find it challenging to establish an effective decision-making structure. The challenge starts at the management level as managers fail to recognise the digital opportunities or are incompetent to lead the digitalisation journey. Over-reliance on the management decisions create further problems because the viewpoints of employees in the front-line of the business are not considered and communicated through. There is also a misalignment of decision-making authority, in which manufactures struggle to understand not only how to make decisions but also who should make the decisions.

Lack of digital skills of managers and employees. A dominant challenge that lays across the different levels of individuals involved in the digital investment is the lack of digital skills. Manufactures lack of experience, knowledge and expertise of digitalisation internally. They also have limited understanding of the funding sources and mechanisms in the digital environment. When manufactures seek external help and support, they face the expertise-sourcing challenge, that is, the difficulty to acquire digital competencies from outside the organisation. It is particularly tough for manufactures in geographic locations that have no digital tradition and environment to find high-level of digital experts. The digital hubs in developed cities have been the go-to-destinations for digital professionals because they provide rich opportunities and systematic support for talents to grow and achieve their potential. Consequently, manufactures outside the digital hubs are much less attractive to digital talents. Due to the lack of existing expertise internally and externally, manufactures might decide to invest in developing digital expertise within the organisation. However, many manufactures emphasis only on technologies while overlooking the significance of investing in people. As a result, when digital technologies are ready to use, people who interact with the digital technologies are incapable of achieving the targets.

Challenge related to resistance. A challenge that can put the entire digital investment at risk is the resistance from employees. Digital investment brings dramatic changes in jobs, in which employees might lose the traditional positions but, at the same time, struggle to build digital skills required by the new positions. It also disrupts the existing routine, which requires employees to adjust and

adapt to the new workflows. Therefore, employees question the digital investment decisions and refuse to cooperate. It is challenging to align employees with divergent interests and career paths, to get the influential leaders on board, and to create a cooperative environment to stimulate communication and learning.

People cost. Sourcing digital expertise from outside and developing digital expertise from inside both lead to people cost. Some employees might start building digital capabilities from scratch, which requires massive education and training expenses. Moreover, digital investment is a dynamic process in which the digital skills constantly need to be upgraded and renewed. Thus, manufactures face upskilling costs in order to keep up with latest technology trends.

Table 3. Challenges related to the individuals involved in making digital investment decisions

People themes	References
Lack of decision-making structure • **Managers fail to recognise the digital opportunities** • **Fail to involve employee representatives in decision-making** • **Misalignment of decision-making authority**	Branstetter et al. (2019), Colas et al. (2014)
Lack of digital skills of managers and employees • **Digitalisation expertise availability** (lack of digitalisation expertise, limited understanding of funding knowledge, sources, and mechanisms) • **Expertise sourcing challenge** (difficult to acquire digital competencies from outside, lack of digital talents outside the digital hubs) • **Expertise development challenge** (excessive emphasis on technologies obscures the importance of developing people skills, lack of expertise development for human and robot interactions in multimode tasks, lack of plans to support employees' personal development)	AliReseach (2022a)*, Branstetter et al. (2019), China Academy of Industrial Internet (2021)*, Colas et al. (2014), Da Roit and Iannuzzi (2022), Ferreira et al. (2021), Fraunhofer Institute (2022), Get It Right Initiative (n.d.), Innovation Finance Advisory (2019), Ogbeibu et al. (2021), Ricci et al.(2021), Rose and Jones (2020), Wang (2021)*, Xue (2021)*, Zhu et al. (2020)*
Challenge related to resistance • **Job destruction** (reducing employment in traditional job positions, employees struggle to build digital skills and mindsets that are required by the digital jobs) • **Fail to create employee buy-in** (Fail to get employees on board, fail to create high-	Domini et al. (2021), Sandrini (2021)

performance and attractive jobs, fail to improve working conditions) • **Union challenges organisational decisions**	
People cost • **Education and training cost** • **Upskilling cost**	Bokrantz et al. (2020), Da Roit and Iannuzzi (2022), Get It Right Initiative (n.d.)

* The Chinese references are provided separately in the Appendix

Technology

The technology-category focuses on the challenges related to the required software and hardware that forms part of the digital investment. Specific challenges identified that fall into this category include:

Challenges related to cost of digital technology. A dominant barrier to digital Investment is the cost of technology. Manufactures face direct costs including search, purchase, and implementation costs, in which the budget may not be available. In addition, the cost-challenge is associated with the underlying economy of scale that drives the unit cost. While a lot of digital investments are highly scalable, manufactures need the scale to obtain an acceptable unit cost. Unless the scale is achieved, digital investments may seem very expensive. Manufactures also face switching costs when they replace the old with new technologies. The notion of switching costs is particularly strong in the digital economy, whereby technology vendors provide products/services for free to attract manufacturers in the beginning but increase price later when manufacturers are locked in. This results in a high switching cost when technology vendors change the pricing model.

Challenges related to attributes of digital technology. The intrinsic attributes of digital technology make it difficult to attract digital investment. Digital technologies are characterised by their evolving nature and uncertainties, where the technology iteration is increasingly accelerated. Any digital investment may quickly be outdated, which requires continuous investments that add to the technology cost. Moreover, information systems often need to interact with one another to create value, which requires the investment in a bundle of interdependent digital technologies. A lack of interoperability and compatibility between information systems may be a great concern in this case. The value of digital technologies and information systems heavily depends on the data, and accordingly, traditional manufactures have an urgent need to understand data, e.g. data integrity, data volume, and extracting value from data.

Challenges related to the understanding of technology. Making digital investment decisions requires a full understanding of digital technologies, which is concerned with the change of mindset, frame-breaking, and paradigm shift. However, there are gaps in understanding digital technologies

and their use among manufacturers. Manufacturers lack dynamic capabilities that are essential to putting digital technologies to use. The dynamic nature of digital transformation requires capabilities to engage in constant re-evaluation and reconfiguration of technologies. Moreover, manufacturers face digital opportunity ambiguity, in which different markets and environments suggest different technological trajectories. Digital technology is not just a set form, but a platform for optionality.

Challenges related to the management of technology. There are also management challenges that make it difficult to make an effective business case for digital investment. To begin with, manufactures are overwhelmed by the different types, categories, and packages of digital technologies. The diversified pricing models and solutions of technology vendors make it even more difficult to choose the right technology at the right cost. In addition, manufacturers have the option of developing the technologies in-house. In the complex technology-environment, technology vendors do not share design rules and make the integration across systems difficult if not impossible. This closely relates to the switching cost, which requires manufacturers to carefully select the technology and technology vendors at the early stage of development.

Table 4. challenges related to the software, hardware and networks required that forms part of the digital investment.

Technology themes	References
Challenges related to cost of digital technology • **Digital technologies are expensive** (digital technologies have a high total cost of ownership, including search, purchase and implementation costs) • **Digital technologies require scale to become affordable** (economy of scale attribute of digital technology) • **Digital technologies create switching costs** (switching cost between new and old technology, switching cost when technology vendors change the pricing model)	Accenture (2020), AliResearch (2022a)*, Beck et al. (2020), Get It Right Initiative (n.d.), Grosch et al. (2021), Ibi Research (2019), iResearch (2019b)*, Kalaitzi and Tsolakis (2022), Ricci et al. (2021), Siemens AG (2019), Sun and Ji (2022), Wischmann et al. (n.d.), Yang and Chen (2020), Zheng and Jiang (2022)*
Challenges related to attributes of digital technology • **Digital technology development pace and uncertainty** (pace of technology change and technology uncertainty) • **Digital technology interdependencies** (information systems need to interact with each other to create value, lack of interoperability and compatibility between information systems) • **Digital technology and data dependency** (data integrity and scalability)	Bhatti et al.(2022), Campagna (2018), Colas et al. (2014), Fraunhofer Institute (2022), Get It Right Initiative (n.d.), Kalaitzi and Tsolakis (2022), Rose and Jones (2020), Trantopoulos et al. (2017),

Challenges related to the understanding of digital technology (mindset change, frame-breaking, paradigm shift) • **Digital technology dynamic understanding** (difficult to build dynamic capabilities that can put technology in use) • **Digital opportunity ambiguity** (multiple markets and different technological trajectories)	Lo et al.(2020), Mandal (2017)
Challenges related to the management of digital technology • **Digital technology choices** (too many technology categories to choose from) • **Digital technology consumption (make or buy)** (difficult decision of develop technologies internally or buy from external) • **Digital technology implementation challenge** (lack of design rules across information systems, system integration)	eBrun (2022)*, Gong et al. (2021), iResearch (2019a)*, Kamble et al. (2020), Panchal and Iyer, (2020), Ricci et al. (2021) Wang (2021)*, Westerweel et al. (2018)

* The Chinese references are provided separately in the Appendix

Infrastructure/network

The infrastructure/network -category focuses on the external parties and their resources that forms part of the digital investment process. Digital value creation is not an isolated job. Hence, the network aspects creates implications and challenges for the digital investment. Specific challenges identified that fall into this category include:

Challenges related to manufacturer network. Digital technologies have the potential to shift manufacturing production away from large-scale manufacturing plants to a network of distributed, smaller-scale localised and customisable manufacturing facilities. The conventional manufacturing supply chains give way to highly flexible and adaptive value networks that are able to meet the rapidly changing demands for new personalised products. Manufactures who are not familiar with the notion of collaborative manufacturing may find it challenging to work together in the form of synergetic whole with blurred boundaries. Moreover, stakeholders in the digitalisation may have divergent interests because they have different structures and goals, which creates barriers to managing multiple inherent risks and redefining organisational boundaries when repositioning in the innovation ecosystem. While some sectors are pioneers in digital transformation, other sectors suffer from weak industrial relations and fragmented policies at the industry level. Manufactures in these sectors may have no consolidated determination for digitalisation and lack of management practices to follow.

Challenge related to manufacturer networking capability. Another challenge relates to the manufacturer's networking capability. Acquiring, processing, analysing, and capitalising information

about market-change through working with suppliers, customers, and partners is important for manufactures to identify digital opportunities. In particular, digital technologies generate a significant amount of data, posing information processing challenges for decision-makers to look for information cues from the broader industry context to enable them to interpret and understand the implication of digital developments that coincide with the emergence of new market categories. Very often, digitalisation requires manufacturers to engage in new knowledge domains, in which the knowledge search in the wider ecosystem and industry context requires both breadth and depth. However, in reality, manufacturers may lack access to the knowledge hubs and/or lack of ability to search for external knowledge.

Challenge related to Customer. Investing in digital requires manufactures to interact with customers in new ways. Customers may have certain reservations to engage with digital. In other words, manufacturers may find themselves trying to sell customers something they don't know they need. The lack of commitment from customers hinders relations and exposes manufacturers to the threat of becoming captive product/service providers. Moreover, many manufacturers have limited understanding and experience of co-creating value with customers, in which they lack systematic approaches to interact with customers and involve customers in their digitalisation agenda. Digitalisation also requires manufacturers to shift from product-centric transactional sales for fixed-price offerings to solution-based long-term contracts for integrated products and services. This requires manufacturers to engage in more strategic conversations about complete solutions for customers rather than product features, as well as to adjust the pricing model from a mere capital expenditure to an operational expense model that is wrapped up in a service contract.

Challenge related to network partner. Investing in digital also requires manufacturers to involve partners in redefining the scope of the market and redesigning the activities in the industry value chain. An important partner that has often been overlooked is the finance partners. Manufacturers may lack interactions with the funding partners. In particular, manufacturers often do not know about the emerging innovative funding models that can accommodate digitalisation. Manufacturers may also be limited by the digital capabilities of third-party supply chain and value network partners. When multiple parties in the supply/value chain make a collective effort at digitalisation, manufactures on the downstream of the supply chain/value chain may struggle to negotiate with upstream suppliers about sharing the costs of digital investment due to a lack of bargaining power.

Table 5. Challenges related to the external parties and their resources that forms part of the digital investment process.

Infrastructure/Network themes	References

Challenge related to manufacturer network • **Lack of responsive networks** (collaborative manufacturing requires highly flexible and adaptive value networks) • **Lack of alignment between multiple stakeholders** (diverse stakeholder interests, lack mechanisms to manage multiple inherent risks among external parties, difficulty to redefine organisational boundaries when repositioning in the industrial ecosystem) • **Fragmented industrial policy and weak industrial relations** • **Lack of understanding of the reshaping global value chain**	Da Roit and Iannuzzi (2022), Gwerder, Figueiredo, and da Silvaa (2019), He (2020a)*, He (2020b)*, Huikkola et al. (2020), iResearch (2021)*, Li (2022)*, Li et al. (2022)*, Song et al. (2022)*, Tsimiklis and Makatsoris (2019), Wu & Song (2020)*, Wu et al. (2022)*, Yao (2022)*, Zhang et al. (2022b)*, Zhang & Yu (2020)*,
Challenge related to manufacturer networking capability • **Digital technology requires information capability** (lack of ability to interpret information cues from the broader industry context, lack of information absorptive ability and capacity to identify digital opportunities, information overload makes the coordination and interaction with stakeholder complicated) • **Digital technology requires new knowledge domains** (lack of external knowledge search in the ecosystem, lack of digital environmental knowledge, lack of access to regional and sectoral innovation and knowledge hubs)	China Academy of Industrial Internet (2021)*, Estrada and Dong (2020), iResearch (2019a)*, Lo et al. (2020), Mandal (2017), Prenzel et al. (2018), Ricci, Battaglia, and Neirotti (2021)
Challenge related to customer • **Lack of engagement and commitment from customers** (fail to develop attractive value propositions for customers, fail to involve customers in digitalisation) • **Lack of capability to co-create value with customers** (lack of understanding of value co-creation, no agile approach to work with customers) • **Lack of new value delivery and capture capability** (customer retention, new customer acquiring, monetising IT services)	AliResearch (2020)*, AliResearch (2022a)*, AliResearch (2022b)*, Boehmer et al. (2020), iResearch (2021)*, Jiao & Liu (2020)*, Sjödin et al. (2020), v. Wangenheim, Wünderlich, and Schumann (2017), Yu & Wang (2022)*
Challenge related to network partner • **Lack of interaction with finance partners** (access to external capital, lack of expertise on external funding) • **New interaction with supply chain partners** (lack of IT investment from third parties in the supply chain, lack of IT capability of partners in	Accenture (2020), atene KOM (n.d.), Ficarra et al. (2021) Get It Right Initiative (n.d.), Gong, Kung, and Zeng (2018), Innovation Finance Advisory (2019), Yang and Chen (2020), Yu & Wang (2022)*

the value network, lack of bargaining power when sharing costs with partners) • **Digitalisation requires new long-term relationships**	

* The Chinese references are provided separately in the Appendix

Goals

The goals -category focuses on the focal direction that drives the digital investment process. Specific challenges identified that fall into this category include:

Challenge related to goal development. Lack of agreement on digital goals is a major stumbling block for justifying the business case of digital investment. Decision-makers and managers struggle with defining and agreeing on the goals and scope of the digital change. It is difficult to align the organisation around the potential value of digital technologies. More broadly, multiple participants in the digital revolution like partners and suppliers may have even more diversified goals of digitalisation, which results in conflicting visions and strategies in investing in digital.

Challenge related to goal quality. There are challenges around the quality of the actual goal. Digital investment requires holistic thinking that consists of several levels like digital strategy, digital business model innovations, and digital technology implementation. Manufacturers put emphasis on the technological goals but ignore the strategic and operational levels that should align with the digital investment. Moreover, digital investment may be misaligned with the overall organisation goals. Aligning the goals requires manufacturers to develop a clear link between digital and strategy, which not only helps a manufacturer make smarter choices but also creates a clear path to value creation and capture. However, manufactures may lack a strategic vision, in which the overarching business strategy does not connect with the investment behind disparate digital priorities and initiatives. A clear direction guides all choices on digital investments, e.g. what, where, why, and with whom. Without this link, any digital activity would be aimless, resulting in blurred path to value-creation.

Challenge related to ambition in goal. Other challenges are related to the ambition in the goals. The greatest challenge lies in investing in digital manufacturing in a financially sustainable manner. Digitalisation requires manufacturers to understand and create the business case for scaled implementation of digital technologies. Small-sized manufacturers particularly face the barrier to building a scalable digital base. Manufacturers that focus on short-term results and lack long-term vision may lose patience quickly, whereas there is an inevitable time interval between digital investment and its desired performance effects. Consequently, the potential cost-reduction in the

supply chain, which are due to changes in reliability, production costs, and production lead-time, are neglected. Thus, the outcomes-led mindset should be expansive, accounting for value beyond short-term financial wins to include measures of growth, profitability, sustainability, and trust, all of which contribute to competitiveness. This provides a long-term strategic goal for the digital investment, which prevents manufacturers from going down the rabbit-hole of what's hot now in digital. The last challenge is the lack of ambition in the national goal, which fails to drive manufacturers in certain countries or areas to invest in scalable digital technologies and get involved in the advanced communities of digital manufacturing.

Table 6. Challenges related to the focal direction that drives the digital investment process

Goal themes	References
Challenge related to goal development • **Lack of agreement on goals**	Bokrantz et al. (2020), Siemens AG (2019)
Challenge related to goal quality • **Lack of holistic thinking of goals** • **Over focus on technological goals but ignore the bigger picture** • **Lack of alignment of goals** (digital investment and competitive strategy)	AliResearch (2022a)*, Belvedere and Grando (2017), CapGemini Consulting (2011), China Academy of Industrial Internet (2021)*, Cognizant (2020), Fraunhofer Institute (2022), Get It Right Initiative (n.d.), Rose and Jones (2020), Wang (2021)*, Warwick Management Group (2021)
Challenge related to ambition in goal • **Lack of scale in digital manufacturer goals** • **Lack of macro-level vision** (create monopoly power that kills SMEs vs. drive the development of the ecosystem/industry sector) • **Lack of long-term vision and targets** • **Lack of ambition in national goal**	Campagna (2018), CapGemini Consulting (2011), Cheng et al. (2018), China Academy of Industrial Internet (2021)*, Cognizant (2020), Cui and Liu (2022)*, Cognizant (2022), Get It Right Initiative (n.d.), Innovation Finance Advisory (2019), Siemens AG (2019), Warwick Manufacturing Group (2021), Westerweel, Basten, and van Houtum (2018)

* The Chinese references are provided separately in the Appendix

Culture

The culture-category focuses on the behaviours, institutions, and norms found in that drives the digital investment process. Specific challenges identified that fall into this category include:

Challenge related to buy-in. The lack of top-level sponsorship is an important barrier to digital investment because when top management teams are less skilled and more conservative about digital investments, this may limit the adoption of digital technologies. Leaders are obliged to spearhead the digital development, understand the performance potential of digital technologies, and ensure the digital change does not result in a sense of exclusion among employees. At the higher level, leaders are required to have the ability to formulate, communicate, and establish the values, visions, and culture to successfully manage change. During the digital transformation, there is a widespread perception among employees that their participation and involvement are limited to requests for partial, subordinate contributions relevant to secondary and minor aspects of organizational and projection dynamics, in which they suffer from the legacy power structures and find it difficult to challenge vertical decision-making processes. The impact of digital investment cuts across traditional silos, affecting multiple functions and departments of the manufacturer like R&D, production, marketing, customer experience and operations. Thus, digital touches every corner of the organisation, in which there are no clear owners of digital decision rights. This requires managers to have a firm-wide view that forms the unified cognitive basis for the digital transformation.

Challenge related to uncertainty and risk tolerance. The low tolerance for uncertainty is a major challenge to making digital investments. It is particularly difficult for manufacturers who traditionally have limited R&D activities to understand and undertake digital projects with high risks. By their very nature, digital technologies invite experimentation in a test-learn-tweak development environment. However, manufacturers may not have a systematic approach to carrying out the experimentations. The experimentations need to fit the overall digital strategy and serve the purpose of learning to continually enhance a living roadmap of digital interventions that amplify each other. The experimentations are also related to the ability to learn from inside and outside of the organisation, including summarising and reflecting on the lessons learned and best practices emerged. Digital investment also requires manufacturers to develop a long-term oriented culture, whereases, a clash between digital investment and traditional accounting and finance policies is common in reality because these policies do not support benefits that are only recognizable at the much later stage.

Challenge related to lack of trust. Another challenge that is typical in manufacturers that have limited digital experience is the lack of trust in digital technologies. There is an anxiety about the issues of trusting “black box” digital technologies like algorithms. Building the understanding of digital technologies entails a substantial cultural transition.

Table 7. Challenges related to the behaviors, institutions, and norms found in that drives the digital investment process

Culture themes	References
Challenge related to buy-in • **Lack of top-level sponsorship** (skills and willingness of top-level management, the ability of top-level management to manage change) • **lack of cross-level ownership** (fail to build a unified cognitive foundation for digitisation, lack of integrated organisational culture; vertical vs. horizontal decision-making; legacy power structures)	Bokrantz et al. (2020), Campagna (2018), Da Roit and Iannuzzi (2022), Kalaitzi and Tsolakis (2022), Ricci et al. (2021), Rose and Jones (2020), Siemens AG (2019)
Challenge related to uncertainty and risk tolerance • **Uncertainty tolerance** (lack of R&D focus, lack of experimentation-oriented culture, zero tolerance of failure) • **Lack of organisation learning** (lack of reflection on lessons learned, lack of learning from outside organisations) • **Lack of long-term focus** • **Lack of solid organisational culture**	Bokrantz et al. (2020), Brecher et al. (n.d.), Campagna (2018), Colas et al.(2014), Ficarra et al.(2021), Grosch et al.(2021), iResearch (2019b)*, Rose and Jones (2020), TCS (2021)
Challenge related to lack of trust • **Lack of trust in digital technologies**	Bokrantz et al. (2020)

* The Chinese references are provided separately in the Appendix

Good practices to stimulate digital investment

The second part of the literature review focused on the identification of good practices. These are suggestions or models that manufacturers should follow to help them overcome the challenges. Our review has identified a number of good practices and suggestions for manufactures to overcome the challenges. The range of themes capturing the good practices are summarized below.

Reconceptualizing the manufacturer as a digital first organisation

The need to reconceptualize the manufacturer as a digitally-driven organisation has emerged as a critical theme in a number of the literature sources examined. Manufacturers may traditionally consider digital as a set of enabling tools. However, there is a strong case that manufacturers reimagine digital as a critical extension of their core competencies hereby acknowledging its strategic role within manufacturers. Specific good practices that emerged under this theme include:

- The need to **develop a shared digital vision** across the organisation. At this point digitalisation and digital investments are often approached in silos, by different product-lines or individual business functions. However, digitalisation reaches across the

manufacturer and capturing the value of digitalisation requires manufacturers to develop a shared vision for the organisation that aligns and guides their range of digital investments.

- A further core mind-set change manufacturers require is the need to develop a culture of **continuous exploration of digital technologies**. Manufacturers already have established practices for material-based explorations as part of their R&D activities but often do not have a culture of exploration when it comes to digital activities. Building a culture that embraces an understanding of the latest digital developments and the capability for digital innovation is critical for appreciating the scope and implications of digital investments.

Change in locus of decision making

In line with the reconceptualization of the manufacturer as a 'digital-first' organisation, the need to clearly locate and elevate the locus of digital decision-making has emerged as a critical theme in a number of the literature sources examined. The common manufacturer practise of localizing digital decision making within the core value -adding functions does not sufficiently take the cross-organisational nature of digitalisation and digital investments into account. Specific good practices that emerged under this theme include:

- The need to **develop a shared evaluation process for digital projects** across the organisation. Such a process would involve a central committee that acts as a guardian of the digital transformation and stirs and evaluates the individual projects with a firm-level perspective ensuring alignment across the different agendas and initiatives. Such a firm-wide wide approach for evaluation would not only ensure the critical alignment among individual projects and between projects and strategy, but also would help to justify projects based on their strategic contribution instead of just the short- and medium-term ROI considerations that would otherwise apply.

Change in performance framework

Another one of the core themes that emerged from the literature is the need to adjust the manufacturer's performance framework. Traditionally, performance frameworks among manufacturers are heavily focused on departmental profit and loss accounts with little room or incentive for strategic or riskier investments which limits the willingness to engage in digital investment. Specific good practices that emerge under this theme include:

- **Re-evaluation of organisational KPIs.** A number of the reviewed literature sources specifically emphasize the need to revise the organisational KPI's to reflect the change in priorities digitalization requires from manufacturers and remove the barriers to effective

digital investments. Particular KPI's that could play an important role in guiding the digitalization journey of manufacturers include: number of pilots or option portfolio value.

- **Integration of Risk.** The need to treat and integrate risk evaluation and tolerance has emerged as another area of development manufacturers should consider. At his point there is little reward for risk-taking activities within manufacturing performance management frameworks even though risk-taking is an essential feature of digitalisation and is required in enabling and evaluating digital investments.

Change in scope

Another core theme identified focuses on the scope that should be applied to conceptualize and evaluate digital investments. Digitalization not only changes the boundaries within the organisation and the time-frame of initiatives but also the external boundaries and the evaluative scope of any innovation. Specific good practices that emerged under this theme include:

- **Organisational scope.** The value of a large number of digital initiatives are not limited to the manufacturer themselves but will affect (and often improve) the activities of supply chain partners and customers. Current investment considerations that do not take these external beneficiaries into account provide a limited picture of the possible benefits a digital investment can create. Taking into account the external implication is critical to get a holistic understanding of the of any digital investment.
- **Time frame.** The time-frames traditionally considered for evaluating investments often prioritise short-term gains over long-term opportunities. Digital investments are recognised for requiring long lead-times and follow S-shapes. It is important for manufacturers to acknowledge this differentiated value-creation trajectory digital investments create and provide frameworks that explicitly acknowledge these trajectories in the formal evaluation process.

Change in evaluation methods

An important core theme is also the need to add fundamentally new methods to evaluate the investments. The methods manufacturers traditionally adopt are limited in the way they can reflect some of the core strengths of digitalization. Hence, there is a need to explore the opportunities additional methods could offer for manufacturers and their digital investment decisions. Specific good practices that emerged under this theme include:

- **Portfolio method.** Digital investments capture a large variety of initiatives which represent different features but effectively interact and are interdependent on each other. A portfolio perspective acknowledges this simultaneous divergence and interaction and would help

manufacturers to ensure the essential features are captured in the evaluation of the digital investment decision (more in future research).

- **Real options analysis.** Digital investments are interdependent in the sense that they often build up on each other hereby creating opportunities. While an individual investment may not create a tangible value on its own, it might create an option that other investments can build upon. Recognising the options that digital investments create is essential to build up a long-term architecture of digital initiatives. Real option analysis is a method that specifically focuses on the recognition of these opportunities, and it would be important for manufacturers to consider how these can be integrated into their established evaluation methods.
- **Business model focus.** Digital investments go beyond the considerations of what digital technologies to purchase or develop, which may be concerned with the re-design of the fundamental business logic. This requires manufacturers to evaluate whether the existing business model can survive future competition and explore future business models. Thus, digital investments with a business model focus have the potential to create value for new customer segments, deliver value to the new and existing customer segments more effectively, and capture value more innovatively.

Theories & perspectives used

In addition to the core themes illustrating the range of challenges and good practices of digital investment, the review also examined the theories or theoretical perspectives used to drive the investigations. Current studies have explored digital investment in manufactures from a diverse range of theoretical perspectives (see table 8 for a summary):

Organisational theories

A number of theoretical perspectives that discuss or illustrate the digital investment challenges focus on the social context and its impact on the digital investment.

Resource based view (incl. knowledge-based view). The resource-based view provides a static perspective on the focal resources that enable a firm to achieve a sustainable competitive advantage. The theory emphasises the combination of internal resources, instead of its market position, as the source of success. The knowledge-based view of the firm identifies the knowledge resource as the most critical among the resources. The resource-based view has been used in several reviewed studies to highlight the importance of the availability of the firm's internal resources in making the most of their digital investments and the need to develop additional resources to compete in the digitalisation process (Felsberger et al. 2022)

Dynamic capability theory. Dynamic capability theory provides a process perspective to illustrate how critical resources are developed and renewed. Dynamic capabilities are often understood as the important buffer between a firm's existing resources and the ever-changing business environment, so that the firm can dynamically adjust its resource-base to maintain its sustainability and competitiveness (Wilden, Devinney, and Dowling 2016). Consequently, research draws on dynamic capability theory to understand how manufacturers can effectively align their resource base in order to match the market requirements and hereby draw value from the digital investments for themselves (Felsberger et al. 2022) and business partners (Gong, Kung, and Zeng 2018).

Organisational boundary theory and value co-creation. Organisational boundary theory provides an essential theoretical lens to investigate the strategic repositioning of manufacturers in the value network. The repositioning is complex and dynamic because the focal firm needs to move the boundaries based on the moves of other firms like partners and competitors. It is an interplay between the manufacture's identity, power, capability, and dependency (Huikkola et al. 2020). A successful boundary delineation requires manufacturers to answer the critical questions such as how we should position ourselves in the markets, what governance mechanism should be employed in different parts of the value system, how our identity should be changed, and how our organisational capability should be altered?

The repositioning in the value network and ecosystem often relate to value co-creation between manufacturers and other participants like partners, suppliers, customers, and sometimes competitors. An agile approach is key to value co-creation because it allows manufacturers to respond quickly to the power dynamics and seize developmental opportunities. Sjödin et al. (2020) proposed an agile co-creation model that provides insights into the phases, activities, and organisational principles that manufacturers can draw on partners' and customers' resources for successful cooperation.

Knowledge search strategy. Knowledge search strategy explains how manufacturers can source external knowledge from actors like technology vendors, universities, research centres, suppliers, and customers, which accelerates their adoption of digital technologies (Ricci, Battaglia, and Neirotti 2021). Such broad and in-depth knowledge search may trigger a phase of digital opportunity recognition, through which manufacturers understand, assess, and deploy digital technologies (Ricci, Battaglia, and Neirotti 2021).

Contingency theory. Contingency research focuses on context (contingencies that are exogenous to the organisation), response (organizational actions taken in response to contingencies), and performance (effectiveness between contingencies and responses), which can be used to explain

manufacturer's organisational change due to the digitalisation (Bokrantz et al. 2020). Within contingency theory, organizational change is the process of undergoing structural adjustment as a response to the contingencies, in which manufacturers face adjustment costs of money, time, and resources. In addition, adjustment costs are likely to be higher when change efforts involve simultaneous change of a set of complementary projects.

Portfolio theory. Several articles draw on a portfolio theoretical perspective to structure the decision-making approach. A portfolio theoretical perspective prioritises investments in order to maximize the value and risk trade-offs, and thus, optimises the organisational overall return of investment. A portfolio approach is the continuous process of selecting and managing the optimum set of project-oriented initiatives to deliver maximum business value and strategic alignment.

The application of the portfolio theorical approach to digital investment highlights the need to move away from considering projects and their funding individually and instead select and manage these optimum set of diverse projects that deliver maximum business value and strategic alignment. The resources highlight the need to centralize investment decision-making to achieve this portfolio approach (Colas et al. 2014). The portfolio approach also requires the dynamic management of project resources (Vedantam and Iyer 2021).

Real options theory. Real options theory puts an emphasis on providing decision makers with systematic and structured flexibility to adapt decisions in response to subsequent developments. Traditional methods (e.g. net present value) fail to accurately capture the economic value of investments in an environment of widespread uncertainty and rapid change. The real options method seeks to quantify the value and guide management flexibility in a world of uncertainty. The application of options theory to digitalization recognizes the uncertainty that these investments imply. In a simplified model some digital investments can be viewed as consisting of first-stage and second-stage investments. For example, a first-stage investment may be made in a data lake, and a second-stage investment may be made in a technology that uses the data lake for further value adding analysis. By undertaking the first-stage investment, the investor acquires a right (but not an obligation) to make a second-stage investment. However, the value of the second-stage investment is not known exactly at the time of first-stage investment. Hence, traditional ROI models may not be directly applicable to digital investments.

Economic theories

Also economic theories have been applied in the studies that highlight the digital investment's monetary value and the pricing mechanisms behind digital technologies.

Transaction cost theory. Transaction cost theory explores the choices that can achieve economic efficiency by minimizing the costs of exchange. In the digitalisation context, for example, manufacturer's decision of developing digital technologies in-house or purchasing digital technologies externally requires the decision-maker making a choice to use a firm structure or source from market by comparing the internal production cost with external coordination costs (Gong, Cheng, and Nault 2021).

Game theory and pricing models. Game theory is useful to study the interactions between technology vendors/IT infrastructure platforms and manufacturers. The digital investment decision of manufactures is affected by the pricing models of the platforms that provide digital infrastructure (Sun and Ji 2022). Moreover, technology vendors can use different pricing strategies to motivate the adoption of digital technologies. For example, depending on the competition in a market, technology vendors can use incentives or exclusive period to motivate massive or early adoption of the digital technologies (Tang, Wang, and Xu 2022).

Technology theory

Technology theory put an emphasis on the specific nature of the technology resource that is being considered and investigated.

Technical debt. Technical debt conceptualises the accumulation of the technology work that has previously not been carried out which now constrains the future technological trajectory. It is the accumulation of the short-cuts and missed innovations that create disproportional costs and interventions in the future. In the digitalisation context, technical debt describes the missed opportunities and their future costs as a consequence of a lack of investment. It stretches across lack of standardisation that prevents future high-value integration of data sources and applications.

TOE model. The TOE model considers technological, organisational, and environmental dimensions that simultaneously affect innovation adoption at the firm level. Digital investment is concerned with the technological factors, but more importantly, can be influenced by the organisational and environmental context (Kalaitzi and Tsolakis 2022). Thus, the TOE model is valuable in capturing the multi-dimensional characteristics of the digital investment decisions (Li, Chen, and Miao 2022).

Table 8. Challenges related to the behaviors, institutions, and norms found in that drives the digital investment process

Organisational theories	
Resource based view. The manufacturer's combination of resources as source of sustainable competitive advantage. Knowledge based view of the	(Bhatti et al. 2022), (Felsberger et al. 2022), (Gong et al. 2018), (Trantopoulos et al. 2017)

firm emphasises knowledge as the most critical resource.	
Dynamic capability theory. The manufacturer's ability to effectively adjust its core competencies.	(Bhatti et al. 2022), (Felsberger et al. 2022), (Gong et al. 2018), (Mandal 2017)
Organisational boundary and value co-creation. The manufacture's strategic repositioning in the value system. The agile approaches required to value co-creation.	(Huikkola et al. 2020), (Sjödin et al. 2020)
Knowledge strategy. Knowledge sourcing from external actors that enable the identification of digital opportunities and adoption of digital technologies.	(Ricci, Battaglia, and Neirotti 2021)
Contingency theory. The manufacturers' organisational actions taken in response to external contingencies result in adjustment costs	(Bokrantz et al. 2020)
Decision-making theories	
Portfolio theory. Assessing a portfolio of investments that reflect the diverse impacts, time-horizons, and risk levels of the individual investments.	(Colas et al. 2014), (Vedantam and Iyer 2021)
Real options theory. Prioritising investments that provide manufacturers with the flexibility to respond to the future opportunities digital innovations may offer.	(Lo et al. 2020), (Vedantam and Iyer 2021), (Strother and Ravens 2019), (Louis, Geisert, and Blessing 2020), (Made Smarter n.d.), (Behrendt et al. 2021)
Economic theory	
Transaction cost theory. Cost (e.g. production costs and/or coordination costs) is one of the primary determinants of the digital investment decision.	(Gong, Cheng, and Nault 2021)
Game theory and pricing model. The interaction between technology vendor/digital infrastructure platform's pricing strategies and the manufacturer's technology investment.	(Tang, Wang, and Xu 2022), (Sun and Ji 2022)
Technology theory	
Technical debt. The missed opportunities and their future costs due to a lack of technology investment.	(Panchal and Iyer 2020)
Technological, organisational, and environmental (TOE) framework. Technological, organisational, and environmental dimensions that simultaneously affect the strategic decision of technology adoption.	(Kalaitzi and Tsolakis 2022), (Li et al. 2022)

Comparison between literature sources

The literature review captured the core discussions and identified the emerging themes in both academic and grey literature considering different language outlets. While a systematic comparative analysis of the different outlets is beyond the scope of the study a number of observations have emerged during the course of the research.

Comparing Grey and academic literature

The review of the academic and grey literature side-by-side provided an opportunity to observe differences in the overall breadth, depth and rigor of the publications. Our review suggests that the grey literature offers significantly more breadth in the approaches used to investigate the topic and the range of themes that were considered. For example, the explicit considerations of the role the external finance partners play as well as the exploration of the goal and technology-related challenges are more prominently discussed in the grey literature then in the academic literature.

At the same time we found that the grey literature offers significantly more depth in the way the topics are examined and the explanations that are provided. The grey literature was found to be particularly strong in showcasing different scenarios in detail, perhaps limiting the generalisation opportunities through this as well. However, and perhaps expectedly, our research identified the academic literature to apply more rigor in the research process and to invest more time in ensuring the credibility of the findings. It is clear that there are plenty of critical opportunities to apply the academic approaches to investigate several of the core themes identified in the grey literature to enhance rigor and credibility of the research findings and provide better grounding of the management implications.

Comparing English, Chinese and German literature

The key themes identified across the three language domains with regards to the grey literature are largely the same, which shows that manufacturers face common challenges in relation to processes, people, technology, infrastructure, goals, and culture.

In contrast, differences in the English and Chinese academic studies emerged[1]. Chinese academic literature tends to focus on two specific topics that are highly relevant to Chinese manufacturers. First, due to the large scale of exporting activities among Chinese manufacturers this topic has received prominence. For example, a few studies emphasized measuring the exporting performance in measure development (Chen & Wang, 2022*; Chi et al., 2020*; Liu, 2020*; Qi & Cai, 2020*; Wang,

[1] As German scholars publish their work in English language no specific German language academic discourse has been identified.

2021*; Xie & Wang, 2022*; Zhang et al., 2022a*; Zhu et al., 2021*). Second, a closely related topic is the understanding of the global value chain when it comes to the challenges in infrastructure and networks. The studies demonstrate that manufacturers operating in the global markets face challenges of positioning and competing in the global value chain, which makes the investment in digital technologies urgent but complex (He, 2020a*; He, 2020b*; Wu et al., 2022*; Yao, 2022*; Zhang et al., 2022b*; Zhang & Yu, 2020*). The English language academic literature seems to be approaching the topic more widely.

Feedback from the review panel

The preliminary findings of the research was sent to a review panel for comments and feedback. The panel consists of experts in both academic and industry, which provided valuable insights into the digital investment among manufacturers. The comments are synthesised in this section.

The review panel agreed on the challenges identified in the literature review. They believed that investing in digitalisation among manufacturers is concerned with multiple levels and aspects of factors that go beyond the digital technologies themselves. Thus, the framework of the socio-technical system captures the complexity in making digital investments comprehensively. It provides an overview of the technological, organisational, and social challenges that manufacturers face when investing in digitalisation. To overcome the challenges, we suggested critical questions that are relevant to each challenge in the mini-guide for manufacturers to consider (please see the questions in the mini-guide). The review panel believed these questions valuable and insightful. They provided the right starting point for manufacturers to frame their digital investment strategy and to capture the opportunities digitalisation offers.

The review panel suggested further directions to investigate the challenges and develop systematic solutions to the digital investment among manufacturers. The suggestions include:

Goals of digital investment and the dynamic investment. The review panel pointed out that manufacturers almost over-focus on digitalisation itself rather than what the strategy is and what the business drivers are. Manufacturers often start by looking at the cost of digital investment and may be scared off by this heavy cost. Consequently, manufacturers may overlook the opportunities and benefits digitalisation can bring into the businesses. Thus, it is crucial for manufactures to understand the goal of digital investment and appreciate the dynamic nature of digital investment, in which they can take incremental steps to achieve the business goals.

> *"Digital is a solution to your everyday problems. If you understand what goals you are trying to achieve, what the business drivers are, and what problem you are trying to fix,*

when you start putting together a roadmap for digital, you can actually do it in very affordable way. You don't have to invest 250 million to put a complete digital capability in place. You could invest small incremental chunks and drive a value...You can build it [digital] in lots and lots of components. The annual cost at the beginning of the journey is negative for the first year, and every year after that is net neutral to positive. So digital investment theoretically does not cost me anything because it has been paid for out of the benefits." (Bruce Lawson, VP Services Strategy, Rolls-Royce[2])

"The implementation of digital investment is an interesting point for further exploration. Investing in digital requires manufacturers to take a dynamic approach. Agility would be the key." (Dr Stephan von Delft, Senior lecturer in Strategy, University of Glasgow[2])

People and talents. The review panel believes that people lie at the heart of the digital investment. This theme is broadly related to managers' awareness, willingness, and knowledge of investing in digital manufacturing.

"The challenges are in line with our research that the top barriers are lack of skills and talents, lack of financing, and lack of understanding of what digital can do...It seems that many SMEs, especially family firms, are not aware of digitalisation... They wait to be approached rather than actively look for funding for digitalisation... It is difficult to reach out to manufacturers who are not aware of digitalisation and include them in the overall digitalisation effort." (Nina Gryf, Senior Policy Manager, Make UK[2])

"I think the one area which is particularly critical for manufacturing digitalisation is people and their expertise. Senior leaders may not know what digitalisation is and what to do with digitalisation. They may not have the background or prior experience." (Professor Mayasandra Ravishankar, Professor of Technology & Globalisation, Dean & Head of Queen's Management School, Queen's University Belfast[2])

It is also crucial for manufacturing, as a sector, to develop strategies for attracting the next generation of talent. Digital talents in the UK often consider the high-tech, Internet, and finance industry as their natural choices for career development, whereases the manufacturing industry suffers from a lack of exposure to this crowd.

"People sometimes find it a bit hard to recruit in the right areas in manufacturing companies because there is always the perception that digital talents go to technology

[2] Permission to name the panel member has been obtained

> *giants. Digital managers and engineers go to certain kinds of companies and do not necessarily go to manufacturing. I think there is a little bit of a marketing story to be told to try and attract very talented people to the manufacturing sector."* (Professor Mayasandra Ravishankar, Professor of Technology & Globalisation, Dean & Head of Queen's Management School, Queen's University Belfast[2])

Ecosystem and network. While the good practices identified in the literature review dominantly focus on manufacturers, the review panel highlights the importance of the ecosystem in driving digital investment in manufacturing collectively. This requires the government, universities, industry associations, technological vendors, and participants in the value chain to form a collective power to raise the awareness of digitalisation, provide proof-points for successful digitalisation, and share the lessons learned from digitalisation.

> *"A crucial task of Make UK is to build a regional hub to raise the awareness of digital manufacturing and bring people together. The benefits derived from interactions, especially through peer-to-peer learning."* (Nina Gryf, Senior Policy Manager, Make UK[1])

Research agenda

Drawing on the challenges identified in the literature, the need for developing good practices, and the insights from the review panel, this literature review provides the basis for the development of a research agenda. The development of the research agenda aims to ensure that the diverse perspectives in making digital investment decisions and their interconnections are captured. It also aims to ensure that future research effectively responds to the urgent needs of the manufacturing industry in engaging in digital transformation.

Table 9 below provides a summary of the future research. The future studies are grouped according to the five themes, i.e. process/procedure, people, technology, infrastructure/network, goals, and culture. In each of the themes, we propose focal research questions that address the challenges identified from the literature review. In addition, we make suggestions of the suitable theoretical perspectives that can provide the grounding for addressing the research questions and directing theoretical contributions.

- To address the process/procedure-related challenges, future research is suggested to focus on investigating the specific measurement tools and processes that can effectively guide the investment decision.

- To address the people-related challenges, future research is suggested to focus on discovering the mechanisms that create buy-in across the organisation and exploring the approaches that ensure learning is penetrated throughout the organisation.
- To address the technology-related challenges, future research is suggested to focus on helping manufactures develop a comprehensive and in-depth understanding of the antecedents, processes, and outcomes of digital technologies.
- To address the network related-challenges, future research is suggested to focus on supporting manufacturers understand the increasing network inter-dependency in the wider industrial sectors and ecosystems as well as boost manufacturers' skills to benefit from the active interactions with the network participants.
- To address the goal-related challenges, future research is suggested to focus on identifying the ways that align goals among the manufacturers' network partners as well as investigating the approaches that set appropriate and systematic goals for digital investments.
- To address the culture-related challenges, future research is suggested to examine the pathways that establishes a unified cognitive foundation for the digital transformation and explore the rationale for embracing uncertainty in making digital investments.

Table 9. Future research opportunities

Digital investment challenge	Focal research questions	Proposed guiding theories and perspectives
Process/procedure challenges		
Challenges related to existing measurement (The KPI's used by the manufacturers do not appropriately capture the contributions of digital technology)	• Which KPIs are most effective in directing investment decisions into digitalization?	Performance measurement system design (e.g. Neely, Gregory, and Platts 1995), Viable Systems Approach (e.g. Choong 2014)
	• What scope should be considered for the development of the KPIs directing the investment decisions into digitalization?	Stakeholder Theory (e.g. Barro 2009)
	• How do manufacturer attributes (e.g. size, digitalization maturity, industry) affect the KPI adoption and effectiveness?	Contingency theory (e,g, Taylor and Taylor 2014)
	• How should the KPIs change in the course of the manufacturer's digitalisation trajectory?	Life-cycle approach (e.g. Nudurupati et al. 2011)

Challenges related to the investment processes	• How should the manufacturer plan the investment in digitalisation?	Portfolio theory (e.g. Drake and Byrd 2006), Real option theory (e.g. Kim and Sanders 2002)
	• How should the manufacturer integrate flexibility in its planning process?	Real option theory (e.g. Yeo and Qiu 2003)
Challenges related to organisational structure	• Which structures should manufacturers use to facilitate digital investment decision making?	Governance theory (e.g. Tiwana and Kim 2015)
Challenges related to people		
Lack of decision-making structure	• How to structure an effective decision-making process?	Empowering leadership theory (e.g. Sharma and Kirkman 2015)
Lack of digital skills of managers and employees	• How to effectively use pilots to disseminate learning about digitalisation across the manufacturer	Organisational learning; the learning organisation (e.g. Odor 2018)
Challenge related to resistance	• How to overcome resistance to digital innovation and exploitation across the hierarchies	Theory of interpersonal influence and leadership (e.g. Yukl, Falbe, and Youn 1993)
Challenges related to technology		
Challenges related to cost of digital technology	• How to evaluate the cost of not investing in digitalization?	Opportunity cost theory (e.g. Renkema and Berghout 1997)
Challenges related to attributes of digital technology	• How can manufacturers understand and prepare for future technological change?	Foresight theory (e.g. Piirainen and Gonzalez 2015)
Challenges related to the understanding of digital technology	• How to frame the different and potentially diverging opportunities (exploration vs exploitation) that digitalisation offers manufacturers?	Ambidexterity theory (e.g. Turner, Swart, and Maylor 2013)
Challenges related to the management of digital technology	• How to make a decision on whether to outsource or not digital technology	Transaction cost theory, resource based view (e.g. Watjatrakul 2005)
Infrastructure/Network		
Challenge related to manufacturer network	• How to ensure shared investment commitment among network partners?	Resource dependency theory (e.g. Schroeder et al. 2020)
Challenge related to manufacturer networking capability	• How should manufacturers exploring new relationships providing critical expertise	Dynamic capability theory (e.g. Mu et al. 2017)
Challenge related to customer	• How to ensure commitment from customer to justify investment into digital?	Agency theory (e.g. Hypko, Tilebein, and Gleich 2010)

Goals		
Challenge related to goal development	• How to create a shared vision for digitalisation across the business ecosystem?	Resource-based theory (visioning & orchestration capability) (e.g. Teplov et al. n.d.)
Challenge related to goal quality and ambition	• How to overcome inertia and lack of ambition in visioning a digital pathway?	Theory of organisational frame of reference (e.g. Shrivastava and Schneider 1984)
Culture		
Challenge related to buy-in	• How to facilitate a wider engagement with the digitalisation journey?	Psychological ownership theory (e.g. Pierce, O'driscoll, and Coghlan 2004)
Challenge related to uncertainty and risk tolerance	• How to create a culture that values experimentation?	Knowledge-based theory of the firm (knowledge friendly organisational culture) (e.g. G. Liu, Tsui, and Kianto 2021)

Conclusion

The research set out to i) create an understanding of the investment challenges manufacturers are facing with their investment into digitalisation, ii) develop a scientific foundation to facilitate academic research on the topics and iii) develop a research agenda to guide future investigation to address the core challenges. The socio-technical systems framework was used as an investigative lens to analyse the diverse range of challenges among manufacturers and to give an indication on how multifaceted the approaches need to be to overcome these challenges.

InterAct Network

The investigation forms part of the InterAct Network project that aims to bring together economic and social scientists, UK manufacturers, and digital technology providers to address the human issues resulting from the diffusion of new technologies in industry. Although technology is important in the digitalisation of the UK Manufacturing Industry, the InterAct Network recognises that there are many social and economic factors that will be hugely influential in achieving this aim. The InterAct Network has two primary roles:

- Develop and support the creation of an effective digital innovation ecosystem to accelerate the innovation and diffusion of Industrial Digital Technologies.
- Ensure that the full range and depth of social and economic science insights are accessed across the Made Smarter challenge and wider UK manufacturing sector.

To find out more about the project, access funding and make use of the latest outputs from the ongoing research projects visit https://interact-hub.org/.

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Appendix: The literature catalogue

Reference	Academic /Grey	Language	Process	People	Technology	Network/ Infrastructure	Goal	Culture	Theory/theoretical perspective
AliResearch (2020)*	Grey	Chinese				✓			
AliResearch (2022a)*	Grey	Chinese	✓	✓	✓	✓	✓		
AliResearch (2022b)*	Grey	Chinese				✓			
atene KOM (n.d.)	Grey	German	✓		✓	✓			
Bai and Sarkis (2017)	Academic	English	✓						
Beck, Plekhanov, and Wörter (2020)	Grey	German			✓				
Belvedere and Grando (2017)	Academic	English	✓				✓		
Behrendt et al. (2021)	Grey	English							✓
Bhatti et al. (2022)	Academic	English			✓				✓
Branstetter, Drev, and Kwon (2019)	Academic	English		✓					
Brecher et al.(n.d.)	Grey	German	✓					✓	
Boehmer et al. (2020)	Academic	English				✓			
Bokrantz et al. (2020),	Academic	English	✓	✓			✓	✓	✓
Campagna (2018)	Grey	English	✓		✓		✓	✓	
CapGemini Consulting (2011)	Grey	English					✓		
China Academy of Industrial Internet (2021)*	Grey	Chinese		✓		✓	✓		
Chen et al. (2021)*	Academic	Chinese	✓						
Chen and Wang (2022)*	Academic	Chinese	✓						
Cheng et al. (2018)	Academic	English	✓				✓		
Chi et al. (2020)*	Academic	Chinese	✓						
Cui and Liu (2022)*	Academic	Chinese					✓		
Cognizant (2020)	Grey	English					✓		

Colas et al. (2014)	Grey	English	✓	✓	✓			✓	✓
Da Roit and Iannuzzi (2022)	Academic	English		✓		✓	✓	✓	
Dong et al. (2021)*	Academic	Chinese	✓						
Domini et al. (2021)	Academic	English		✓					
Ding et al. (2019)	Academic	Chinese	✓						
Estrada and Dong (2020)	Academic	English				✓			
eBrun (2022)*	Grey	Chinese			✓				
Falkenberg et al. (2020)	Grey	German	✓		✓				
Felsberger et al. (2022)	Academic	English	✓						✓
Ferreira, Figueira, and Amorim (2021)	Academic	English		✓					
Ficarra et al. (2021)	Grey	English						✓	
Fraunhofer Institute (2022)	Grey	German	✓	✓	✓			✓	
Gawankar et al. (2020)	Academic	English	✓						
Get It Right Initiative (n.d.)	Grey	English		✓	✓	✓	✓		
Gwerder, Figueiredo, and da Silvaa (2019)	Academic	English				✓			
Gong, Kung, and Zeng (2018)	Academic	English							✓
Gong, Cheng, and Nault (2021)	Academic	English			✓	✓			✓
Grosch et al. (2021)	Grey	German	✓		✓			✓	
He (2020a)*	Academic	Chinese				✓			
He (2020b)*	Academic	Chinese				✓			
Huikkola et al. (2020)	Academic	English				✓			✓
Huawei (2017)	Grey	English	✓						
Ibi Research (2019)	Grey	German			✓				
IBM (2021)	Grey	English	✓						
iResearch (2019a)*	Grey	Chinese			✓	✓			
iResearch (2019b)*	Grey	Chinese	✓		✓			✓	
iResearch (2021)*	Grey	Chinese				✓			

Innovation Finance Advisory (2019)	Grey	English		✓		✓	✓		
Jiao & Liu (2020)*	Academic	Chinese				✓			
Kalaitzi and Tsolakis (2022)	Academic	English	✓		✓			✓	✓
Kamble et al. (2020)	Academic	English	✓						
Knofius, van der Heijden, and Zijm (2019)	Academic	English	✓						
Kromann and Sørensen (2019)	Academic	English	✓						
Kwak et al. (2018)	Academic	English	✓						
Li (2022)*	Academic	Chinese				✓			
Li et al. (2022)*	Academic	Chinese				✓			✓
Liu (2020)	Academic	Chinese	✓						
Lo et al. (2020)	Academic	English			✓	✓			✓
Louis, Geisert, and Blessing (2020)	Grey	English							✓
Mandal (2017)	Academic	English			✓	✓			✓
Made Smarter (n.d.)	Grey	English							✓
Ogbeibu et al. (2021)	Academic	English	✓	✓					
Panchal and Iyer (2020)	Grey	English			✓				✓
Prising, Sorenson, and Weinelt (2018)	Grey	English			✓				
Prenzel et al. (2018)	Academic	English				✓			
Choi and Cai (2020)*	Academic	Chinese	✓						
Ricci et al.(2021)	Academic	English	✓	✓	✓	✓		✓	✓
Rose and Jones (2020)	Grey	English	✓	✓	✓		✓	✓	
Sandrini (2021)	Academic	English		✓					
Siemens AG (2019)	Grey	English	✓		✓		✓	✓	
Song (2022)*	Academic	Chinese	✓			✓			
Sjödin, Parida, and Visnjic (2022)	Academic	English				✓			✓
Strother and Ravens (2019)	Grey	English	✓						✓

Sun and Ji (2022)	Academic	English			✓				✓
Tang et al. (2022)	Academic	English	✓						✓
TCS (2021)	Grey	German						✓	
Trantopoulos et al. (2017)	Academic	English			✓				✓
Tsimiklis and Makatsoris (2019)	Academic	English				✓			
Vedantam and Iyer (2021)	Academic	English	✓						✓
Wang (2021)*	Academic	Chinese	✓	✓	✓		✓		
v. Wangenheim, Wünderlich, and Schumann (2017)	Academic	English	✓			✓			
Warwick Manufacturing Group (2021)	Grey	English	✓				✓		
Westerweel et al. (2018)	Academic	English	✓		✓		✓		
Wischmann et al. (n.d.)	Grey	German	✓		✓				
Wu and Song (2020)*	Academic	Chinese	✓			✓			
Wu et al. (2022)*	Academic	Chinese				✓			
Xie and Wang (2022)*	Academic	Chinese	✓						
Xue (2021)*	Academic	Chinese		✓					
Yang and Chen (2020)	Academic	English			✓	✓			
Yao (2022)*	Academic	Chinese				✓			
Yu and Wang (2022)*	Academic	Chinese				✓			
Zhang and Yu (2020)*	Academic	Chinese				✓			
Zhang et al. (2022a)*	Academic	Chinese	✓						
Zhang et al. (2022b)*	Academic	Chinese				✓			
Zheng and Jiang (2022)*	Academic	Chinese			✓				
Zhu et al. (2020)*	Academic	Chinese		✓					
Zhu et al. (2021)*	Academic	Chinese	✓						

Appendix: Chinese references

English citation	English title	Original Chinese references
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AliResearch (2022b)*	Xiniu Smart Manufacturing: Enable the on-demand fashion production	阿里研究院. 犀牛智造给产业数字化转型带来什么启示? 2022. http://www.aliresearch.com/ch/information/informationdetails?articleCode=362842575415152640&type=%E6%96%B0%E9%97%BB
China Academy of Industrial Internet (2021)*	The digital transformation of SMEs: Value co-creation with the platforms of Industrial Internet of Things	工业互联网平台赋能中小企业数字化转型. 中国工业互联网研究院,2021: 1-40.
Chen et al. (2021)*	Exploring the mechanisms and paths of manufacturing digital enablement on business model innovation	陈一华,张振刚,黄璐.制造企业数字赋能商业模式创新的机制与路径.管理学报,2021,18(05):731-740.
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