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From failure to success: a framework for successful deployment of Industry 4.0 principles in the aerospace industry

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Abstract

Purpose – The paper proposes a framework for the successful deployment of Industry 4.0 (I4.0) principles in the aerospace industry, based on identified success factors. The paper challenges the perception of I4.0 being aligned with de-skilling and personnel reduction and instead promotes a route to successful deployment centred on upskilling and retaining personnel for future role requirements.

Design/methodology/approach – The research methodology involved a literature review and industrial data collection via questionnaires to develop and validate the framework. The questionnaire was sent to a purposive sample of 50 respondents working in operations, and a response rate of 90% was achieved. Content analysis was used to identify patterns, themes, or biases, and the data were tabulated based on specific common attributes. The proposed framework consists of a series of gates and criteria that must be met before progressing to the next gate.

Findings – The proposed framework provides a feedback mechanism to review minimum standards for successful deployment, aligned with new developments in capability and technology, and ensures quality assessment at each gate. The paper highlights the potential benefits of I4.0 implementation in the aerospace industry, including reducing operational costs and improving competitiveness by eliminating variation in manufacturing processes. The identified success factors were used to define the framework, and the identified failure points were used to form mitigation actions or controls for inclusion in the framework.

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Originality/value – The paper provides a framework for the successful deployment of I4.0 principles in the aerospace industry, based on identified success factors. The framework challenges the perception of I4.0 as being aligned with de-skilling and personnel reduction and instead promotes a route to successful deployment centred on upskilling and retaining personnel for future role requirements. The framework can be used as a guideline for organizations to deploy I4.0 principles successfully and improve competitiveness.

Keywords Aerospace industry, Aerospace manufacturing, Aerospace sector, Change model, Digitalization, Industry 4.0

Paper type Research paper

1. Introduction

In the current digital era, the Industry 4.0 (I4.0) technologies have transformed manufacturing firms into smart factories (Resman *et al.*, 2021), where real-time data are utilized for planning, logistics and development (Jagtap *et al.*, 2020; Usuga Cadavid *et al.*, 2020). The seamless linkage of systems within factories and across the supply chain optimizes and adjusts process control at the execution point (Jagtap *et al.*, 2021a, b; Zhong *et al.*, 2017). This integration improves operational efficiency and productivity in manufacturing. However, the deployment or adoption of I4.0 principles needs better documentation in many global firms (Bellantuono *et al.*, 2021; Ebrahimi *et al.*, 2019). The high-level examples of literature outline the corporate process, which can be difficult to understand. As a result, implementations suffer from partial deployment or restricted benefits (Veile *et al.*, 2019). Deployments are often discussed at senior management levels to merge efficiency and productivity for financial gains (Lee *et al.*, 2022). The element of technical enablement, a wider understanding of interlinking systems and support infrastructure requirements still needs to be fully considered (Meyer *et al.*, 2019).

There have been a variety of challenges in the way of a successful deployment of I4.0 including issues in joined-up leadership, concerns around data privacy and ownership, as well as difficulties integrating assets and real-time data, knowledge and skills (Williams, 2019). According to Xu *et al.* (2018), the entire potential of the I4.0 key components is often watered down, which leads to harmful challenged-based viewpoints. According to Bongomin *et al.*'s 2020 research, Industry 4.0 (I4.0) is a collection of breakthroughs that have the potential to be disruptive and need targeted implementation as well as expert leadership. According to Agarwal *et al.* (2022) and Marnewick and Marnewick (2019), effective execution calls for a significant amount of training and development on the part of personnel. This is done to guarantee that the relevant knowledge and skill sets are in place.

Core components of I4.0 have been re-engineered in order to optimize the amount of efficiency achieved in processes (Bhatia and Kumar, 2022; Garcia-Garcia *et al.*, 2021). Despite this, the aerospace sector in every part of the world is still struggling with a broad variety of issues, and the integration of I4.0 components remains a difficult task. According to Zhou *et al.* (2015), some of the obstacles that need to be overcome include a questionable return on investment, concerns about cybersecurity, a lack of clarity on the advantages and safeguarding intellectual property. According to Balasubramanian *et al.* (2022), Siqin *et al.* (2022), businesses need a dependable framework that can be put into practise immediately in order to reap the advantages of smart technology.

The primary objective of adopting I4.0 technologies in the manufacturing domain is to enhance process efficiency and product quality (Dalenogare *et al.*, 2018; Joslin and Müller, 2016). The concept of cyber-physical systems enables decision-making to be decentralized, transferring the authority from senior management to frontline workers and necessitates upskilling the workforce during implementation under the guidance of shop floor managers (Mak *et al.*, 2020). However, it is crucial not to overlook the challenges associated with decentralized decision-making (Rizova *et al.*, 2020). In pursuit of this objective, organizations can conduct technology competency mapping to further their efforts. Effective deployment of

I4.0 technologies requires upskilling the workforce and reestablishing their sense of direction (Kovrigin and Vasiliev, 2020). To increase employee engagement and give them an early grasp of these technologies, employees should also receive training in a production environment (Mak *et al.*, 2020). Moreover, employees should receive training in a production environment to boost their engagement and provide them with early exposure to these technologies (Dalenogare *et al.*, 2018; Kovrigin and Vasiliev, 2020).

Based on the preceding discussion, two research questions have been formulated to guide the implementation of I4.0 principles:

RQ1. What are the success factors for the deployment of I4.0 principles in aerospace manufacturing?

RQ2. How can the various success factors be used as learning points to guide the deployment of I4.0 principles into a mature manufacturing company?

The study presents a framework based on success criteria to help manufacturing engineers use I4.0 ideas in aerospace. The proposed system assures quality checks at each gate and includes a feedback mechanism to assess the fundamental requirements for successful deployment, which are connected to current developments in capacity and technology. The framework provides a guideline for deploying I4.0 principles in aerospace manufacturing, based on identified success factors and can be customized to suit organizational needs.

Finally, this paper is structured as follows: Section 2 provides a comprehensive literature review on the principles of I4.0 in manufacturing. In Section 3, the research methodology used to develop the proposed framework is described. The development of the framework is discussed in Section 4, while Section 5 covers the validation process for the developed framework. The results and discussion of a case study are presented in Section 6. Section 7 explores the implications of the research, and in Section 8, the paper concludes with recommendations for successfully deploying I4.0 principles in aerospace manufacturing.

2. Literature review

Over the last few years, there has been a significant increase in the level of interest that has been shown by policymakers, academics and manufacturing practitioners in I4.0 techniques. In a similar vein, the findings of studies that were just recently made public in this field indicate a significant amount of interest among manufacturing practitioners in the aerospace manufacturing industry. Therefore, the search results were filtered based on date and the terms “Manufacturing” and “Aerospace,” which were used to guarantee that the literature evaluated was relevant. The most important search keywords and databases that were used when looking for information and compiling the literature review are shown in Table 1. By using these sources and search strings, the literature’s correctness and dependability for this study are ensured.

	Database results				
Search string	Scopus	Kings Norton library	ASME	IEEE Xplore	Google Scholar
I4.0 Deployment in Aerospace	49,778	36	81,742	3	26,400
Manufacturing I4.0 Readiness	10,657	245	248,836	26	32,800
Implementation of Smart Manufacturing I4.0	50,060	648	282,472	102	88,200

Source(s): Authors’ own work

Table 1. Literature database search and results

2.1 Industry 4.0 (I4.0) technologies

The successful adoption of I4.0 relies on the coordination of nine technologies, including robotics and automation, advanced simulation and big data analytics (Jagtap *et al.*, 2021a, b; Safi *et al.*, 2019), which enable companies to innovate and create competitive advantages. However, the deployment of I4.0 requires substantial financial investment, particularly in training, recruitment, software and technology, highlighting the importance of advanced planning and budgeting (Kovrigin and Vasiliev, 2020). Organizations must develop governance and structured planning levels, including formulating roadmaps for the future (Jauhari *et al.*, 2019), to overcome the fear of scaling artificial intelligence due to the limited understanding of the technology among employees (Ahmad *et al.*, 2021). Interconnectivity on-demand across the whole supply chain can bring the risk of technology-based attacks such as hacking, viruses and ransomware, along with people-targeted attacks to gain personal information (Mak *et al.*, 2020). Fear of these threats is a significant barrier for I4.0 in larger manufacturing companies. This major concern arises when data security policies of systems information are overlooked (Wood and Banks, 1993), highlighting the need for firms to identify their readiness and maturity levels in terms of an I4.0 deployment action plan (Wagire *et al.*, 2019).

2.2 Industry 4.0 (I4.0) nine dimensions

The nine dimensions of I4.0 prevalent in the academic literature, including strategy, leadership, customer, product, operations, culture, people, governance and technology (Schumacher *et al.*, 2016), have been found to enable the effectiveness and successful adoption of I4.0 principles. Poor management and communication lead to ineffective strategy and implementation planning (Kumar *et al.*, 2021), resulting in low commitment and a lack of collaboration and standardization among functions (Kovrigin and Vasiliev, 2020). Manufacturing firms encounter significant challenges during technology deployments when transferring technology from research centers to the company, particularly concerning the non-technical aspects such as intellectual property and return on investment (Wagire *et al.*, 2019; Wan *et al.*, 2021).

2.3 Themes from literature review

According to Qamsane *et al.* (2021) planning the implementation of I4.0 tools requires a thorough understanding of the needs and mapping these requirements to the state of knowledge on the deployment environment, interactions and capabilities. Systems engineering (SE) frameworks, such as digital manufacturing engineers, who assist with requirements gathering and the implementation of manufacturing systems (Sage, 1995; Papadopoulos *et al.*, 2022), can be instrumental in deploying complex systems effectively.

To extract success factors, the literature was reviewed for incidents or occurrences that were considered causes of a particular phenomenon through analysis (Akhavan *et al.*, 2006; Jafari *et al.*, 2007). Eleven common themes were identified in the literature, as shown in Table 2. The literature review aimed to identify and highlight important common themes, and the frequency of occurrence each theme was recorded. This approach necessitates an interactive process, involving moving between various selected manufacturing sources.

Seven literature sources were reviewed to identify and highlight 11 common themes. The final column, labeled "Count", utilizes a heat scale to indicate the most prevalent theme, marked as deep red. The literature sources that were extracted and reviewed include *I4.0: Challenges and solutions for the digital transformation and use of exponential technologies* (Deloitte, 2015), *Towards the next generation of manufacturing: Implications of big data and digitalization in the context of industry 4.0* (Papadopoulos *et al.*, 2022), *Barriers in the Integration of Modern Digital Technologies in the System of Quality Management of Enterprises of the Aerospace Industry* (Kovrigin and Vasiliev, 2020), *Adoption of Information Technology in Modern Manufacturing Operation* (Mak *et al.*, 2020), *A maturity model for*

Table 2. Common themes from literature

Themes mentioned in literature	Literature 1	2	3	4	5	6	7	Count	Mean count
Capability readiness					Yes	Yes	Yes	*3*	0.428571
Change management	Yes	Yes	Yes	Yes			Yes	*5*	0.714286
Clear requirements	Yes	Yes	Yes	Yes	Yes		Yes	*6*	0.857143
Collaboration	Yes	Yes	Yes	Yes		Yes	Yes	*6*	0.857143
Communication			Yes	Yes	Yes	Yes	Yes	*5*	0.714286
Governance	Yes	Yes	Yes	Yes	Yes	Yes	Yes	*7*	1
Leadership	Yes	Yes	Yes	Yes	Yes			*5*	0.714286
Management policies	Yes	Yes	Yes	Yes		Yes		*5*	0.714286
Roadmaps	Yes	Yes	Yes		Yes		Yes	*5*	0.714286
Security	Yes	Yes		Yes		Yes		*4*	0.571429
Strategy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	*7*	1
Substantial Investment	Yes	Yes	Yes			Yes	Yes	*5*	0.714286
Technology readiness		Yes			Yes	Yes	Yes	*4*	0.571429
Training		Yes	Yes	Yes	Yes	Yes	Yes	*6*	0.857143

Note(s): 'Count' column utilizes a heat scale to indicate the most prevalent theme
Source(s): Authors' own work

assessing I4.0*readiness and maturity of manufacturing enterprises* (Schumacher *et al.*, 2016), *Artificial-Intelligence-Driven Customized Manufacturing Factory: Key Technologies, Applications, and Challenges* (Wan *et al.*, 2021), *A Methodology to Develop and Implement Digital Twin Solutions for Manufacturing Systems* (Qamsane *et al.*, 2021). The data were analyzed to identify commonalities across the literature, irrespective of whether they were associated with success or failure. This approach reveals 11 themes across different deployments and experiences, which can now be reliably used to form success factors.

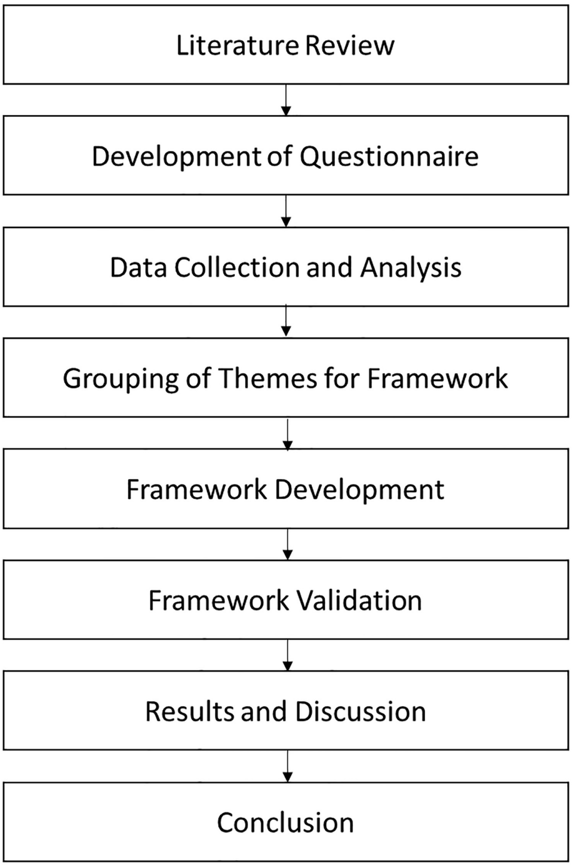
The aforementioned discourse highlights the clear presence of technological progress and the resultant impact on the fundamental nature of processes and interactions between humans and machines. The adoption of technology is significantly shaped by the strategies employed in its implementation (Biazzo, 2002). Business process mapping (BPM) can serve as a valuable tool in conducting collaborative working sessions involving stakeholders affected by digital transformation, thereby enabling the development of efficient solutions. An examination of the cultural and political factors associated with major transformations can contribute to the development of an effective strategy for implementing digital deployment (Antons and Arlinghaus, 2022; Holmström, 2022; Ardito *et al.*, 2019). The findings of the literature review and analysis indicate that the effective implementation of I4.0 technologies in the aerospace manufacturing sector necessitates a comprehensive and integrated approach. This approach should encompass a range of factors including strategy, leadership, customer relations, product development, operational processes, organizational culture, human resources, governance and technology. Manufacturing enterprises bear the obligation of ensuring that their workforce is adequately trained and equipped with the necessary skills to effectively utilize the tools and technologies associated with the Fourth Industrial Revolution (I4.0). Additionally, it is imperative that employees possess a comprehensive comprehension of the deployment context and its corresponding requirements. Moreover, it is imperative to establish a systematic methodology that can effectively facilitate the execution of I4.0 initiatives and ascertain the key determinants that contribute to favorable results. Aerospace manufacturers can achieve a competitive advantage in the global market by satisfying specific prerequisites and criteria, thereby improving their efficiency, productivity and quality. In order to bridge this existing gap, a comprehensive framework has been devised to facilitate the implementation of I4.0 within the aerospace sector. This framework has been meticulously constructed, considering the pivotal factors that contribute to its successful execution.

3. Research methodology

The research aimed to accomplish two objectives: firstly, to establish a framework for implementing I4.0 in the aerospace sector, and secondly, to identify the critical success factors associated with its implementation. To achieve these goals, a survey in the form of a questionnaire (shown in Appendix) was conducted, which was distributed across various business sectors to gather responses. The collected data from the survey was then analyzed, combining it with insights from literature studies and the perspectives of end-users, in order to identify the key variables that contribute to the success of the project (Bagur Pons *et al.*, 2021; Tashakkori and Creswell, 2007; Williams, 2011).

3.1 Research design

The research has been structured with the aim of generating valuable insights for the aerospace sector. Figure 1 illustrates the organization of the research design. The study was



Source(s): Authors' own work

Figure 1.
Research design

built upon an extensive literature review that encompassed reputable sources, serving as the conceptual basis for the research. Through this review, gaps in the existing literature were identified. The questionnaire was then developed and analyzed, taking into account these identified gaps and the predetermined objectives. The themes that emerged from the analysis were further explored to establish a comprehensive framework for the deployment of I4.0 in the aerospace industry.

3.2 Development of questionnaire

Developing a well-structured and comprehensive questionnaire is crucial for collecting relevant data (Melzack, 1975). Multiple pieces of literature were reviewed to design the questionnaire in this study, ensuring that respondents could understand the questions and provide articulate answers (Stone, 1993). To eliminate any ambiguity and biases, the questionnaire was reviewed by subject experts and industry professionals, and revisions were made accordingly (Krosnick, 2018).

In addition, the questionnaire (Appendix) included a write-up on digital manufacturing engineering and its branding to familiarize the respondents with internal processes, and two open-text field questions to increase the validity of responses and better understand the situation of the responder. The target population for this research was the global business unit of an anonymous aerospace company. The purposive sampling technique was employed to overcome the limitation of not all employees being subjected to I4.0 advancements. This technique allowed for the selection of participants based on their characteristics relevant to the research (Teddlie and Yu, 2007). Respondents were selected from cross-functional areas impacted by I4.0 deployments, including operations, manufacturing engineering and manufacturing services across the company's manufacturing sites in Europe and the USA. This selection ensured that the data collected was representative of the company's experience with I4.0 advancements.

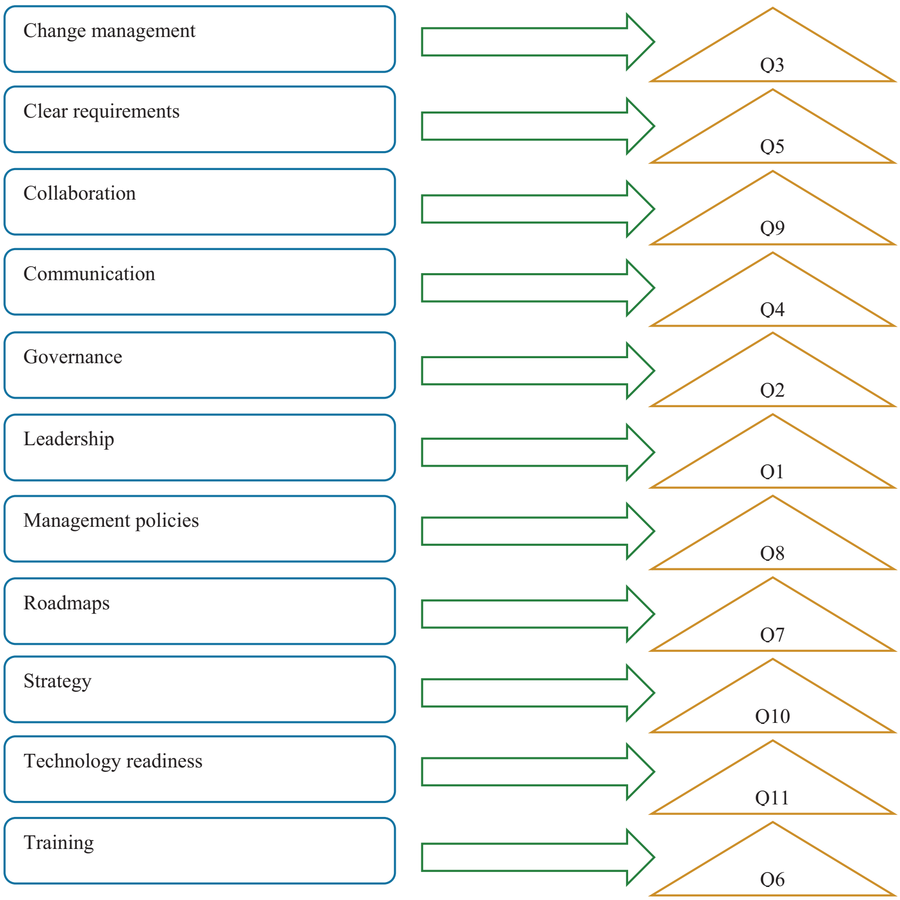
3.3 Data collection and analysis

The research approach used was descriptive, which identifies attributes of a particular event by observing or questioning those affected by it (Leedy and Ormrod, 2020). The attributes and commonalities identified through this approach are then tabulated to provide statistical insights, revealing patterns of successful and failed deployments. The research used a questionnaire to gather data from 50 respondents working in operations, as this area is more impacted by I4.0 deployments. The response rate achieved was a commendable 90%, which is considered acceptable (Gupta *et al.*, 2018).

The success factors and failure points identified from the questionnaire responses were then used to develop a framework. The identified failure points were used to form mitigation actions for inclusion in the framework, and a subject matter expert was involved in providing feedback and validating the proposed framework. The data collected through the literature review were analyzed using the content analysis technique (Leedy and Ormrod, 2020). This technique helps identify patterns, themes or biases in the data. Data extracted from various sources were tabulated based on specific common attributes such as leadership, communication, budget and more. Finally, real-life experiences were presented from various research studies and categorized for analysis to show success factors and failure points.

A non-response bias assessment was conducted to evaluate potential disparities in responses. The present study employed an independent *t*-test to compare the variables of interest between the early and late respondents of the survey. Following the approach suggested by previous scholars such as Armstrong and Overton (1977) and Lambert and Harrington (1990), the present study treated the late respondents as non-respondents for the purpose of comparison. The present investigation involved a sample of 50 participants who were categorized into two groups based on their response time: early (n = 22, 44%) and late (n = 190, 48%) respondents. Independent *t*-test analysis was utilized to compare the mean values of the nine constructs and determine if there were any statistically significant differences. The statistical analysis revealed that there was no significant difference between the early and late respondents in terms of all variables at the 5% level of significance. This indicates that no non-response bias was observed and that it did not pose any issue in the present study.

The questionnaire consisted of 11 questions linked with 11 themes identified from the literature review, with the terms "other" and "why" included to cover any missing or overlooked themes. The text input fields were reviewed independently for common phrases. Figure 2 shows how these themes were mapped to respective questions. While the questionnaire survey had a response rate of 64%, only 56% of the questionnaires were completed. The obtained responses were tabulated to extract the count and number of responses, and a weighting was applied to the choices for each question based on the number of responses.



Source(s): Authors' own work

Figure 2.
Mapping of questions

The same approach was used for text responses, and a mean weighting was applied based on the text input from where the questions were set. The results were presented in Table 3, with the highest combined score highlighting the most common theme.

3.4 Analysis of consolidated data

The data collected from the literature and questionnaire were combined to determine the synergy of themes. Table 4 shows clear synergies between both sources of data. Similarly, the theme synergy chart shown in Figure 3 helps to visualize that all the themes are correlated; but three themes, i.e. clear requirement, strategy and training, are strongly correlated.

Common themes	Questionnaire data Multiple choice	Text input	Combined score
Capability readiness	0	0.3	0.3
Change management	2.45	0.3	2.75
Clear requirements	3.2	0.55	3.75
Collaboration	1.62	0.6	2.22
Communication	2.3	0.25	2.55
Governance	1.52	0.9	2.42
Leadership	0	1.45	1.45
Management policies	1.64	0.85	2.49
Roadmaps	1.54	0.3	1.84
Security	0	0.25	0.25
Strategy	1.88	1.45	3.33
Substantial Investment	0	0.3	0.3
Technology readiness	1.72	0.6	2.32
Training	2.5	0.9	3.4

Source(s): Authors' own work

Table 3. Common themes from questionnaire responses

Common themes	Questionnaire score	Literature score	Combined score	Levelling of 4.57*Lit score	Combined levelled score
Clear requirements	3.75	0.857	4.607	3.917	7.667
Strategy	3.33	1	4.33	4.57	7.9
Training	3.4	0.857	4.257	3.917	7.317
Change management	2.75	0.714	3.464	3.264	6.014
Governance	2.42	1	3.42	4.57	6.99
Communication	2.55	0.714	3.264	3.264	5.814
Management policies	2.49	0.714	3.204	3.264	5.754
Collaboration	2.22	0.857	3.077	3.917	6.137
Technology readiness	2.32	0.571	2.891	2.611	4.931
Roadmaps	1.84	0.714	2.554	3.264	5.104
Leadership	1.45	0.714	2.164	3.264	4.714
Substantial Investment	0.3	0.714	1.014	3.264	3.564
Security	0.25	0.571	0.821	2.611	2.861
Capability readiness	0.3	0.428	0.728	1.958	2.258

Source(s): Authors' own work

Table 4. Consolidation of data sources

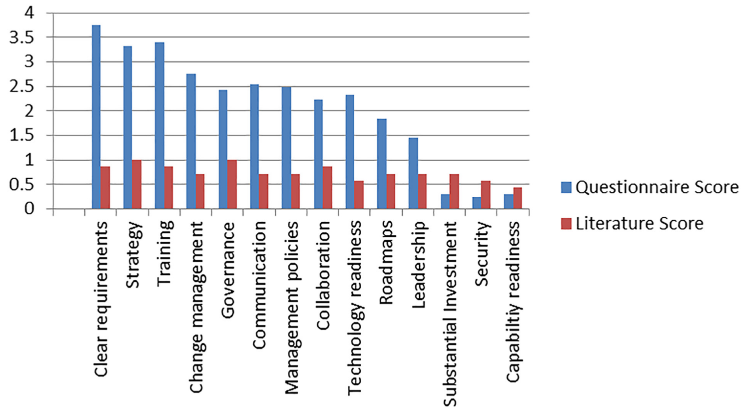


Figure 3.
Theme synergy chart

Source(s): Authors' own work

3.5 Grouping of themes for proposed framework

As a result, some groups of respondents were asked to participate in a discussion on the topics. The whole list of topics was condensed down to its four most important components. Figure 4 presents the themes consolidation map for your perusal. These fundamental ideas

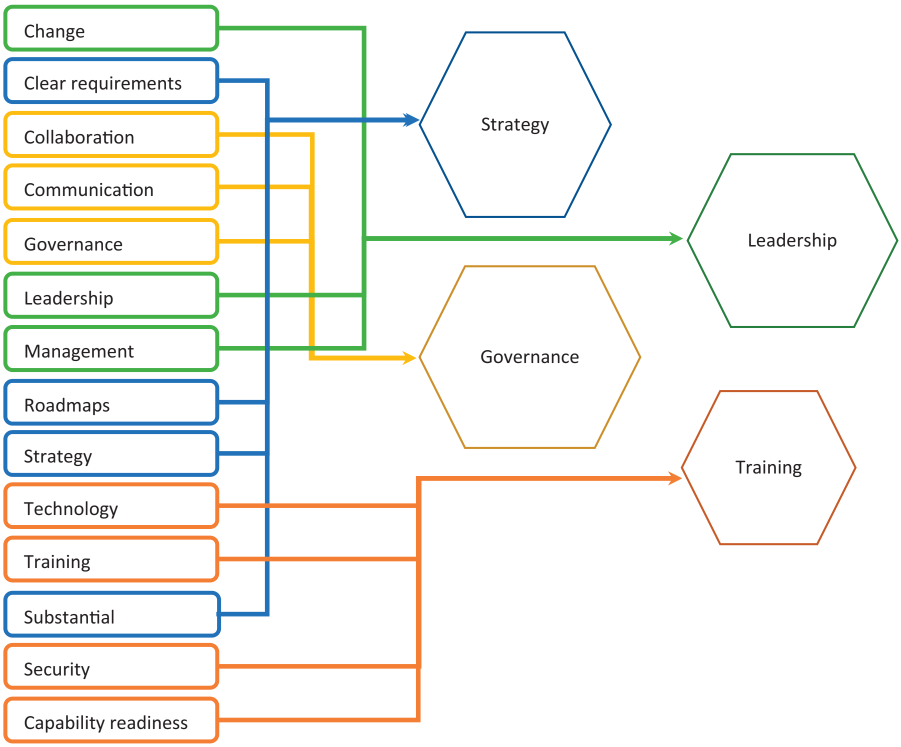


Figure 4.
Theme consolidation map

Source(s): Authors' own work

form the basis of both the success criteria and the framework that has been presented. According to the findings of the investigation, the most important factor in the implementation of I4.0 is strategy, followed by governance, leadership and training.

In the end, these four success elements are identified by using significant phrases, terms and terminologies from text-based replies and literature. Table 5 provides an overview of the success factor as well as the specifics of the success factor to explain the prioritized topics.

4. Development of a framework

The framework was developed through a systematic process that incorporated insights from the existing literature and the survey conducted as part of the research. The development process aimed to address the specific needs and challenges of deploying I4.0 principles in the aerospace manufacturing industry.

The first step in developing the framework involved identifying relevant success factors from the literature. These success factors served as key attributes that contribute to the successful implementation of I4.0 in aerospace manufacturing businesses. The literature review helped establish a foundation of knowledge and provided insights into best practices and critical factors for success.

Next, the survey was conducted to gather empirical data from industry practitioners. The survey aimed to validate and further refine the identified success factors and understand their applicability in the specific context of mature aerospace manufacturing businesses. The survey responses provided valuable input to shape and strengthen the framework.

The success factors derived from the literature and survey responses were then incorporated into the framework. The factors were given prominence within the framework based on their importance and influence on achieving a successful deployment of I4.0 principles. The framework was designed as a structured and comprehensive guide, consisting of five gates, each representing a critical aspect of the deployment process.

Table 5. Themes to success factors

Success factors ranked in order of importance (based on occurrence)

	Literature theme	Resulting success factors
1	Strategy	Shared future vision
2	Governance	Control and rigor for all aspects of deployment and scoping
3	Clear requirements	Full comprehensive list of what's required to achieve the future vision step by step
4	Training	Up skill the workforce to maintain the sense of worth to all
5	Collaboration	Cross functional teams pulling for interconnectivity Links with customers and suppliers to simplify communications
6	Leadership	Lead from the front consistently following the strategy Empower people - attract and retain talent
7	Management policies	Policies and procedures in place to support development and protect people and technology
8	Change management	Open strategy, clear communications, and engagement at all levels of the company
9	Communication	Push synergy across the business
10	Roadmaps	Clear method of achieving the vision
11	Substantial Investment	Budget is built into the strategy and aligned to deliver the requirements
12	Security	Specific knowledge and teams formed to define and manage data security
13	Technology readiness	Ensure the technology is fit for purpose and lessons learnt are captured
14	Capability readiness	Ensure the capability is fit for purpose and lessons learnt are captured

Source(s): Authors' own work

To ensure the robustness and validity of the framework, citations and references were used to support the various elements and steps outlined. This helped strengthen the framework's credibility and ensured that it was grounded in existing research and industry knowledge.

Overall, the development of the framework involved a combination of theoretical insights from the literature, empirical data from the survey, and expert knowledge in the field of aerospace manufacturing. It aimed to provide a practical and effective roadmap for organizations looking to implement I4.0 principles, tailored to the specific context of mature aerospace manufacturing businesses.

The deployment of I4.0 principles in a mature aerospace manufacturing business requires a well-developed framework that incorporates success factors derived from the literature and survey data. These success factors are integrated into multiple stages of the framework, which follows a gated process with each gate including a thorough review. The framework must pass through four gates, each corresponding to a success factor theme, and which are interdependent and build upon one another. Figure 5 provides a brief description of each gate and its intended audience. By adopting this framework, businesses can ensure successful deployment of I4.0 principles in their manufacturing processes.

4.1 Gate 1: strategy

The initial gate, Gate 1, in the framework is strategy, which has been identified as the most significant theme. It requires senior management to establish direction, requirements, funding and a roadmap for success. The vision and strategy should be owned by the senior management and endorsed by the entire leadership team. The requirements need to be clear, and the vision shared among all team members at every level. Roadmaps help visualize the journey and investment required at each stage. The management can plan resources in advance based on the type of strategic decisions. To pass this gate, senior management should plan conscientiously and promote their plan passionately while ensuring consistency throughout the organization. If the resources, budget and implementation directions are not appropriately set, the gate closes here and further movement for I4.0 implementation is not permitted.

4.2 Gate 2: governance

The second gate, governance, is the next significant theme identified in the framework. It focuses on providing control and rigor to deliver the strategy. This gate requires a strong engagement at all levels of the organization and a robust stakeholder mapping of the communication plan. Collaboration across different functions is crucial. The data need to be standardized to be easily shared with the relevant stakeholders and aligned with the vision and roadmaps. Robust project management guidelines are required to regulate the implementation effectively. It is the responsibility of the business implementation led to configure governance sessions and control the deployment in terms of scope, risk, budget and resources. This gate can be passed only when senior and middle-level leadership positions across the organization accept the plans, resources and communication strategy. Effective governance can lead to a transparent and responsive system, ensuring a stable transition and accelerating the I4.0 implementation. However, the gate closes if the governing structure cannot control the implementation process.

4.3 Gate 3: leadership

The third gate, leadership, focuses on leaders across the business which are leading from the front. They need to develop an understanding among people about the impact of I4.0 on working conditions and business. They promote digital technologies through active listening

Source(s): Authors' own work

Figure 5.
Framework for the deployment of I4.0 principles

and learning sessions. Such leaders need to be open and honest about the influence of technology on work opportunities and maintain clear accountability for the work done. They should be quick decision-makers who can remove barriers, deliver change and manage the transition empathetically. To pass this gate, a leader should map the requirements for training and testing. Any leader who cannot connect, collaborate and create a continuous learning environment will not survive the I4.0 advancement. The gate can be passed only if the leaders build a team that is eager and passionate about new technologies. They encourage team members to provide feedback for improvement and mutual progress. The gate closes immediately if a leader fails to support their teams and communicate the new business feel to stakeholders.

4.4 Gate 4: training

The final gate, Gate 4, focuses on training, which is the fourth significant theme identified in the framework. Organizations need to plan modified training programs for hard and soft skills to bridge the existing digital skills gap. They should adopt an asset-based approach (Kozhakhmet *et al.*, 2022) to understand employees' increased value in learning capabilities. Customized training modules should be integrated into the process to suit the needs of a group of employees. The focus should be on the agility and adaptability of the workforce to develop interdisciplinary competencies. A connection should be fostered across multiple lines of technology and people. Ultimately, it will guide companies to measure the impact of training programs on the productivity and performance of the trainee. This gate can be navigated by maintaining training records of those involved at various digitization levels. A special training policy to guide the process should be published and available to all. There should be a mutually agreed cooling-off period with increased support and continuity plans for unforeseen circumstances. Periodic competency mapping with outcome-based learning content can lead to the easy and fast acceptance of a suite of I4.0 technologies. If the training gate is not passed, organizations may face difficulties in adapting to new technologies, leading to a decrease in productivity and performance. Therefore, it is crucial to follow the training gate to ensure a successful implementation of I4.0 principles in a mature aerospace manufacturing business.

5. Validation of framework

To validate the developed framework's applicability, it underwent review and feedback from small and medium-scale enterprises (SMEs) who are experts in digital and industrialization functions as shown in Table 6. These SMEs have extensive experience in deploying new capabilities and technology into their mature manufacturing processes. Their feedback was used to confirm the gates and identify any missing success factors in the framework.

To maintain confidentiality, the SMEs were anonymized while reporting their feedback. The SMEs provided valuable feedback, summarized with the quote, "a well-constructed framework that should help manufacturing engineering robustly deploy I4.0 initiatives." The feedback received led to key changes in the framework, which are

(1) The gate titles were reworded to aid the identification of deployment stages.

(2) A business case review is now included at each gate.

(3) A review of previous deployments and training requirements is now held at Gate 1.

(4) Business continuity plans are now integrated into Gate 3.

(5) Risk capture and lesson learned in corporate toolsets are ensured.

The updated framework based on the feedback obtained from the SMEs is presented in Figure 6. Notable modifications based on the feedback include the inclusion of specific wording in gate titles to facilitate the identification of deployment stages, incorporating a

Table 6. SME Feedback for proposed framework

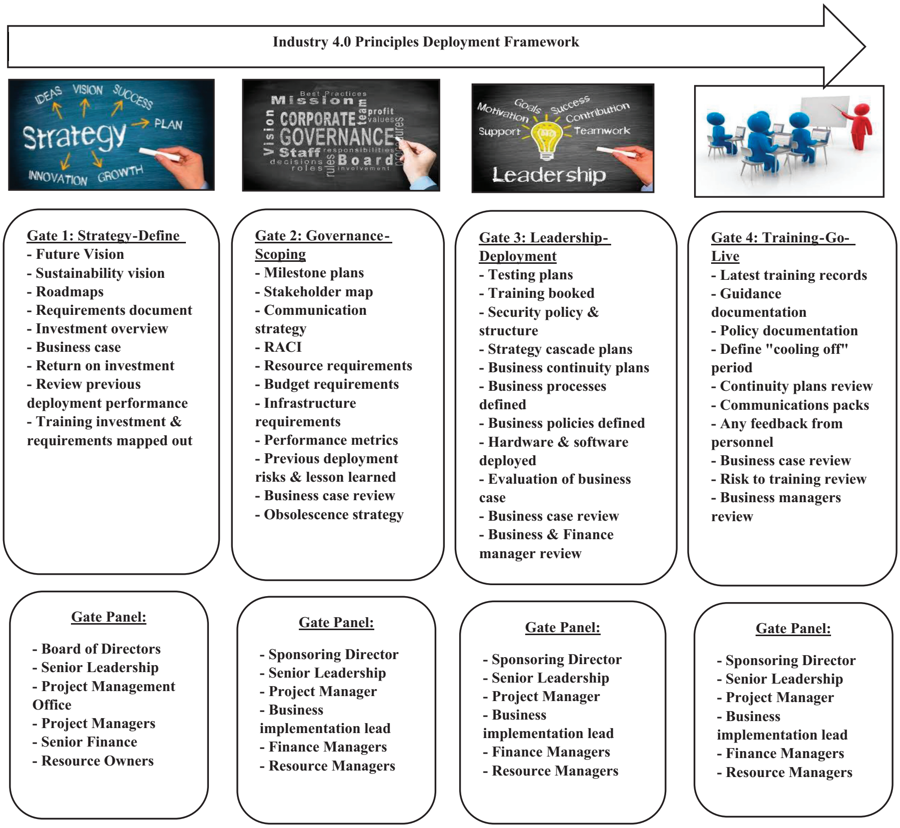
Subject matter expert	Experience	Approve/ Comments	Feedback for each gate/Success factor Gate 0	Gate 1	Gate 2	Gate 3	Gate 4	General comments
SME 1	Senior leader in digital manufacturing Engineering and Digital implementation specialist	Approve	As below, sustainability piece would be a good addition	Maybe a review to understand previous projects similar and reviewing lessons learnt	Revisit the business case and confirmation with key stakeholders within the business and finance manager	Revisit business case	How do we capture and make lessons learnt available globally and across functions?	
SME 2	Senior Leader in Industrialization Manufacturing Engineering and Product Introduction Specialist	Approve	Training plans should be included here, or at least discussed and built into investment		Change to training booked?	Consider moving training to earlier in the framework strategy? Or a single theme from Gate 0 to 4?	Minimum standard review and update would complement this gate	Titles for gates misleading, Leadership and Training don't portray Deployment and Go-Live well enough. What does good look like? Does this need a supporting minimum standard?
SME 3	Manufacturing Engineering Specialist	Approve		Could benefit from risk register and reviewing previous lessons learned at this early stage				A well-constructed framework that should help Manufacturing Engineering robustly deploy I4.0 initiatives

(*continued*)

Table 6.

Subject matter expert	Experience	Approve/ Comments	Feedback for each gate/Success factor Gate 0	Gate 1	Gate 2	Gate 3	Gate 4	General comments
SME 4	Manufacturing Engineering Specialist	Approve	Include Sustainability element	Include re-evaluation of business case	Inclusion of obsolescence Strategy? Maybe Gate 1 as part of infrastructure requirements? Is "Hardware and Software deployed" the deployment plans or successful gate 2 would be completion of deployment? Include re-evaluation of business case	Maybe pull continuity plans forward to gate 2? Include re-evaluation of business case	Include key practitioners/ key end users in gate panel	

Source(s): Authors' own work



Source(s): Authors' own work

Figure 6.
Validated framework

business case review at each gate, conducting a review of previous deployments and training requirements at Gate 0, advancing the integration of business continuity plans into Gate 2, and ensuring that risks and lessons learned are documented in corporate toolsets. However, the suggestion to entirely relocate the training success factor was disregarded, as it was deemed sufficient to address by altering the wording in Gate 2. The feedback from the SMEs has helped in refining the framework and making it more comprehensive, enabling businesses to deploy I4.0 principles in their manufacturing processes successfully.

6. Results and discussion

The 11 common themes associated with the implementation of I4.0 principles in manufacturing organizations were derived from the literature, and their reliability was strengthened through alignment with an established maturity model (Schumacher *et al.*, 2016). To further validate the significance of these themes, industry data was gathered through questionnaires distributed to individuals involved in I4.0 deployments related to process control automation. The results revealed a notable correlation between the 11 themes and the literature, confirming their importance in the industry. These 11 themes were consolidated into four key success factors based on their alignment with tasks and accountabilities within a manufacturing organization. For example, the strategy theme encompasses future vision, roadmaps, clear requirements, and substantial investment, recognizing that the strategy needs to be more probabilities than certainties due to the continual evolution of technology, the market, and people (Kadar *et al.*, 2014). Similarly, governance includes processes, controls, and responsibilities that collectively deliver the project while managing internal and external stakeholders (Joslin and Müller, 2016). Therefore, project management, collaboration, communication, and engagement are grouped under governance. The same approach is followed for the themes of leadership and training, with consistent factors grouped under each theme.

These four key success factors have guided the development of the framework, which aims to support the deployment of I4.0 by taking these factors into consideration. The framework includes a feedback loop that helps identify any shortcomings or missed aspects of a specific success factor or theme during the project, thereby preventing progression until they are adequately addressed. This feedback loop is essential for continuous improvement. The developed framework establishes a set of minimum standard requirements for I4.0 deployments. It assigns the responsibility of defining deployment-specific criteria and overseeing each stage to the business implementation lead or project manager, who acts as the chair for each gate. The proposed framework advocates for a top-down approach, ensuring that the journey is aligned with a clear future vision. It emphasizes the need to map out I4.0 tools and processes while ensuring their scalability and alignment with the business strategy (Qamsane *et al.*, 2021). The framework acknowledges the importance of feedback and highlights the need to incorporate it into the strategy for continuous evolution (Kadar *et al.*, 2014). It provides an opportunity to reshape the landscape, assess roadmaps, and evaluate technologies while maintaining a trajectory toward achieving the future vision. Additionally, the feedback loop aims to promote inclusion, collaboration, and open communication, mitigating concerns about job loss or uncertainties regarding the value of data (Kovrigin and Vasiliev, 2020).

The proposed framework aims to facilitate the adoption of tools such as road mapping, business process mapping, and system engineering, thereby harmonizing deployment resources, policy formulation, and decision-making processes (Sage, 1995). In contrast to previous studies that focused on de-skilling and reducing headcount (Biazzo, 2002), this framework emphasizes the upskilling of operations and the retention of personnel to meet future role requirements. The framework supports a gated process and recognizes the significant impact of how technology is introduced on its acceptance and approval (Mak *et al.*, 2020). It highlights the importance of open and collaborative communication to enable the decentralization of decision-making and transfer of technology deployment from senior management to front-line workers and leaders. The implementation of I4.0 has greatly enhanced the operational excellence of the aerospace industry. The framework that has been developed provides a minimal set of standard requirements for I4.0 deployments and promotes a top-down approach to ensure alignment with company objectives. It also aims to minimize adverse effects on employees by fostering their participation, cooperation, and open communication.

The primary objective of the framework is to facilitate the effective implementation of I4.0 by promoting the utilization of well-defined I4.0 tools. It emphasizes the alignment of resources, policy formation, and the decision-making process within large organizations to strengthen the framework. One specific focus of the framework is the utilization of Automated Process Control to enhance machine efficiency and product quality. This involves ensuring that the supporting Information Technology (IT) hardware meets the minimum requirements for I4.0 implementation. Additionally, the numerical controller and machine hardware must meet the minimum criteria for machining operations. The information provided by the framework will prove valuable to engineers, managers, and policymakers involved in the deployment of I4.0 initiatives.

7. Conclusion

The purpose of this research was to identify the crucial elements for implementing I4.0 principles in the aerospace manufacturing industry. Through a comprehensive literature review focused on industrial and aerospace sectors, 11 distinct themes were identified and consolidated into four key success factors. The research employed a combined analysis of industry data and literature to better understand the synergies between them. The resulting gated structure consists of four gates, each with its own significance and stakeholder engagement requirements. Feedback from several small and medium-sized businesses facilitated an iterative development process, resulting in a framework suitable for various types of organizations. The framework was further strengthened by incorporating digital and industrialized components. However, there is still potential for further development by incorporating perspectives from diverse industries. In summary, the framework provides a set of standard requirements for I4.0 deployments and promotes a top-down approach to ensure alignment with business strategy. It emphasizes inclusion, cooperation and open communication to mitigate any negative impacts on employees. Additionally, the framework is expected to assist manufacturing engineers in successfully implementing I4.0 principles and enhance the efficiency and quality of machining operations in aerospace manufacturing. Future research could explore the extension of the framework to other manufacturing domains or investigate its customization for specific organizational needs.

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Appendix

Questions	
Q.1	Have you been affected by changes to the way you operate due to digital advancements in the last 12 months? – Selected Choice
Q.2	In your view how are these changes perceived in the operations environment?
Q.3	How do you feel about digital advancements in your role? – Selected Choice
Q.4	What is important to you during implementation of digital tools? – Selected Choice
Q.5	What does Automated Process Control mean to you?
Q.6	Do you feel you can influence the process to ensure a conforming part? – Selected Choice
Q.7	How important is it to see the future expectations of your role when new digital controls are rolled out?
Q.8	How important is it to you to have access to the process to influence the quality of the product?
Q.9	How important is it to you to be involved in any digital deployments from the definition phase of roll out?
Q.10	How important do you believe moving to digital controls and automation is for manufacturing?
Q.11	How important is it to be provided with opportunity to influence digital controls and how they are applied?

Source(s): Authors' own

Table A1.
Questionnaire

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