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Article

Industrial Insights on Digital Twins in Manufacturing: Application Landscape, Current Practices, and Future Needs

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Abstract: The digital twin (DT) research field is experiencing rapid expansion; yet, the research on industrial practices in this area remains poorly understood. This paper aims to address this knowledge gap by sharing feedback and future requirements from the manufacturing industry. The methodology employed in this study involves an examination of a survey that received 99 responses and interviews with 14 experts from 10 prominent UK organisations, most of which are involved in the defence industry in the UK. The survey and interviews explored topics such as DT design, return on investment, drivers, inhibitors, and future directions for DT development in manufacturing. This study's findings indicate that DTs should possess characteristics such as adaptability, scalability, interoperability, and the ability to support assets throughout their entire life cycle. On average, completed DT projects reach the breakeven point in less than two years. The primary motivators behind DT development were identified to be autonomy, customer satisfaction, safety, awareness, optimisation, and sustainability. Meanwhile, the main obstacles include a lack of expertise, funding, and interoperability. This study concludes that the federation of twins and a paradigm shift in industrial thinking are essential components for the future of DT development.

Keywords: digital twins; federation of twins; industrial current practices; interviews; survey

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1. Introduction

Digital twins (DTs) are becoming increasingly popular in the manufacturing industry as they offer the potential for the application of concepts like smart manufacturing, industry 4.0 [1,2], and digital factories [3]. DTs are digital replicas of physical assets, which can be used to improve the speed, quality, and cost efficiency of manufacturing systems. They enable the simulation of production scenarios, allowing manufacturers to identify and resolve issues before they occur in the physical world. This is supported by studies like those of Biesinger, Kraß and Weyrich that show the potential of DTs in production planning [4].

DT technology can also be applied from the early design phase of the product life cycle to improve the cost efficiency of asset management. This is supported by studies like Panarotto, Isaksson and Vial that show the benefits of DTs in the design phase [5]. Additionally, DT technology is widely recognised for its ability to effectively support the maintenance of complex systems. Studies show that DTs can be used for real-time monitoring, maintenance prediction, and decision support for maintenance activities [6]. Furthermore, DTs can be used for anomaly detection, as seen in studies like that of Calvo-Bascones et al. [7]. They can also be used in combination with ontologies for failure detection [8].

This study aims to examine the current state of DT usage in the industry through a mixed-methods exploration of the applications, drivers, inhibitors, properties, and future needs of DTs. Data were gathered from UK industry experts through a combination of an online survey and interviews, with a focus on the application areas, development process, investment requirements, lessons learnt, and future needs for DT development. The three research questions guiding this study are as follows:

1. *What is the application landscape of DT in manufacturing?*
2. *What are the current practices in manufacturing?*
3. *What are the future needs?*

The main contribution to knowledge is an insight into the current industry practices in the adoption of the DT paradigm, and the future steps and requirements. This paper provides experts' points of view on the potential impacts of DT utilisation. This article also provides a summary of the challenges/barriers involved in the adoption of DT and how to overcome those, as well as a roadmap for the adoption of DT technology.

The authors focused on a broad catchment area with the survey. At this point, it was important to gather information from as many companies as possible and map out the present landscape of DT applications. The authors aimed to go deeper into understanding the DTs' features, drives, inhibitors, and future requirements when conducting the interviews. The survey in the first phase was utilised to determine participants who were involved with DTs to capture their general understanding of the application landscape and the state of the project. As part of the survey, participants were invited to a second interview phase to capture specific knowledge on the DT projects they were associated with. Thus, for the second interview phase, only participants who agreed to disclose further information were involved in a semi-structured interview. This paper thus presents the outcomes from the survey together with the information captured as part of the interview phase. Care was taken to keep the information to a generic level due to the commercial sensitivity associated with the information shared. It must also be noted that the analysis and opinions presented do not represent any specific organisation and are based on the interpretation of the authors.

The methodology and the results have been divided into two sections, one dedicated to the online survey and one dedicated to the interviews, to separate and compare the results obtained from each data collection method. Therefore, the remainder of the paper is structured as follows: Section 2 presents a literature review, Section 3 presents the online survey methodology and related results, Section 4 presents the methodology and results of the interviews, Section 5 presents the discussion, and the conclusions are presented in Section 6, including limitations and future works.

2. Background and Literature Review

In this section, we explore the usage of DT both in industry and academia. In Section 2.1, an analysis of the current industrial reports is presented, while in Section 2.2, a review of the academic literature, along with the current gaps, is reported.

2.1. Industrial Reports

With an increasing number of companies designing a digital workforce in manufacturing, Deloitte has provided some general guidelines outlining that four components are necessary for creating a framework for a digital workforce. These include collaboration, technology, governance, and value [9]. Some important actions that are shaping the future of the digital workforce are:

- Reskilling the team;
- Hiring individuals with the necessary skills;
- Building an environment that attracts talent;
- Retaining that talent.

Although the study of DTs in infrastructure is still in its infancy, substantial investments and efforts are being made worldwide, including in the UK, to establish DT ecosystems. To implement the recommendations from the National Infrastructure Commission's 2017 "Data for the Public Good Report", for instance, the Centre for Digital Built Britain created the National Digital Twin Project (https://www.cdbb.cam.ac.uk/what-we-did/national-digital-twin-programme (accessed on 4 May 2023)) [10].

Accenture, in a report of 2022, states that manufacturing executives that are successful in implementing this next-generation manufacturing systems architecture will fundamentally outperform their competitors by increasing productivity, raising customer happiness, and lowering costs [11]. Based on another analysis, between now and 2030, DTs can save CO_2 emissions by 7.5 Gt and add up to USD 1.3 trillion in economic value [12].

ISO 23247:2021 is a set of standards for the development and use of DTs in manufacturing. It provides a framework for defining, developing, and deploying DTs, and defines some functional entities that are supported by DTs. The standard is divided into four parts with the following scopes: (i) ISO 23247-1: general principles and requirements for developing DTs in manufacturing; (ii) ISO 23247-2: reference architecture with functional views; (iii) ISO 23247-3: list of basic information attributes for the observable manufacturing elements; and (iv) ISO 23247-4: technical requirements for information exchange between entities within the reference architecture [13].

ISO 23247 defines DT as a "*(manufacturing) fit for purpose digital representation of an observable manufacturing element with synchronisation between the element and its digital representation*", where digital representation is defined as a "*(manufacturing) data element representing a set of properties of an observable manufacturing element*", and an observable manufacturing element (OME) is an "*item that has an observable physical presence or operation in manufacturing*", such as personnel, equipment, material, process, facility, environment, product, and supporting documentation [13]. This standard is intended to be used by manufacturers to develop and deploy DTs that can improve their manufacturing processes. It is also intended to be used by researchers and practitioners to develop new and innovative applications for DTs.

The AMRC report [14] "*Untangling the Requirements of a Digital Twin*" provides a comprehensive overview of the requirements for developing and deploying DTs. The report highlights some quantitative benefits of the implementation of the DT in the industry, such as:

- 50% reduction in unplanned downtime (EUR 40,000/minute by a German automotive).
- 40% reduction in maintenance costs (forging line proactively fixing saves USD 200,000).
- 1–3% reduction of capital equipment costs.
- 5–10% reduction in energy cost.

The AMRC report also highlights some gaps in the current state of DT development and deployment. These gaps include:

- Lack of a unified definition of DT. There is no single, agreed-upon definition of DT. This can make it difficult to communicate about DTs and to compare different approaches to DT development and deployment.
- Lack of a systematic approach to DT development. There is no single, agreed-upon approach to developing DTs. This can make it difficult to develop DTs robustly and reliably.
- Lack of empirical evidence on the benefits of DTs. There is limited empirical evidence on the benefits of DTs. This makes it difficult to assess the value of DTs and to justify the investment in DT development and deployment.
- Lack of standards for DT development and deployment. There are no standards for DT development and deployment. This can make it difficult to develop and deploy DTs in a consistent way.
- Lack of skilled personnel. There is a shortage of skilled personnel with the knowledge and experience to develop and deploy DTs. This can make it difficult to develop and deploy DTs in a timely and cost-effective way.

2.2. Academic Literature Review

DT definitions, features, applications, and design ramifications were thoroughly investigated by Barricelli et al. [15]. As of 2019, the authors looked at 75 articles from a range of disciplines, including manufacturing, precision medicine, hospital administration, and aviation. It must be noted that the study did not report DTs for infrastructure. DTs were also the subject of literature reviews by Trauer et al. [16] and Jones et al. [17], which looked at a total of 57 and 92 publications, respectively. These studies covered the definitions and traits of DTs, but they did not directly examine whether they were accepted in business, particularly the infrastructure sector. DT definition, functional components and differences between DT and cyber–physical systems are the subjects of the paper submitted by Boyes and Watson [18]. In their study, information management, architecture and design, life cycle, and safety and security are the areas that need further research. DT definition, application context, and research challenges are the subjects of the systematic review published by Semeraro et al. [19].

Despite the growing interest in DTs and their potential benefits, there is still a lack of understanding of the current industrial practices of DTs [18]. This lack of understanding is also reflected in the difficulties that companies are facing when it comes to designing and implementing DTs. Many companies are struggling to find standardisation and guidance for designing DTs, which can lead to errors and inefficiencies in the process. This paper is an initial attempt at filling this gap, providing the current application landscape and future needs from an industrial point of view.

Biesinger et al. [4] argue that the benefits of a DT outweigh the costs. The article concludes by arguing that automotive manufacturers should consider implementing a DT to improve their efficiency, reduce their costs, improve their quality, and increase their flexibility. The article identifies several gaps in the literature on DTs. First, there is a lack of research on the specific benefits that DTs can provide for different types of businesses. Second, there is a lack of research on the specific challenges that businesses face when implementing DTs. Third, there is a lack of research on the specific strategies that businesses can use to overcome the challenges of implementing DTs. Broo et al. [20] also highlight the lack of a common set of standards for DTs. There is currently no common set of standards for DTs, which makes it difficult to share data and information between different DT implementations.

Other studies have covered various aspects of the application of DT technologies in the industry. Ferko et al. [21] conducted a literature review article including a survey with 33 respondents and four semi-structured interviews to investigate the current state of the art of the alignment between the ISO 23247 and DT software architectures in industries. The study highlighted how the adoption of standard architectures in the industry is still in the early stages and remains a gap in the interoperability aspect and maintainability. Liu et al. conducted semi-structured interviews with six companies for an industrial symbiosis network to analyse the needs of digital twins in supply chain collaboration, finding that large companies favour customised digital twins with an emphasis on environmental impact, while smaller companies prefer standardised digital twins focusing on cost and personnel reduction, leading to the development of an inter-company emission-monitoring framework and a general digital twin framework for supply chain collaboration [21].

Durão et al. [22] analysed 19 articles and interviewed industry experts to identify the main criteria for developing DTs and industry understanding of the concept, highlighting that real-time data, integration, and fidelity are the key requirements in the literature. While the industry views DT as a coexistence of digital and physical worlds with a focus on simulation models, emerging research trends suggest a shift towards system independence and implementation over DT design requirements. Xie et al. [23] presented a DT four-dimension (4D) fusion modelling method to solve issues, such as low model accuracy, response delay, and insufficient production line control accuracy, in discrete manufacturing lines.

According to Timperi et al. [22], DT can have a substantial impact on the business models of manufacturing organisations. DT may improve operations, provide cost savings and business growth, and enable stakeholders to concentrate on core strengths while growing their organisations. Several barriers to exploiting DT have been highlighted in this study, including data ownership, resource allocation, internal bureaucracy, and the difficulty of showing the actual value of data-based services to prospective consumers.

Both in industry and academia, there is a need for studies that outline insights about DT applications from numerous perspectives such as areas of use, benefits achieved, challenges experienced, and development methods. This paper represents a first attempt to address these gaps through the analysis of the results of a detailed industrial survey and a series of interviews with experienced stakeholders. Over 45 organisations were involved in this research and shared their point of view on DTs. Capturing and collating insights from industrialists presents valuable guidance on current and future research needs.

3. Online Survey

This section presents the methodology and the results of the online survey. The online survey was conducted within a series of workshops run by industry experts from several companies.

3.1. Methodology

The online survey aimed to map the current application landscape of DTs in manufacturing, primarily in the UK. The survey was conducted online and consisted of 16 questions, 12 of which required short answers or multiple-choice responses. The authors used the Forms tool within the Office 365 suite to collect the data. The results were then analysed using MS Excel and elaborated in a .xlsx spreadsheet. The questions (see Appendix A) were grouped into themes: the first six pertained to the DT project itself; the next five (questions 7–11) focused on the size of the project, status, and investment; and the final five (questions 12–16) were about the company, including contact information and industry sector. Overall, we found significant interest in DTs among participants in the manufacturing industry.

The survey has been promoted through a series of workshops delivered by the Team Defence Information (TD-Info) group (https://www.teamdefence.info/ (accessed on 4 May 2023)), within the TD-Info—Digital Twin Community of Practice (DefSp DTCOP). A working group on DT mapping was hosted by Prof. John Ahmet Erkoyuncu from Cranfield University (UK) and an online survey was launched on the 23rd of June 2021. A total of 99 responses were collated from 49 organisations.

The outcomes have been divided into four macro groups: (i) challenges; (ii) area of implementation; (iii) maturity; and (iv) impact. This approach allowed the authors to present the content in a logical structure so that the reader can interpret the key findings of the study and how they relate to the research question.

3.2. Results from the Survey

The individuals responding to the survey typically occupied senior positions such as 'Director', 'C' level, 'Head of Unit', 'Manager', or 'VP'. The distribution of the occupation level of the respondents is illustrated in Figure 1. Around 13% of the respondents were in junior-level positions. This is also an interesting observation, as senior personnel expressed interest in facilitating a faster development and implementation of DTs.

3.2.1. Challenges

The challenges to be addressed where the DT technology has been initially considered have been divided into categories and subcategories as reported in Table 1.

The result, reported in Figure 2, was derived from responses to the open-ended questions in the online survey. According to the survey respondents, the most significant challenge that DT is being utilised to tackle is optimising asset performance through life, followed by maintenance and health management, as well as production/process optimisation. Additionally, the topic of interoperability was brought up during this phase, indicating that this matter is gradually garnering attention from businesses.

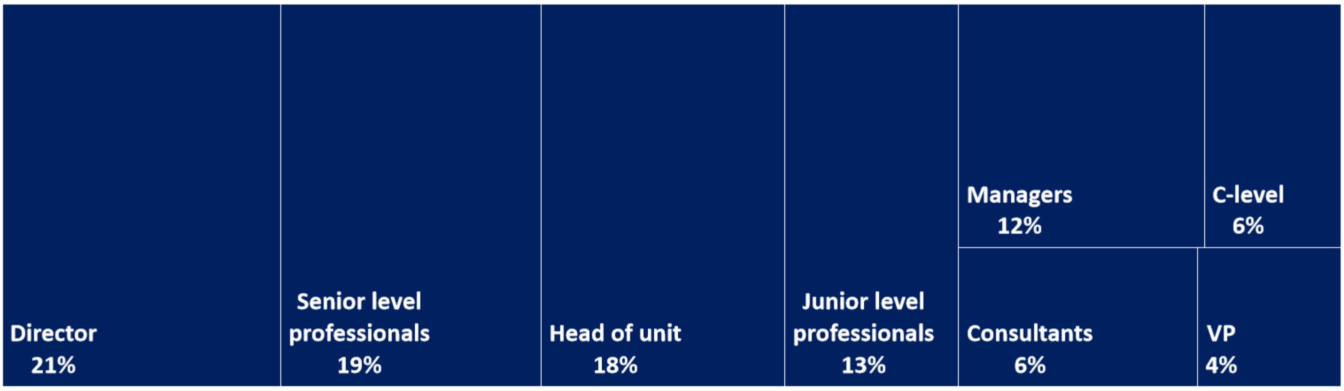

Figure 1. Distribution of job roles of respondents.

Table 1. Categorisation of challenges derived from the answer to the online survey, where (MA) represents the category managing assets, (A) represents assurance, and (S and P) represents strategy and planning.

Categories	Subcategories	Definition
S and P	Feasibility assessment	In this field, the challenges regarding helping enterprises to understand the digital maturity level and what tools they require; IT support is included.
A	Safety	In this field, the challenges regarding the safety of the system are included.
MA	Asset performance optimisation through life	In this field, the challenges regarding the optimisation of the asset performance throughout its life cycle including modelling and simulation to find optimal working operation; historic, current, or predicted conditions; performance validation are included.
MA	Maintenance and health management	In this field, the challenges regarding health monitoring; increasing availability; monitoring of the remaining useful life; management of resources to perform maintenance; degradation assessment; increasing the endurance of the asset are included.
MA	Production/process optimisation	In this field, the challenges regarding optimisation of the production processes, such as the design process, development process, and manufacturing process are included.
MA	Interoperability	In this field, the challenges regarding the interoperability of different systems, such as cross-department communication, are included.
MA	Fleet Management	In this field, the challenges regarding the management of a fleet of assets are included.
MA	Environmental impact	In this field, the challenges regarding the monitoring of the environmental impact are included.

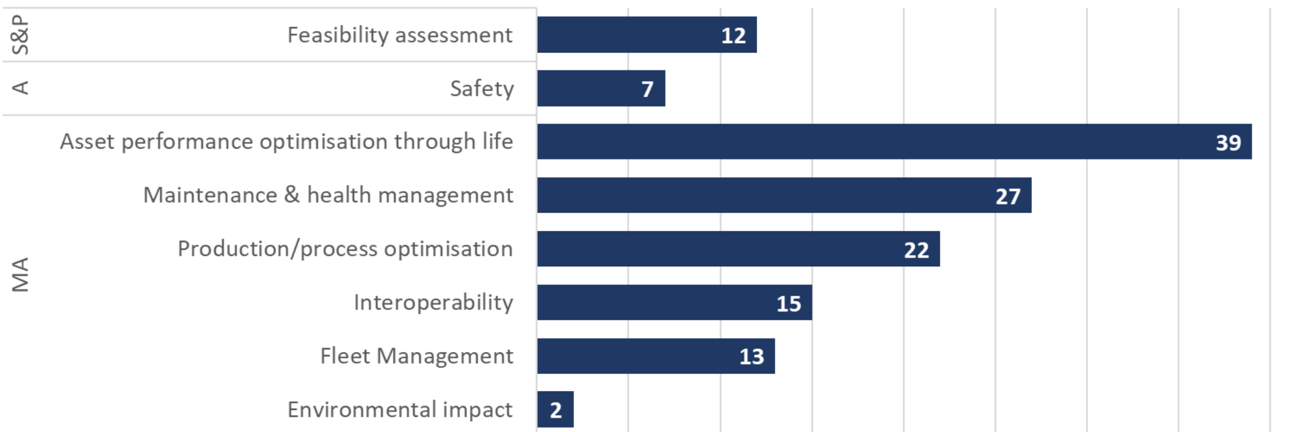

Figure 2. Challenges to address with DT adoption, where (MA) represents the category managing assets, (A) represents assurance, and (S and P) represents strategy and planning.

3.2.2. Area of Implementation

From the question *What sector is your digital twin applied to?*, the authors mapped the areas of implementation of DTs in terms of industrial sectors. The question had multiple-choice answers and the users just needed to select the industrial sector(s).

The defence, aviation, and maritime sectors are the primary sources for DT deployment according to the companies involved in the survey, as illustrated in Figure 3.

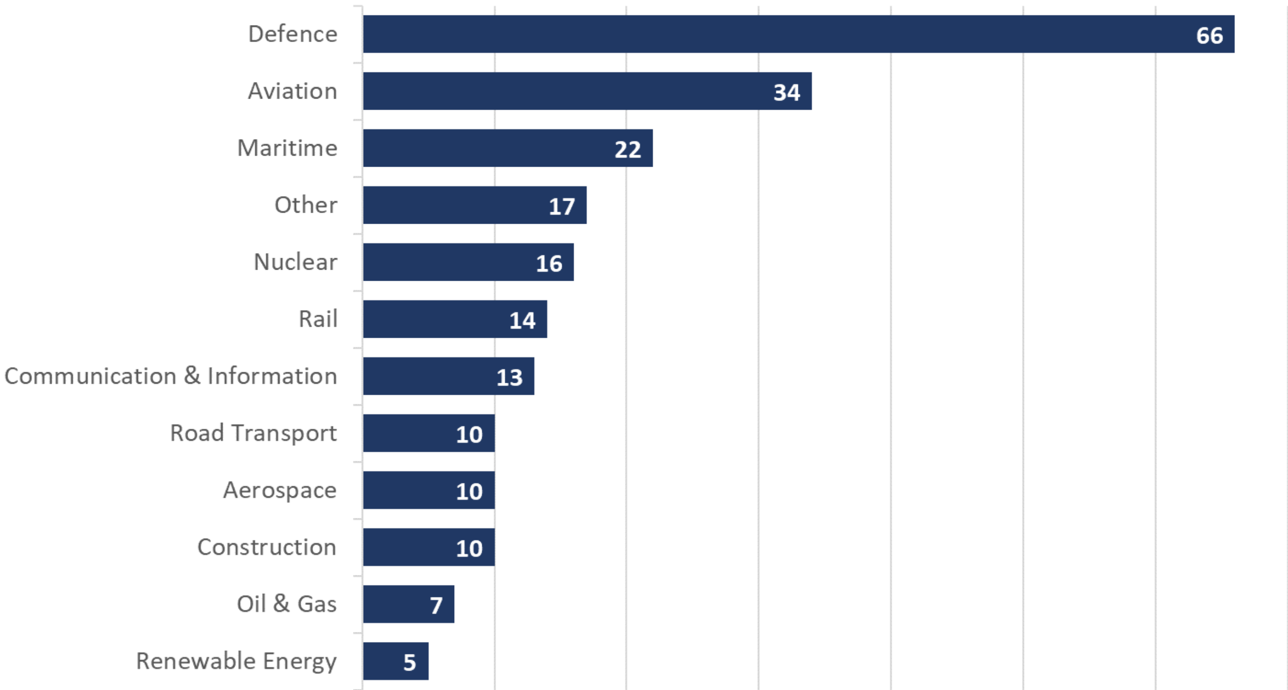

Figure 3. Sectoral representation of respondents.

From the question *What areas are applicable to your digital twin?*, the authors wanted to investigate the phases of the life cycle the DT was applied to.

The phases of the life cycle during operation, including in-service optimisation, maintenance, repair, and overhaul (MRO), and mid-life upgrade and modification, play a significant role in the implementation of DTs, as reported in Figure 4.

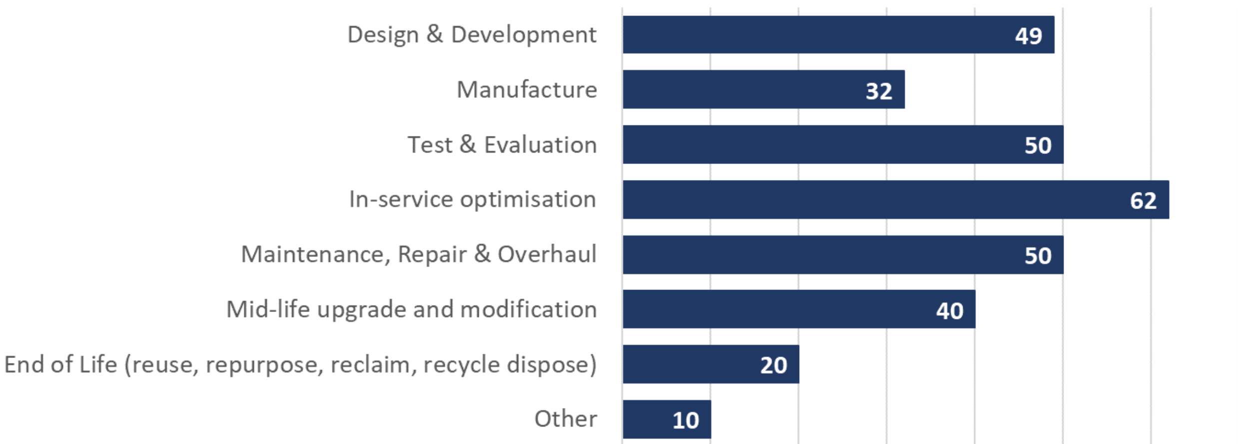

Figure 4. Interest in DT implementation across the life cycle.

From the question *What is the scale of the project?*, the authors investigated the size of the DT projects.

The distribution is almost evenly distributed between small, medium, and large projects, as reported in Figure 5.

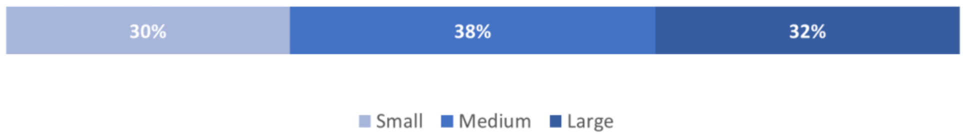

Figure 5. The size of the DT projects.

From the question *What is the complex system scope or focus?*, the authors investigated the focus area of the DT project.

The study highlights that across the proposed DT examples, there has been an emphasis on having a better understanding of the 'end-to-end capability' and 'processes' linked to the asset, as reported in Figure 6. This emphasis on understanding the full life cycle of the asset suggests that the goal of using DT technology is to improve the asset and the outcomes that can be achieved from the asset.

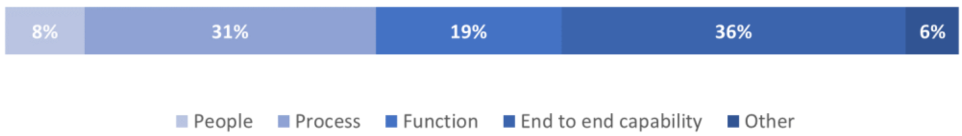

Figure 6. The focus area of DT.

With the question *What is the theme of the digital twin application?*, the authors investigated whether the DT is applied to products or systems. The results are reported in Figure 7.

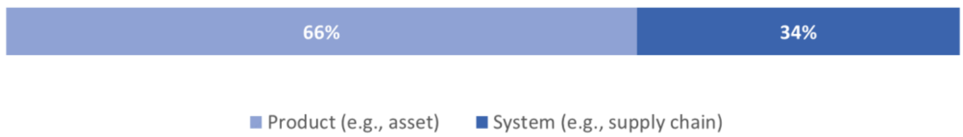

Figure 7. Purpose area of DT.

The purpose of DT has primarily been centred around the product (e.g., asset), as declared by 66% of the survey respondents. Only 34% of the responses focused on the system (e.g., processes) that consisted of, among other things, the supply chain. This is an important message, which may indicate that DT has commonly been considered for products that generate commercial and performance gains for organisations. This could be because organisations can make a connection between the commercial/performance gains that can be accumulated from the asset and the added value that a DT can bring. This may have led to justifying the value that can be gathered from DTs for improving systems/processes to be more difficult. Moving forward, it is likely that there will be a growing interest to enhance systems/processes to improve outcomes that can be achieved through the product.

3.2.3. Maturity

From the question *What is the status of your project?*, the authors looked into the status of the DT projects of the companies taking part in the online survey. The results are reported in Figure 8.

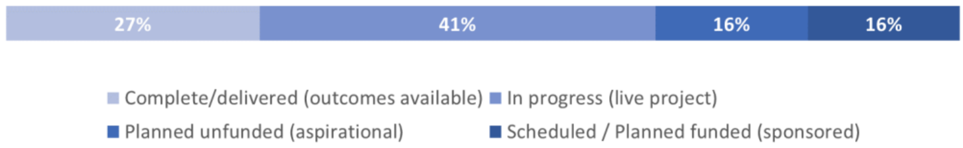

Figure 8. Status of the DT project.

The distinction here is between completed DT projects (with available outcomes), in-progress DT projects, scheduled DT projects (planned and funded), and aspirational DT projects (planned and unfunded). It is interesting to see that the combination of the shares of completed DT projects and in-progress projects together is more than 50% (about 68%), with the largest portion (41%) being dedicated to projects that are currently in progress. The two remaining portions are divided between planned and scheduled projects, each making up approximately 16% of the chart, as reported in Figure 8.

Additionally, with the question *What level of maturity is your project?*, the authors investigated the stage of the DT project. Specifically, the DT project maturity is considered across the conceptual process, prototype, proof of value, initial operating capability, or full operating capability.

Almost one-third of the DT projects investigated have full operating capabilities (27%). There is an equal share of conceptual projects, which could enforce the premise that interest in this technology is growing and new projects have been considered by the companies involved, as reported in Figure 9.

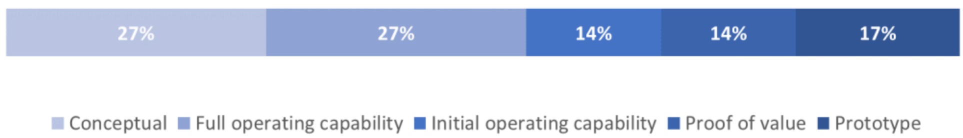

Figure 9. Level of maturity of DT projects.

3.2.4. Impact

Return on investment (ROI) is a financial metric used to evaluate the efficiency of an investment. It is calculated by dividing the net benefit of an investment by the cost of the investment and expressing the result as a percentage. A positive ROI indicates a profit from the investment, while a negative ROI indicates a loss. It is commonly used to measure the performance of an investment over time and is expressed as a percentage or a ratio. It is used in many industries to assess the profitability and effectiveness of specific investments [24].

What has been reported in Figure 10 is called the breakeven point (BEP) in the literature. The breakeven point is the point in time at which the total revenue from a project or investment equals the total costs associated with that project or investment. In other words, it is the point at which the revenue generated by an investment or project is sufficient to cover all of its associated costs, resulting in a net profit of zero [25].

The results from the combination of question 10 *What is the project start date?* and question 11 *What is the forecast return on investment (when will benefits in the business case be realised)?* are reported in Figure 10. The forecasted return on investment is expressed in years and indicates the breakeven point (BEP) of the DT projects. The three charts in the figure indicate the BEP in years for completed DT projects (on the left), for large DT projects (in the centre), and for small DT projects (on the right). Across the completed projects that were declared, the BEP was less than 2 years. Furthermore, the BEP for large projects was just under 4 years, and it was around 2 years for small projects.

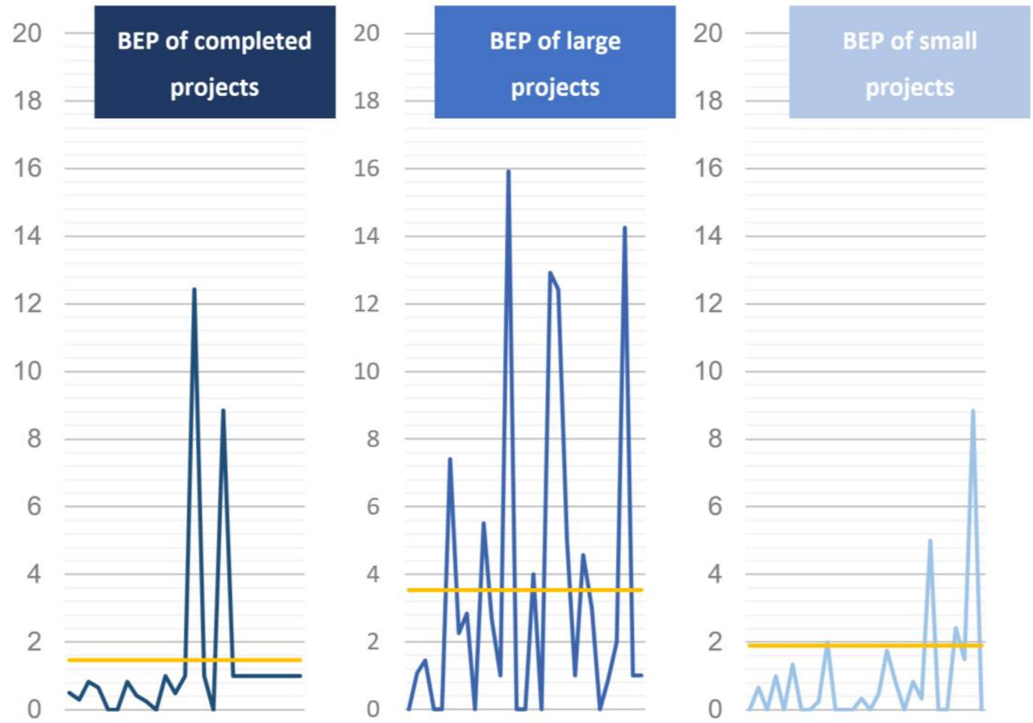

Figure 10. BEP (in years) of DT projects, divided between completed projects (**left**), large projects (**centre**), and small projects (**right**). In the abscissa, the number of the project, while in the ordinate, the time length in years. The yellow line represents the average value.

4. Interviews

This section presents the methodology and the results deduced from the interviews. The interviews were conducted based on the availability and preference selected from the online survey.

4.1. Methodology

Using the list of volunteers provided in the last question of the survey, the researchers contacted 14 experts from 10 companies based in the UK. These experts agreed to participate in the interview and provided valuable information on their DT projects, including requirements, lessons learnt, and future scenarios. The interview questions were refined based on the information gathered during the interview process to ensure the use of a consistent set of answers for analysis. The profile of the 14 experts from the 10 companies that participated in the interview is reported in Table 2. The questions evolved during the interview timeframe based on the experience gained over the other interviews in order to have a homogeneous set of answers to analyse.

Table 2. Profiles of interview meetings (online and 60 min duration) and participants' details.

Agent	Company	Location	Date	Years of Experience	Role	Industry
A00	Co_01	UK	14/09/2021	42	IT manager	European multinational aerospace corporation
A01	Co_02	UK	21/09/2021	21	Head of Digital	European multinational company for the aerospace, defence, transportation and security sectors
A02	Co_03	UK	24/09/2021	32	Experimental and MRO Functional Lead	Aerospace design and manufacturing
A03	Co_03	UK	24/09/2021	13	Head of Innovation and New Product Design	Aerospace design and manufacturing

Table 2. *Cont.*

Agent	Company	Location	Date	Years of Experience	Role	Industry
A04	Co_04	UK	24/09/2021	14	Commanding officer	British government department
A05	Co_05	UK	30/09/2021	10	Propositions Manager	Multinational logistics, supply chain, manufacturing and consultancy company
A06	Co_05	UK	30/09/2021	26	Chief of Staff and Enterprise Architect	Multinational logistics, supply chain, manufacturing and consultancy company
A07	Co_05	UK	30/09/2021	23	Head of Solutions	Multinational logistics, supply chain, manufacturing and consultancy company
A08	Co_06	UK	12/10/2021	37	Partner	Engineering and technology consultancy company
A09	Co_07	UK	13/10/2021	14	Systems Engineering Information Technologist	Multinational Aerospace, Arms industry, and Information security company
A10	Co_07	UK	13/10/2021	40	Engineering Manager	Multinational Aerospace, Arms industry, and Information security company
A11	Co_07	UK	13/10/2021	12	Service Integration Manager	Multinational Aerospace, Arms industry, and Information security company
A12	Co_08	UK	19/10/2021	40	Head Of Business Intelligence	Multinational Aerospace, Defence, and Space industry
A13	Co_09	UK	19/10/2021	22	Head of Data & Analytics	Information technology consulting and services
A14	Co_10	UK	21/10/2021	25	Head of Digital Integration	Multinational Aerospace and Defence company

The strategy for the interviews in this study was to use open-ended questions to gather as much detailed information as possible from the interviewees. The goal of the interviews was to understand the companies' perspective on digital transformation (DTs) and how they approach it. The questions were based on a semi-structured format, which means that they were open-ended but still followed a general structure. To avoid bias, the participants did not know the questions beforehand and were not aware of the answers provided by other participants, which allows for more objective data collection.

Thematic analysis is a method of analysing qualitative data, such as interview transcripts, that involves identifying and coding recurrent themes in the data. This method, as described by Braun and Clarke [26], is systematic, meaning that it is a step-by-step process that is applied consistently to all of the data. The steps of the thematic analysis, inspired by a paper by Braun and Clarke [27], include initial familiarisation with the data, development of a coding scheme, identification of themes, and interpretation of the themes, as reported in Table 3. The specific steps may vary depending on the study and the research question being addressed. Thematic analysis can be useful in identifying patterns and themes in data, which can help to guide further research and analysis.

Table 3. Steps of the thematic analysis.

Step	Description of the Process	Application to This Work
Familiarising with data	Transcribing the interviews, reading and re-reading the transcripts, and noting down initial ideas.	Manual transcription of the recorded interviews.
Generating initial codes	Coding interesting features of the interviews in a systematic fashion across the entire data set, collating data relevant to each code.	Find common codes among all the interviews. Creation of codes in the NVivo tool.
Searching for themes	Collating codes into potential themes, gathering all data relevant to each potential theme.	Grouping codes based on themes and creation of themes.
Reviewing themes	Checking if the themes work in relation to the coded extracts and the entire data set.	Validate the themes by checking the codes for each interview.

Table 3. *Cont.*

Step	Description of the Process	Application to This Work
Defining and naming themes	Generating clear definitions and names for each theme.	See Table 4.
Producing the report	Reporting the results obtained in a paper.	Writing the final paper.

Table 4. Themes resulted from the thematic analysis.

Theme	Description
Drivers and inhibitors	This theme gathers the factors that drive or interfere the DT development. Those factors include the benefits, the challenges that the DT undertake, the barriers, and the problems.
Digital twin properties	This theme gathers the factors that characterise the DT. Those factors include the attributes, the elements that constitute the DT, the semantic properties, and the visualisation properties.
Finance	This theme gathers the factors that characterise the economic aspect of the DT. Those factors include the return on the investment, and the funding used to start a DT project.
Next steps and needs	This theme gathers the factors that provide a future vision in the DT context. Those factors include the future scenario, the suggestions, the needs, and the next steps.

4.2. Results from the Interviews

The 10 interviews were recorded and the transcripts of these interviews were manually noted in 10 separate Microsoft Word documents. The authors chose not to use any speech-to-text tools to transcribe the interviews in order to become familiar with the content of each interview. The transcripts were then formatted to be used in the NVivo 12 qualitative analysis tool. NVivo is a software tool used for coding and analysing qualitative data. For this research, a university (site-level) license was used to access the tool.

As the first step, each interview transcript was coded and the codes were grouped by a predefined subject based on the information provided during the interview. The subjects were then grouped with similar subjects to form themes. This process allowed the researcher to identify patterns and commonalities in the data, which was then used to identify key themes and insights. The use of NVivo software in this process allowed for a more systematic and efficient way of coding and analysing data.

The coding phase in qualitative research is a crucial step in the process of organising, analysing, and making sense of the data collected from interviews. The process typically begins with transcribing the interviews. This involves taking the recorded audio or video of the interview and writing down exactly what was said by the participants. Transcribing the interviews allows the researcher to have a written record of the data that can be easily read and analysed. Once the interviews have been transcribed, the researcher begins the process of reading through the answers provided by the participants. This is typically carried out multiple times in order to identify key themes or concepts that emerge from the data.

After identifying key themes or concepts, the researcher summarises them into a single sentence or "code" that represents the main idea being expressed. This allowed the researcher to analyse and understand the data and identify patterns or trends in the responses. This process is called thematic analysis. The four themes that have been extracted from the data in this study are *drivers and inhibitors*, *DT properties*, *finance*, and *next steps and needs*. These themes represent the key concepts or patterns that emerged from the data collected from the interviews with experts from different companies. The themes are reported in Table 4, which provides more detailed information on each theme and how they were identified from the data.

The tables (Tables 5–12) include codes (listed in alphabetical order) that have been extracted from the transcripts of the interviews and grouped into themes. The tables also include additional information, such as the source and reference for each code.

Table 5. Table of DT drivers.

Drivers	Sources	References
Autonomy	1	1
Customer satisfaction	1	1
Enable system of systems	1	1
Improve the company's efficiency	2	2
Improve knowledge and awareness	3	4
Optimisation	2	4
Safety	2	2
Simplify complexity	1	1
Sustainability	1	1

Table 6. Table of inhibitors.

Inhibitors	Sources	References
Company's mindset, lack of skills, and understanding	4	9
Complexity	4	7
Expensive	1	1
Interoperability issue	8	17
Quality of data	2	3
Uncertainty	2	2

Table 7. Table of DT attributes.

Attributes	Sources	References
Not necessarily real time	1	1
Portability, scalability, and interoperability	3	3
Through life support of the real entity	1	1

Table 8. Table of DT design.

DT Design	Sources	References
Defined procedure	4	4
Diversity of the team	7	9
DT for data validation	1	1
Focus on safety	1	1
Focus on simulation	1	2
No formal procedure	5	5
Start from a research problem	1	2
Start from the purpose	6	8

Table 9. Table of DT visualisation.

Visualisation	Sources	References
Dashboards	1	2
Focus on data	2	2
Focus on value	7	13
Headsets	3	4

Table 10. Table of DT semantics.

Semantics	Sources	References
Not aware	1	1
Ontology	3	3
Standard approach	6	9
Still research topic	2	2

Table 11. Results from the return-on-investment questions.

Return of Investment	Sources	References
2-year ROI	1	1
30–40%	1	1
Accept longer period returns	1	1
Opportunity benefit rather than investment	4	6
Optimise to not waste money later	3	4
Reduce time-to-market	1	1
ROI not considered	2	2
Significant return on the investment	2	3
Usually short	4	4

Table 12. Next steps and needs.

Next Steps and Needs	Sources	References
Change the company's mindset and reskill the team	8	26
Customer satisfaction	2	2
Focus on data	4	8
Improve predictive maintenance	2	2
Keep pace with progress	1	1
Marketplace, registry of best practice	4	4
Migration to cloud	3	3
More grants	2	2
Self-defining DT	1	1
System of systems, ecosystem, the federation of twins	9	29
Think big, start small	7	8

- The *'Sources'* column in the table indicates the likely number of interviews in which the specific code was mentioned. This allows the reader to see how frequently a particular driver or inhibitor was mentioned across the interviews.
- The *'References'* column in the table indicates how many times a specific code was mentioned within the interviews. This allows the reader to see how important a particular driver or inhibitor was to the participants.

4.2.1. Drivers and Inhibitors

This subsection focuses on the theme of drivers and inhibitors, and the results are presented in two separate tables, one for drivers and one for inhibitors. The tables allow the reader to see the specific drivers and inhibitors that were identified in the study and how frequently they were mentioned. This information provides insight into the benefits and barriers that companies are experiencing when implementing DT technology and can be used to understand the current state of DT implementation in the industry.

Various advantages associated with the DT development process categorised into themes based on the codes derived from the interview transcripts are reported in Table 5. These benefits include the enhancement of the knowledge base and awareness of the twinned asset, as well as the ability of the DT to transition the workload from the physical to the virtual world, providing more flexibility and autonomy for digital engineering tasks. The table also indicates that a DT brings about customer satisfaction. It is noted that DTs facilitate the integration of different systems under the "system of systems" paradigm, and also contribute to improving the overall efficiency of a company. The development of DTs also allows for the optimisation of costs and performance of assets, leads to better safety outcomes, encourages companies to simplify complexity, and supports overall sustainability.

An extract from the interview, Agent A12: "*The opportunity the DT provide us is to make that much more dynamic and real-time and lead to more true predictive maintenance, and better data coming out*".

Inhibitors of the DT development process, most notably "interoperability issues" and "company's mindset", are reported in Table 6. "Interoperability issues" refer to the lack of standardised approaches in data and information sharing, which can hinder effective communication between different DT systems. "Company's mindset" relates to the reluctance in adopting innovative technologies due to decision-makers' skill gaps or lack of understanding. The data in the table also indicate other inhibitors like "complexity" of managing complex tools, "quality of data" referring to poor input data, "uncertainty" indicating discrepancies between data and physical models, and "expense" as a financial constraint, particularly in the case of large companies initiating a pilot DT project.

An extract from the interview, Agent A08: "*Dealing with uncertainty is a difficult part of the DT. In the work that we have done, we generally have data and a physical model, and we deal with some sort of uncertainty. Bringing those three things together is what gives you something that allows you to make decisions which you can trust. As your physical model gets better, or as the available data gets better, the uncertainty can reduce, and so you are not dependent so much on the sort of math too*".

4.2.2. DT Properties

This theme provides an in-depth look into the different factors that make up a DT and the processes used to create and interpret them. This information is useful for understanding the current state of DT technology and can be used to improve the design, visualisation, and interpretation of DTs.

The main attribute mentioned in the interview is the set composed of "portability, scalability and interoperability", as reported in Table 7. "Portability" refers to the ability of a DT to be transferred or adapted to different platforms, environments, or systems without loss of functionality or performance. This attribute is important for companies as it allows for flexibility in using the DT in different situations or contexts. "Scalability" refers to the ability of a DT to adapt or grow to accommodate changes in the volume or complexity of the data or asset being twinned. This attribute is important for companies as it allows for the DT to be used in a wide range of applications and to handle different levels of complexity. "Interoperability" refers to the ability of a DT to communicate and share data with other systems, platforms, or DTs. This attribute is important for companies as it allows for the DT to be integrated into existing systems and for data to be shared across different departments or organisations.

The second attribute reported in the table is that a DT does not have to work "necessarily in real-time". Depending on the purpose and the asset, discrete communication might also work. For example, if a DT is used for monitoring and analysing the performance of a machine or equipment, it may only need to update at specific intervals or when certain conditions are met.

The third attribute reported in the table is that DT has to "support the twinned asset through life", and it is not specifically for one part of the life cycle. This means that a DT should be able to support the asset throughout its entire life cycle, from design to disposal, and not just a specific part of it. This is important as it allows companies to gain insights and make decisions throughout the entire life cycle of the asset and not just during specific stages.

An extract from the interview, Agent A01: "*There is an attribute evaluation during the design process. Attributes that we consider would be portability, scalability and interoperability. So different DT solutions will require to focus on different attributes*".

A defined procedure for DT design is not universally adopted, with diversity in the design team being highlighted as crucial for innovation and comprehensiveness, as reported in Table 8. It has been shown that a blend of experienced operators and newly graduated data scientists adds value to the DT design, allowing for diverse expertise to inform the process. The data reported in the table underscore the importance of a clear purpose as the starting point of the DT design process, alongside other strategies such as initiating design through a research project. Other factors like a focus on simulation, safety, and DT for data validation, which refers to the use of DT for verifying collected asset data, are also mentioned.

An extract from the interview, Agent A03: "*We did not apply all this modern AI technology to our engine specifically for DT development, but to optimise operation and costs, and because we have created this kind of digital thread across our organisation. Talking about the DT hierarchy, people do not often know where to start to become a DT organisation and I always say, you just start everywhere. If you do not forecast your fleet, start forecasting your fleet, and start creating models. If you do not have digital inspection across everything, including MRO, start implementing it. If you do not look at how to manage individual components through your supply chain, there will be a value proposition associated with just that*".

From the interviews, a strong emphasis on the significance of visualisation in the context of value and data in the DT design emerged, rather than focusing on visualisation aesthetics alone, as reported in Table 9. "Focus on value" implies that visualisation should facilitate decision-making by providing simplified, standardised, and graphically represented information. "Focus on data" underscores the need to trust the data and the analytical abilities of the DT over the final product. As for the visualisation tools, extended reality technologies (AR, VR and MR) are increasingly popular for DT visualisation, while dashboards remain useful for presenting decision-making information. This insight portrays how interviewees perceive the role of visualisation in DT design and the elements they deem significant.

An extract from the interview, Agent A14: "*I think building up that trust in the data in there and the analytics capability, I think is key. I think the other aspect is being able to visualise the data in the right context, dependent on the user, and ensure that what the data is projecting or saying is truly understood and interpreted in the right way. I have seen examples of dashboards being created to almost tell the story that somebody wants to tell as opposed to undertaking analysis of the data to determine what could be done or should be done*".

A range of awareness and application of semantic approaches in the DT design process has emerged, as reported in Table 10. Some interviewees employ ontologies, while others are attempting to apply standard approaches including the use of standard ontologies, open-source solutions, or a shared language across devices. Conversely, some participants regard semantics in DT design as a research topic still lacking a widely recognised standard approach, suggesting discrepancies in understanding and utilisation of these strategies.

An extract from the interview, Agent A08: "*I think the modularisation of ontologies, from an application level to a top-level one is very important, mostly in the space domain. I am less familiar with the temporal side, which I think is a trickier problem. The other problem is how you deal with uncertainty within the context of ontologies*".

4.2.3. Finance

The focus of this part of the interview regarded the length of time it takes for a company to see a return on their investment in a DT project. There is diversity in breakeven points and ROI estimates for DT projects among interviewees, with some expecting a significant ROI or a short breakeven point, while others do not consider ROI in their projects, as reported in Table 11. Qualitative insights reveal that several interviewees view DT as an opportunity for uncovering and addressing inefficiencies, optimising processes, and reducing time-to-market, rather than purely as an investment. The breakeven point can vary based on several factors including industry, company size, and the type of DT project.

An extract from the interview, Agent A04: "*If the DT is working well, you will not necessarily see where it is saving money. You are dealing with an issue before it becomes an issue, so therefore, you are not necessarily having to invest money to solve a problem later down the line, because you are solving it before it becomes a problem. So, it might be difficult to identify that kind of return on investment because it might look like it is quite a process rather than financial reward or a financial benefit*".

4.2.4. Next Steps and Needs

One critical progression identified in this part of the interview is to establish a "system of systems" approach. This aspiration aims for a network of interconnected and semantically interoperable DTs, enhancing the overall knowledge of this network. To achieve this, various methods were proposed, including the use of ontologies, shared language approaches, and standard methods.

Another significant need is a fundamental change in the company's mindset and reskilling of their teams. This change involves not just incorporating data experts and domain experts into the design team but also fostering collaboration both within and outside the company. The goal is to transition from a traditional mindset to a more data-centric one, embracing a system of systems thinking in the process.

A commonly suggested strategy is to "think big, start small," which advises starting with small projects to realise benefits quickly while keeping the larger objective in sight. In parallel, an emphasis on data was recognised, with plans to improve the quality of input data, thereby increasing the consistency and overall value of the DT.

Looking towards collective growth and learning, the creation of a marketplace or registry for best practices and experiences in the development of DTs was suggested. This resource would serve as a database for companies to learn from past experiences, common challenges, and successful strategies in implementing and using DTs.

In terms of practical tools, the development of plug-and-play tools, customisable for specific applications, was emphasised. Such tools would save time and resources for companies, avoiding the need to start from scratch in developing their DT solutions. Moreover, a marketplace for DT solutions was suggested to efficiently connect supply and demand.

Companies also noted the need for cloud migration, emphasising more cloud storage solutions and the creation of a defence cloud for companies operating in both the defence and commercial sectors. This need for migration aligns with the growing popularity of cloud technology in the commercial sector. Calls for more grants to initiate future DT projects, focusing on customer satisfaction and staying updated with the field's progress, were also highlighted.

Another area where companies saw a need for improvement was in predictive analytics and predictive maintenance capabilities in DTs. Predictive maintenance enables proactive upkeep of equipment, saving costs, and improvements in equipment uptime. Lastly, the intriguing concept of "self-defining Digital Twins" was brought up. In the future, DTs might adjust parameters and settings based on the state and condition of the physical entity they are monitoring, potentially enhancing the efficiency of DTs. All the results are reported in Table 12.

An extract from the interview, Agent A14: "*I personally think that as we get into low-code no-code environments, I think that digital twins almost be self-defining in that based upon all sorts of scans the original entity, how that is interpreted, how I can apply proven analytics models to that capability. I think that is just the future of digital. And I think it is a strap-on and try and hold on for the ride. Because I think it is going to take people much further, a lot quicker. It requires things like comms infrastructures to be in place and searchlight*".

5. Discussion

The three main contributions are presented and answer the three research questions posed in the introduction section.

(1) What is the application landscape of DT in manufacturing? According to the sample analysed in this paper, DT projects are primarily applied in the defence, aviation, and maritime sectors. Their pivotal role spans different asset lifecycle phases such as in-service optimisation, maintenance, repair, and overhaul (MRO), and mid-life upgrades. Most DT projects, distributed fairly across small, medium, and large scales, focus predominantly on individual products (assets) rather than the broader systems they belong to, like supply chains. Financially, DT project returns typically materialise within two years for smaller projects and under four years for larger ones.

(2) What are the current practices in manufacturing? The process of designing DTs in manufacturing begins by determining the purpose and motivation of the DT. It also involves considering its elements, semantic properties, and visualisation attributes. Once the design process is established, the properties of DTs become critical. They include attributes such as portability, scalability, and interoperability, which directly influence their utility and effectiveness in the manufacturing processes.

On the financial side, the views on the use of DTs differ. Some companies utilise them as tools to identify hidden operational benefits, disregarding the need for a specific ROI for these projects. In contrast, others focus on the ROI and the BEP. This calculation can vary based on factors such as the industry, company size, and nature of the project.

(3) What are the future needs? Based on the results presented in the paper, the future needs for DT technology in manufacturing industries are as follows:

- More focus on the system rather than just the product. The study found that the focus of DT technology has primarily been centred on the product (e.g., asset) rather than the system (e.g., processes) that consisted of, among other things, the supply chain. Thus, there is a need to shift the focus towards the system to achieve better outcomes.
- Addressing the inhibitors of DT technology. The inhibitors of DT technology such as interoperability issues, the company's mindset, complexity, quality of data, uncertainty, and expense need to be addressed to promote the implementation of DT technology in companies.
- Achieving semantic interoperability between DTs. Semantic interoperability between DTs is a necessary step for building an ecosystem or federation of twins. This can be achieved through a "system of systems" approach.
- Reskilling the team. There is a need to change the company's mindset and reskill the team to enable the effective implementation and use of DT technology.
- Cloud migration. There is a need for cloud migration to enable better accessibility and scalability of DT technology.
- Marketplaces and registries of best practices. The need for marketplaces and registries of best practices can enable companies to learn from each other and achieve better outcomes.
- Plug-and-play tools. The need for plug-and-play tools can enable companies to quickly and easily implement DT technology.
- Grants. More grants can enable companies to invest in DT technology and achieve better outcomes.
- Improving predictive analytics and maintenance capability in DTs. This can enable companies to optimise processes and achieve better outcomes.
- Self-defining DTs. The concept of "self-defining DTs" could increase efficiency and effectiveness in the future.

Both in the survey and from the interviews, one of the aspects highlighted concerns the challenges and the barriers in DT development. The authors collected the main ones along with the solutions to overcome those barriers in Figure 11.

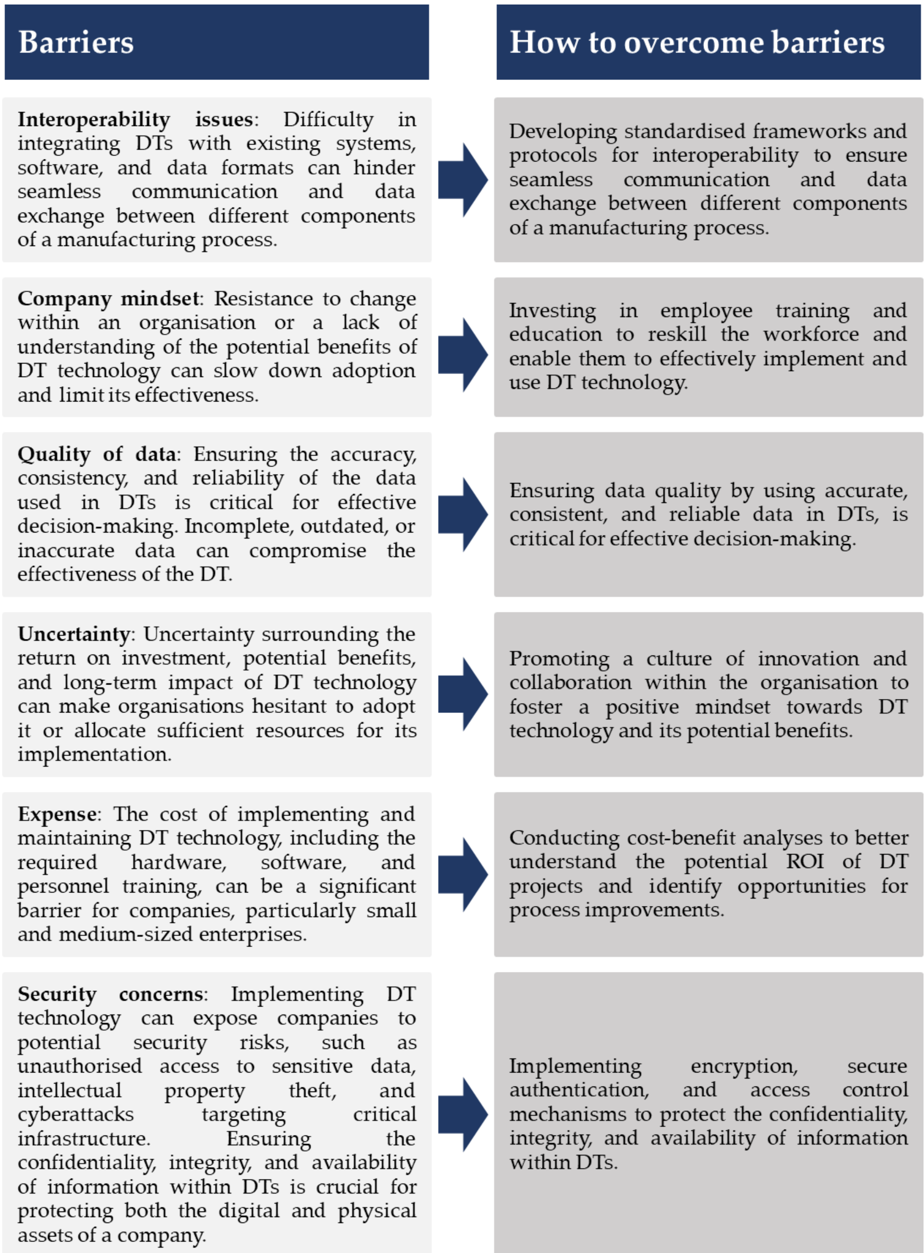

Figure 11. Barriers and how to overcome them.

Based on the findings presented in the paper, there is evidence to suggest that the use of DTs is likely to increase in the manufacturing industry. The study found that the majority of DT projects are in progress or completed, with an even distribution of sizes, and that the return on investment for DT projects was generally realised within two years for small projects and under four years for large projects. Furthermore, the paper highlights future needs for DT technology, including a focus on the system rather than just the product, achieving semantic interoperability between DTs, reskilling the team, cloud migration, marketplaces of best practices, plug-and-play tools, and improving predictive analytics and maintenance capability in DTs. These needs suggest that there is a growing interest in and recognition of the potential benefits of DT technology in the manufacturing industry and that efforts are being made to overcome some of the challenges identified in the study. Additionally, the increasing interest in the literature on DTs and their potential applications in various industries, including manufacturing, suggests that there is a growing awareness and understanding of the benefits of DT technology, which is likely to contribute to its increased use in the future.

The biggest impact of DT technology is likely to be made in improving efficiency and productivity in the manufacturing industry. The study found that DT projects were primarily focused on optimising the asset's life cycle during operation, including in-service optimisation, MRO, and mid-life upgrade and modification, which can lead to better efficiency and productivity. Additionally, the study identified the properties of DTs, such as transparency, traceability, responsiveness, adaptability, and connectivity, as well as the financial aspects of DTs, such as ROI and BEP, as important considerations for their implementation. Addressing the challenges identified in the study, such as interoperability issues, mindset shifts, reskilling, and data focus, can also contribute to the successful implementation of DT technology and its impact on improving efficiency and productivity in the manufacturing industry.

By addressing these challenges, organisations can more effectively implement DT technology and leverage its potential benefits to improve efficiency, productivity, and other key performance indicators in the manufacturing industry.

One of the points that emerged in this paper is with regard to the current mindset of companies, which, from the authors' perspective, is a hindrance to the development of DTs. This mindset needs to change for the development and progression of DTs. The current mindset of companies refers to the way companies currently approach the development and implementation of DTs. This can include a lack of understanding of the technology and its potential benefits, internal managerial and procedural issues, and a lack of necessary skills among team members. This mindset can act as a hindrance to the development of DTs, as it can limit the implementation, adoption and successful use of the technology.

The adoption of DT technology in the manufacturing industry can be a powerful catalyst for boosting efficiency, productivity, and optimising various other performance indicators. In order to achieve widespread adoption and maximise its potential benefits, a comprehensive and strategic roadmap has been proposed and illustrated in Figure 12. The first step is to conduct a comprehensive assessment of the company's capabilities and identify opportunities where DT technology can boost efficiency and productivity (Step 1). This is followed by the development of a clear strategy, including stakeholder identification, goal setting, and timeline establishment (Step 2). Then, the roadmap emphasises the importance of workforce reskilling to effectively utilise DT technology (Step 3), and the establishment of standardised frameworks for interoperability (Step 4). Secure information handling within DTs is also key (Step 5), as well as conducting cost–benefit analyses to comprehend the potential ROI from DT projects (Step 6). The latter part of the roadmap visualised in the figure highlights the role of cloud technology in improving DT technology accessibility and scalability (Step 7). It also underscores the value of fostering a culture of innovation and collaboration (Step 8) and the creation of best-practice marketplaces (Step 9). The final steps focus on the development of easy-to-implement tools for DT technology (Step 10), advocating for more grants (Step 11), and staying updated with DT technology advancements, particularly in predictive analytics and maintenance capabilities (Step 12).

Figure 12. Roadmap for wider adoption of DT technology in the manufacturing industry.

6. Conclusions and Future Work

This paper aims to fill the gap in the literature about the current industrial practices of DTs. This paper addresses this gap by providing insights into the scientific literature about the application landscape, current practices, and future needs of DTs directly from the people who work and manage DT projects in the industry. Those insights have been extracted from the analysis of the results from an online survey and semi-structured interviews.

The key takeaways from this study on DT technology in the manufacturing industry include the following:

1. Growing interest and adoption. This study shows that there is an increasing interest in and adoption of DT technology in various sectors, such as defence, aviation, and maritime, with a focus on assets rather than systems.
2. Identified challenges. Interoperability issues, company mindset, complexity, data quality, uncertainty, expense, and security concerns are the primary challenges faced during the implementation of DT technology in the manufacturing industry.
3. DT properties and financial aspects. Key properties of DTs, such as transparency, traceability, responsiveness, adaptability, and connectivity, are essential considerations for their implementation. ROI and BEP are significant financial aspects that influence the adoption of DT technology.
4. Future needs and developments. This study identifies several future needs and potential developments in the field of DT technology, including a "system of systems" approach, semantic interoperability, mindset shifts, reskilling, data focus, cloud migration, marketplaces of best practices, plug-and-play tools, and improving predictive analytics and maintenance capabilities.
5. Roadmap for wider adoption. A strategic roadmap is proposed for the wider adoption of DT technology in the manufacturing industry, including steps such as conducting assessments, developing a clear vision and strategy, reskilling the workforce, standardising frameworks and protocols, implementing security measures, conducting cost–benefit analyses, and fostering a culture of innovation and collaboration.

6. Collaboration between industry and academia. This study highlights the importance of collaboration between industry and academia to advance the understanding and implementation of DT technology, leading to the development of best practices, innovative solutions, and the effective dissemination of knowledge.

One of the main needs arising from the interviews is the concept of the Federation of Twins. The authors have already published a systematic literature review about the concept of the Cognitive Digital Twin [28]. The Cognitive DT concept is proposed as *a DT with augmented semantic capabilities for identifying the dynamics of the virtual model evolution, promoting the understanding of interrelationships between virtual models and enhancing the decision-making based on DT* [29]. The authors see the Cognitive DT model as one of the enablers and facilitators of the creation of the Federation of Twins. The semantic tools (such as ontologies and graph databases) bring to the DT a more human-like method [30] of processing data and information. This article empowers the need for research in the field of cognitive DT, thus contributing to the field of cognitive computing.

However, this research is constrained by the limited sample size of companies surveyed, all of which were located in the UK and predominantly engaged in the defence sector. It is known that DT represents an innovation for many industries, and it is not yet extensively adopted; therefore, it is always difficult to find industries ready to invest time in this type of study. A more comprehensive study, employing a larger sample size and incorporating international representation, would yield a broader and more holistic perspective on the subject matter. Future research could encompass a wider array of companies and industries to assess the progress of ongoing projects and identify new initiatives that have emerged in the interim. This approach would facilitate the collection of more extensive data and insights into the current state and future potential of DT technology across various sectors and geographical locations.

It would be beneficial to conduct further investigation to assess the implementation of DTs across a broader range of companies. As the research progresses, it would be advantageous to delve deeper into the subject matter using a more balanced survey that encompasses all relevant sectors and enables cross-sectoral comparisons. Furthermore, subsequent rounds of surveys and interviews can be carried out to evaluate the progress of current DT projects and identify any new initiatives that have been launched. This would contribute to a more comprehensive understanding of the present state of DT implementation and its ongoing evolution.

This article yields numerous results that can be employed as a foundation for further research projects or to generate new investigative endeavours. The aspects of DTs highlighted in response to the third research question represent key areas that companies are keen to explore in the near future.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Appendix A

Following the questions used in the online survey.

1. What business challenge is your digital twin project looking to address? [Open]
2. What level of maturity is your project? [Multiple choice]
3. What is the theme of the digital twin application? [Multiple choice]
4. What areas are applicable to your digital twin? [Multiple choice]
5. What is the complex system scope or focus? [Multiple choice]
6. Would you like to share any further details? [Open]
7. What sector is your digital twin applied to? [Multiple choice]
8. What is the status of your project? [Multiple choice]
9. What is the scale of the project? [Multiple choice]
10. What is the project start date? [Short answer]
11. What is the forecast return on investment (when will benefits in the business case be realised)? [Short answer]
12. Enter your organisation, department, and role. [Short answer]
13. If this is a consortium/team, who else is involved? [Open]
14. Who is the end customer, user, or target audience? [Open]
15. Please provide your name and contact details. [Short answer]
16. We may wish to contact you to gather additional information in relation to the creation of the compendium of Digital Twinning Implementation. If you would like to become a member of the Community of Practice. Please provide your consent below: [Multiple choice]

Below are the questions used in the interviews:

1. How do you define a Digital Twin?
2. How do you design a DT and how is the DT design team composed? Do you have any formal procedures?
3. How long is the ROI that a DT project should have?
4. How did you obtain the funding and where from?
5. How did you launch the design process? How do you validate the design process? What steps do you go through? Do you have any milestones to reach?
6. Have you considered any ontology/semantic approach in DT development?
7. Do you see a common approach that could be developed across the industry, or do you think it is going to have to be company-driven? (Federation of Twins) Talking about interoperability, and the link between software platforms, how much of a challenge do you see in interoperability, and how do you think that will become addressed over time?
8. How do users make decisions? Where does the visualisation (Dashboard, VR, AR, XR, etc.) have a role here in terms of improving the process of making a decision?
9. What are the challenges you faced, and why did you need a DT? What business challenge is your digital twin project looking to address?
10. What worked and what did not work?
11. What are the lessons learned from the whole process (business case definition, design, and development)?
12. What do you think are the next steps?

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