Constraint-Aware Joinability Verification for Early Engineering Decision Support

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Abstract: ***The growing adoption of lightweight and multi-material products has increased the complexity of engineering decisions associated with joining during the early stages of product development. Although Industry 4.0 has significantly improved process monitoring, digital manufacturing, and production optimization, limited methodological support is available for evaluating joinability before detailed design and manufacturing planning. This paper presents a Constraint-Aware Joinability Verification Framework (CAJVF) to support engineering decision-making during conceptual product development. The framework incorporates a Requirement-to-Joining Intelligence Architecture (RJIA) that systematically relates product requirements, manufacturing constraints, and joining process capabilities through four complementary components: Product Requirement DNA (PR-DNA), Joining Capability DNA (JC-DNA), the Requirement–Capability Compatibility Matrix (RCCM), and the Joinability Intelligence Score (JIS). These components establish a structured reasoning process for assessing, comparing, and justifying alternative joining concepts before significant engineering resources are committed to detailed design, process planning, simulation, or physical prototyping. The proposed methodology is demonstrated using a representative multi-material mobility case study, illustrating its ability to transform engineering knowledge into transparent, traceable, and explainable joinability assessments. By integrating engineering requirements with manufacturing capabilities within a unified reasoning framework, the proposed approach establishes a digital decision-support layer between conceptual product development and manufacturing planning. Consequently, the framework extends the application of Industry 4.0 beyond manufacturing execution, enabling more systematic, knowledge-driven, and constraint-aware engineering decisions during the earliest phases of integrated product development.***

Keywords: Joinability Verification, Engineering Decision Support, Constraint-Aware Design, Integrated Product Engineering

1. Introduction

1.1 Background and Motivation

The growing use of lightweight and multi-material designs has significantly increased the complexity of engineering decisions during product development. Modern mobility systems increasingly combine advanced high-strength steels, aluminium alloys, polymers, and composite materials to achieve improved structural performance, reduced weight, enhanced sustainability, and competitive manufacturing costs. Consequently, the selection of an appropriate joining solution has evolved beyond a manufacturing task and become an important engineering decision that influences product functionality, structural integrity, production efficiency, maintainability, and lifecycle performance [4], [5].

In parallel, the emergence of Industry 4.0 has transformed manufacturing through technologies such as cyber-physical systems, digital twins, intelligent automation, and data-driven production environments. These developments have considerably improved process monitoring, quality management, predictive maintenance, and production optimisation. However, most digitalisation initiatives are primarily applied after key engineering decisions have already been completed, focusing mainly on manufacturing execution rather than supporting decision-making during product development [1]–[3], [12].

In industrial practice, deficiencies related to joinability are frequently discovered during process planning, prototype manufacturing, or production ramp-up. Addressing these issues at later stages often requires design modifications, tooling changes, additional validation activities, and increased development costs. Such challenges become even more significant for multi-material products, where numerous interacting variables influence the feasibility of a joining solution. Consequently, there is an increasing demand for methodologies capable of assessing joinability during conceptual product development before substantial resources are invested in detailed design, process planning, simulation, and physical prototyping.

1.2 Problem Statement

In conventional engineering practice, conceptual product development and joining process planning are generally treated as separate activities. Although advanced engineering tools such as CAD, CAE, and manufacturing simulation [6], [7], [8] provide extensive support during detailed design and production planning, relatively little methodological support exists for evaluating joinability during the conceptual design stage.

The suitability of a joining solution depends on multiple interrelated factors, including material compatibility, structural performance requirements, geometric accessibility, production objectives, quality expectations, lifecycle considerations, and available manufacturing capabilities. In many industrial environments, these aspects are assessed primarily through engineering experience and expert judgement rather than through a systematic and transparent engineering reasoning methodology.

Furthermore, most Industry 4.0 applications are designed to improve manufacturing performance after joining technologies have already been selected. Comparatively limited attention has been given to supporting the engineering reasoning required to evaluate alternative joining concepts before process planning begins. As a result, a disconnect remains between early engineering decision-making and the digital manufacturing systems that support downstream product development activities [1]–[3].

1.3 Research Objective and Contribution

To address these limitations, this study presents a **Constraint-Aware Joinability Verification Framework (CAJVF)** for supporting engineering decision-making during the conceptual stages of product development within Industry 4.0 environments.

The proposed framework is centred on a structured engineering reasoning methodology comprising four interconnected components:
- Product Requirement DNA (PR-DNA)
- Joining Capability DNA (JC-DNA)
- Requirement–Capability Compatibility Matrix (RCCM)
- Joinability Intelligence Score (JIS)

Rather than improving the performance of a predefined joining process, the proposed methodology evaluates the feasibility and suitability of alternative joining concepts before detailed design, process planning, manufacturing system development, and production resource allocation. By systematically relating engineering requirements, manufacturing constraints, and joining process capabilities, the framework enables transparent, traceable, and knowledge-driven joinability verification during conceptual product development.

The proposed approach establishes a digital engineering reasoning layer that bridges conceptual design and manufacturing planning, providing a foundation for future engineering decision-support systems capable of integrating engineering knowledge, manufacturing expertise, and digital production technologies within Industry 4.0-enabled product development environments.

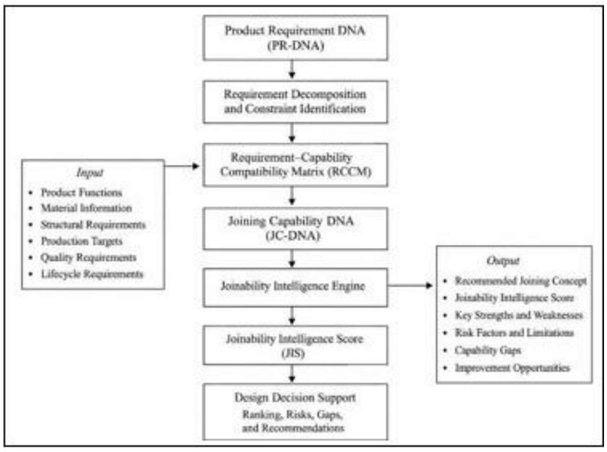

Figure 1: Evolution from process-centric joining research toward early-stage joinability verification

2. State of Research and Research Gap

2.1 Current Developments in Joining Engineering

The increasing use of lightweight structures and multi-material assemblies has expanded the importance of joining technologies within modern manufacturing. Contemporary mobility products frequently integrate advanced high-strength steels, aluminium alloys, polymers, and composite materials into a single product architecture to achieve improved structural performance, reduced weight, enhanced sustainability, and competitive production costs. As material diversity increases, the engineering requirements associated with joining become more demanding, requiring simultaneous consideration of structural behaviour, manufacturing feasibility, durability, and long-term product performance [4], [5].

To address these challenges, considerable research has been directed toward the development and improvement of joining technologies such as resistance spot welding (RSW), self-piercing riveting (SPR), resistance element welding (REW), clinching, structural adhesive bonding, and various hybrid joining methods. At the same time, advances in computational modelling and numerical simulation have enabled engineers to analyse joint formation, material interaction, fatigue behaviour, and structural integrity before physical prototypes are produced [4], [5].

Manufacturing systems have also evolved through the adoption of robotics, intelligent sensing technologies, and adaptive process control. These developments have improved production consistency, automation capability, and manufacturing flexibility, contributing to the broader industrial implementation of advanced joining solutions [1], [2].

2.2 Digitalisation and Industry 4.0 in Joining Engineering

The introduction of Industry 4.0 has accelerated the digital transformation of joining engineering by incorporating cyber-physical systems, digital twins, Industrial Internet of Things (IIoT) infrastructures, intelligent monitoring, and data-driven quality management into manufacturing environments. These technologies have enhanced production visibility, process reliability, predictive maintenance, and overall manufacturing performance [1]–[3], [12].

In addition, digital engineering platforms and ontology-based knowledge models have improved the exchange of engineering information across product design, manufacturing planning, and production activities, promoting greater integration throughout the product lifecycle [6], [7]

Despite these developments, current digitalisation efforts remain largely focused on manufacturing execution after joining technologies have been selected. Consequently, Industry 4.0 has contributed more significantly to process optimisation than to supporting engineering decisions during the early stages of product development [1]–[3].

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2.3 Research Gap

A common limitation of existing research is the assumption that an appropriate joining technology has already been selected before engineering evaluation begins. Consequently, most available methodologies concentrate on optimising joining processes instead of verifying whether a particular joining concept is suitable for a given product during conceptual development [4], [6], [7].

In practice, engineers must evaluate multiple joining alternatives while considering numerous interacting factors, including material compatibility, structural requirements, geometric accessibility, production objectives, automation readiness, lifecycle expectations, and manufacturing constraints. These decisions are typically made under conditions of incomplete information and often rely heavily on engineering experience.

Current approaches provide limited methodological support for integrating these engineering considerations into a structured, transparent, and traceable decision-making process. As a result, unsuitable joining decisions may remain undetected until detailed design, process planning, prototype manufacturing, or production ramp-up, where corrective actions become significantly more expensive and time-consuming [6]–[8].

This challenge becomes increasingly important in Industry 4.0 environments, where engineering decisions are expected to be knowledge-driven, digitally traceable, and consistently integrated throughout the product lifecycle.

Table 1: Comparison of Existing Approaches and Identified Research Gap.

Phase	Main Focus	Stage	Limitation
Joining Process Simulation	Joint formation prediction	Detailed Design	Requires selected joining process
Digital Twins	Production monitoring	Manufacturing	Post-selection support
Process Monitoring	Quality assurance	Production	No technology selection support
Ontology-Based Knowledge	Information representation	Engineering Support	Limited decision

2.4 Positioning of the Present Research

The identified research gap demonstrates the need for a methodology capable of systematically relating engineering requirements, manufacturing constraints, and joining process capabilities before detailed design and manufacturing planning activities begin.

To address this need, the present study introduces the Requirement-to-Joining Intelligence Architecture (RJIA) as the reasoning component of the proposed Constraint-Aware Joinability Verification Framework (CAJVF).

Unlike existing approaches that primarily optimise predefined joining processes, the proposed methodology addresses a more fundamental engineering decision:

Which joining concept best satisfies the engineering requirements of a product, and what engineering rationale supports that decision?

The proposed framework establishes explicit relationships between product requirements, manufacturing constraints, and joining process capabilities through a structured engineering reasoning methodology. By introducing systematic joinability verification during conceptual product development, the approach extends the role of Industry 4.0 beyond manufacturing optimisation and provides a transparent, traceable, and knowledge-driven foundation for early engineering decision support.

3. Requirement-to-Joining Intelligence Architecture (RJIA)

3.1 Architectural Principle

The proposed **Requirement-to-Joining Intelligence Architecture (RJIA)** is founded on the principle that joinability should not be regarded as an intrinsic property of an individual joining technology. Instead, it is considered an engineering outcome that emerges from the interaction between product requirements, manufacturing constraints, and the capabilities of alternative joining processes.

Conventional engineering approaches generally begin by selecting a joining technology and subsequently focus on process optimisation, simulation, quality assurance, or manufacturing control. The proposed architecture adopts the opposite perspective by starting with engineering requirements and systematically evaluating their compatibility with available joining concepts before process selection.

Accordingly, RJIA functions as an engineering reasoning layer linking conceptual product development with manufacturing planning. By structuring engineering knowledge before detailed design activities commence, the architecture enables systematic joinability verification during the earliest stages of product development.

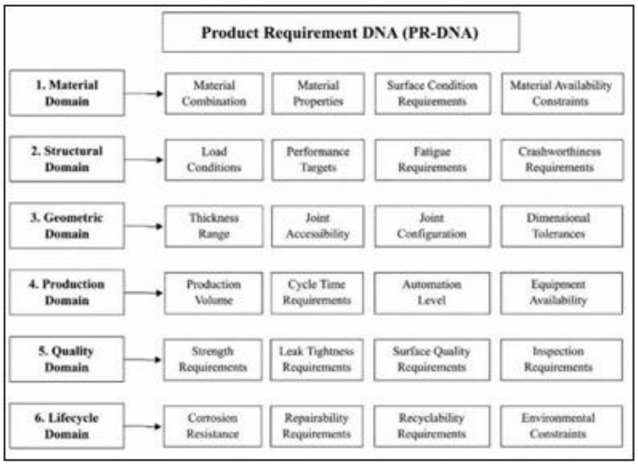

Figure 2: Requirement-to-Joining Intelligence Architecture (RJIA)

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3.2 Product Requirement DNA (PR-DNA)

The first stage of the architecture transforms engineering requirements into a structured knowledge representation referred to as **Product Requirement DNA (PR-DNA)**.

Rather than considering individual design requirements independently, PR-DNA organises joinability-related information into six interconnected requirement domains that collectively represent the engineering intent of the product. This technology-independent representation establishes a consistent basis for evaluating alternative joining concepts throughout the reasoning process.

Table 2: Product Requirement DNA (PR-DNA) domains and representative attributes.

Requirement Domain	Representative Attributes
Material Domain	Material combinations, thickness, surface conditions
Structural Domain	Static loads, dynamic loads, crash requirements
Geometric Domain	Accessibility, flange dimensions, joint locations
Production Domain	Volume, takt time, automation level
Quality Domain	Leak tightness, fatigue life, tolerances
Lifecycle Domain	Repairability, recyclability, sustainability

3.3 Joining Capability DNA (JC-DNA)

To enable consistent comparison between alternative joining concepts, each joining technology is represented using a structured **Joining Capability DNA (JC-DNA)**.

JC-DNA defines the operational capability profile of a joining process using a standardised set of engineering capability dimensions derived from industrial joining knowledge. This common representation allows fundamentally different joining solutions- including welding, riveting, clinching, adhesive bonding, and hybrid processes to be evaluated using a unified engineering framework.

Table 3: Joining Capability DNA (JC-DNA) capability dimensions

Capability Dimension	Description
Material Compatibility	Ability to join similar and dissimilar materials
Structural Performance	Load-bearing capability
Automation Readiness	Suitability for automated production
Process Flexibility	Adaptability to design variation
Quality Potential	Capability to achieve required quality
Sustainability Potential	Lifecycle and environmental performance

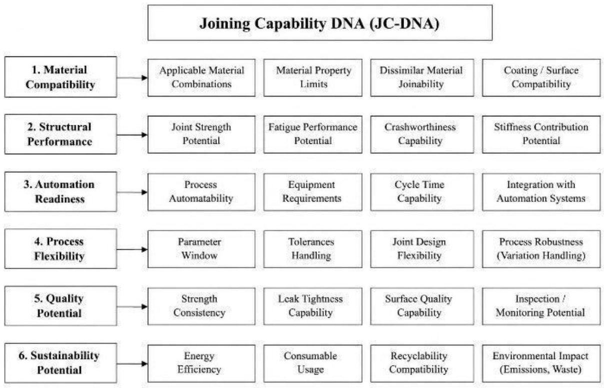

Figure 3: Product Requirement DNA (PR-DNA) structure.

3.4 Requirement-Capability Compatibility Matrix (RCCM)

The **Requirement–Capability Compatibility Matrix (RCCM)** constitutes the principal reasoning mechanism within the proposed framework.

Its purpose is to systematically evaluate the relationship between engineering requirements defined within PR-DNA and the capabilities represented by JC-DNA.

Rather than relying on binary feasibility decisions, the framework applies a graduated engineering evaluation scale that reflects varying levels of compatibility. This enables competing joining concepts to be assessed under identical engineering conditions while maintaining transparency throughout the decision-making process.

Table 4: Engineering compatibility evaluation scale**.**

Score	Interpretation
0	Not Feasible
1	Severe Limitations
2	Partially Feasible
3	Feasible
4	Highly Suitable

Requirement Category	Requirement (R_i)	Joining Process / Capability (C_j)				Importance Weight (w_i)
		Resistance Spot Welding (RSW)	Self-Piercing Riveting (SPR)	Structural Adhesive Bonding	Hybrid (Adhesive + SPR)	
Material	R_1: Material Compatibility	2	4	4	4	0.15
	R_2: Dissimilar Material Joinability	1	3	4	4	0.10
Structural Performance	R_3: Static Strength	4	4	3	4	0.15
	R_4: Fatigue Performance	3	4	3	4	0.10
Quality	R_5: Leak Tightness	1	2	4	4	0.10
	R_6: Surface Quality	2	3	4	4	0.05
Production	R_7: Automation Readiness	4	4	2	3	0.10
	R_8: Cycle Time Capability	4	3	2	3	0.10
Sustainability	R_9: Energy Efficiency	3	3	3	3	0.05
	R_{10}: Recyclability	3	4	2	3	0.05

Note: Compatibility scale – 1: Poor, 2: Fair, 3: Good, 4: Excellent.

1 – Poor; 2 – Fair; 3 – Good; 4 – Excellent

Figure 4: Requirement–Capability Compatibility Matrix (RCCM) reasoning logic

3.5 Constraint-Aware Evaluation Layer

Engineering feasibility alone does not necessarily imply industrial applicability. Consequently, the proposed framework incorporates a **Constraint-Aware Evaluation Layer** that explicitly accounts for manufacturing conditions frequently overlooked during conceptual product

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development.

The evaluation considers constraints including:
- Equipment availability
- Automation maturity
- Accessibility limitations
- Production volume
- Investment constraints
- Workforce capabilities
- Sustainability objectives

This enables the framework to distinguish between:

Theoretical Joinability
Can the product be joined? and

Industrial Joinability
Can the product be joined within the available manufacturing environment?

Incorporating these practical constraints increases the industrial relevance of the assessment while reducing the likelihood of manufacturing-related issues emerging during later development stages.

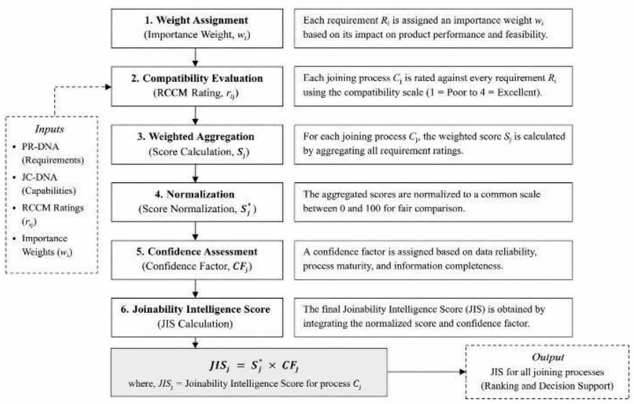

Figure 5: Constraint-Aware Joinability Evaluation Layer

3.6 Joinability Intelligence Score (JIS)

The final stage of the framework generates a quantitative **Joinability Intelligence Score (JIS)** that summarises the compatibility between engineering requirements and joining process capabilities.

The score is calculated by aggregating weighted compatibility evaluations across all requirement domains.

$$JIS = \sum_{i=1}^{n} (W_i \times C_i)$$

where:
- $W_i$represents the weighting assigned to the engineering requirement.
- $C_i$represents the corresponding compatibility score.

Higher JIS values indicate stronger alignment between product requirements and the capabilities of a given joining concept.

Beyond ranking alternative solutions, JIS also assists engineers in identifying requirement conflicts, capability deficiencies, and potential opportunities for design refinement during conceptual product development.

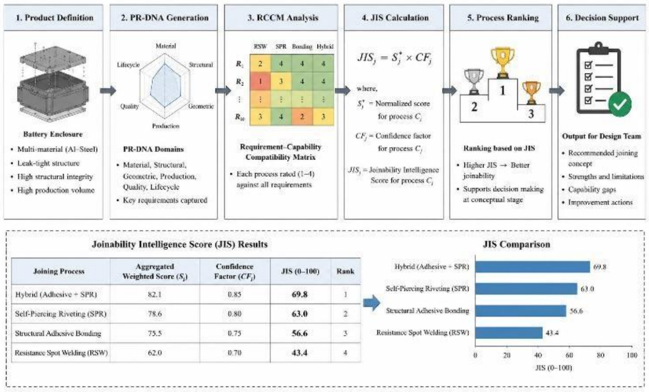

Figure 6: Joinability Intelligence Score (JIS) decision framework

3.7 Architectural Contribution

The proposed RJIA establishes a structured engineering reasoning architecture that connects conceptual product development with manufacturing planning.

By integrating **Product Requirement DNA**, **Joining Capability DNA**, **Requirement–Capability Compatibility Analysis**, manufacturing constraints, and quantitative evaluation into a unified methodology, the framework enables systematic verification of joinability before substantial engineering effort is invested in detailed design and manufacturing preparation.

From an Industry 4.0 perspective, the engineering artefacts generated by the framework can function as structured digital engineering objects capable of interacting with Product Lifecycle Management (PLM) systems, Manufacturing Execution Systems (MES), simulation environments, Digital Twin frameworks, and future cyber-physical production systems [1]–[3].

Consequently, joinability verification is transformed from an experience-driven activity into a transparent, traceable, and knowledge-driven engineering decision process that supports early-stage product development.

4. Industrial Demonstration and Evaluation

4.1 Demonstration Scenario

To illustrate the practical application of the proposed methodology, an industrially representative multi-material mobility component is selected as the demonstration case. Such products present a challenging engineering environment in which multiple design objectives—including structural strength, corrosion protection, sealing performance, manufacturing efficiency, and scalable production must be addressed simultaneously.

During the conceptual design phase, engineers generally investigate several feasible joining concepts before advancing to detailed design and manufacturing planning. To demonstrate the proposed framework, four joining technologies that are widely used in industrial practice are considered for comparison.

The purpose of this demonstration is not to establish a universally optimal joining technology. Instead, the objective is to identify the joining concept that best satisfies the engineering requirements defined for the selected product while providing a transparent engineering rationale for the decision.

Table 5: Joining technologies considered for the industrial demonstration

Alternative	Joining Technology
JT-1	Resistance Spot Welding
JT-2	Structural Adhesive Bonding
JT-3	Self-Piercing Riveting
JT-4	Hybrid Joining

4.2 Product Requirement DNA Generation

Following the methodology described in Section 3, the engineering requirements of the selected product are organised into the **Product Requirement DNA (PR-DNA)**. For the demonstration case, particular importance is assigned to characteristics associated with joining multi-material structures, including crashworthiness, leak-tightness, corrosion resistance, production automation, manufacturing scalability, and long-term service considerations. These weighted requirements collectively define the engineering profile against which each joining alternative is assessed.

Table 6: Product Requirement DNA for the Demonstration Scenario

Requirement	Weight
Multi-material Compatibility	5
Crash Performance	5
Leak Tightness	4
Corrosion Resistance	4
Automation Readiness	4
Production Scalability	3
Repairability	2
Sustainability	3

4.3 Requirement–Capability Compatibility Evaluation

The **Requirement–Capability Compatibility Matrix (RCCM)** is employed to analyse the degree of compatibility between the engineering requirements defined in the PR-DNA and the capabilities represented within the JC-DNA for each joining alternative.

The assessment demonstrates that every joining concept offers a distinct capability profile. Resistance Spot Welding is particularly suited to high-volume automated manufacturing, whereas Structural Adhesive Bonding provides advantages where sealing and corrosion resistance are critical. Self-Piercing Riveting performs well in applications involving dissimilar materials, while Hybrid Joining combines the complementary strengths of multiple joining mechanisms to satisfy a broader range of engineering requirements.

Rather than producing a simple pass-or-fail outcome, the RCCM provides a structured comparison that clearly explains the relative strengths and limitations of each joining concept [4].

4.4 Joinability Intelligence Assessment

The compatibility results obtained from the RCCM are subsequently aggregated using the proposed **Joinability Intelligence Score (JIS)** methodology to generate an overall engineering assessment for each joining alternative.

Among the evaluated technologies, Hybrid Joining achieves the highest JIS, indicating the strongest correspondence with the engineering requirements defined for the demonstration product. This finding reflects the growing industrial preference for hybrid joining solutions in lightweight and multi-material structures, where several functional and manufacturing requirements must be satisfied simultaneously.

More importantly, the proposed methodology extends beyond ranking candidate technologies. By explicitly linking engineering requirements, manufacturing constraints, and process capabilities, the framework provides a transparent and traceable justification for the recommended joining concept [4], [5].

Table 7: Joinability Intelligence Score (JIS) Results

Technology	JIS Score
Resistance Spot Welding	92
Structural Adhesive Bonding	113
Self-Piercing Riveting	118
Hybrid Joining	131

4.5 Industry 4.0 Perspective

In addition to supporting engineering decision-making, the proposed framework produces structured engineering artefacts that can be incorporated into digital product development environments.

The generated **PR-DNA**, **JC-DNA**, **RCCM**, and **JIS** provide reusable engineering knowledge that can be stored, exchanged, and updated throughout the product development lifecycle. These artefacts offer a structured basis for connecting joinability verification with existing digital engineering platforms and manufacturing information systems.

Possible application areas include:

- Product Lifecycle Management (PLM) systems
- Manufacturing Execution Systems (MES)
- Digital Twin frameworks
- Process simulation platforms
- Smart manufacturing environments

Accordingly, the proposed framework establishes a foundation for future engineering decision-support systems capable of combining engineering knowledge with manufacturing feedback to continuously improve joinability assessment within digitally connected production environments [1]–[3], [12].

5. Discussion

The proposed **Constraint-Aware Joinability Verification Framework (CAJVF)** contributes to an area that remains comparatively underexplored within both joining engineering and Industry 4.0 research. Existing studies have predominantly concentrated on improving manufacturing performance after the selection of a joining technology through approaches such as process optimisation, simulation, quality assurance, Digital Twins, and intelligent production systems. In comparison, considerably less attention has been directed towards methodologies that support engineering decisions during the technology-selection stage itself.

The methodology presented in this study addresses this deficiency by repositioning the engineering focus from manufacturing process optimisation to early-stage joinability assessment. Instead of enhancing an already selected joining process, the framework evaluates the suitability of alternative joining concepts before detailed product design, simulation activities, tooling development, and manufacturing planning are initiated. This enables engineering decisions to be supported at a stage where design modifications remain comparatively inexpensive and technically feasible.

An important contribution of the proposed framework lies in the introduction of **Product Requirement DNA (PR-DNA)** and **Joining Capability DNA (JC-DNA)** as structured engineering knowledge representations. Together, these representations establish a common engineering language through which product requirements can be systematically related to manufacturing capabilities. Building upon this foundation, the **Requirement–Capability Compatibility Matrix (RCCM)** provides a transparent reasoning mechanism that identifies capability deficiencies, requirement conflicts, and implementation constraints that may remain undetected when conventional technology-selection practices are applied.

From the perspective of Industry 4.0, the proposed methodology extends digital engineering beyond manufacturing execution by introducing a structured decision-support capability during conceptual product development. The engineering artefacts generated throughout the evaluation process may serve as reusable digital knowledge representations that can interact with Product Lifecycle Management (PLM) systems, Manufacturing Execution Systems (MES), Digital Twin frameworks, and future cyber-physical production environments.

Despite these contributions, certain limitations should be recognised. The framework represents a conceptual engineering methodology and therefore requires further validation using a broader range of industrial case studies involving different product architectures, material combinations, joining technologies, and manufacturing environments. Furthermore, the weighting factors incorporated within the **Joinability Intelligence Score (JIS)** are currently determined using engineering judgement. Future investigations should explore objective weighting methodologies supported by industrial datasets together with AI-assisted capability modelling to improve the adaptability and robustness of engineering decisions.

Overall, the proposed framework demonstrates how structured engineering reasoning can strengthen joinability verification during conceptual product development. By systematically capturing and organising engineering knowledge, the methodology provides a foundation for more transparent, traceable, and digitally integrated engineering decision-making within future manufacturing systems.

6. Conclusions & Future Work

The increasing use of lightweight structures, multi-material product architectures, and digitally connected manufacturing systems has significantly increased the complexity associated with selecting appropriate joining solutions during product development. Although substantial progress has been achieved in manufacturing simulation, intelligent production systems, process monitoring, and digital manufacturing technologies, comparatively little attention has been devoted to supporting engineering decisions related to joinability during the earliest stages of design.

This research introduced the **Constraint-Aware Joinability Verification Framework (CAJVF)** as a structured methodology for evaluating joinability before detailed engineering and manufacturing planning activities begin. The proposed approach integrates four complementary elements-**Product Requirement DNA (PR-DNA)**, **Joining Capability DNA (JC-DNA)**, the **Requirement–Capability Compatibility Matrix (RCCM)**, and the **Joinability Intelligence Score (JIS)**-to establish a systematic relationship between engineering requirements and the capabilities of alternative joining concepts.

In contrast to conventional methodologies that primarily optimise predefined joining processes, the proposed framework supports engineering decision-making by enabling objective comparison of alternative joining concepts during conceptual product development. The industrial demonstration illustrated how engineering requirements can be transformed into structured engineering knowledge representations, allowing technology-selection decisions to become more transparent, traceable, and technically justified.

Within the broader context of Industry 4.0, the proposed methodology establishes an engineering reasoning layer positioned between conceptual product development and manufacturing planning. The engineering artefacts generated during the evaluation process provide structured digital knowledge that can support future integration with Product Lifecycle Management systems, Manufacturing Execution Systems, Digital Twin frameworks, and other digital engineering environments.

Future research will concentrate on validating the proposed methodology across a wider range of industrial applications while extending the underlying engineering knowledge base to include additional joining technologies, material combinations, and manufacturing scenarios. Further investigations will also examine AI-assisted capability modelling, adaptive requirement weighting, and automated engineering decision-support techniques. These developments are expected to enhance the framework

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towards self-improving engineering decision-support systems capable of continuously refining joinability assessments through accumulated engineering knowledge and manufacturing feedback.

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