Supporting Wind Energy Deployment through Improved Design–Manufacturing Coordination in the Wind Turbine Industry

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by

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In partial fulfilment of the requirements for the degree of

Master of Science

in Construction Management and Engineering

at the Delft University of Technology

Faculty of Civil Engineering and Geosciences

To be defended in public on:

5 June 2026, in Delft

Faculty of Civil Engineering and Geosciences, Hall E

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Summary

The wind industry is expanding rapidly, but this expansion has also increased pressure on turbine industrialization and reliable delivery. Turbines and blades have become larger, more complex and more dependent on globally distributed manufacturing networks. In this setting, failures and disruptions cannot be understood only as technical or logistical problems. They also reflect how effectively design and manufacturing are coordinated across firms during the transition from product development to stable serial production. This is especially important in the blade context where manufacturing is labour intensive, materially sensitive and highly dependent on execution quality. The thesis therefore addresses a non-technical aspect of scale-up that has received far less attention in the wind industry research, the design–manufacturing interface (DMI) across firms.

The aim of this thesis is to examine how inter-firm coordination at the DMI in the wind turbine blade industry can be strengthened to support more reliable turbine scale-up. More specifically, the thesis investigates how coordination mechanisms identified in mature industries can be used to understand the wind blade context, how these mechanisms currently appear in the wind industry and how they should be adjusted to better fit this context. The main research question is therefore how the DMI across firms in the wind turbine blade industry can be strengthened to support more reliable turbine scale-up under increasing deployment pressure, using coordination mechanisms identified in more mature industries.

To answer this question, the research followed a qualitative design. First, the thesis reviewed mature industry literature on design–manufacturing integration, coordination theory and inter-firm coordination mechanisms. This was used to develop Framework A and then Framework B as the analytical reference structure for the empirical work. Second, the study examined the wind blade context through semi-structured expert interviews with participants from OEM, manufacturing and hybrid roles. The interview material was analysed through directed qualitative content analysis, using Framework B as the starting point while also allowing repeated non-fitting material to remain visible. Third, the findings were compared across mechanisms and phases and were then used to refine Framework B into Framework C, a framework tailored to the wind blade industry.

The findings show that the wind industry does not lack coordination mechanisms altogether. Several mature industry mechanisms are already visible, especially in the later phases of industrialization. Sign-off and acceptance routines, producibility reviews, manufacturing interface roles, engineering change routines, site support, prototype builds and launch continuity are all present in the wind blade context. However, the findings also show that this coordination base is uneven. The strongest mechanisms are concentrated in design finalization, launch and problem solving after key decisions have already been made. By contrast, upstream coordination remains weaker. Early manufacturing involvement in concept and early design is limited, and many problems are still managed late rather than prevented early.

The findings also show that the wind blade DMI is weakened by fragmented cross-enterprise coordination baselines and by weak supplier development and participation. The industry has adopted selected standardization practices but these do not yet extend far enough across firms to create a sufficiently shared coordination foundation. In practice, one OEM blade design may be industrialized across several manufacturing organizations, while the same limited supplier base may also work with more than one OEM, each with different routines, expectations and decision logics. Under such conditions, manufacturability judgments, deviation handling, change prioritization and escalation routines can diverge across firms. At the same time, supplier learning logic remains underdeveloped. Supplier coordination and support are present to a limited extent through recurring supplier meetings and structures related to quality, but the evidence does not show a strong equivalent of the more direct supplier development interventions described in more mature industry practice. The problem is therefore not only weak standardization of non-proprietary coordination structures across firms but also the tendency to treat supplier capability as something assumed at execution rather than built progressively over time.

Another major finding is that prototype and validation mechanisms are present in the wind industry but their learning value is often weakened by commercialization pressure. The industry does use prototypes, trial builds and launch-stage validation. However, repeated interview evidence shows that these mechanisms are sometimes compressed by the push to introduce larger turbines quickly. In practice, this reduces the time available for learning and root-cause resolution before commercialization. A further finding is that the original mature industry mechanism set did not fully capture one recurring issue that proved important in the blade context, the shop-floor capability. The interviews showed repeatedly that manual composite manufacturing remains highly sensitive to worker skill, process discipline and factory stability during ramp-up.

Based on these findings, the thesis develops Framework C as its main outcome. Framework C does not simply repeat the mature industry reference. Instead, it shows which mechanisms already provide a useful coordination base in the wind blade industry, which should remain central, which need stronger implementation and where additional strengthening directions are needed. Mechanisms such as digital data exchange, sign-off, producibility reviews, interface roles, site support, and launch continuity remain important and are retained. Mechanisms such as compatibility standards, capability development schedules, tacit manufacturing knowledge, design rules, prototype learning and engineering change routines are carried forward but require strengthening. Early joint development is identified as a major gap, while relationship assessment, supplier development teams, guest engineers, downstream feedback roles, and shop-floor capability are carried into Framework C as added strengthening directions. In this way, the thesis moves beyond diagnosis and provides a more structured basis for improvement.

The contribution of the thesis is both theoretical and practical. Theoretically, it shows that the DMI and coordination theory provide a useful lens for understanding wind blade industrialization. Rather than treating coordination problems as general communication failures, the thesis explains them more precisely as problems of dependency management across firms, phases and knowledge boundaries. It also shows that mature industry coordination logic is transferable to wind only selectively, which makes the refinement from Framework B to Framework C more than an empirical adjustment. Practically, the thesis gives the wind industry a clearer and more structured basis for strengthening blade industrialization. It shows that more reliable scale-up depends on earlier OEM–supplier coordination, stronger cross-enterprise coordination structures, stronger supplier development and firmer protection of prototype learning from commercialization pressure, among other factors.

The study has limitations. It focuses on the blade context and is based on a limited number of expert interviews, which means that the findings should not be treated as a complete representation of the whole wind industry. Framework C should therefore be understood as a grounded but still developing framework. Further research could test it in other wind turbine components, in a broader set of firms and supply chain settings and through additional empirical work on the mechanisms that remained weakly evidenced but analytically important. Even with these limits, the thesis provides a clearer explanation of how inter-firm coordination at the DMI affects wind blade industrialization and how that interface can be strengthened to support more reliable turbine scale-up.

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Abbreviations

Abbreviation	Definition
APQP	Advanced Product Quality Planning
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control
DfM	Design for Manufacturing
DFX	Design for Excellence
DMI	Design–Manufacturing Interface
DoD	Department of Defense
DRBFM	Design Review Based on Failure Mode
EDI	Electronic Data Interchange
MRR	Manufacturing Readiness Review
NPD	New Product Development
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PPAP	Production Part Approval Process
PRR	Production Readiness Review
STEP	Standard for the Exchange of Product Model Data

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Introduction

1.1. Background Information

Climate change is one of the most crucial threats to our planet. To address it, governments have introduced measures to mitigate and reverse its effects. One of the most important strategies is the energy transition, moving from fossil fuels to renewable energy sources. Wind energy is a key part of this transition, as over the last 20 years it has shown that it can be a viable green source of electricity.

As a result, the wind energy sector is undergoing rapid global expansion, driven by both state and private initiatives aimed at achieving decarbonization and energy transition goals (Veers et al., 2022). As of 2024, Europe hosts 129 operational offshore wind farms and is projected to hold 45% of global offshore wind capacity by 2033—roughly 177 GW of a forecasted 394.4 GW total (World Forum Offshore Wind, 2024). Countries such as the Netherlands, Germany, and the United Kingdom continue to expand their programs, underscoring the sector's increasing strategic and economic relevance. While offshore capacity is growing, the majority of Europe's new wind installations remain onshore. In 2024, 84% of the 16.4 GW of newly installed capacity was onshore, led by Germany, Finland, and Spain. By 2030, cumulative onshore capacity across the EU is expected to reach approximately 304 GW, accounting for 75% of all new installations (WindEurope, 2024). Wind power already supplies about 19% of the EU's electricity, yet meeting the Union's targets of 34% by 2030 and more than 50% by 2050 requires a sharp increase in deployment (European Commission, 2025; Power Technology, 2024).

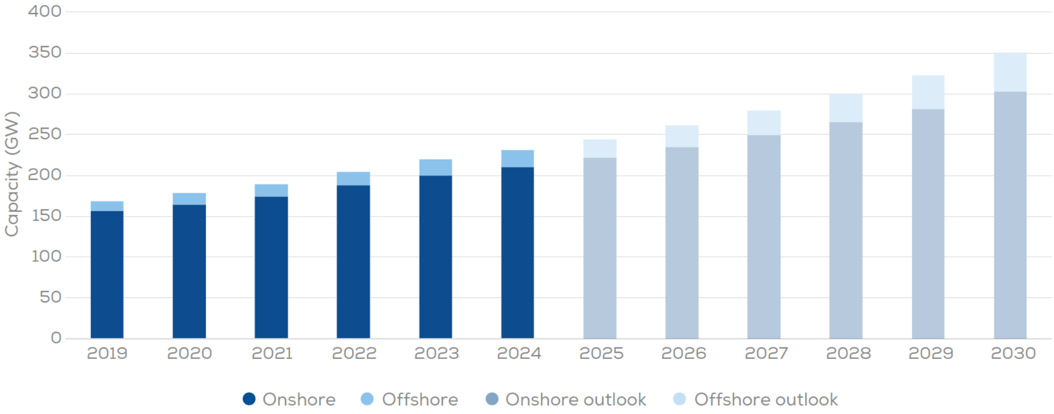

Figure 1.1: Wind Power Capacity Development in the EU, 2019–2030

This growth has driven a rapid escalation in turbine size, particularly offshore. In less than a decade, models such as the Vestas V164 (8 MW, 164 m rotor diameter, 80 m blades) have been surpassed by the Siemens Gamesa SG 14-236DD (up to 15 MW, 236 m rotor, >115 m blades). Manufacturers are already designing 20–26 MW turbines with blades beyond 130 m (Siemens Gamesa Renewable Energy, 2021; Wind Turbine Models, 2024). These larger turbines place greater technical and operational demands on component design and manufacturing, intensifying pressure on supply chains and production systems. These industrial and technological shifts have also increased the complexity of coordination across global manufacturing networks, linking turbine design and component production.

To meet the demand of increasing wind deployment, original equipment manufacturers (OEMs) employ globally outsourced production models that enhance scalability and cost efficiency (European Commission, 2025). High-level design and final assembly remain centralised near engineering hubs, while fabrication of major components such as towers, nacelles, and blades is transferred to third-party manufacturers in cost-competitive regions (Musial et al., 2023). Although this structure gives OEMs access to specialised capabilities and labour markets, it also creates long, complex supply chains that span different countries, regulations, and corporate cultures. Coordination across these distributed actors becomes a major determinant of system performance (Prostean et al., 2014).

Within this system, wind turbine blades are among the most technically complex and vulnerable components. They are large composite structures subjected to cyclic loading and harsh environmental conditions throughout their service life. Manufacturing involves labour intensive processes such as lay up, bonding, and curing, which are sensitive to material properties, environmental conditions, and operator skill. Quality deviations in these stages can cause defects such as voids, delamination, or poor bonding, often undetected until operation, when correction is far more costly (Ashwill et al., 2013; Mishnaevsky, 2022). Blades therefore represent both a technical and logistical bottleneck in turbine production.

Global outsourcing also adds coordination challenges. Design functions are usually located in Europe or North America, while serial production is conducted in Asia, Eastern Europe, and other low-cost regions (European Commission, 2025). The transfer of design intent, tolerances, and process requirements from OEM design teams to production engineers depends on documentation and communication routines that are frequently affected by language barriers, divergent standards, and inconsistent digital infrastructure. At the same time, escalation of production or quality issues for resolution is often slow and fragmented. These interface inefficiencies can be translated into schedule delays and cost overruns (Yu et al., 2021). Typical mitigation strategies such as buffer inventories or schedule compression address symptoms but not the root coordination problems (Son, 2018).

Persistent coordination and quality issues have led both researchers and industry actors to emphasise the need for more resilient and better integrated management strategies. Such strategies require structured coordination mechanisms that link OEMs and suppliers through standardised procedures, clearly defined responsibilities, and shared information systems (Kramer & Schmidt, 2022; Liu et al., 2022; Onukwulu et al., 2023).

Wind turbine manufacturing represents a large scale engineering system in which the management of interfaces and information flow, and coordination across organizational boundaries, determines production performance and resilience. The same principles apply across complex engineering and construction projects, where interdependent design and production activities require structured coordination mechanisms to manage uncertainty, integrate knowledge, and ensure the continuity of the system.

1.2. Problem Definition

1.2.1. System Description

The design and manufacturing of wind turbine components is organized through globally distributed production networks. This system involves companies located in various countries that work in different national and institutional settings. OEMs typically maintain control over high-level design and final assembly, while fabrication tasks are subcontracted to third-party manufacturers located in regions with specialized capabilities or cost advantages (Musial et al., 2023). This production model has enabled rapid growth, but it also increases reliance on inter-firm coordination as design and manufacturing complexity of new larger wind turbines increases to meet accelerating deployment demands.

The global capacity is unevenly distributed. China has become a dominant manufacturing base for multiple wind turbine components, while Europe retains significant capability in selected segments such as towers and rotor-related manufacturing (European Bank for Reconstruction and Development, 2023). Key components such as blades, generators, and electrical systems are often manufactured in Asia, especially in China, India, and other regions that are cost-competitive, and are imported through global supplier networks (David, 2021; European Bank for Reconstruction and Development, 2023). As this network expands, the number of inter-firm handoffs grows, increasing the number of points at which product and process decisions must be aligned across organizations.

Wind turbines require input from hundreds of specialized firms, spanning materials, tooling, composite processing, machining, electronics, and assembly. In this context, the system's ability to scale depends not only on technical design and process capability, but also on how effectively organizations coordinate during the transition from design to stable serial production. As wind turbines are scaled to meet deployment targets, the effectiveness of these inter-firm interactions becomes increasingly consequential for schedule adherence and rework rates.

1.2.2. Problem Statement & Research Gap

The wind industry has entered a phase of rapid expansion in which deployment targets require substantial increases in both wind turbine sizes and reliable delivery performance. However, in recent years, high-profile component failures and disruptions have damaged the industry financially and harmed its reputation, as they have made investors more hesitant about funding new wind farms. These outcomes indicate that the industry is struggling to scale wind turbines efficiently and meet deployment demands reliably at the required pace.

Although failure can be caused by many factors in such technologically complicated systems, companies and industry investigations in recent years have cited both design and manufacturing issues as contributors to defects. Many studies have focused on solving these issues by improving the technical integrity, material selection, and manufacturing processes of wind turbines, and by reducing deployment risk through improvements in logistics and installation. However, despite the large amount of technical and logistical research, failures and disruptions continue to occur as the industry attempts to scale wind turbines and deliver them reliably under increasing technical and operational demands. This suggests that purely technical and logistical explanations may be insufficient to account for persistent reliability problems and disruptions during rapid scale-up to meet deployment targets.

Work in mature industries has highlighted the significance of non-technical aspects in new product development (NPD) and production, including the management of the design–manufacturing interface (DMI), where design intent is translated into production specifications and work instructions and where manufacturing learning is fed back into design to support stable serial production. Studies in sectors such as automotive show that effective DMI management (particularly when multiple firms and functions are involved) relies on coordination mechanisms that integrate product design and manufacturing process knowledge throughout product development and the transition from design to stable serial production (Swink, 1999; Twigg, 2002). Accordingly, DMI management can be viewed as one plausible non-technical contributor to whether industrialization succeeds at speed and scale in multi-firm manufacturing networks.

However, limited research has examined how the design–manufacturing interface is coordinated between firms in the wind turbine industry under current scale-up conditions. This gap has become more important as turbine programs have grown larger and more complex, deployment pressure has intensified, and OEMs have increasingly relied on globally distributed suppliers and manufacturing partners. Under these conditions, the number and criticality of inter-firm handoffs increase. Yet it remains unclear which coordination mechanisms are currently used at this interface in the wind industry. This research addresses that gap by constructing a reference framework of inter-firm DMI coordination mechanisms from mature industry literature, examining how these mechanisms are currently applied in the wind industry through expert interviews and refining this into a wind-specific framework for strengthening coordination at the DMI. The thesis therefore does not evaluate factory technologies or capacity planning. It focuses on how inter-firm coordination is organized at the point where design and manufacturing knowledge must be aligned to support more reliable turbine industrialization and scale-up.

1.3. Research Scope

Building on the definition of the problem, this section defines the analytical boundaries of the study. This research focuses on inter-firm Design–Manufacturing Interface (DMI) coordination mechanisms in outsourced wind turbine manufacturing. The unit of analysis is how OEM design organizations and supplier manufacturing organizations coordinate to integrate product design and manufacturing process knowledge during the transition from design to stable serial production.

Blade manufacturing is chosen as the study case because these interface disruptions are particularly visible and operationally critical here. The blades are the primary energy-harvesting element of the turbine, exposed to continuous cyclic loading and environmental conditions that make their structural integrity crucial for both performance and safety (Kim & Cho, 2025; Veers et al., 2022). Failures arising from process or quality issues at manufacturing stages propagate quickly to operational disruptions, with immediate implications for generation efficiency, mechanical stability, and maintenance (Kong et al., 2023; Zhou et al., 2020).

Blade production also represents a major share of manufacturing complexity and cost. Its large scale, use of composite materials, and manual intensity make quality assurance a persistent bottleneck. Defects such as poor bonding, voids, and delamination are often introduced during fabrication and only become visible in the field, where repair is far more expensive (Ashwill et al., 2013; Mishnaevsky, 2022). Operational data show that many blades contain manufacturing defects before service, exposing critical gaps in production processes and quality control systems (Ashwill et al., 2013).

Within the blade case, the scope includes DMI coordination mechanisms for the translation of design intent into production specifications, work instructions and manufacturability alignment. These elements capture the practical ways in which inter-firm DMI is managed and where coordination breakdowns may contribute to delays, quality issues, and reduced manufacturing stability.

The scope excludes upstream activities such as raw material extraction, composite formulation R&D, as well as downstream activities such as logistics, installation, field repair and operational maintenance. The study also excludes technical blade design optimization and structural modeling.

1.4. Research Objective

This research addresses the difficulty of the wind industry in coping with rapid expansion by investigating a non-technical factor that has been shown to matter in mature industries and which is how the design–manufacturing interface (DMI) is managed across firms. The aim of this research is to examine how inter-firm DMI coordination mechanisms support (or constrain) the integration of product design and manufacturing process knowledge and to identify how these mechanisms can be strengthened to support more reliable turbine scale-up.

To achieve this aim, the research has three objectives. First, it constructs a literature based reference framework of inter-firm DMI coordination mechanisms from mature manufacturing industries. Second, it uses this framework to examine how inter-firm DMI is currently coordinated in the wind industry through semi-structured expert interviews in the blade manufacturing context. Third, it refines the reference framework on the basis of the empirical findings by identifying how mechanisms appear in the wind context, where they are adapted, absent, or underdeveloped, and by synthesizing these insights into a wind-specific framework for strengthening inter-firm DMI coordination.

The study uses wind turbine blades as a case because blades combine high technical complexity, manual-intensive composite manufacturing, and frequent outsourcing. These characteristics make them sensitive to misalignment between design intent and manufacturing execution and therefore suitable for observing inter-firm DMI challenges under scale-up pressure.

1.5. Research Questions

The rapid expansion of the wind industry has increased the reliance on globally distributed and outsourced manufacturing networks. Despite extensive technical and logistical research, disruptions and quality issues continue to occur as the industry introduces larger wind turbines, increasing the design and manufacturing complexity. This thesis therefore examines a non-technical factor that has been shown to influence the performance of new product development (NPD) in mature industries: how the design–manufacturing interface (DMI) is managed across firm boundaries.

Building on this problem framing, the study addresses the following main research question:

> How can the design–manufacturing interface across firms in wind turbine blade manufacturing be strengthened to support more reliable turbine scale-up under increasing deployment pressure, using coordination mechanisms identified in mature industries?

To answer this question, the research investigates the problem through the following sub-questions:

1. Which coordination mechanisms are identified in mature industries for managing the design–manufacturing interface across firms?
2. To what extent do these coordination mechanisms appear in wind turbine blade manufacturing, and how are they adapted, absent, or underdeveloped?
3. How should these coordination mechanisms be adjusted to better fit the wind turbine blade context and strengthen inter-firm design–manufacturing coordination in support of more reliable scale-up?

Table 1.1: Research Design

Research Question	Research Method	Outcome(s)	Chapter
SQ1. Which coordination mechanisms are identified in mature industries for managing the design–manufacturing interface across firms?	Systematic literature review and structured synthesis of mature-industry evidence.	Framework A and Framework B: literature based reference framework of inter-firm DMI coordination mechanisms identified in mature industries.	2
SQ2. To what extent do these coordination mechanisms appear in wind turbine blade manufacturing, and how are they adapted, absent or underdeveloped?	Semi-structured expert interviews with participants from OEM, blade manufacturing and hybrid roles and analysis using a hybrid deductive–inductive coding approach.	Empirical mapping of how Framework B mechanisms appear in the wind blade context, including clear matches, adapted forms, gaps, and absent or underdeveloped mechanisms.	4.1–4.5
SQ3. How should these coordination mechanisms be adjusted to better fit the wind turbine blade context and strengthen inter-firm design–manufacturing coordination in support of more reliable scale-up?	Cross-analysis of the literature based framework and interview findings, refinement and synthesis of mechanisms into a framework for the wind industry.	Framework C: refined framework for the wind industry showing which mechanisms should be retained, strengthened, added, or adjusted to strengthen inter-firm DMI coordination.	4.6–4.7
Main Research Question: How can the design–manufacturing interface across firms in wind turbine blade manufacturing be strengthened to support more reliable turbine scale-up under increasing deployment pressure, using coordination mechanisms identified in mature industries?	Qualitative research design combining a systematic literature review, semi-structured expert interviews, and cross-analysis.	A refined framework specific to the wind industry for strengthening inter-firm DMI coordination in blade manufacturing in support of more reliable turbine scale-up.	2–4

1.6. Thesis Structure

This thesis is organized into six chapters. Together, these chapters define the research problem, develop the analytical framework, explain the research design, present the empirical findings, interpret their meaning, and conclude by answering the research questions and outlining the study's limitations and recommendations.

Chapter 1: Introduction presents the background, problem definition, research gap, scope, objective, and research questions of the study. It introduces the wind industry context, explains why the design–manufacturing interface across firms is important under current scale-up conditions, and defines the focus on outsourced wind turbine blade manufacturing.

Chapter 2: Literature Review reviews the relevant literature on wind turbine manufacturing networks, design–manufacturing integration in new product development, coordination theory, and inter-firm DMI coordination mechanisms. It synthesizes evidence from mature industries and develops Framework A and Framework B as analytical mechanism structures for the empirical part of the research.

Chapter 3: Research Methodology explains the research design and the methods used in the study. It describes the qualitative approach, the use of semi-structured expert interviews, data collection and participant selection, human research ethics, the development of the initial coding framework, the coding and analysis procedure, and the analytical steps used to move from Framework B to Framework C.

Chapter 4: Interview Findings and Framework Development presents the empirical findings of the study. Using Framework B as the analytical reference structure, the chapter examines how inter-firm DMI coordination mechanisms appear across the pre-project, design, and manufacturing and launch phases in the wind turbine blade context. It then develops a cross-phase synthesis of the main patterns and refines these findings into Framework C for strengthening the design–manufacturing interface in the wind industry.

Chapter 5: Discussion interprets the findings in relation to the mature-industry literature and the wind industry context. It discusses the usefulness of the mature-industry lens, explains what the wind case supports and where adaptation is needed, and sets out the theoretical contribution of the study together with its contribution to the wind industry.

Chapter 6: Conclusion concludes the thesis by answering the sub-questions and the main research question. Then it reflects on the limitations of the study and presents recommendations for industry practice and future research.

2

Literature Review

2.1. Introduction

This chapter reviews the literature that forms the basis for this research. Section 2.2 outlines the wind turbine manufacturing network context in which design and manufacturing are increasingly distributed across firms. Section 2.3 then positions the DMI within NPD. Section 2.4 introduces coordination theory as the theoretical lens for analyzing how interdependent activities are managed across organizational boundaries. Section 2.5 reviews the coordination mechanisms reported in mature industries for managing the inter-firm DMI. Based on this review, Section 2.6 develops Framework A as a reference framework based on the literature, while Section 2.7 develops Framework B as the intermediate framework used for the empirical analysis. Finally, Section 2.8 presents the conclusions of the literature review.

2.2. Wind Turbine Manufacturing Networks

Global wind turbine production has evolved into an internationally distributed manufacturing system. Wind turbine capacity is heavily clustered in Asia, with particularly strong dominance in China, which accounts for a substantial majority of global manufacturing volume. This concentration stands in contrast to the relatively limited production capacity in Europe and the Americas, where domestic manufacturing capacity is insufficient to meet current and future levels of demand and bottlenecks are projected. Several regions, including Europe and North America, face persistent supply gaps and rely on imported blades and components to meet deployment targets (Global Wind Energy Council & Boston Consulting Group, 2023; Hallinan, 2025).

As components such as blades are both material and labour intensive (relying on large quantities of composite materials and long duration manual processes) cost differentials between regions (particularly in labour intensive stages such as layup and finishing) put pressure on firms to locate production in lower cost economies. International trade data over the past decade show that despite the logistical challenges associated with transporting long turbine blades, sizable shares of installed capacity in the United States and Europe continue to be supplied by imports from countries with lower manufacturing costs. This dynamic is reinforced by the increasing size of modern blades, which requires costly retooling and facility expansion. Many existing plants in higher-cost markets face difficulty adapting to larger blade formats and therefore lose competitiveness relative to newer, larger facilities in emerging manufacturing centers (James & Goodrich, 2013; U.S. Department of Energy, Wind Energy Technologies Office, 2023).

As a result, the globalisation of blade manufacturing introduces substantial coordination challenges, especially under the current condition of constantly introducing larger wind turbine packages. Long distances between engineering hubs and production sites extend communication chains and can slow technical decision-making.

This physical separation of engineering and manufacturing roles, combined with differing levels of operational maturity among suppliers, requires carefully structured communication interfaces to ensure consistent interpretation of designs, specifications, and alignment of expectations especially on NPD of increasingly larger wind turbines. Weak coordination mechanisms can increase vulnerabilities, particularly during periods of high market demand or rapid technological change. These characteristics highlight the need for effective interface management and solid coordination mechanisms that will enable the flow of information between design and manufacturing, and thus avoid quality failures.

2.3. Design–Manufacturing Integration in NPD

New product development (NPD) is commonly described as a set of activities that move a product from opportunity identification and concept work to design specification and market introduction. These activities are not independent. NPD involves complex and interdependent tasks, and performance depends on how well organizations coordinate knowledge and decisions across participants (Mishra & Shah, 2009; Tai, 2017). The same point is made in operations research on NPD, where NPD is treated as “a highly interdependent process” and firms are expected to develop routines and practices that support collaboration both internally (cross-functional teams) and externally (suppliers) (Mishra & Shah, 2009). One important place where this broader integration problem becomes concentrated is the design–manufacturing interface (DMI). Integration of design–manufacturing has been defined as the interaction and collaboration between design/engineering and manufacturing aimed at achieving mutually acceptable outcomes and this interaction is argued to extend across product-development stages rather than being limited to a downstream handoff after design is complete (Thomé & Sousa, 2016). The same connection is reinforced in work that restricts product design and engineering to activities related to new product development and treats the interface between product design/engineering and manufacturing as a starting point for integral management approaches (Dekkers et al., 2013). In this thesis, the DMI is therefore introduced as the specific locus within NPD where the broader integration problem becomes concentrated.

A central way in which DMI becomes visible in NPD is through the tight coupling between design decisions and manufacturing outcomes. Swink (1999) defines new product manufacturability as the degree of fit between product design specifications and the capabilities of the production process. When that fit is weak, firms face “heavy penalties” such as costly rework and delays that can erase time gained earlier in development, while also compromising early quality and reliability. The study further indicates that factors like project complexity and higher levels of design outsourcing are associated with poorer manufacturability, whereas integration processes (including manufacturing involvement and supplier influence on design) are associated with better manufacturability.

This design–manufacturing dependency becomes especially visible when firms transition from development to industrialization and start of serial production. Production ramp-up is typically defined as the period between the end of product development and full production capacity (Terwiesch et al., 2001). The ramp-up period is characterized by low yields and low production rates because the new production process is not yet well understood, and learning is required to stabilize output and quality. Research that links NPD and ramp-up argues that ramp-up outcomes depend on earlier design and production-preparation decisions, meaning that ramp-up cannot be analyzed in isolation from preceding NPD stages (Wlazlak et al., 2019). This shows that the same broader DMI problem does not disappear once design is complete. It continues into industrialization, where later production problems often reflect earlier failures to align product and process decisions. In that framing, integration is not an “extra” but a way to adapt product design and the production system to each other before ramp-up, thereby reducing disturbances and ramp-up problems.

Because of this dependency, integration is a persistent theme in both NPD and operations literature. It appears in arguments for concurrent approaches (overlap between design and manufacturing activities), in practices such as early manufacturing involvement, and in routines intended to prevent late discovery of manufacturability issues. However, the need for integration is not limited to coordination within a single company. In many industries, NPD has increasingly become inter-organizational, with focal firms relying on external partners to expand their development capabilities and knowledge base (Suurmond et al., 2020b). Flankegård et al. (2021) summarize this shift directly: product development is “seldom an effort carried out by individual organizations”, and there is a tendency for external collaborations to play an increasingly important role.

Crossing firm boundaries makes this integration problem harder because design-related and production-related knowledge now have to be aligned across organizations rather than only across internal functions. Supplier participation may improve speed, cost, and quality, but these effects depend on the specific form and dimensions of involvement rather than participation alone (Primo & Amundson, 2002; Suurmond et al., 2020a). This matters for the present thesis because it suggests that inter-firm integration is not simply a matter of "involving suppliers earlier", but of establishing workable forms of collaboration through which relevant knowledge can actually be integrated into product development.

The inter-firm extension of the DMI also has a knowledge-boundary dimension. Takeishi's study of automotive product development emphasizes that when automakers outsource component design and manufacturing to suppliers, the challenge becomes how to partition and integrate knowledge effectively across the inter-firm division of labor (Takeishi, 2001). Related work on R&D–manufacturing coordination argues that design-for-manufacturing guidelines are useful but often cannot encapsulate all relevant manufacturing information, and that outsourcing makes it particularly challenging to understand suppliers' processes and to obtain manufacturability feedback (Olausson et al., 2009). In that sense, inter-firm DMI problems are not only about organizational separation, but also about how design decisions and supplier manufacturing realities are translated into one another across the interface (Olausson et al., 2009).

As the DMI extends across phases and across firms, it becomes increasingly dependent on explicit coordination arrangements. Tai (2017) frames inter-organizational collaboration in NPD as involving intense inter-organizational processes that require coordination mechanisms to cultivate mutual understanding and align partner activities with the focal firm's objectives. This reinforces the point that cross-boundary integration is not only a "people issue" but also a systems and information processing issue. This is also consistent with research on the design/manufacturing interface showing that both interdependence and appropriate coordination mechanisms vary across project phases, and with work showing that similar coordination problems persist when design and manufacturing activities are distributed across firms (Adler, 1995; Twigg, 2002).

In sum, the literature supports three points that are directly relevant for this thesis. First, integration is a known and persistent issue in product development because NPD is interdependent and because design decisions shape manufacturability, ramp-up performance, and early quality outcomes (Hilletofth & Eriksson, 2011; Mishra & Shah, 2009; Swink, 1999; Terwiesch et al., 2001; Wlazlak et al., 2019). Second, this broader integration problem becomes concentrated at the design–manufacturing interface, where product and process decisions must be aligned both within and across firms (Dekkers et al., 2013; Thomé & Sousa, 2016). Third, once the DMI extends across phases and across firm boundaries, the central issue becomes how it is coordinated in practice, including through coordination mechanisms and information-processing arrangements that enable aligned decisions and rapid problem solving (Adler, 1995; Tai, 2017; Twigg, 2002).

This thesis focuses on exactly such an inter-firm integration challenge in a context where OEMs rely on global supplier networks and outsourcing for critical components. Having located that broader problem at the design–manufacturing interface, the next section turns to coordination theory in order to explain how DMI is managed across phases and across firms.

2.4. Coordination Theory for Inter-firm DMI

When design and manufacturing are distributed across firms, integration at the design–manufacturing interface (DMI) becomes less straightforward than in an internal, cross-functional setting. Twigg argues that when product development occurs between firms, design–manufacturing integration is less well developed, even though outsourcing and supplier involvement increase interdependence between the focal firm and suppliers of design and development information (Twigg, 2002).This indicates the need for a clear theoretical lens to explain what "coordination" means and how "coordination mechanisms" should be identified and classified in the inter-firm DMI literature.

A standard starting point in coordination theory is that coordination concerns the management of dependencies between activities. Malone and Crowston define coordination in exactly these terms and propose that progress can be made by characterizing different kinds of dependencies and identifying the coordination processes used to manage them (Malone & Crowston, 1994). Under this view, coordination problems are not random communication failures. They arise because one party's activity requires inputs or compatibility with another party's activity. As a result, coordination mechanisms can be framed as the repeatable arrangements that manage these dependencies in a reliable way.

Coordination theory also implies that mechanism choice should depend on the characteristics of the work, especially uncertainty and the degree of coupling. As such, coordination mechanisms can be classified into impersonal, personal, and group modes and empirical evidence shows that coordination shifts with uncertainty. As tasks become more uncertain, organizations substitute away from purely impersonal coordination toward more horizontal communication and group meetings (Van de Ven et al., 1976). This logic is important for inter-firm DMI because interface work combines both stable and unstable elements. Some coordination can be "programmed" through documentation, interface specifications, and standardized procedures (impersonal mode). Other coordination cannot be reliably prespecified, because novel production situations, deviations, or ambiguous requirements require interpretation, negotiation, and joint problem solving (personal and group modes) (Van de Ven et al., 1976). A consistent explanation is provided by Galbraith's information processing view which states that as task uncertainty increases, the amount of information that must be processed between decision makers increases, which pushes organizations toward either greater pre-planning capacity or greater lateral relations to handle exceptions. Together, these perspectives provide a basis for expecting that mature industries will use a portfolio of mechanisms (some emphasizing pre-specification, others emphasizing feedback and adjustment) rather than relying on a single coordination approach.

Okhuysen and Bechky (2009) propose that coordination mechanisms work by generating three integrating conditions, accountability, predictability, and common understanding. These integrating conditions can be particularly relevant at inter-firm interfaces. Accountability matters because cross-firm work depends on clear responsibility for design decisions and change approvals. Predictability matters because manufacturing performance depends on reliable design specifications and engineering responses. Common understanding matters because the interface requires a shared interpretation of what design intent means in practice and what manufacturing constraints imply for feasibility and quality. This lens clarifies that mechanisms are not only channels for information exchange, but can be seen as arrangements that create the conditions for interdependent work to proceed with efficiency.

Additionally, Gittell (2006)'s relational coordination perspective argues that effective coordination in interdependent settings is supported by shared goals, shared knowledge, and mutual respect, enacted through frequent, timely, accurate, problem-solving communication. This reinforces that inter-firm DMI coordination can be constrained not only by missing information, but also by the relational and interpretive conditions that shape how information is exchanged.

Carlile (2002) explains that boundaries are not only about transferring knowledge. In many settings they also require representing knowledge in a form that another party can work with and transforming knowledge so that differences and dependencies can be negotiated and integrated. This is especially relevant for inter-firm DMI because design artifacts (drawings, specifications, models, test results) often function as boundary objects as they help coordinate work across organizational and functional differences, but they do not automatically ensure shared interpretation. Carlile (2002)'s argument provides a concrete theoretical reason why coordination mechanisms at the DMI often include more than documentation, as where meanings differ or where novelty creates ambiguity, additional mechanisms are needed to transform and reconcile interpretations across the boundary.

To sum up, coordination theory provides a clear foundation for analyzing inter-firm DMI coordination. It treats coordination as the management of dependencies between activities, recognizes that approaches vary with uncertainty and coupling, and highlights that mechanisms matter because they generate accountability, predictability, and shared understanding across boundaries where knowledge often must be represented and transformed. This perspective provides the basis for section 2.5, which reviews how industry literature conceptualizes the inter-firm DMI and the coordination mechanisms used to manage it.

2.5. Inter-firm DMI Coordination Mechanisms

This section identifies and synthesizes how mature industries coordinate the inter-firm design–manufacturing interface (DMI), with the specific objective of identifying and organizing the coordination mechanisms reported in the literature into a coherent typology and matrix. Rather than presenting an unstructured list of practices, the analysis uses an explicit organizing framework so that mechanisms can be compared across studies and traced back to documented applications (Twigg, 2002).

The unit of analysis is a coordination mechanism, defined here as a repeatable arrangement, practice, role, routine, or artifact that aligns interdependent activities across firms by structuring information exchange, decision-making, and responsibility at the DMI. This definition is consistent with coordination theory, which treats coordination as the management of dependencies among activities (Malone & Crowston, 1994), and it fits the inter-firm DMI context because design outputs and manufacturing execution are coupled through interpretation and feasibility dependencies.

Mechanisms described in mature-industry research vary widely in naming and granularity, and similar practices are often described using different terms. Okhuysen and Bechky (2009) note that coordination research contains a “remarkable array of terms” for similar mechanisms, which makes an explicit synthesis framework important for comparability. For this reason, the synthesis is organized using Twigg (2002)’s inter-organizational typology of DMI coordination mechanisms, which provides a DMI specific structure that is explicitly grounded in outsourced/inter-firm product development settings.

Within this approach, Twigg’s mechanism categories are used as the primary classification and evidence from other mature-industry sources is used to (a) triangulate the mechanism meaning, and (b) document how comparable mechanisms are implemented in practice across industries (automotive, aerospace, defense). This enables the analysis to remain focused on the DMI while also meeting the SQ1 requirement to characterize what mature industries do in applied terms, not only conceptually.

Mechanisms are extracted from the source literature (peer-reviewed articles, company documents) as concrete practices (e.g., EDI regimes, PPAP/APQP/FAI gates, resident representatives, supplier development teams, transition teams) and then allocated to one primary mechanism family based on their dominant coordination function. This keeps the chapter readable while preserving traceability from each mechanism family back to the underlying sources.

Because Twigg’s inter-organizational coordination mechanisms are complementary and phase dependent rather than mutually exclusive, some mature industry practices span more than one mechanism. This overlap is not evenly distributed across the typology. Mechanisms in the standards/rules and schedules/plans categories are generally more discrete and self-contained in the literature, because they are typically expressed through identifiable rules, gates, data standards, or planned review points. By contrast, mechanisms in the mutual adjustment and teams categories are more relational and interaction-intensive by nature, and therefore more likely to overlap in practice. For example, a joint product/process team may contain producibility reviews, manufacturing engineers or resident supplier specialists within the same broader coordination arrangement. In this review, each documented practice was therefore assigned to one primary mechanism according to its dominant coordination function at the DMI. Where a practice also contained features of another mechanism, these were recorded as secondary or boundary notes in the literature evidence table rather than used to create duplicate classifications in the chapter. This keeps comparability and readability while maintaining traceability from each synthesized mechanism back to the sources. It is also consistent with Twigg (2002)’s argument that coordination mechanisms vary across development phases and are best understood as complementary arrangements rather than isolated tools.

Although Twigg’s typology was developed primarily from mature manufacturing settings, especially automotive, its use in this study is justified by structural similarities between the automotive and wind industries in the inter-firm DMI. Both industries are organized around OEM-led system integration, specialized external suppliers for major subsystems, and increasing modularization of product, production, and supplier systems. Wind therefore resembles automotive not at the level of sector identity, but at the level of coordination structure. This makes Twigg an appropriate analytical baseline for examining wind-industry DMI coordination, while still leaving room for sector specific adjustments.

This section constructs Framework A, an initial reference framework based on the literature and derived from Twigg’s inter-organizational DMI typology and operationalized through mature industry evidence.

2.5.1. Standards and rules as inter-firm coordination mechanisms at the DMI

Twigg (2002) classifies “standards and rules” as a programming-type coordination approach for the inter-firm design–manufacturing interface (DMI) (Hong et al., 2009). Within this framework, integration is facilitated by the pre specification of product definitions, constraints, and operating expectations, thereby reducing the need for extensive reciprocal discussion during later stages. Standards in this context extend beyond purely technical specifications to include established rules for product definition, digital data exchange, cost coordination, early release of design information, and manufacturing capabilities, all of which serve to mitigate downstream disruption.

A1 Compatibility Standards

Establishing standards during the initial phases (whether as project-specific decisions or corporate policy) minimizes the requirement for later reciprocal alignment, as downstream stakeholders can operate from a stable and consistent decision making baseline. This logic is depicted by component variant reduction strategies, such as limiting fastener variety. Furthermore, the early involvement of manufacturing engineers is critical, as standardization decisions strongly influence manufacturability. Standards at this stage encompass producibility guidelines, approved-parts databases, and centralized product definition environments involving compatible CAD/CAM facilities (Twigg, 2002).

A practical example of early standardization is visible in automotive product and process approval systems. The Production Part Approval Process (PPAP) serves as a global standard through which OEMs operationalize supplier instructions and structured evidence submission. PPAP is designed to demonstrate serial production capability relative to customer requirements, acting as a repeatable baseline that reduces ambiguity at the DMI. Although formal submission of PPAP occurs later in the Advanced Product Quality Planning (APQP) cycle, the development of essential documentation commences during the initial product design and development stages (Rudolf & Roszak, 2022).

A2 Electronic data interchange (EDI)

EDI is defined as the computer-to-computer transfer of information both within and across organizational boundaries, evolving from routine transactions (such as purchase orders and invoicing) into broader applications including engineering graphics and machine-programming data exchange (Twigg, 2002). Standardized formats and routines reduce manual translation at handoff points, enhancing the speed and reliability of inter-firm coordination.

Institutional proof of this mechanism is found in automotive supplier networks where standardized message families (such as VDA/DELFOR for releases, VDA/DELJIT for call-offs, and VDA/DESADV for shipping notices) are utilized (Ford Motor Company, 2006). These systems require implementation standards, illustrating EDI’s role as an institutionalized coordination infrastructure (Ford Motor Company, 2006). In the aerospace industry, Electronic Data Interchange (EDI) is the most-studied inter-organizational information system and remains a fundamental, standardized tool for managing critical dyadic exchanges between customers and suppliers. While newer supplier portals introduce broader collaborative visibility, EDI provides the essential transactional framework for one-to-one information flows within the upstream supply chain. Consequently, EDI continues to be a central and institutionalized coordination mechanism for organizations requiring reliable, standardized data transfers (Garcia et al., 2019).

A3 CAD/CAM data exchange

Twigg treats CAD/CAM exchange as a critical subset of EDI, as product definition exchange is fundamental to inter-firm DMI coordination. This involves a shift from physical blueprint drawings toward electronic design-data transfer, where compatibility and exchange reliability are paramount for iterative supplier relationships (Twigg, 2002).

In the aerospace industry, ISO 10303 STEP AP242 is utilized to support configured model based definition interoperability across CAD-to-CAD and CAD-to-CAM interfaces, particularly with equipment suppliers (Delaunay, 2019). Neutral product-data exchange via STEP translators is operationally implemented across major aerospace and automotive organizations to maintain production environments (SCRA, 2006).

A4 Cost management systems

Cost management systems are categorized under “standards/rules” because the visibility of design, development, and production costs focuses attention on the “total design”, supporting coordinated cross-firm trade-offs. Operational examples include the Rover RG2000 system, which required detailed supplier operating costs and assigned component cost responsibility to design engineers, and Ford’s practice of utilizing joint OEM–supplier teams to apply cost-reduction analysis across the design-to-vehicle value stream (Twigg, 2002).

A5 Designers’ tacit manufacturing knowledge

The tacit manufacturing knowledge of designers functions as a coordination mechanism because upstream manufacturability awareness reduces the frequency of later engineering changes. This knowledge is often cultivated through job rotation and internship schemes, though it is noted that such knowledge may become no longer useful if active contact with manufacturing is not maintained (Twigg, 2002).

Empirical research emphasizes that organizational integration practices, such as job rotation and co-location, must align with manufacturing complexity as a lack of fit can negatively impact quality and delivery (Thomé & Sousa, 2016). In aeronautical and automotive settings, manufacturing experience often remains localized within production departments, leaving manufacturability opportunities missed unless specific mechanisms exist to capture and transfer that experience to the design function (Andersson et al., 2008).

A6 Design rules

Design rules mechanism involves the codification of downstream manufacturability constraints into design rules, applied either manually or via software. Examples include CAD-enforced design rules that prevent geometry errors from impacting CNC programs, and software based rule checking that improves Printed Circuit Board (PCB) specifications by verifying conformance to producibility standards (Twigg, 2002).

This is a standard industrial practice where manufacturability evaluation checks the design against process capability (Radhakrishnan et al., 1996). Applied evidence includes the deployment of DFX (Design for Excellence) rule environments at Rockwell Collins, involving extensive DFM (design for manufacturing)/DFA (design for assembly)/DFT (design for testability) rule sets validated across production designs (SCRA, 2006).

A7 Early manufacturing start with early design data

Twigg posits that the early release of design data allows manufacturing to commence preliminary verification of producibility and process design in parallel with design activity. This overlap reduces the need for “workarounds” that typically occur when manufacturing is forced to interpret finalized drawings without prior input (Twigg, 2002).

Conceptualizing this as the release of “preliminary information”, research indicates that it introduces trade-offs as the early information may be unstable or imprecise (Terwiesch et al., 1997). In the studied OEM–supplier ramp-up project, early informal sharing of design-change information before formal release enabled at least one supplier to begin production preparations earlier, while late supplier influence after design freeze led to infeasible tolerances and manufacturing workarounds. (Wlazlak et al., 2019).

A8 Manufacturing flexibility

Manufacturing flexibility acts as a post-design coordination response. When upstream programming fails to eliminate misfit, flexibility buffers the operational consequences and is utilized extensively, second only to engineering changes (Twigg, 2002).

In the Toyota/NUMMI case, high efficiency and exceptional flexibility coexisted through organizational mechanisms supported by rigorous training and inter-firm trust (Adler et al., 1999). Flexibility is also integrated into cross-organizational change-management processes, offering significant potential within complex manufacturing environments (Stanev et al., 2008). However, outsourcing configurations influence this capability and while modular sourcing can enhance flexibility, excessive outsourcing can erode it, leading to quality and cost issues (Miltenburg, 2003).

2.5.2. Schedules and plans as inter-firm DMI coordination mechanisms

Schedules and plans are defined as a programming-oriented coordination family that aligns interdependent work to prescribed objectives, milestones, and decision points. The underlying logic is that coordination improves when capabilities and activities are synchronized "to a prescribed set of objectives and schedules" and when downstream planning is undertaken with explicit awareness of other functions' activities (Twigg, 2002).

B1 Capability development schedules

Integrating the various strategies and capabilities prior to the development process enables conflicts to be resolved and coordination to facilitate downstream benefits. Coordination can be greatly enhanced if all capabilities are working uniformly to a prescribed set of objectives and schedules (B1) both internally and externally (Twigg, 2002).

Aerospace readiness gate practices provide additional applied proof. The Aerospace Corporation defines a Manufacturing Readiness Review (MRR) as a determination of readiness to proceed with manufacturing (Hastings & Gardner, 2011). Kongsberg similarly requires a Production Readiness Review (PRR) report that confirms readiness and includes explicit expectations that the supplier can implement the production program as scheduled (Kong et al., 2023). As a result, these readiness review practices operationalize Twigg (2002)'s B1 by converting "capability development" into scheduled checkpoints rather than leaving readiness implicit.

B2 Relationship assessment programmes

Twigg frames relationship assessment (B2) as a coordination catalyst that can surface deficiencies in existing mechanisms and processes, noting that formal appraisal of customers by suppliers is often uncommon despite iterative communication needs (Twigg, 2002).

In the automotive industry Rover is rating the supply base through supplier assessment procedures, linking assessment to the selection of suppliers capable of supporting deeper design and operational integration (Twigg, 1998).

UK aerospace supplier-development evidence also shows relationship assessment formalized as practice. A development team is assembled, an in-depth supplier assessment is conducted, and a joint development plan is created and monitored through review meetings (Reed & Walsh, 2002). Multiple supplier manuals provide additional applied proof of structured assessment routines proving that B2 coordination mechanism is indeed applied in many industries (Safran Cabin, 2025).

B3 Sign-off / acceptance

Sign-off (B3) is defined as a procedure at the end of design that enables manufacturing to accept or refuse responsibility for making the product to specification, and he notes the added complexity of inter-firm sign-off when specifications remain fluid (Twigg, 2002).

Ford's APQP guideline operationalizes the same logic through Team Feasibility Commitment, where a cross-functional team assesses whether the proposed design "can be manufactured within the guidelines and specifications" and at milestone level Ford further requires that design must be completed with manufacturing sign-off. TRW states that Manufacturing Feasibility is required for every new or modified product design or manufacturing process, and that the feasibility form is signed at the end of a design review to document manufacturability consensus. ITW states the same requirement almost verbatim. Taken together, these sources support Twigg's B3 as a formal manufacturability sign-off mechanism at the DMI, where manufacturing feasibility must be explicitly confirmed before the program can move forward.

B4 Production prototypes / fit–build–test cycles

Production prototypes (B4) are a schedule based coordination mechanism in manufacturing and notes design–build–test cycles that address product/process fit issues at the pilot production stage (Twigg, 2002).

The Toyota/NUMMI case provides direct applied evidence as two pilot builds were conducted prior to start of production, including an on-line pilot build on the regular assembly line with parts from suppliers' regular production lines. The authors report that far more problems were identified than was possible off-line (Adler et al., 1999).

Automotive supplier manuals also institutionalize prototype-like production trials through significant production run requirements. Rudolf and Roszak report that PPAP production parts are taken from a defined production run (Rudolf & Roszak, 2022). Volvo defines a Significant Production Run (SPR) as a sample run using production tooling/equipment, environment/operators, facility, and cycle time (Volvo Group, 2022). DaimlerChrysler requires PPAP parts to be taken from a significant production run (DaimlerChrysler Corporation, 2004). These documents provide direct applied proof that B4-type build events are formalized as DMI coordination checkpoints in mature industries.

In a case study of 12 projects at a major US defense contractor, prototype and sample builds were used before final release to surface manufacturability and design-integration issues. In the Amsterdam project, the supplier developed a prototype for RF-performance evaluation and manufacturability assessment, and some manufacturability problems were resolved before the final design was solidified. In Liverpool, the buyer ordered two prototype units and then worked with the supplier to create the custom chassis design before drawings were released. In Rivoli, suppliers built mechanical samples before the buyer released drawings or executed orders. Cohee et al. also report that heavy early prototyping contributed to strong production outcomes, which supports treating production prototypes as a practical design–manufacturing coordination device rather than just a conceptual mechanism (Cohee et al., 2019).

2.5.3. Mutual adjustment mechanisms at the inter-firm DMI

Mutual Adjustment mechanisms are distinguished from programming-type coordination (standards, rules, schedules). They are mechanisms used when coordination cannot be achieved only by prespecifying information and responsibilities, and instead requires interactive alignment across the interfirm interface during design and manufacturing (Twigg, 2002).

C1 Supplier development committees

Supplier development committees (C1) create recurring inter-firm forums in which selected suppliers and the focal firm review issues, align expectations, and coordinate improvement activity. Twigg positions such committees as mechanisms that allow customers and suppliers to surface and resolve cross-boundary issues before they escalate downstream. (Twigg, 2002).

Similar arrangements are documented in mature aerospace supply networks, where structured supplier development is enacted through dedicated teams that assess suppliers, agree joint development plans with milestones and responsibilities, and review progress regularly (Reed & Walsh, 2002).

Toyota's kyohokai can be understood as a concrete organizational expression of this mechanism. It brought selected suppliers together in a formal, recurring forum built around information exchange, mutual development, and joint learning. Through regular meetings and specialized committees focused on areas such as cost, quality, and safety, the association created a collective space for coordinating improvement efforts across the supplier base rather than leaving development to isolated buyer–supplier interactions. Its reliance on the open sharing of valuable knowledge further suggests that the effectiveness of the arrangement rested on more than structure alone as it also depended on openness between participating firms. In that sense, the kyohokai provides a clear practical example of how supplier development can be institutionalized at the network level (Dyer & Nobeoka, 2000).

C2 Gatekeepers

The gatekeeper mechanism (C2) is conceptually distinct because it relies on a boundary-spanning individual or role that gathers, translates, and channels technological or manufacturing knowledge across the interface. Twigg's earlier design-chain work already suggested that gatekeeping is especially relevant when supplier involvement increases and the focal firm must bridge not only organizational boundaries but also differences in technical language, process assumptions, and development timing (Twigg, 1998). Gatekeeper roles are most explicitly described in Twigg's automotive cases, while other interfirm boundary-spanning roles are often documented under different labels (e.g., guest engineers, resident representatives, supplier quality representatives) (Twigg, 1998, 2002).

C3 Producibility design reviews (Design Phase)

Producibility design reviews is a mechanism for aligning design intent with manufacturing constraints during the design phase, including specialist reviews that incorporate manufacturing/producibility engineers. The underlying logic is that manufacturability cannot be assumed from performance-optimized design, and review timing matters because a design can be performance-optimised but not producible “in manufacturing’s view” thus late discovery of non-producibility typically forces rework and coordination disruption (Twigg, 2002).

Toyota provides a clear example of producibility-oriented design review through its DRBFM system, in which supplier representatives and Toyota’s production-related functions jointly discuss and confirm design changes. The broader obeya setting further supports this by bringing Toyota functions and supplier representatives together to resolve development problems and coordinate design decisions across functions (Aoki & Wilhelm, 2017). The key point is that DRBFM is not simply general collaboration but a review system whose main purpose is to question design changes against likely failure and production implications. It therefore fits C3 most closely, even though it operates inside a broader integrated/teams development setting. This is a good example of the boundary rule used in this thesis. When a practice spans multiple mechanisms, it is assigned to the one that best reflects its main coordination role, while overlaps are noted but not separately classified.

Defense guidance shows a similar logic. The DoD Producibility and Manufacturability Engineering Guide repeatedly treats producibility and manufacturability review as part of formal design-phase activity, emphasizing manufacturing input throughout technical reviews and detailed design. This does not create an identical institutional setting to automotive DRBFM, but it supports the same analytical point: specialist review remains a distinct coordination device for aligning design intent with process capability before problems become embedded in released designs. (Office of the Under Secretary of Defense for Research and Engineering [DoD], 2024).

C4 Producibility/manufacturing engineers (Design Phase)

A second design-phase mechanism in this family is the producibility/manufacturing engineer (C4). Twigg distinguishes this mechanism from design review by shifting attention from an event to a role. Here, manufacturing expertise is inserted directly into the design process through an individual or specialist function that advises designers. In Twigg’s Rover example, design responsibility remained with the OEM, but critical process and tooling knowledge resided externally, so a producibility engineer advised the design team on the process requirements for manufacture during the design phase. C4 is therefore coded as an advisory manufacturing role embedded in design work, not as a general cross-functional team.

In the Toyota case, suppliers do not simply work from completed specifications but they make suggestions on how design drawings can be improved, while design engineers remain connected to production conditions rather than handing designs over at the end of the process. The same pattern appears in suppliers’ own internal practices, where design engineers go to the ”gemba” to confirm manufacturability and reflect plant-floor information back into the drawings, and where simultaneous-engineering activities bring suppliers and manufacturing personnel together so that production outcomes can be incorporated into design work during development. Taken together, these practices show manufacturing and supplier expertise entering the design process early enough to influence the design itself, rather than only reacting to problems after release (Aoki & Wilhelm, 2017).

A similar logic appears in the ramp-up study of a Swedish manufacturing company, where the strongest cases are those in which supplier input was incorporated before component specifications were fixed and the OEM’s R&D staff could access the production site for fast feedback on production issues. In that setting, potential changes could be discussed before the formal engineering change request was released, allowing manufacturing knowledge to influence the developing design. The contrast case is equally revealing: once the component design had already been fixed, manufacturing representatives identified tolerances that were not feasible in the current production process, leaving the supplier to rely on extra machining and process improvements rather than design-side correction (Wlazlak et al., 2019).

Lastly, in the case of defense manufacturing, supplier involvement in design-for-manufacturability, assembly, and test is treated as a distinct early-integration activity that allows fabrication options to be considered in design and is identified as one of the strongest contributors to project performance (Cohee et al., 2019).

C5 Guest engineers (Design Phase)

Guest engineers are supplier employees who reside permanently or semi-permanently at the customer organization to ensure that supplier technological expertise is integrated with the customer's needs. The difference between C5 and C4 is the content of work and duration of involvement. Unlike a producibility engineer (C4) who advises design, guest engineers are resident specialists who work day to day with the host customer's development team. (Twigg, 2002).

Toyota's guest engineer system offers the clearest applied example. Aoki and Wilhelm (2017) describe guest engineers from suppliers working with Toyota across major auto-parts development areas and solving problems jointly during product development. Their day-to-day presence gives Toyota and suppliers a deeper ability to share information and synchronize development logic than documentation alone would allow. For this reason, the Toyota guest engineer system is coded here as C5, even though it coexists with broader organizational systems such as obeya and DRBFM. Again, the classification depends on dominant coordination function: embedded resident supplier expertise is primary here, while team based integration is secondary.

C6 Engineering change routines

Engineering changes are a central mutual-adjustment mechanism in manufacturing phases and according to the literature their effectiveness depends on timing and communication, including infrastructures that ensure changes are returned accurately and quickly to upstream decision makers (Twigg, 2002).

Volvo explicitly prohibits product/process changes after PPAP approval without prior approval (Volvo Group, 2022). Adient formalizes a Supplier Change Request process and requires advance notification and written approval prior to product or process changes (Adient, 2019). Modine similarly requires notification and approval for deviations and changes affecting fit, form, function and related attributes, and indicates that customer approval is obtained where required (Modine Manufacturing Company, 2019).

Engineering change routines are most clearly visible in automotive and aerospace/defense settings, where changes to already released parts, drawings, or software are handled through formal cross-functional procedures rather than through ad hoc approvals. In the automotive literature, recent evidence from a major OEM shows that part engineering changes are a routine feature of production and product support rather than exceptional events. The case study covers a formal engineering change management process involving Purchasing, Production, Development, and other functions, and reports 1,211 changes over a 20-month period in the middle of a product's lifecycle. It also shows that changes arise from quality improvement, cost reduction, safety, legal requirements, and ergonomic issues, indicating that engineering change routines remain active well after initial release. Classic automotive process research makes the same point more explicitly by defining ECO handling as an administrative process running from the emergence of a change, through approval, to final implementation, and by showing that such routines can consume weeks or months if not well managed (Knackstedt et al., 2023; Terwiesch et al., 1997).

The same mechanism is strongly evidenced in aerospace. A recent aerospace case study of an aircraft-engine manufacturer shows a structured engineering change management process in which a change board approves the change, while an integrated product team is assembled to analyse the request, develop solution options, and support evaluation. The process also includes designated-group review, configuration-management control, revision tracking, and engineering approval forms where customer approval is required. In parallel, current Airbus Canada A220 supplier requirements show that such routines are institutionalised in industry practice: suppliers must maintain configuration-management arrangements covering established configuration change implementation, control of engineering change processes, and historical records of change processing and implementation. Airbus also requires advance notification of changes affecting manufacturing site location, manufacturing processes, or related organisational arrangements, together with the scheduled incorporation point and the expected impacts on manufacturing, quality, and logistics (*A220 Suppliers Quality Requirements*, 2024; Pourzarei et al., 2024).

A comparable pattern appears in defense-related aerospace and broader manufacturing practice. In the British Aerospace Military Aircraft Division case, design changes may originate from customers, manufacturing, subcontractors, or design reviews. Affected departments are notified to assess the implications, after which an Engineering Change Control Board decides whether to proceed. Once a change is approved, drawings and related documentation are updated and released as the new baseline. More generally, survey evidence from 100 UK manufacturing companies shows that engineering change management is predominantly formalised: nearly 95 per cent of respondents reported a formal approach, with well-structured procedures, engineering change boards or committees, meetings, and formal documents such as engineering change requests and notices. Taken together, these sources indicate that this mechanism is most strongly associated with automotive and aerospace/defense industries, while also being widely present across manufacturing more generally (Huang & Mak, 1999; Kidd & Thompson, 2000).

C7 Site engineers

Site engineers are customer employees positioned at supplier firms to address ongoing prototype or manufacturing difficulties and accelerate resolution through direct cross-boundary interaction (Twigg, 2002).

This mechanism is explicitly institutionalized in aerospace/defense supplier governance as Kongsberg reserves the right to assign resident representative personnel at supplier facilities and specifies access to work areas, documentation, and meetings as part of conformance monitoring and support (Kongsberg Defence & Aerospace, 2024).

C8 Product support engineers

Product support engineers are coordination roles that assist with assembly quality/fit/finish issues and enable learning to flow back from field performance into design (Twigg, 2002).

Applied industry evidence for formalized post-launch feedback roles is explicit in the DaimlerChrysler PSO manual, which requires suppliers to provide warranty quality representation to support warranty processes and evaluate field returns (DaimlerChrysler Corporation, 2004).

In the automotive industry, practices related to this mechanism are institutionalised both at assembly and in post-launch warranty support. During launch and ramp-up, supplier representatives may be present at the OEM site to assist with coordination and to respond directly to assembly-related problems. Mercedes-Benz U.S. International, for example, invites critical suppliers to attend “Supplier Maturity Vehicle” builds and welcomes supplier representatives on site during launch and ramp-up. In post-launch support, Faurecia requires suppliers to appoint a dedicated warranty engineer, participate in regular warranty-part reviews, analyse returned parts and dealer information, and feed lessons learned from warranty analysis into supplier processes and new product development. Related peer-reviewed studies likewise show that warranty information is used to evaluate engineering changes and that communication between product support and design functions is necessary to ensure that field learning is translated into subsequent product improvement (Majeske et al., 1997; *Supplier Quality Assurance Manual (SQAM)*, 2014; *Supplier Requirements Manual*, 2018).

2.5.4. Integration through teams

Team-based mechanisms constitute a deeper form of coordination than standards, schedules, or role based mutual adjustment because they create an organizational arrangement for sustained joint work across firm boundaries. Twigg (2002) treats this family as necessary where inter-firm alignment at the design–manufacturing interface cannot be achieved primarily through pre-specified rules or isolated review events, but instead requires regular interaction and shared problem solving over time. The analytical challenge, however, is that team mechanisms often incorporate role based or review based practices inside them. The purpose of this section is therefore to distinguish the dominant team arrangement from the additional mechanisms that may operate within it.

D1 Supplier development teams (Pre-Project Phase)

Supplier development teams work with selected suppliers to improve operational performance, with typical applications in quality improvement and in eliminating design and manufacturing problems. A key feature is that such teams are intended to be temporary as the purpose is to raise supplier competence so the supplier can then sustain the required performance without continued intensive support (Twigg, 2002).

Toyota’s OMCD aligns closely with this mechanism because it operates through consulting and problem-solving teams that provide direct on-site assistance to suppliers in solving operational problems and improving their operational performance, although the source frames OMCD more broadly as part of Toyota’s network-level knowledge-sharing system rather than explicitly as a temporary supplier development measure (Dyer & Nobeoka, 2000).

This mechanism is documented in mature-industry practice in multiple forms. In an OEM setting, (Forman, 2001) case describes “supplier development groups (SDG)” primarily staffed by process engineers and deployed to support suppliers through improvement projects. The case also notes that Deere maintained a significant number of SDG employees and illustrates team based interventions through a formal charter and a dedicated project team assembled to redesign a supplier’s manufacturing process.

Supplier Development Teams are also described as an institutionalized organizational function in automotive. Bayne’s case of Toyota South Africa Motors (TSAM) reports a purchasing structure that includes a dedicated “Supplier Technical Support (STS)” team, characterized as multifunctional (including industrial engineers and quality specialists) and explicitly split between “Production Preparation” and “Supplier Development”, linking supplier development activity to new model introduction and production readiness (Bayne, 2010).

D2 Joint development

Joint development involves inter-organizational supplier involvement at the pre-concept stage, with the specific value of resolving manufacturing issues upstream before they become downstream problems. He further notes that D2 can involve the mutual-adjustment mechanisms C4 and C5, but at an earlier phase (Twigg, 2002). This point is crucial for the present study as D2 is a team based arrangement whose defining feature is when coordination occurs and what it seeks to shape (the product concept itself, carry-over choices, technology selection, and broad manufacturing constraints before specifications are fixed).

Joint development is most evident where suppliers are involved before specifications are fixed and contribute directly to shaping the emerging design concept. In Japanese automotive product development, this begins in the planning stage, where the automaker presents the development concept, the supplier proposes how it can be realized, and the joint task is defined as finding the optimum fit between vehicle development concept and component design (Takeishi, 2001). Automotive research also describes suppliers as partners from the early concept stages of design who help shape component designs (Liker et al., 1996). More broadly, supplier integration in NPD can extend from consultation on design ideas to responsibility for component or system design when suppliers participate as true members of the development team (Petersen et al., 2003).

Aoki and Wilhelm (2017) provide applied evidence consistent with this joint development logic through Toyota’s cross-functional, supplier-including problem solving in an obeya (“big room”) setting, where multiple internal functions and suppliers jointly discuss issues and make joint decisions.

D3 Joint product/process design teams (Design Phase)

Joint product/process design teams are teams that allow manufacturing engineers to begin process design early and provide informal producibility guidance to product designers as designs emerge. These teams become necessary when weaker mechanisms (such as designers’ tacit knowledge, design rules, sign-off procedures, or design reviews) cannot sufficiently capture manufacturing needs. Although preliminary definition may have been discussed at the pre-project stage, it is joint teams that manage the finer detail at the project phase. In other words, D3 is not mainly about deciding what concept to pursue, it is about coordinating the detailed co-development of product and process once development has started (Twigg, 2002). For this reason, the same organizational practice (for example, obeya) may be coded as D2 or D3 depending on whether its dominant function is early concept shaping or ongoing detailed product–process coordination during development.

The clearest defense-sector expression of D3 is Integrated Product and Process Development (IPPD) delivered through Integrated Product Teams (IPTs). The 1998 DoD IPPD Handbook defines IPPD around the concurrent development of products and processes and emphasizes early and continuous life-cycle planning, cross-functional participation, and team based integration. The more recent DoD Producibility and Manufacturability Engineering Guide reinforces the same logic, stating that product and process should be developed concurrently by a multidisciplinary team and that manufacturing and quality specialists should be included in the IPT structure to influence design as it progresses. These sources are coded as D3 because their dominant coordination function is concurrent product/process design during development, even though they also recognize very early concept-phase manufacturing input (DoD, 1998, 2024).

Toyota's obeya can also be understood in this way when its main function is to bring people together to solve development problems during the design process. Aoki and Wilhelm (2017) describe engineering, purchasing, production, and supplier representatives working together in a "big room" to discuss issues and make joint decisions. When the main purpose of this arrangement is to support ongoing coordination during development and to align product and process decisions, it is coded here as D3 rather than D2. The difference is the stage and purpose of the coordination. D2 refers to early joint involvement in the shaping of the concept, while D3 refers to continued joint work during detailed development.

This also helps to explain how D3 is related to the mutual-adjustment mechanisms discussed earlier. A D3 team may include C3-type design reviews, C4-type manufacturing engineers, or even C5-type guest engineers. This means that team based mechanisms often provide the broader setting within which more specific review and specialist role mechanisms operate. In this thesis, team mechanisms are therefore coded according to the main team arrangement, while embedded review activities and specialist roles are treated as secondary features.

D4 Transition teams

The transition team is a mechanism created by collocating design engineers in manufacturing after design sign-off so that early-stage manufacturing problems can be resolved quickly and so that design engineers gain first-hand experience of design/process fit issues for future learning. The mechanism is presented as a response to a recurring integration failure mode. Design personnel move on after release to manufacturing and are then reluctant or unavailable to revise older designs, which increases coordination delay during early production (Twigg, 2002).

Empirical evidence of transition team structures in the ramp-up of components from supplier is provided by Özer and Uncu, who describe how, during the transition from pilot production to mass production at a component supplier (Hitachi GST), the supplier forms a transition team consisting of development and manufacturing engineers and assigns substantial engineering resources to monitor the transition and ensure pilot-run learning is implemented (Özer & Uncu, 2013).

This continuity logic is also supported in the DoD IPPD Handbook, which notes that the Boeing 777 experience supported continuing IPTs through the entire program to provide continuity and reduce overall schedule, treating the continuity of team knowledge across phase boundaries as a schedule and coordination advantage (DoD, 1998).

This supports why transition-team mechanisms are practical in inter-firm DMI settings as they create an organizational bridge across the development-to-production boundary precisely where learning and exception handling are most intensive.

2.6. Framework A: Reference mechanism structure from the literature

Chapters 2.5.1 to 2.5.4 identified and organized the inter-firm DMI coordination mechanisms found in mature industry literature by using Twigg (2002)'s framework and mechanisms as the main structure and codes, respectively.

The result is a reference mechanism structure based on the literature that groups the mechanisms by family and phase and links them to concrete applied examples from automotive, aerospace, and defense.

This framework is not yet the final framework for the thesis. At this stage, its purpose is to provide a complete baseline that shows how mature industries coordinate the DMI across firms. It keeps the full set of mechanisms so that they can later be reviewed, simplified, and adjusted.

The resulting matrix therefore forms Framework A, which serves as the reference mechanism structure for developing Framework B as an intermediate framework aligned with mature industry coordination practices and used later to analyse the wind industry context.

Table 2.1: Framework A for inter-firm DMI coordination in mature industries

Phase	Family	Mechanism	Coordination role at the DMI	Anchor mature-industry example	Main source(s)
Pre-project / concept	A	**A1** Compatibility standards	Establishes common technical and coordination baselines across firms at the outset.	APQP / PPAP logic as structured upstream planning and alignment.	(Rudolf & Roszak, 2022; Twigg, 2002)
	A	**A2** Electronic data interchange	Standardizes routine inter-firm information exchange.	EDI based OEM–supplier exchange routines.	(Ford Motor Company, 2006; Garcia et al., 2019; Twigg, 2002)
	A	**A3** CAD/CAM data exchange	Enables interoperable digital product-definition exchange across firms.	EDI routines and STEP AP242 interoperability.	(Delaunay, 2019; SCRA, 2006; Twigg, 2002)
	A	**A4** Cost management	Makes cross-firm design–cost trade-offs visible early.	Rover RG2000 / Ford joint cost-reduction analysis.	(Twigg, 2002)
	B	**B1** Capability development schedules	Aligns capability-building and readiness before development advances.	Readiness and capability milestones.	(Hastings & Gardner, 2011; Kong et al., 2023; Twigg, 2002)
	B	**B2** Relationship assessment programmes	Assesses supplier capability and structures development planning.	Formal relationship / supplier assessment.	(Reed & Walsh, 2002; Safran Cabin, 2025; Twigg, 1998, 2002)
	C	**C1** Supplier development committees	Creates recurring inter-firm forums for joint improvement and learning.	Toyota kyohokai.	(Dyer & Nobeoka, 2000; Reed & Walsh, 2002; Twigg, 2002)
	C	**C2** Gatekeepers	Uses boundary-spanning roles to gather, translate, and channel technical knowledge.	Technological gatekeeper role.	(Twigg, 1998, 2002)
	D	**D1** Supplier development teams	Uses dedicated teams to raise supplier capability.	Toyota OMCD / supplier support arrangements.	(Bayne, 2010; Dyer & Nobeoka, 2000; Forman, 2001; Twigg, 2002)
	D	**D2** Joint development	Involves suppliers before specifications are fixed to shape the concept.	Planning-stage supplier concept shaping / early supplier integration.	(Aoki & Wilhelm, 2017; Liker et al., 1996; Petersen et al., 2003; Takeishi, 2001; Twigg, 2002)
Design	A	**A5** Designers' tacit manufacturing knowledge	Brings manufacturing awareness into design judgment through accumulated production knowledge.	Tacit manufacturing knowledge developed through job rotation.	(Andersson et al., 2008; Thomé & Sousa, 2016; Twigg, 2002)
	A	**A6** Design rules	Codifies manufacturability constraints into rules used during design.	DFX / rule based manufacturability checks.	(Radhakrishnan et al., 1996; SCRA, 2006; Twigg, 2002)
	A	**A7** Early manufacturing start with early design data	Allows manufacturing to begin preparation before final release.	Preliminary release of design data for manufacturing preparation.	(Terwiesch et al., 1997; Twigg, 2002; Wlazlak et al., 2019)
	B	**B3** Sign-off / acceptance	Provides formal manufacturability acceptance before release.	PPAP / feasibility sign-off.	(Ford Motor Company, 2006; Twigg, 2002)
	C	**C3** Producibility design reviews	Reviews evolving designs against manufacturing constraints.	Toyota DRBFM / specialist producibility reviews.	(Aoki & Wilhelm, 2017; DoD, 2024; Twigg, 2002)
	C	**C4** Producibility / manufacturing engineers	Brings manufacturing specialists directly into design decisions.	Rover producibility engineer / manufacturing engineering interface role.	(Aoki & Wilhelm, 2017; Twigg, 2002; Wlazlak et al., 2019)
	C	**C5** Guest engineers	Embeds supplier engineers at the customer site during development.	Toyota guest engineer system.	(Aoki & Wilhelm, 2017; Twigg, 2002)
	D	**D3** Joint product / process design teams	Coordinates detailed co-development of product and process during development.	IPPD / IPTs / obeya during ongoing development.	(Aoki & Wilhelm, 2017; DoD, 1998, 2024)

Table 2.1: Framework A literature synthesis table for inter-firm DMI coordination in mature industries (continued)

Phase	Family	Mechanism	Coordination role at the DMI	Anchor mature-industry example	Main source(s)
Manufacturing / ramp-up	A	**A8** Manufacturing flexibility	Buffers downstream effects of earlier design/-manufacturing misfit.	Flexible manufacturing response to late changes.	(Adler et al., 1999; Miltenburg, 2003; Stanev et al., 2008; Twigg, 2002)
	B	**B4** Production prototypes / fit-build-test cycles	Tests product–process fit before serial production.	Pilot builds / prototype runs / production validation cycles.	(Adler et al., 1999; Cohee et al., 2019; Rudolf & Roszak, 2022)
	C	**C6** Engineering change routines	Manages formal approval and implementation of changes after release.	ECO / ECM systems.	(Huang & Mak, 1999; Kidd & Thompson, 2000; Knackstedt et al., 2023; Terwiesch et al., 1997)
	C	**C7** Site engineers	Places customer representatives at supplier sites to solve manufacturing problems.	Resident representatives / on-site support.	(Kongsberg Defence & Aerospace, 2024; Twigg, 2002)
	C	**C8** Post-launch support and feedback roles	Feeds launch, assembly, and field issues back into design.	Launch / quality / fit-and-finish support roles.	(Majeske et al., 1997; *Supplier Quality Assurance Manual (SQAM)*, 2014; *Supplier Requirements Manual*, 2018)
	D	**D4** Transition teams	Bridges design release and early production learning.	Transition teams supporting early manufacturing handover.	(DoD, 1998; Özer & Uncu, 2013; Twigg, 2002)

2.7. Framework B: Intermediate mechanism structure for the empirical analysis

Framework A was developed as the reference mechanism structure for inter-firm DMI coordination based on the literature. The next step was to review whether this complete set of mechanisms could be simplified using the same mature industry literature already examined in Sections 2.5.1-2.6. The aim is not to replace Twigg (2002)'s framework, but to reduce the detail where the reviewed literature showed a strong overlap in coordination function. On this basis, Framework B was developed as an intermediate framework which will be used to track and identify the coordination mechanisms in the wind industry.

The first change concerns A2 Electronic Data Interchange and A3 CAD/CAM data exchange. In Framework A, A2 was supported by literature showing the use of standardized digital message families and inter-organizational data transfer routines across customer-supplier interfaces (VDA/DELFOR, VDA/DELJIT, and VDA/DESADV), as well as by research treating EDI as a core interorganizational information system (Ford Motor Company, 2006; Garcia et al., 2019; Twigg, 2002). A3 was supported by literature on digital product-definition exchange across CAD-to-CAD and CAD-to-CAM interfaces, especially through STEP AP242 (Delaunay, 2019; SCRA, 2006; Twigg, 2002). However, the literature reviewed in this chapter already presents A3 as a critical subset of the broader EDI logic. In both cases, the main coordination function is the same, a reliable and standardized digital exchange of design and production information across firm boundaries. For that reason, Framework B merges A2 and A3 into one broader mechanism concerned with digital inter-firm data exchange and interoperability..

The second change concerns A8 Manufacturing flexibility. In Framework A, A8 was included because the literature shows that flexibility can reduce the operational effects of upstream misfit and engineering changes. The reviewed sources support this point by showing that flexibility can coexist with efficient production systems and be embedded in change management processes (Adler et al., 1999; Miltenburg, 2003; Stanev et al., 2008; Twigg, 2002). At the same time, the literature describes flexibility mainly as something used after coordination problems or changes have already appeared. In that sense, A8 functions more as a buffering capability than as an inter-firm coordination mechanism like standards, reviews, engineering roles or team structures. For that reason, A8 was not retained as a separate mechanism in Framework B.

The third change concerns C8 Product support engineers. The reviewed literature clearly showed that mature industries use roles and routines that connect launch support, assembly problem solving, warranty handling, and field feedback. However, the evidence base is broader than the specific label "product support engineers". In the reviewed literature, applied examples include warranty quality representatives, supplier participation during launch and ramp-up, dedicated warranty engineers, regular warranty reviews, analysis of returned parts, and the transfer of lessons learned into later improvement activity (*Supplier Quality Assurance Manual (SQAM)*, 2014; *Supplier Requirements Manual*, 2018; Twigg, 2002). For that reason, Framework B keeps C8 but uses a broader label, post launch support and warranty feedback roles, which reflects the reviewed literature more accurately than the narrower original wording.

The fourth change concerns C2 Gatekeepers. In Framework A, C2 was retained because Twigg's work identifies gatekeeping as a conceptually distinct boundary spanning function at the inter-firm DMI especially where supplier involvement increases and firms must bridge differences in technical language, timing and process assumptions (Twigg, 1998, 2002) (Twigg, 1998, 2002). However, the mature industry literature reviewed in this chapter does not consistently operationalize gatekeepers as a clearly separate and stable mechanism family. Instead, similar functions are often used in more concrete roles, such as guest engineers (C5). Thus C2 was not retained as a separate mechanism in Framework B as the coordination role captured by C2 frequently appears in practice through mechanisms that are already represented elsewhere in the framework.

Framework B is therefore defined in this thesis as an intermediate framework, derived from Framework A and based on coordination mechanisms identified in mature industries. It is used to identify coordination mechanisms in the wind industry through interview data and serves as the basis for developing a refined, more fit-for-purpose framework to strengthen the DMI in the wind industry.

Table 2.2: Framework B for inter-firm DMI coordination in mature industries

Phase	Family	Mechanism	Coordination role at the DMI	Anchor mature-industry example
Pre-project / concept	A	**A1** Compatibility standards	Establishes common technical and coordination baselines across firms at the outset.	APQP / PPAP logic as structured upstream planning and alignment.
	A	**A2/A3** Digital inter-firm data exchange and interoperability	Standardizes routine inter-firm information exchange and enables interoperable digital product-definition transfer across firms.	EDI exchange and STEP AP242 interoperability.
	A	**A4** Cost management	Makes cross-firm design–cost trade-offs visible early.	Rover RG2000 / Ford joint cost-reduction analysis.
	B	**B1** Capability development schedules	Aligns capability-building and readiness before development advances.	Readiness and capability milestones.
	B	**B2** Relationship assessment programmes	Assesses supplier capability and structures development planning.	Formal relationship / supplier assessment.
	C	**C1** Supplier development committees	Creates recurring inter-firm forums for joint improvement and learning.	Toyota kyohokai.
	D	**D1** Supplier development teams	Uses dedicated teams to raise supplier capability.	Toyota OMCD / supplier support arrangements.
	D	**D2** Joint development	Involves suppliers before specifications are fixed to shape the concept.	Planning-stage supplier concept shaping / early supplier integration.
Design	A	**A5** Designers' tacit manufacturing knowledge	Brings manufacturing awareness into design judgment through accumulated production knowledge.	Tacit manufacturing knowledge developed through job rotation.
	A	**A6** Design rules	Codifies manufacturability constraints into rules used during design.	DFX / rule based manufacturability checks.
	A	**A7** Early manufacturing start with early design data	Allows manufacturing to begin preparation before final release.	Preliminary release of design data for manufacturing preparation.
	B	**B3** Sign-off / acceptance	Provides formal manufacturability acceptance before release.	PPAP / feasibility sign-off.
	C	**C3** Producibility design reviews	Reviews evolving designs against manufacturing constraints.	Toyota DRBFM / specialist producibility reviews.
	C	**C4** Producibility / manufacturing engineers	Brings manufacturing specialists directly into design decisions.	Rover producibility engineer / manufacturing engineering interface role.
	C	**C5** Guest engineers	Embeds supplier engineers at the customer site during development.	Toyota guest engineer system.
	D	**D3** Joint product / process design teams	Coordinates detailed co-development of product and process during development.	IPPD / IPTs / obeya during ongoing development.
Manufacturing / ramp-up	B	**B4** Production prototypes / fit-build-test cycles	Tests product–process fit before serial production.	Pilot builds / prototype runs / production validation cycles.
	C	**C6** Engineering change routines	Manages formal approval and implementation of changes after release.	ECO / ECM systems.
	C	**C7** Site engineers	Places customer representatives at supplier sites to solve manufacturing problems.	Resident representatives / on-site support.
	C	**C8** Post-launch support and feedback roles	Feeds launch, assembly, and field issues back into design.	Launch / quality / fit-and-finish support roles.

Phase	Family	Mechanism	Coordination role at the DMI	Anchor mature-industry example
	D	**D4** Transition teams	Bridges design release and early production learning.	Transition teams supporting early manufacturing handover.

2.8. Literature review conclusions

This chapter reviewed the literature relevant to inter-firm coordination at the DMI. It first explained why coordination at the DMI matters in outsourced and globally distributed product development, then introduced coordination theory as the main analytical lens and finally identified and organized the coordination mechanisms reported in mature industries by using Twigg (2002)'s inter organizational DMI typology. Based on this review, the chapter developed Framework A as the reference framework based on the literature and Framework B as an intermediate framework.

The literature review shows that mature industries manage the inter-firm DMI through a structured set of coordination mechanisms rather than through one single practice. Following Twigg (2002), these mechanisms can be organized in two ways. First, they can be grouped into four coordination families: *standards and rules*, *schedules and plans*, *mutual adjustment*, and *integration through teams*. These four families reflect different coordination logics. Standards and rules mainly support coordination through pre-specification and codified guidance. Schedules and plans support coordination through timing, checkpoints, and formal progression through the development process. Mutual-adjustment mechanisms support coordination through direct interaction, feedback, and issue resolution when uncertainty remains. Integration through teams provides a deeper form of coordination through joint work across organizational boundaries.

Second, the literature shows that these mechanisms are also structured across the main phases of product development, the *pre-project phase*, the *design phase*, and the *manufacturing phase*. In the pre-project phase, coordination is more strongly oriented toward defining common rules, aligning expectations and preparing the basis for later collaboration. In the design phase, the emphasis shifts toward integrating manufacturability knowledge into developing designs through reviews, specialist roles. In the manufacturing phase, coordination becomes more focused on handling remaining uncertainty, solving production problems, managing engineering changes and supporting transition into stable production. In this sense, the reviewed literature shows that mature-industry DMI coordination is structured both by *type of coordination mechanism* and by *phase of application*. This is the basis on which Framework A was constructed.

Based on this synthesis, Framework B was developed as an intermediate framework derived from Framework A and aligned more closely with mature industry practices. The adjustment remained limited. A2 Electronic Data Interchange and A3 CAD/CAM data exchange were merged because the reviewed literature showed that both primarily serve the broader function of digital inter-firm data exchange and interoperability. A8 Manufacturing flexibility was not retained as a separate mechanism because the literature described it mainly as a downstream buffering response rather than as a core coordination mechanism at the DMI. C2 Gatekeepers was also not retained as a separate mechanism, because in the reviewed literature its boundary-spanning role appeared mainly through more concrete embedded roles, particularly C5 Guest Engineers. C8 Product support engineers was retained with a broader interpretation, since the reviewed literature pointed more generally to post-launch support and feedback roles. No further merges or removals were made at this stage, as the literature described the remaining mechanisms as related but still distinct in how they support coordination.

Framework B is the intermediate analytical framework developed from the mature-industry literature reviewed in this chapter. It is used in Chapter 4 as the reference point for examining how these coordination mechanisms appear in the wind turbine blade context through the interview data. Based on that analysis, the thesis then identifies which mechanisms should be retained, which need strengthening or adjustment, and which additional directions are needed in Framework C to strengthen the DMI in wind turbine blade manufacturing and support more reliable turbine scale-up under deployment pressure.

3

Research Methodology

3.1. Introduction

This chapter explains the research design and methods used in this study. Section 3.2 presents the research design. Section 3.2.1 explains the qualitative research design and justifies the use of semi-structured expert interviews with directed qualitative content analysis. Section 3.2.2 describes the data collection process and participant selection, showing how the interview sample was built for examining the DMI in the wind turbine blade context. Section 3.2.3 outlines the human research ethics procedures followed in the study. Section 3.3 then explains the data analysis. Section 3.3.1 introduces the directed qualitative content analysis as the main analytical approach. Section 3.3.2 explains how the initial coding framework was developed from Framework B, thereby translating the literature based mechanism set into the starting code structure for the empirical analysis. Section 3.3.3 describes the coding procedure used to analyse the interview material. Section 3.3.4 presents the analytical displays and cross-case comparison used to identify broader patterns across the data. Section 3.3.5 explains how these findings were interpreted in order to refine Framework B into Framework C. In this way, the chapter sets out the methodological basis for the empirical analysis and for the later development of the refined framework.

3.2. Research Design

3.2.1. Qualitative research design

This study adopted a qualitative research design using semi structured expert interviews and directed qualitative content analysis. Directed qualitative content analysis is a qualitative approach in which analysis starts from theory or relevant previous research, and these are used to guide the initial coding categories (Hsieh & Shannon, 2005). In the present study, this approach was appropriate because the literature on the wind turbine blade DMI provides a limited explanation of the non-technical coordination mechanisms through which this interface is managed across firms. For this reason, the study started from an existing framework developed from more mature industries (Framework B) in order to investigate how coordination at the interface appears in the wind context and where the main weaknesses and improvement needs lie. Framework B therefore served as the initial analytical framework for examining how these coordination mechanisms appear in the wind turbine blade development.

More specifically, the study examined whether the mechanisms from Framework B were clearly evidenced in the interview material, appeared in adapted form, remained weak or absent, or indicated the need for extension in the wind context. In this sense, the framework was not treated as something to be copied directly into the empirical setting but it was used as a structured starting point for investigating the wind blade context and for interpreting how the DMI could be understood and strengthened. This logic is also consistent with deductive qualitative approaches that begin from a guiding theory or conceptual framework and then use qualitative data to assess, refine and expand it where necessary (Fife & Gossner, 2024).

The purpose of the study was therefore to investigate how inter-firm coordination at the wind turbine blade DMI works in practice, where its main non-technical weaknesses lie and how this interface can be strengthened. Framework B was used as an analytical starting point for this investigation because it provided a set of structured mechanisms derived from the previous literature. Based on the interview evidence, this starting framework was then assessed and refined to Framework C.

3.2.2. Data collection and participant selection

Participants were selected by purposive sampling. Potential participants were identified and contacted through LinkedIn based on their professional experience and relevance to the wind turbine blade DMI. This sampling strategy was appropriate because the study did not aim for statistical representation but for informed perspectives from positions directly involved in the DMI of wind turbine blades. The final sample consisted of seven experts with experience in roles relevant to blade design, industrialization, manufacturing, process engineering, materials, and cross-functional coordination between design and production. Taken together, these roles covered OEM, manufacturing, and hybrid perspectives across the blade development system and were therefore suitable for examining how coordination mechanisms appear across the interface in practice.

The interview guide was used to provide a common structure across interviews but it was not treated as a fixed script. Instead, questions were adjusted where needed to fit the participant's role, experience and relevance to particular parts of the interface. This was important because not all participants had the same visibility across design, manufacturing, industrialization and later feedback processes.

Table 3.1: Interview participants

Code	Role	Company type	Experience
SBE-01	Specialist Blade Structural Engineer	OEM	14
MIS-02	Manufacturing and Industrial Strategy Director	Manufacturing & OEM	18
LSBM-03	Lead Specialist Blades and Materials	OEM	8
CCE-04	Chief Consulting Engineer	OEM	32
SEM-05	Senior Engineering Manager	OEM	18
BME-06	Blade Manufacturer Engineer	Manufacturing	9
PEM-07	Process Engineering Manager	Manufacturing & OEM	15

In line with directed qualitative content analysis, the interviews combined broad opening questions with more specific follow-up questions. Participants were first asked where the DMI breaks down in practice. This was then followed by more targeted questions on selected Framework B mechanisms and, where relevant, on the researcher's emerging interpretation. Hsieh and Shannon (2005) note that, in a directed approach, interviews may begin with an open-ended question and then proceed with targeted questions about predetermined categories. Similarly, Fife and Gossner (2024) argue that interviews in a deductive qualitative study should be structured so that the guiding framework can be examined empirically, and that if participants do not raise a relevant construct on their own, the interviewer may ask about it more directly. This logic matched the design of the present interviews, where broad opening questions were followed by more specific questions on mechanisms such as design rules, tacit manufacturing knowledge, digital data exchange, prototype cycles, and feedback routines.

The interview guide (Appendix A) also evolved during the study. The earlier interviews were broader and were used mainly to elicit how the interface was experienced in practice and where participants saw the main breakdowns, tensions, and weaknesses. As the analysis progressed and clearer empirical issues emerged, later interviews became more focused on specific mechanisms, possible gaps and points where the initial framework appeared either strong, weak or incomplete. In this way, the interview process retained an open exploratory element while also becoming more analytically focused as the study moved forward.

After Framework C was developed, the framework was shared with the interview participants for validation. The aim of this validation was to examine whether the final framework and the main strengthening directions were recognizable, relevant, and useful for the wind turbine blade context. The validation also aimed to check whether important coordination mechanisms or practical issues had not been sufficiently captured in the framework.

3.2.3. Human Research Ethics

Following the HREC application that was approved by the HREC committee, before the interviews took place, participants were clearly informed about the aim of the research and agreed to participate voluntarily. After the interviews were completed, the audio recordings were transcribed and the transcripts were anonymized so that neither participants nor their organizations could be identified. All interview materials are stored in anonymized form on the TU Delft Drive and will be deleted after the completion of this research.

3.3. Data Analysis

3.3.1. Directed qualitative content analysis

The interview data was analysed using directed qualitative content analysis. Hsieh and Shannon (2005) describe this as an approach in which analysis begins from theory or relevant previous research and uses these as guidance for the initial coding categories. In procedural terms, this means that key concepts from the guiding framework are identified in advance, operational definitions are developed for them, and the empirical material is then coded in relation to these predefined categories. In studies using a directed qualitative content analysis approach, data collection may combine open-ended questions with more targeted questions about the predetermined categories, and the analysis remains open to material that does not fit the initial scheme. Such material should not be ignored but examined further to determine whether it indicates a new category or a subcategory of an existing one (Hsieh & Shannon, 2005). The method is therefore suitable for studies that begin from an existing framework to assess, refine and extend that framework where necessary, rather than only describing empirical material. In this study, this logic was followed by using Framework B as the starting analytical structure, by translating its mechanisms into initial coding categories, by coding the interview material against those categories, and by retaining the material that did not fit for later refinement and possible extension in Framework C.

This approach was appropriate for the present study because a prior analytical framework already existed before the interviews were analysed. Framework B had been developed in Chapter 2 from literature on inter-firm coordination at the DMI in more mature industries. The analysis therefore did not begin from open category generation alone. Instead, the mechanism set in Framework B was used as the starting structure for coding the wind interview material. The purpose of the analysis was to examine how these mechanisms appeared in the wind turbine blade context, whether they were clearly evidenced, appeared in adapted form, remained weak or absent, or suggested the need for extension. Directed qualitative content analysis was therefore suitable because it allowed the study to begin from an existing framework while still remaining open to empirical material that did not fit that framework fully.

This analytical logic is also consistent with broader deductive qualitative approaches. Fife and Gossner (2024) argue that deductive qualitative analysis is appropriate when a study begins from a guiding theory or conceptual framework and then uses qualitative data to examine whether that framework is supported, contradicted, refined or expanded. Although the present study is anchored primarily in directed qualitative content analysis, it follows a similar overall logic. Framework B was used as the initial analytical reference, and the interview material was examined not only to identify evidence for its mechanisms, but also to determine where the framework required adjustment in the wind context. The analysis was therefore directed by the literature, but not confined to it.

3.3.2. Initial coding framework

The initial coding framework was developed from Framework B as previously mentioned. In directed qualitative content analysis, Hsieh and Shannon (2005) explain that analysis begins from theory or relevant previous research and that key concepts from this prior knowledge are identified as the initial coding categories. They also note that operational definitions for these categories should be determined using the theory. Following this logic, the mechanism set in Framework B was converted into the initial coding framework used for the empirical analysis and were not used only as background literature. Each mechanism in Framework B therefore functioned as an initial coding category for examining how coordination at the DMI appeared in the wind turbine blade context.

To make Framework B usable for systematic coding, the mechanisms were organized into a codebook in Excel. For each mechanism, the codebook recorded the mechanism ID, mechanism label, main phase, working definition, inclusion rule, exclusion rule, mature industry anchor example and main literature source. In this way, the framework developed in Chapter 2 was translated into an operational structure for coding the interview material. The purpose of this step was to reduce ad hoc interpretation during coding and to make clear what counted as relevant evidence for each mechanism. This is also consistent with broader deductive qualitative approaches in which an existing conceptual framework is made analytically usable before the empirical material is coded and interpreted (Fife & Gossner, 2024). Table 3.2 summarizes how Framework B was operationalized into the initial coding categories used in the analysis. The full table is provided in Appendix B. The table does not reproduce the full codebook, but presents the main structure that guided coding, thus the individual mechanisms, their working definitions in the empirical analysis, the kinds of interview material that counted as evidence for each mechanism. In this sense, the coding framework did not consist of random keywords, but of categories derived from the literature and defined in advance for systematic use in the analysis.

As the analysis progressed, this initial coding framework remained the main reference structure but it was not treated as closed. If interview material suggested that a mechanism needed clarification, narrowing, broadening, or internal refinement, this was noted during coding and considered later in the analytical process. The starting point of the empirical analysis nevertheless remained the codebook derived from Framework B. This ensured that the interview material was examined in a structured way against the coordination mechanisms identified in the literature while still leaving room for empirical refinement where necessary.

Table 3.2: Initial coding framework

Phase	Mechanism	Working definition used in coding	What counted as evidence in interviews
Pre-project / concept	**A1** Compatibility standards	Shared technical, procedural, or coordination baselines that create a common cross-firm starting point for development and handover.	Statements about common interface definitions, shared specifications, aligned release logic, APQP structures, or lack of such common baselines across firms.
Pre-project / concept	**B1** Capability development schedules	Structured alignment of capability building, plant readiness, and development timing before project progression.	Statements about manufacturing baseline packages, readiness milestones, capability schedules, plant preparation timing, or misalignment between readiness and development pace.
Pre-project / concept	**D2** Joint development	Early manufacturing or supplier involvement before major specifications are fixed.	Statements about concept stage manufacturing involvement, early supplier integration, early manufacturability shaping, or lack of involvement before design freeze.
Design	**A6** Design rules	Explicit codification of manufacturability constraints into formal design guidance, tolerances, or software supported checks.	Statements about DfM rules, acceptance criteria, tolerances, software checks, parameterized rules, or lack of explicit manufacturability rules.
Manufacturing / launch	**C7** Site engineers	Site level technical support roles that connect design/manufacturing knowledge to startup or production problems.	Statements about on-site engineering support, launch support, factory side troubleshooting, or lack of direct technical presence during startup.
Manufacturing / launch	**D3** Joint product / process teams	Cross-functional teams jointly coordinating product and process development during design and industrialization.	Statements about joint teams, cross-functional design/manufacturing teams, industrialization teams or bundled arrangements combining design, reviews and interface roles.

3.3.3. Coding procedure

Using the coding framework summarized in Table 3.2, the interview transcripts were read repeatedly and then broken into coded segments that could be assessed against the initial Framework B categories. In directed qualitative content analysis, Hsieh and Shannon (2005) explain that coding may proceed through predetermined categories derived from theory or previous research, while still remaining open to material that does not fit those categories fully. Following this logic, the transcripts were divided into smaller coded segments with each segment treated as the smallest meaningful unit expressing one coordination practice, one gap, one tension or one suggestion relevant to the DMI. This was necessary because a single interview answer often contained more than one relevant point.

Each coded segment was then entered into the Excel workbook and assigned a structured set of coding fields. The first and most important field was the initial coding category from Framework B which identified the main mechanism to which the segment related. Where a segment also contained a second relevant mechanism this was recorded separately rather than forcing the material into only one category. Each segment was also coded for phase, practice status, interpretation, provisional framework implication, and where relevant any sign that the segment pointed to an enhancement within an existing mechanism or to a possible extension beyond the initial framework.

Practice status distinguished between segments describing a clearly present practice, a partly present practice a gap or absence or mainly an aspiration or recommendation. The interpretation field briefly explained why the segment had been coded in that way how it related to other mechanisms where necessary and whether it appeared important for later framework refinement. These coding fields were used to keep the analysis clear and structured. The initial coding category located the segment within the Framework B mechanism set, while the secondary mechanism field allowed overlap to remain visible where two mechanisms worked together. Practice status helped distinguish between data describing what was already happening in the wind context and data describing what was weak, missing or still desired. The interpretation field was used to explain how the segment should be understood in relation to the initial framework, especially where the material was incomplete or pointed beyond the original mechanism definition. In this way, the coding process did not reduce the interview material to a simple ”yes or no” classification but preserved the main differences between clear evidence, weak practices, gaps and possible directions for refinement.

In line with directed qualitative content analysis, segments that did not fit the initial coding categories were not discarded. Hsieh and Shannon (2005) note that data which cannot be coded within the initial scheme should be identified and later examined to determine whether they indicate a new category or a subcategory of an existing one. Following this logic, interview material that did not align neatly with a Framework B mechanism was retained and recorded through interpretation notes and where relevant through enhancement or extension fields in the coding sheet. This was important because the analysis did not aim only to confirm Framework B, but also to identify where the framework required clarification, refinement or possible expansion in the wind context. This is also consistent with deductive qualitative approaches in which empirical material is used not only to support an initial framework, but also to contradict, refine or expand it Fife and Gossner (2024). In practical terms, this meant that poorly fitting data was not forced into the nearest category without comment. Instead, it remained visible as data that could later be interpreted as a refinement within an existing mechanism, a boundary condition or a possible extension note.

Table 3.3 provides a small set of examples showing how this coding procedure worked in practice. The purpose of the table is to make visible the path from an interview segment to its main point, its coding category, its practice status, its interpretation, and its framework implication. In this way, the table shows more clearly how the initial coding framework summarized in Table 3.2 was actually applied to the interview material and how the coded material supported later interpretation. The full table is on the Appendix B and Table B.2.

Table 3.3: Example coding trail from interview segment to framework implication

Raw segment (shortened)	**Main point**	**Initial coding category (Framework B mechanism)**	**Practice status**	**Interpretation**	**Framework implication**
“The first month should always be working on the shop floor…”	Designers need direct factory exposure to understand real manufacturing limits.	**A5** Designers’ tacit manufacturing knowledge	Gap / strengthening need	The segment shows that direct manufacturing exposure for designers is seen as necessary, but currently weak.	Strengthen A5 in Framework C; supports the broader pattern of weak early integration.
“They are not very involved in the early phase… but I think it is something to improve on… they see something that we don’t.”	Manufacturing knowledge enters too late and should be involved earlier in design.	**D2** Joint development	Weak / absent upstream effect	The segment shows that early manufacturing involvement is limited, but also identifies this as a missing contribution that could improve design decisions.	Supports treating D2 as a major upstream gap and strengthening direction.
“The OEM sends a project team to review the process documentation, and an on-site team supervises the blade manufacturing process.”	OEM technical personnel remain present at the manufacturing site to review documents and supervise production.	**C7** Site engineers	Clearly present	The segment shows direct technical involvement at the manufacturing site rather than a simple handover from design to production.	Retain C7 as a clear mechanism in the wind context.

Raw segment (shortened)	Main point	Initial coding category (Framework B mechanism)	Practice status	Interpretation	Framework implication
“All these three departments will sit together and they will design the process… there will be designers… process guys… equipment experts… all these guys are sitting together and they are discussing these issues.”	Product and process are shaped jointly through a cross-functional team arrangement.	**D3** Joint product / process teams	Clearly present	The segment shows the team based coordination logic of D3, where design, process, and equipment knowledge are brought together while the process is still being shaped.	Retain D3 as a clear mechanism; supports the central design-phase coordination bundle.
“Workers today don’t get composite training… yesterday you were working in a different job, today you are making a blade.”	Shop-floor capability and worker skill are critical, but not well captured by the initial framework.		Weak relation to existing category	The segment relates partly to manufacturing knowledge, but points beyond designer knowledge toward shop-floor capability as a distinct issue.	Supports candidate strengthening direction A5* / shop-floor capability.

3.3.4. Analytical displays and cross-mechanism comparison

After the transcripts had been coded at segment level, the coded segments were not interpreted one by one in isolation. Instead, they were brought together into a set of analytical displays in Excel so that the evidence could first be reviewed by mechanism and then compared across mechanisms. This step formed the link between the segment level coding described in Section 3.3.3 and the higher level interpretation reported later in the thesis. Hsieh and Shannon (2005) describe qualitative content analysis as a process that identifies patterns in the material and examines the relationships between categories. In the present study, this stage therefore moved the analysis beyond individual coded segments and toward grouped evidence, recurring issues and framework level interpretation. This was also consistent with the broader deductive qualitative logic described by Fife and Gossner (2024), in which coded material is reviewed not only to support an initial framework, but also to refine or expand it where necessary.

Three main analytical displays were used for this purpose: the “mechanism summary” sheet, the “pattern matrix” and the “Framework C decision” sheet. Each of these had a different role in the analysis. Together, they formed the bridge between the coded segments and the later chapters of findings. This stage was therefore important for making the analytical path visible rather than leaving the impression that the interpretation moved directly from selected quotations to final conclusions.

The “mechanism summary” sheet brought together coded evidence by mechanism. For each Framework B mechanism, it recorded the dominant practice status, a short summary of the main evidence, the main tension or weakness associated with that mechanism and, where relevant, any enhancement suggestions or possible boundary or extension needs. This sheet was used to bring together all the coded material that had been linked to the same mechanism and to summarise what that material showed overall. This made it possible to assess each mechanism in a more systematic way and formed the direct basis for the mechanism by mechanism reporting structure later used in Chapter 4. At the same time, this sheet also kept visible cases where the empirical material suggested that an existing mechanism was too narrow, too broad, or only partly suitable for the wind context.

The “pattern matrix” was then used for comparison across mechanisms. While the “mechanism summary” remained mainly organized around one mechanism at a time, the “pattern matrix” made it possible to compare mechanisms across phase, practice status, recurring cross-mechanism patterns, repeated enhancement suggestions and possible extension candidates and recurring data that pointed in the same direction that was not captured by any predefined mechanism. In this way, the analysis did not remain only at the level of separate mechanisms but also examined how several mechanisms pointed to the same broader issue. For example, this sheet made it easier to see patterns such as stronger coordination later in the process but weaker early integration, or repeated concerns around prototype learning and validation.

It also played an important role in keeping non-fitting material visible. Where a coded segment did not sit comfortably within one mechanism, but similar issues appeared repeatedly across interviews, the “pattern matrix” allowed these repeated issues to be traced as a broader pattern or as a possible extension direction rather than being lost as isolated exceptions. This is the level at which material such as shop floor capability became visible not only as a single unusual segment, but as a repeated issue that was not fully captured by the initial mechanism set.

The “Framework C decision” sheet was the final display used in this stage. It brought together the mechanism level evidence and the cross-mechanism comparisons in order to decide how each part of Framework B should be treated in the final framework. For each mechanism, this sheet recorded whether the evidence suggested that it should be kept, modified, strengthened or linked to a possible addition. It also recorded the reasoning behind that judgment and the main empirical basis for it. It also documented what should happen to repeated non-fitting material, whether it should remain only as a contextual note, be treated as a refinement within an existing mechanism or as an addition to Framework C.

This stage connected the segment level coding to the higher levels of interpretation used later in the thesis. The “mechanism summary” supported the mechanism level reporting by combining evidence for each Framework B mechanism. The “pattern matrix” and the “Framework C decision” then supported the later pattern level and refinement level interpretation by making it possible to compare recurring issues across mechanisms and to document how these comparisons informed the development of Framework C. In this way, the analytical displays provided a visible path from coded interview segments, to grouped mechanism evidence, to broader recurring patterns, and finally to framework refinement. The full tables are provided in Appendix B.

Table 3.4: Analytical displays used in the analysis

Analytical display	**Main role in the analysis**	**Contribution to the thesis**
“Mechanism summary”	Brought together coded evidence by mechanism.	Supported interpretation at mechanism level and the reporting of findings by mechanism in Chapter 4.
“Pattern matrix”	Compared recurring issues across mechanisms.	Supported interpretation of broader recurring issues across the dataset.
“Framework C decision”	Recorded final decisions on framework refinement.	Supported the move from Framework B to Framework C by showing how the evidence informed framework refinement.

3.3.5. Interpretation and framework refinement

In the present study, this meant that the coded and summarized interview material was interpreted not only to describe coordination practices in the wind context but also to identify the main weaknesses, recurring issues, and improvement needs at the blade DMI and on that basis refine the initial analytical framework where necessary.

The analysis proceeded at two linked levels. First, each Framework B mechanism was interpreted on its own terms. At this level, the question was whether the mechanism appeared clearly in the wind context, appeared in adapted form, remained weak or largely absent or was discussed mainly as something that still needed to be developed more strongly. These judgments were not based on individual quotations in isolation. They were based on the combined reading of the coded segments, the mechanism summaries, the repeated tensions associated with each mechanism and the way the same issue appeared across multiple interviews. In this way, the mechanism level interpretation brought together the evidence already organized in the earlier analytical displays and translated it into an empirical judgment for each part of Framework B.

Second, the analysis moved beyond single mechanisms and considered broader recurring issues that emerged across the dataset. Some of the main findings of the study did not concern one mechanism alone but arose from repeated combinations of mechanisms, gaps, tensions and absences. At this level, the purpose of interpretation was to identify the larger coordination patterns that became visible only when the mechanisms were read together rather than separately. This made it possible to see, for example, where several mechanisms pointed to the same upstream weakness, where later phase coordination appeared stronger than earlier integration, or where repeated tensions around validation, shared baselines or supplier involvement could not be understood adequately through one mechanism alone. The analysis at this level therefore did not replace the mechanism based reading but built on it in order to identify the broader structure of the findings.

This stage was also important for the treatment of material that did not fit neatly within the initial framework. Some of this material could be understood as a refinement within an existing mechanism. Some remained better treated as a boundary condition or contextual note. Some, however, recurred strongly enough across interviews to indicate that the initial framework did not capture the issue sufficiently. In such cases, the material was carried forward as a candidate strengthening direction or addition. This meant that the interpretation remained guided by Framework B, but was not closed to empirical issues that became visible only through the wind data. This broader logic is also consistent with deductive qualitative approaches (Fife & Gossner, 2024).

The ”Framework C Decisions” sheet was used to make this final interpretive step explicit. It recorded whether each mechanism should be retained, modified, strengthened or linked to a possible addition, together with the reasoning behind that judgment. It also recorded what should happen to repeated non-fitting material, so that possible refinements and additions were not introduced only on the basis of general impressions but remained tied to the evidence base developed through coding, mechanism summaries and cross-mechanism comparison. In this way, the move from Framework B to Framework C was made visible as an interpretive process grounded in the analysis rather than as a final synthesis added only at the end. Figure 3.1 summarizes the analytical process through which the interview material was moved from Framework B to Framework C.

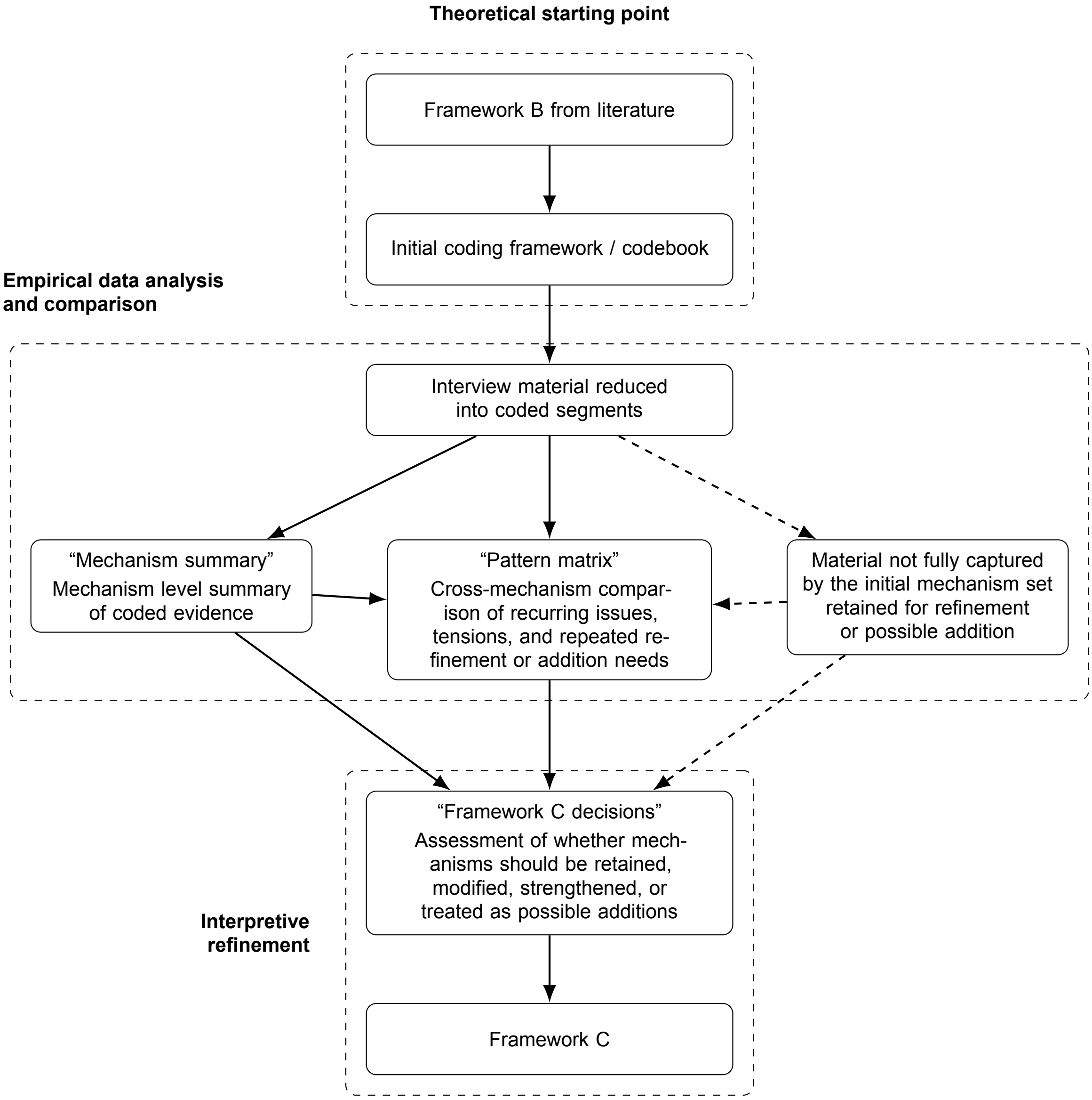

Figure 3.1: Overview of the data analysis process

3.3.6. Expert Validation Methodology

After Framework C was developed, a validation step was included to assess the practical relevance of the final framework. The framework was shared with the interview participants because they had already provided empirical input on the wind turbine blade DMI. The aim of this validation was to examine whether Framework C and its main strengthening directions were recognizable, relevant and useful for the wind turbine blade industry. The validation also aimed to check whether important coordination mechanisms or practical issues had not been sufficiently captured in the framework. Any feedback received would be used to refine the final interpretation of Framework C where necessary.

4

Interview Findings and Framework Development

4.1. Introduction

This chapter presents the interview findings of the study and examines how the coordination mechanisms in Framework B (2.2) appear in the wind turbine blade context. Framework B, developed from the literature review, is used here as the analytical reference structure for interpreting the interview data. Section 4.2 first provides an overview of how Framework B fits the wind context by showing which mechanisms are clearly present, which appear in adapted or partial form, and which remain weak or not identified. Sections 4.3, 4.4, and 4.5 then examine the findings by development phase. Section 4.6 then develops a cross phase synthesis of the interview findings by identifying the broader recurring patterns that cut across individual mechanisms and phases. Based on these findings, Section 4.7 presents Framework C, the refined framework for strengthening the DMI in the wind industry. Finally, Section 4.8 concludes the chapter. In this way, Chapter 4 serves as the empirical analysis and refinement stage between the literature based framework and the final framework developed for the wind context.

4.2. Framework B in the wind context

Before examining the findings by phase and mechanisms, it is useful to consider the overall fit between Framework B and the wind interview data. Table 4.1 provides this overview by showing which mechanisms are clearly present in the wind context, which appear in adapted or partial form and which remain weak or not identified. The table therefore functions as a chapter map of how the mature industry coordination mechanisms introduced in Chapter 2.5 appear in the current wind industry setting.

Overall, the table shows that coordination in the wind context is uneven across phases, with stronger mechanisms appearing later in the process and weaker coordination appearing earlier where manufacturability should be embedded upstream. The following sections examine this pattern across the pre-project, design and manufacturing/launch phases.

Table 4.1: Framework B mechanisms in the wind context

Phase	Mechanism	Status in wind	Key interpretation
Pre-project / concept	**A1 Compatibility standards**	Present, with important gap	Formal standards and APQP type processes are in place, but shared standards across firms are still incomplete.

Phase	Mechanism	Status in wind	Key interpretation
	A2/A3 Digital inter-firm data exchange and interoperability	Clear match	Shared CAD and STEP-type data exchange is clearly used, although not equally across firms.
	A4 Cost management systems	Present, but with gap	Early cost awareness from designers is visible, but the data do not show equally strong visibility of cycle time or manufacturability.
	B1 Capability development schedules	Adapted form	Readiness and planning logic exists, but supplier bottlenecks and weak schedule coordination still disrupt execution.
	C1 Supplier development committees	Present, but with gap	Supplier meetings and joint review forums exist, but they are less developed than in the mature industry model.
	D2 Joint development	Important gap	Manufacturing is still brought in too late to shape early design choices.
	B2 Relationship assessment programmes	Not evidenced	No evidence in the wind industry.
Design	**A5 Designers' tacit manufacturing knowledge**	Important gap	Design work is not supported by enough direct manufacturing knowledge, partly because designers have no experience from the shop floor.
	A6 Design rules	Present, but weak	Manufacturing constraints, tolerances and robustness are recognised, but the rules are still fragmented, not formal enough and not supported by tool based checks.
	B3 Sign-off / acceptance	Clear match	Formal approval and acceptance routines are well established, even if some interactions still mix formal and informal practice.
	C3 Producibility design reviews	Clear match	Structured manufacturability reviews are clearly part of design work.
	C4 Producibility / manufacturing engineers	Clear match	Manufacturing engineering roles clearly connect design decisions with factory realities.
	D3 Joint product/process design teams	Clear match	Cross-functional product and process teamwork is one of the clearest strengths in the design phase.
	C5 Guest engineers	Not evidenced	No evidence in the wind industry.
Manufacturing / launch	**B4 Production prototypes / fit-build-test cycles**	Clear match, with important gap	Prototype and validation work is clearly present, but learning is often compressed by commercialisation pressure.
	C6 Engineering change routines	Clear match	Engineering change routines are well established. The main issue is handling urgent changes without losing traceability.

Phase	Mechanism	Status in wind	Key interpretation
	C7 Site engineers	Adapted form	Direct technical support at the manufacturing site is clearly used, usually in temporary or hybrid form.
	D4 Transition teams	Present	Continuity from design into launch is present, mainly through start-up support and ongoing project involvement.

4.3. Pre-project phase

4.3.1. A1 Compatibility standards (Standards)

In Framework B, A1 refers to compatibility standards that are set early so that different firms can work from the same baseline. This was linked to mature industry practices such as APQP and PPAP early alignment, where shared process rules and documentation expectations are used to reduce ambiguity before detailed design and production move forward.

The interview data show that this kind of early standardization is clearly visible in wind. BME-06 stated that coordination “typically follows the APQP process requirements” and that “design development, interface transitions and communication must all be carried out in accordance with APQP standards”. This shows that wind projects do not rely only on informal early coordination and that they already use a formal baseline that is close to the mature industry logic described in Chapter 2. SBE-01 confirmed this from the OEM side and said that the wind industry “have started to follow this APQP style in one way or another” as the wind industry has started to look what the automotive industry is doing.

At the same time, the strongest A1 finding is not only that APQP structure exists, but that it does not yet extend far enough across the wider network. The clearest evidence comes from BME-06, who stated that “there is a general lack of systematic definitions for cross-enterprise coordination processes across supply chain stages”. This shows that the main weakness in A1 is not inside one company or one project, but across the interfaces between firms and across the different stages of the supply chain. The same respondent continued that “establishing a collaborative standard system that spans the entire supply chain would help eliminate ‘fragmented rules’ that cause friction in coordination”. This is a much more specific finding than simply saying that standardization is incomplete. It shows that wind has formal standards, but these standards do not yet create a fully shared coordination baseline across enterprises.

PEM-07 reinforced this same A1 gap from a more operational angle. He explained that ”most of the blades are designed by one company and manufactured by another company” and that this creates ”some disconnection between these companies”. The same OEM design may be produced across several different manufacturing organizations, including OEM factories and external manufacturers, each with ”a completely different approach” and in effect ”various ways to manufacture the one design”. From the design side, this means that different manufacturers can raise different requests for change for the same blade, while another manufacturer may say that the same issue ”is not a problem for me”. This is important because it shows more concretely why A1 remains only partly developed in the wind context. The issue is not only whether early standards exist, but whether they create a sufficiently shared baseline across the wider manufacturing network so that manufacturability judgments and requests for change do not diverge strongly from one producer to another.

LSBM-03 also supports this from another angle as explained that outsourced manufacturing can happen under different setups, such as “build to print and design for specs” and that the root causes of misunderstandings differ depending on the setup. He added that “putting everything down on paper, saying exactly how everything should be is very difficult” and that people can still “understand things differently which sometimes cause misunderstandings”. This suggests that written requirements and contractual descriptions alone are not enough to stabilize coordination when firms work under different outsourcing arrangements. In other words, the problem is not only technical standardization, but also the lack of shared coordination definitions across organizational boundaries.

SBE-01 pointed to the same issue in a more practical way. After explaining that APQP type coordination is already used, he argued that stronger standardization beyond the boundaries of one firm could reduce bottlenecks. He said that “if we can standardize our parts and even standardize between the OEMs of turbines” then “this will maybe reduce the supply chain bottlenecks that we sometimes have”. These remarks are important because they show that the gap is named directly by the interviewees as a weakness in the current wind setup.

Taken together, these findings show that A1 is present in the wind industry although gaps and room for improvement are identified. Wind has adopted mature industry style upstream standardization through APQP type coordination baselines. However, the main A1 weakness is that these baselines are not adequate at the level of the wider supply chain. The data therefore suggest that compatibility standards are not yet fully translated into systematic cross enterprise coordination processes across firms and stages. That is the main A1 gap shown in the pre project phase.

4.3.2. A2/A3 Digital inter-firm data exchange and interoperability (Standards)

In Framework B, A2 and A3 refer to the early exchange of product definition data between firms. These mechanisms were linked to mature industry practices such as EDI and more specifically the use of shared digital product files and STEP based interoperability in aerospace, where the same engineering definition can move across design, analysis and manufacturing activities. Because both mechanisms serve the same broader function of digital inter-firm product-data exchange, they are treated together in Framework B.

The interview data show a strong match between this industry logic and current wind practice. SBE-01 explained the link of design to manufacturing by stating that the same CAD source that is used for designing “can also then be used as a source for manufacturing so that teams can cut plies and do the manufacturability, splicing and all this using that same source file which then can be shared by our suppliers and can also feed downstream to the manufacturing” and added ”people are exchanging STEP files”. This is an important finding because it shows that digital exchange in wind is not limited to design communication alone. The same source model is used across engineering analysis, supplier interaction, and downstream manufacturing tasks. SBE-01 also commented that ”the wind industry have started to replicate what goes on in the aerospace industry”. This shows that the wind industry indeed is adopting systems already tested in more mature industries.

At the same time, the interview data also shows a small limit. SBE-01 noted that “not every company uses STEP because it is integrated environment, so you need to build it up”. This means that the main issue in A2/A3 is not whether the mechanism exists. The weak point is that the depth of integration is not yet the same across all firms. Some companies appear to have a more developed shared digital environment than others.

Overall, the interview data show that the mature industry logic described in Chapter 2—especially the use of shared digital source files and STEP style exchange across firms is already being used in wind. The mechanism is clearly present, with the main limitation being uneven implementation rather than absence. A2/A3 also supports later coordination phases, because the same digital source is used not only for early exchange but also for subsequent design, supplier, and manufacturing activities.

4.3.3. A4 Cost Management (Standards)

Cost management (A4) refers to early cost management practices that make the cost implications of design choices visible before detailed design and production move forward.

SBE-01 stated that structural engineers are “very aware of the cost” and that “that is one of the biggest metrics” explained also why this matters in blades as “turbine blades are quite expensive part of the turbine” so engineers work with “very strict budgets”. This indicates that cost management functions as a recognized upstream coordination parameter.

At the same time, the same interview also shows the limit of this mechanism. SBE-01 drew a clear distinction between cost and broader production visibility stating “what we sometimes are not aware of the cycle time implications”, because “a lot of us don’t actually have that knowledge or experience in the shop floor”. The participant added that some design choices may seem feasible in principle but “it takes a lot of time thus bigger costs”. This is important because it shows that A4 is present, but in a narrower form than the full manufacturability problem requires. It also shows that the mechanisms in Framework B do not operate independently in practice. While A4 captures the visibility of cost implications in the pre-project phase, the weaker visibility of cycle-time and manufacturability implications points forward to A5 in the design phase, where tacit manufacturing knowledge becomes more central.

As a result, the wind evidence suggests that A4 is present but perhaps limited lacking the manufacturability cost implications.

4.3.4. B1 Capabilities Development Schedules (Schedules and Plans)

B1 refers to early capability planning and readiness structures that help align resources and development paths before detailed execution begins. This mechanism was linked to mature industry planning and review logic where early readiness is used to reduce later disruption.

BME-06 pointed to structured upstream planning by referring to “well structured product development paths and component breakdowns” and also identified bottlenecks around “authority levels” and “priority setting among multiple projects”. This suggests that readiness and planning structures do exist, but that they are still vulnerable to coordination strain when several actors and projects compete for the same resources.

At this stage, B1 is best treated as partially present but thinly evidenced in the pre-project phase. The available material suggests that some planning and readiness logic exists, but not strongly enough yet to argue that it is a robust pre-project mechanism in wind.

4.3.5. B2 Relationship Assessment Programs (Schedules and Plans)

B2 refers to formal supplier or relationship assessment routines used to identify coordination weaknesses and structure subsequent development planning. However, no comparable mechanism was evidenced in the current interview dataset. This suggests that such routines are not sufficiently visible or institutionalized to appear as a distinct coordination mechanism and the absence is consistent with the broader pattern identified in the pre-project phase, that early upstream coordination in wind remains weaker and less formalized than in the mature industry reference framework. Such a mechanism could be particularly valuable in the wind context, because a formalized upstream assessment routine could help identify coordination weaknesses before they escalate into execution problems during later phases.

4.3.6. C1 Supplier-development committees (Mutual Adjustment)

C1 refers to supplier-development committees that create a recurring forum between customer and suppliers early in the process. In Chapter 2, this mechanism was linked to mature industry practices such as Toyota’s kyohokai, where selected suppliers meet with the OEM to exchange knowledge and improve supplier development programmes together. The point of the mechanism is not only to hold meetings, but to build a repeated collective structure for learning and improvement across the supplier base.

The interview data show that a comparable mechanism is present in the wind industry. SBE-01 stated “we do have such meetings. It’s called supplier quality development (SQD). It is there and it’s very important because you know the wind industry is very dependent on suppliers”. This is important because it identifies a specific supplier-development structure in wind. SBE-01 then added “we also have a yearly supplier meeting where they call all the suppliers into the room”. Taken together, these statements suggest that wind does have a recurring supplier forum logic that is close to the C1 mechanism described in Chapter 2.

At the same time, SBE-01 was also clear that “I don’t think we are at the level of automotive industry. Automotive industry is really, really supply-driven. I don’t think we are still there”. This is an important part of the findings as it means that C1 should not be treated as absent in wind, but neither should it be treated as fully equivalent to the stronger supplier-development committee structures found in the mature industry literature as it appears less mature and less deeply institutionalized than the kyohokai type.

The interview data also contain an empirical hint about how this mechanism could be strengthened. SBE-01 linked the weaker maturity of supplier development in wind to the lower level of standardization and sharing across OEMs. He argued that “if we can standardize it and everybody can share it between the OEMs, maybe that is the way to go”. In a similar direction, although not as direct evidence of C1 itself, BME-06 suggested creating “an industry-wide shared knowledge base to compile disruption cases and corresponding solutions from different companies”. This does not describe the same mechanism as the Toyota-style supplier committee, so it should not be used as primary C1 evidence. However, it does support the same broader improvement direction that stronger shared learning across firms could make supplier-development structures in wind more effective and more mature.

Overall, the findings suggest that C1 is present in wind but in a partial form. The wind industry does show recurring supplier development and supplier meeting structures that are comparable to the mature industry logic described in Chapter 2. However, the interview data also show that these structures are not yet at the same level of maturity as the automotive example and that broader standardization and inter-firm knowledge sharing may be needed to strengthen them further.

4.3.7. D1 Supplier Development Teams (Teams)

D1 refers to supplier development teams that work directly with suppliers to improve operational performance. This mechanism was linked to mature industry practices such as Toyota OMCD where dedicated teams provide direct on-site assistance to suppliers in solving operational, quality and design/manufacturing problems during the pre-project phase. The point of D1 is therefore not simply recurring communication but active intervention to raise supplier capability to the required level.

The interview data do not clearly identify this mechanism in that form. While SBE-01 described supplier quality development and yearly supplier meetings these statements fit better with the supplier forum logic of C1 than with the intervention team logic of D1. In the dataset there is no clear evidence of a dedicated customer team providing the kind of direct on-site supplier support that characterizes practices such as OMCD in the mature industry literature.

D1 is therefore considered an important improvement area in the pre-project phase for the wind industry and thus as a possible direction for strengthening inter-firm coordination in the wind context.

4.3.8. D2 Joint Development (Teams)

D2 refers to early joint development between design and manufacturing before key specifications are fixed. This mechanism was linked to mature industry practices where manufacturing or supplier knowledge is brought into the concept stage early enough to shape the product before later changes become costly or impossible.

The interview data show that this mechanism is one of the weak points in the pre project phase as SBE-01 explained that “manufacturing doesn’t really come very early in” thus product development tends to move forward without strong early manufacturing participation. Thus SBE-01 identified that ”I think it is something to improve on as they see something that we don’t” and that “blades are getting bigger, not on the laptop for a designer, but it’s getting much bigger on the shop floor”. This was made more concrete through an example “when you’re lifting parts of the blade on a computer and on a paper, it’s the same thing. You know, when I lift a 2 meter part or 100 meter part… 100 meter part that is being lifted on a crane has inertia and it’s tough to position it correctly. It gets tougher and tougher. It’s flexible.” He concluded that this group “could come in quite early but that is not done”.

These findings show that D2 is weak in the wind industry. Manufacturing is involved, but not early enough to shape the concept. As a result, this mechanism is treated as a major pre-project gap and a clear area for improvement.

4.3.9. Summary

The findings from the pre-project phase show that the wind industry already contains several formal starting processes for coordination but that these do not yet create equally strong early upstream integration across firms. The clearest strengths in this phase appear in A1 compatibility standards, A2/A3 digital inter-firm data exchange, A4 cost visibility in early decisions, B1 capability development schedules, and C1 supplier development committees.

At the same time, the pre-project phase also reveals important weaknesses in the depth and consistency of this coordination. The clearest gap concerns D2 joint development, where manufacturing input is still brought in too late to shape key design choices before they become hard or even impossible to change. In addition, the findings show that A1 remains incomplete at the wider cross-enterprise level, because company level standards and APQP type coordination baselines do not yet translate into fully shared standards across firms and stages. A2/A3 is clearly present, but still uneven across firms, while B1 also remains vulnerable to bottlenecks and fragmented planning. No clear evidence was found for B2 relationship assessment programmes, indicating that formal upstream assessment of coordination gaps is still weak or not clearly institutionalised in the wind context. Lastly, C1 appears present but not yet as mature or institutionalised as the stronger supplier development structures described in the mature industry literature.

The expert views also point to several strengthening directions in this phase. These include stronger cross-enterprise standardisation across firms and OEMs, broader shared coordination definitions and specifications and more systematic inter-firm learning structures that go beyond isolated company practices. The findings also point clearly to the need for earlier manufacturing involvement in concept and early design decisions, since this is where the pre-project phase remains weakest. In addition, the absence of clear evidence for D1 supplier development teams suggests that more direct intervention in supplier support could be useful as a future strengthening direction. Overall, the pre-project phase appears formally structured, but still weaker in early integration than the later phases of the coordination system.

Figure 4.1 summarises this overall pre-project pattern.

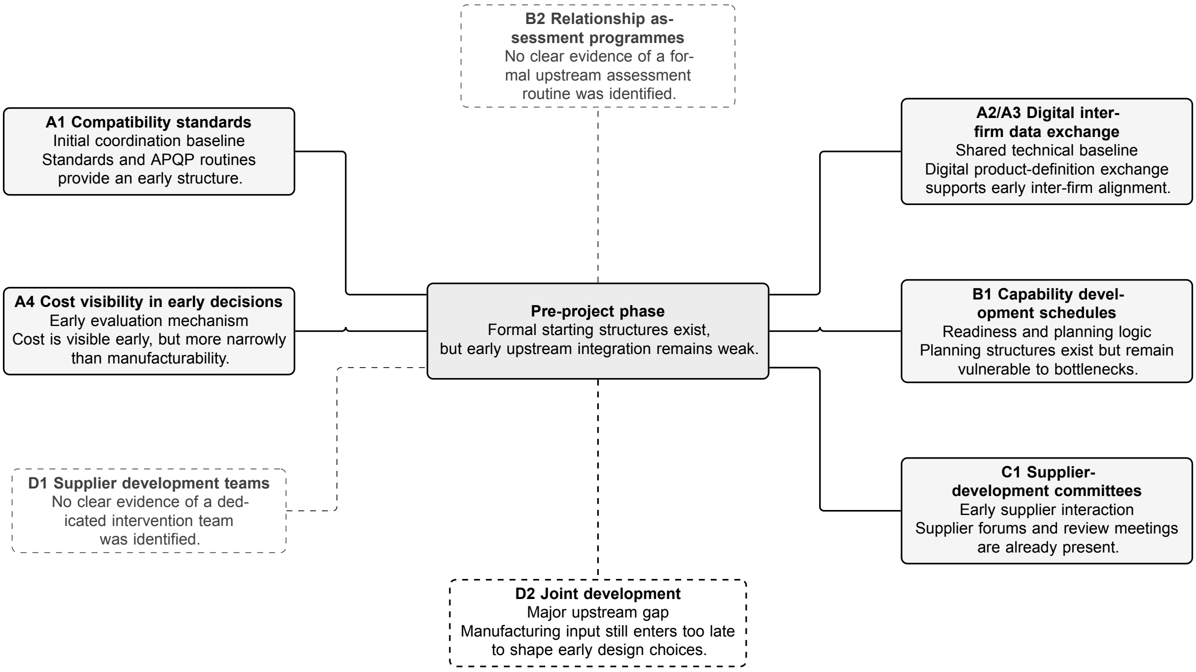

Figure 4.1: Pre-project phase synthesis

4.4. Design phase

4.4.1. A5 Designers' tacit knowledge of manufacturing (Standards)

A5 refers to designers' tacit knowledge of manufacturing and it is linked to mature industry practices such as job rotation and direct factory experience so that designers understand manufacturability from practice and not only from drawings or models. In other words, A5 is about whether manufacturing knowledge is already embedded in the designer's thinking before formal reviews and corrections become necessary.

The interview data show that this is one of the clearest weak points in the design phase. SBE-01 explained that this type of knowledge used to be built much more directly "my first month on the job was to be in manufacturing literally as a manufacturing worker just to learn and go from station to station to get experience there”. However, “nowadays, you don’t see this anymore” because new graduates come into the office and “straight away start designing”. This is an important finding because it shows that direct exposure to manufacturing once played a clear role in developing designers’ tacit knowledge but that this practice has weakened.

CCE-04 described why manufacturing knowledge matters so much in this sector as ”composite blade production is highly sensitive to environmental conditions, tools, equipment and the fabrics that are being used and the final result can change significantly when the same process is carried out in different conditions”. Thus where manufacturing is variable and process sensitive, weak tacit manufacturing knowledge in design becomes a serious interface problem and that can be even more crucial because of the ”physical distance between the design house and the manufacturing plant”.

SBE-01 linked the lack of shop-floor exposure to concrete design consequences, stating that “what we sometimes are not maybe aware of are the cycle time implications” because “a lot of us don’t actually have that knowledge or experience in the shop floor”.

The interviews also suggest that this knowledge problem may extend beyond designers. SBE-01 argued that workers ”don’t get any example composite training” and that in the past, when someone “wanted to work he needed to have a composite technician certificate”, while today anyone can work as a blade worker and concluded that “this knowledge gap is not covered enough”. A similar concern appears in CCE-04’s description of technicians manually cutting balsa pieces to make them fit in large blades which he presented as a sign of how sensitive quality is to execution skill and shop-floor practice. This broader capability issue is larger than A5 itself, but it reinforces the importance of tacit manufacturing knowledge at the design-manufacturing interface.

Taken together, these findings show that A5 is a major gap in the wind design phase. The problem is not that manufacturing is ignored completely but that tacit manufacturing knowledge is not strongly embedded in the design function. Direct plant exposure appears to have weakened while the nature of composite blade manufacturing makes this type of knowledge especially important. That is why SBE-01 said *”if you are a designer, then the first month should always be working on the shop floor because you need to get used to the system”*. The interview data thus point to a clear strengthening direction with more direct shop-floor exposure and rotation that would help designers understand the practical manufacturing realities that are not fully visible in nominal digital design work. This also helps explain why later mechanisms such as design reviews and manufacturing interface roles become so important in the wind data as when tacit manufacturing knowledge is weak at source, more coordination work has to be done later through reviews, interfaces and corrections.

4.4.2. A6 Design Rules (Standards)

A6 refers to formal design rules that translate manufacturing needs into explicit design constraints. These mechanisms are linked to mature industry practice, where producibility is not left only to experience or later review, but is partly built into the design through formal rules and in some cases software tools containing large sets of parameterized design-for-manufacturing, design-for-assembly and design-for-testability rules linked to engineering and manufacturing data.

The interview data show that this mechanism is partially present in the wind context. SBE-01 explained that companies do have design and manufacturing guidelines on *”what to do and what not to do”* but *”They differ actually from company to company. Some will say don’t do this. Some will say do exactly that because they seem to either be able to do that or they have not found any problem with that. So it’s a bit funny sometimes*. This is an important finding because it shows that manufacturability rules do exist but are fragmented and company specific rather than shared and consistent. That can create issues when manufacturing is outsourced and the supplier is manufacturing blades for more that one OEM. Additionally, confusion might even occur when engineers change job to another employee as design robustness *”depends on who is following the guideline. And sometimes people don’t follow or they don’t know, they are not aware of it.*

Regarding this SBE-01 states that an improvement point could be the development of a software tool like the used in mature industries SCRA (2006) as it could warn them during the designing what is not allowed.

To strengthen the importance of this mechanism CCE-04 argued that blade design cannot be based only on a nominal geometry or nominal material case and that *”there needs to be a really big focus on manufacturing variability and that designers should not design something nominal but should also indicate what is the tolerance that the design can have and define the acceptance criteria that manufacturing must meet”*. This is aligned with the recommendation that was given in Ch. 4.3.1 about standardizing parts of the components so *”everybody can share it between the OEMs”* as it suggests that stronger and more consistent design rules would be easier to sustain if firms also worked from a more shared manufacturability baseline.

Taken together, these findings show that A6 is present, but in a fragmented and weakly formalized form. Both the literature and interview data suggest that A6 is a significant design-phase strengthening area. The main issue is not that design rules do not exist, but that they are too company-specific and are not strongly enforced through explicit tool-supported checks.

4.4.3. B3 Sign-off (Schedules and Plans)

B3 refers to sign-off or acceptance of the design specification before work moves forward and is linked to mature-industry practices such as PPAP type acceptance logic, where manufacturing or the supplier accepts responsibility for proceeding against an agreed specification. The key point of B3 is that there is a recognizable approval or acceptance step that confirms readiness to continue.

SBE-01 described this kind of acceptance logic as already well established and *”quite mature as it’s always required that we follow PPAP”*. This suggests that formal sign-off is part of the normal way in which suppliers and OEMs confirm acceptance before moving ahead.

The same mechanism also appears in other interviews, although usually as part of broader review and validation activity. MIS-02 described a sequence in which *”they produce the set and then they validate the set and approve the set”* after which *”they’ll go for a serial production”*. In a similar way, BME-06 stated that technical meetings focus on *”quality acceptance standards for review and confirmation”*. These passages support the presence of B3, but they also show that in wind the mechanism is often embedded within wider review, validation, and handover processes rather than appearing as a single isolated approval event.

This is the main point that should be stressed in the interpretation of B3. The interview data indicates that it is mature. However, in practice it often operates together with other mechanisms, especially design reviews, prototype validation and gate structures. That is fully align with the view that coordination research contains a “remarkable array of terms” for similar mechanisms (Okhuysen & Bechky, 2009). In that sense, B3 is best understood as a clearly covered mechanism that is usually enacted through broader formal review and acceptance routines rather than as a stand alone step.

4.4.4. C3 Producibility design reviews (Mutual Adjustments)

This mechanism was linked to mature-industry practice where structured review events are used to bring manufacturing concerns into design before problems are carried downstream. They are defined as end-of-design-cycle reviews or stage-gate reviews or more focused specialist reviews dealing with producibility. An example is Toyota’s DRBFM, where design is reviewed in a structured way to identify likely failure points and manufacturability risks before release. The key point of C3 is therefore the review itself as a coordination mechanism.

BME-06 stated that in the “Design Planning Stage” the main task is to *”complete the structural design including load calculations and manufacturability reviews”*. The same respondent then described a further review point in the “Technical Handover Stage”, where collaboration takes place through *”technical meetings focusing on design parameters, process feasibility and quality acceptance standards for review and confirmation”*. This is important because it shows that C3 in wind is not limited to one isolated review moment. Instead, producibility review appears as a repeated design-phase logic, first in planning and then again in technical handover and feasibility confirmation.

MIS-02 explained that design and process decisions are reviewed against previous experience and risk assessments stating that *”there are risk assessments and learning from other products. What are the changes against that product? So that’s how we do the evaluation”*. This is a C3 review logic, because the purpose is not only to continue the design but to reassess based on manufacturability, prior lessons and likely deviation points.

Interview data also show that these reviews are often embedded in broader team based coordination. MIS-02 explained that *”all these three departments will sit together and they will design the process and they are discussing these issues in presence of all the cross-functional team”*. This is important because it shows that in practice C3 rarely appears as a stand alone review event. The review is often carried out inside a wider D3 joint product/process design arrangement.

Taken together, these findings show that C3 is a covered mechanism in the wind industry’s design phase. The interviews give strong evidence that manufacturability and process feasibility reviews are already part of wind practice. The main point is therefore not whether C3 exists, but how it operates. In the current data, producibility design reviews are usually embedded in broader team, handover and confirmation structures rather than appearing as fully isolated review events.

4.4.5. C4 Producibility/manufacturing engineer (Mutual Adjustments)

C4 refers to the producibility or manufacturing engineer which is a specialist role that brings process and manufacturing knowledge into the design phase. In literature terms, the role is not a general coordinator but a source of manufacturing expertise brought into design work (Twigg, 2002).

The wind data show a clear match with this role as MIS-02 described *”a manufacturing engineering team that interfaces both the factories and the engineering team”* and called them *”the middle layer”* between design and production. He then made clear that this is not just a generic coordination function but a specialist manufacturing role *”there will be one employee who knows what it is and how it should be done so that person gives the operational perspective or the production perspective”* while others are responsible for *”the risk assessments and the QCRs (Quality Control Reports) since they have the knowledge of all the QCRs”. These people are a perfect interface between the design and the manufacturing real time on the shop floor*.

These findings indicate that C4 is a clearly covered mechanism in the wind design phase as it is a recognized manufacturing-engineering layer that connects the design team with factory realities and feeds operational knowledge back into design decisions. This is closely aligned with the mature industry role described in Chapter 2 and with Twigg’s definition of C4.

At the same time, the interview also suggests that C4 does not operate in isolation. In practice, this manufacturing-engineering role exists inside wider design-phase coordination especially the broader joint product/process work discussed under D3 and it also supports later problem reduction by carrying knowledge of QCRs, risks, and recurring shop-floor issues. So the main point is not whether C4 exists, but how it works in practice and in the interview data it appears as a specialist interface role embedded within broader design-phase coordination.

Overall, C4 should therefore be treated as a clear match between Framework B and the wind interview data.

4.4.6. C5 Guest Engineers (Mutual Adjustments)

This mechanism is linked with Toyota style arrangements, where technical specialists of suppliers work on a permanent or semi permanent basis inside the customer organization. Twigg is clear that the distinctive feature of C5 is the embedded and long duration nature of the role, which allows supplier knowledge to be integrated directly into the customer’s design work over time.

The current wind data do not clearly identify this mechanism in that form. The closest evidence points to technical meetings and review based collaboration rather than a resident supplier engineer arrangement. For example, BME-06 stated that *the primary mode of collaboration is technical meetings, focusing on design parameters, process feasibility and quality acceptance standards for review and confirmation*. This shows that inter-firm technical interaction does take place but it does not show the more specific C5 of a permanent or semi permanent work inside the customer organization.

C5 should therefore be treated as a gap in the wind industry. This matters because such a mechanism could help address two other weak areas already visible in the findings, the limited tacit manufacturing knowledge inside design teams 4.4.1, and the weak early manufacturing involvement highlighted in 4.3.8 D2. In that sense, C5 is a possible direction for strengthening the DMI in the wind industry.

4.4.7. D3 Joint product/process design teams (Teams)

D3 refers to joint product/process design teams and is linked to mature industry practice where product and process people work together during design, so that manufacturing input is built into the development process before downstream problems become harder to solve. The key point of D3 is therefore the broader cross-functional team arrangement not a single review event or one specialist role.

The interview data show that this is one of the clearest covered mechanisms in the wind design phase. MIS-02, described a setting in which design, process, equipment and plant-related knowledge are brought together while the process is still being shaped stating that *"all these three departments will sit together and they will design the process. There will be the designers, the process guys, the equipment experts and together and they are discussing these issues in presence of all the cross-functional team"*. This is a strong D3 match because it shows the exact team based logic described in Framework B, the product and the process are not developed separately and connected only later but are worked on together through a cross-functional arrangement.

From the supplier's side that mechanism is further explained as BME-06 mentioned that *a project based management structure is often used and when multiple companies are involved a liaison project team may be established or dedicated personnel may be assigned for coordination"*. This is important because it shows how this inter-firm mechanism is formed when project coordination spans several organizations. At the same time, the same response noted that "due to varying authority levels and task understandings among the groups, process overlap or confusion can still occur", which shows that even where D3 exists, team based coordination does not remove all ambiguity.

The current data also show that D3 often acts as the broader coordination arrangement inside which other mechanisms operate. In practice, the cross-functional team described by MIS-02 also carries review activity of the kind discussed under C3, while manufacturing-interface roles of the type discussed under C4 appear inside the same arrangement. This is analytically important as it shows that the overlap between D3, C3, and C4 is not a coding problem but part of how coordination actually works in the wind design phase. D3 is the wider team structure, while C3 and C4 are often embedded within it as review and specialist-role mechanisms.

It is important to clarify at this point the difference between the gap identified in mechanism D2 (Section 4.3.8) and the stronger coverage of mechanism D3 in the wind industry. D2 concerns early supplier or manufacturing involvement before the design becomes fixed or reaches a more advanced stage. According to the literature, this mechanism strengthens the DMI by ensuring that manufacturability and producibility are considered from the beginning of product development. D3 addresses related challenges, but at a later stage, when product and process actors work together during the design cycle or close to design finalization. Both mechanisms are important, but they are not the same and do not serve the same purpose. The fact that D3 is more clearly covered in the wind industry does not mean that D2 is also covered, nor does it mean that the DMI is working efficiently, as also shown by the experts' views and suggestions.

Taken together, these findings show that D3 is one of the central covered mechanisms in the wind design phase. The data strongly support the presence of joint product/process coordination through cross-functional teams and project based liaison structures.

4.4.8. Summary

The findings from the design phase show that coordination in the wind context is strongest where it is organised through cross-functional team arrangements, structured reviews and specialist interface roles. The clearest strengths appear in D3 joint product/process design teams, C3 producibility design reviews, and C4 producibility/manufacturing engineers, which together indicate that manufacturability concerns are brought into the design phase through team based interaction, review routines and dedicated manufacturing expertise.

At the same time, the design phase also reveals important weaknesses in its foundations. The clearest gaps concern A5 designers' tacit manufacturing knowledge and A6 design rules. The data suggest that manufacturing knowledge is not strongly enough embedded in day to day design work, while design rules remain fragmented, company-specific and weakly formalised. Expert views also point to possible strengthening directions, including greater shop floor exposure for designers and more formalised tool supported checks during design. In addition, the absence of clear evidence for C5 guest engineers suggests that a more embedded supplier role could be relevant as a future strengthening direction at the DMI. Figure 4.2 summarises this overall design-phase pattern.

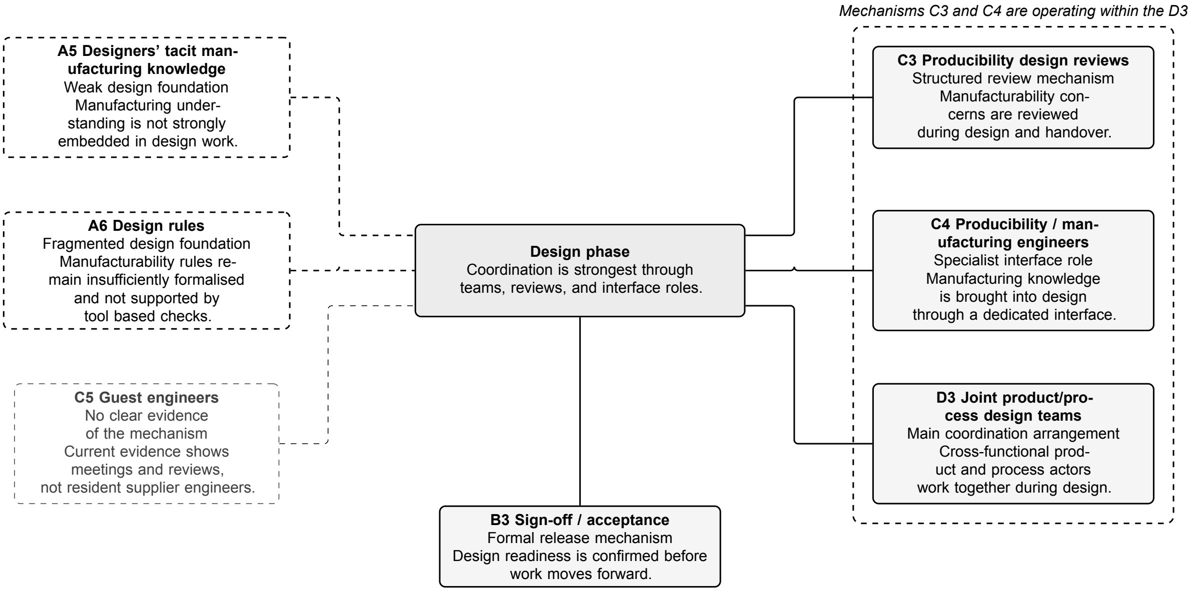

Figure 4.2: Design phase synthesis

As Figure 4.2 shows, D3 should be understood as the central coordination arrangement in the design phase rather than as an isolated mechanism. In the current findings, cross-functional product/process teamwork provides the wider structure within which C3 review routines and C4 specialist manufacturing-interface roles operate. This is important because it clarifies that the stronger coverage of D3 in the wind context does not remove the earlier gap identified under D2. The two mechanisms address related but different coordination needs. D2 concerns early supplier or manufacturing involvement before design becomes more fixed, while D3 concerns coordination during the end of the design phase, when product and process actors are working together around a solid design. The stronger evidence for D3 therefore shows that wind firms have developed more effective later design phase coordination, but it does not mean that early manufacturability involvement is already secured upstream. In this sense, the design phase appears stronger at integrating and reviewing manufacturability concerns once design work is underway than at embedding them early enough to shape initial design choices.

Taken together, these findings suggest that the wind industry is relatively strong in design-phase coordination but weaker in the earlier embedding of manufacturability knowledge and rules that would reduce the need for later corrective coordination.

4.5. Manufacturing and launch phase

4.5.1. B4 Production prototypes and fit-build-test cycles (Schedules and Plans)

B4 refers to production prototypes and fit-build-test cycles used to validate product and process fit before serial production. In Chapter 2, this mechanism was linked to mature-industry practices such as pilot builds, trial sets and build-test cycles, where teams use prototypes not only to check whether the product works, but also whether it can be produced consistently and with the required quality. The key point of B4 is therefore not simply making a prototype, but using prototypes as a structured validation and learning mechanism before full production.

The wind data show that this mechanism is clearly present. MIS-02 explained that teams *"try to do a small proto a trial while also carrying out feasibility studies on the process as well"* and explained the process analytically *"there's a proto set that's made in presence of all the cross-functional team. Then they produce the set and then they validate the set and approve the set, and then after that they will go for serial production"*. This is a strong match with B4 because it shows prototype building, validation, approval, and then serial production in a structured order. A similar logic is described from BME-06 referred to *”conducting trial validations for critical processes in advance and setting up backup plans”*. Taken together, these statements show that wind does use prototypes and trial builds as part of the transition from design into production.

B4 is one of the clearest match and at the same time gap mechanisms in the framework. The issue is not that prototype and validation practices are missing but that their learning function is often compressed by scale-up and commercialization pressure. CCE-04 explained that in earlier periods the market demanded a stronger prototype and track-record discipline, because *”without a proper track record it was difficult to secure insurance and project finance”* contrasting this with later market behaviour where large turbines were commercialized *”without having been validated”*. SEM-05 made the same problem even more explicit by adding that the industry is *”trying to industrialize a new product which hasn’t been tested and at the same time push it into mass production, many units in a very short time. That is the problem statement”*. SEM-05 also recommended *”What is really important is to go through a prototype… allow your engineers the time to learn from the prototype and allow a minimum 2 years between a prototype and commercialization”*.

These findings are important both for the wind industry and for this research. First, they point to a critical problem created by scale-up pressure, that faster commercialization has reduced the reliability and robustness of designs and products. Second, they highlight why this research matters as under such conditions, strong coordination at the DMI becomes essential for reducing wind turbine failures and improving the industry’s ability to meet deployment targets.

Overall, B4 is one of the strongest mechanisms in the wind findings and also one of the most critical. The current data show that wind clearly uses prototypes, trial builds and validation sets in order to secure a stable and reliable production. However, they also show that the main problem lies in the compression of prototype learning and field validation by rapid scale-up and commercialization pressure. In that sense, B4 is not simply a covered mechanism. It is a covered mechanism whose effectiveness is repeatedly undermined when the industry moves faster than the validation cycle can support.

4.5.2. C6 Engineering Changes (Mutual Adjustments)

C6 refers to engineering changes raised during manufacturing or ramp-up, when product or process problems require adjustment after release and it is linked to mature-industry practice where changes are managed through formal routines.

The interview data show that this mechanism is clearly present and mature. SBE-01 stated that *”Change routines are very mature and they’re there, they’re available, and come from the other industries. They fit perfectly into the industry”*. MIS-02 reinforced this by describing engineering change as *”an evolving process in which every month there are a few changes”* showing that change handling is not exceptional but a normal part of ramp-up and production.

The main issue, however, is urgency. SBE-01 explained that although the formal system is mature *”the systems are a bit big sometimes, so when a change is safety relevant there is another urgency path”*, describing how “technical notes” can be introduced through *”the toolbox meeting on the shop floor where the temporary instruction is overriding the stuff but it’s only valid for one month until the formal change request and report catch up. This causes confusion of course because you have something overriding something else”*. BME-06 highlights the same tension noting that *”different stakeholders often have significantly different definitions of what constitutes an urgent change”*.

Taken together, these findings show that C6 is a clearly covered mechanism in the wind manufacturing and launch phase and that the main challenge is not the absence of engineering change routines but the need to handle urgent changes quickly without creating confusion or losing formal traceability.

4.5.3. C7 Site Engineer (Mutual Adjustments)

C7 refers to the practice where customer’s (OEM’s) technical people are present at the supplier or manufacturing site to help solve prototype or production problems directly.

The wind data show that this mechanism is clearly present, although in an adapted form. BME-06 stated that *”the OEM sends a project team to review the process documentation and an on-site team* *supervises the blade manufacturing process while when necessary the OEM's expert team provides remote or on-site technical support"*. This is strong C7 evidence because it shows direct technical involvement at the manufacturing site, but also shows that support is not always permanently resident and may be provided through a hybrid remote/on-site model. This is also supported by LSBM-03 who said *"we're also supporting the process and during startup of this, we would also send a crew of V. (company's) people to ensure that all the processes are as expected and they're followed. The company never produce blades where we simply just hand over the paper saying go and build this blade"*. This is important because it shows that external manufacturing is not treated as a simple handover. Direct technical presence remains part of the coordination logic as LSBM-03 also linked this support to quality verification saying that *"you also want to ensure that the quality is as expected so you go and check that they actually also follow the quality requirements that we have"*.

These findings show that C7 is a clearly covered mechanism in the wind manufacturing and launch phase. In the interview data, C7 appears mainly through startup crews, on-site supervision, final quality checks, and remote or on site expert support.

4.5.4. C8 Product support engineers (Mutual Adjustments)

C8 refers to product support engineers from the supplier side who work alongside the customer's assembly operations to assist with quality, fit and finish and who may also review warranty returns to feed lessons back into design. In this sense, C8 is the reciprocal counterpart of C7, instead of customer employees going to the supplier site, supplier employees support the customer at the point of assembly or early field use.

The current interview data do not clearly identify this mechanism in that form. C8 should therefore be treated as a gap in the wind industry and makes C8 important analytically because it points to a more developed feedback and support loop that was not clearly identified in the wind industry based on the interview data.

4.5.5. D4 Transition Team (Teams)

D4 refers to the transition team mechanism, where design people remain involved after release so that early manufacturing problems can be solved quickly during launch and ramp-up. In Chapter 2 this mechanism was linked to mature industry practice where the handover to manufacturing is not treated as a break but as a phase that still requires continuity between design and production.

The wind data show that this mechanism is clearly present. MIS-02 stated that *"the design guys will be part of the launch"*. LSBM-03's explained from the OEM's point of view that *"we're also supporting the process and during startup of this, we would also send a crew of V. (company's) people to ensure that all the processes are as expected and they're followed. The company never produce blades where we simply just hand over the paper saying go and build this blade"*. These statements show that design and OEM personnel do not disappear after handover, but remain involved during startup and early production.

These findings indicate that D4 is a clearly covered mechanism in the wind manufacturing and launch phase. The main point is that continuity across handover is present, although it appears mostly through launch participation, startup support and project-team involvement rather than through a fully formalized standing transition team. In the wind data, D4 also overlaps with C7, since this continuity is often achieved through site level technical presence and startup support, and with B4 because the transition into production remains closely tied to trials and validation activity.

4.5.6. Summary

The findings from the manufacturing and launch phase show that this is one of the strongest parts of the coordination system in the wind industry. The clearest strengths appear in B4 production prototypes, C6 engineering changes, C7 site engineers, and D4 transition continuity. Together, these mechanisms show that wind firms already use structured validation activity, formal change routines, direct site technical support and continuity across launch and start-up. Figure 4.3 summarises this overall manufacturing and launch pattern.

At the same time, the findings show that the effectiveness of this phase is reduced by two clear operational pressures. The first concerns B4, where prototype learning and field validation are often compressed by commercialisation and scale-up pressure. The issue is therefore not the absence of validation mechanisms but the reduced time available for learning before serial production and market rollout. The second concerns C6, where engineering change routines are clearly established but urgency can create confusion and risks to traceability if rapid changes are not handled carefully. In addition, C8 product support engineers is not clearly identified which suggests that the reciprocal supplier side support loop remains underdeveloped in the wind industry.

The expert views point to several strengthening directions in this phase. The clearest recommendation is to allow more time for learning from prototypes before commercialisation so that validation is not repeatedly undermined by scale-up pressure. The findings also suggest a need for clearer urgency handling in engineering changes, so that fast problem solving does not weaken formal traceability and create competing instructions on the shop floor. More broadly, the current absence of clear C8 evidence suggests that stronger reciprocal support and feedback from the supplier side could improve learning across manufacturing, assembly and early field use. Overall, the manufacturing and launch phase appears highly developed in coordination terms but still vulnerable where time pressure and urgency reduce the full effectiveness of the mechanisms already in place.

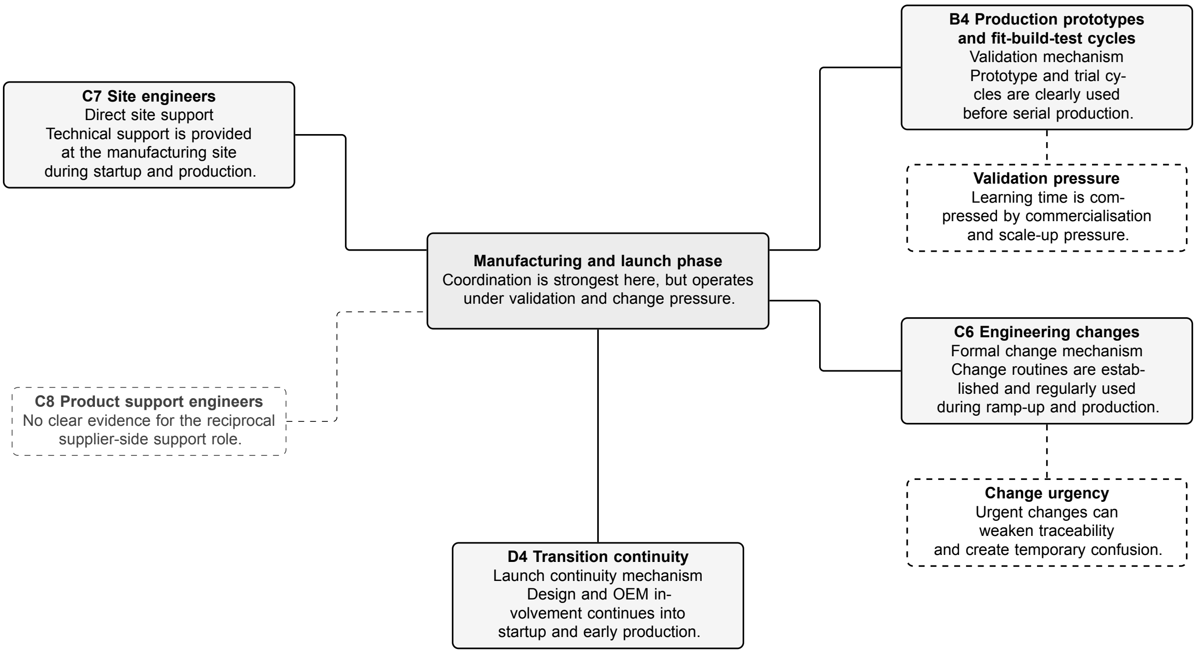

Figure 4.3: Manufacturing and launch phase

4.6. Cross-phase synthesis

While Sections 4.3 to 4.5 examined how the mechanisms in Framework B appeared across the pre-project, design, and manufacturing and launch phases, the interview findings also point to broader patterns that cut across individual mechanisms and phases. The main issue is not that the wind industry lacks coordination overall, but that coordination is uneven across the development process, with stronger evidence of later-stage review, validation, correction, and support than of early manufacturability embedding. This section therefore synthesizes the findings into five cross-phase patterns.

4.6.1. Weak early integration of design and manufacturing

The findings indicate that inter-firm coordination at the design–manufacturing interface in the wind blade industry is not absent but unevenly developed across phases. Several mechanisms already provide meaningful support to the interface, particularly in the later stages of the process. However, this base is concentrated more strongly in later design release, validation, launch support and technical problem solving than in the earlier embedding of manufacturability.

The clearest weakness therefore lies upstream, in the stages where manufacturing knowledge should influence design before key decisions become difficult to reverse. This is most evident in joint development (D2) which emerged as one of the major gaps in the pre-project phase. Although manufacturing is involved, it does not appear to be involved early enough to shape concept development and early design choices. The same diagnosis is reinforced in the design phase by the weak state of designers' tacit manufacturing knowledge (A5), where interviewees described the absence of direct factory exposure for designers and by the fragmented and weakly formalized nature of design rules (A6), including the lack of manufacturability checks from specific software. Compared with the mature industry pattern discussed in Chapter 2, the wind industry therefore appears weaker at embedding manufacturing knowledge early enough to influence design before specifications harden. In that sense, wind industry can adapt and adjust methods from mature industries such as the "Planning Stage" in the automotive industry (4.3.8), job relocation (4.4.1) and develop software for DfX (4.4.3) in order to establish D2 mechanisms and improve A5 and A6 respectively and thus strengthen the overall DMI.

This phase imbalance suggests that coordination in the wind industry currently operates more reactively than preventively. The issue is not that later-phase mechanisms are unimportant or ineffective as they remain central to how the interface is currently stabilized. The problem is that these downstream mechanisms appear to be carrying a larger share of the coordination burden because manufacturability and producibility are not yet embedded early enough to reduce the need for later correction. As a result, the wind industry appears stronger at reviewing, validating, correcting, and supporting design–manufacturing problems later in the process than at preventing them through stronger upstream integration from the outset of product development.

This matters because the thesis addresses a context in which wind turbines are becoming larger and more complex, deployment pressure is increasing and OEMs rely on globally distributed suppliers and manufacturing partners. Under these conditions, the number and criticality of inter-firm handoffs increase and the alignment of design intent with manufacturing realities becomes more consequential for stable industrialization, schedule adherence, avoid of rework and in general reliable scale-up. Because blade manufacturing is both technically complex and operationally sensitive weak early coordination at the DMI increases the likelihood that problems will surface later when they are more difficult and costly to manage. Viewed against mature-industry literature, this suggests that strengthening the wind industry DMI should not focus only on improving late-stage correction mechanisms but also on embedding manufacturing knowledge earlier in development. More systematic joint development, stronger designer exposure to manufacturing environments and more formalized manufacturability rules and checks would help shift coordination from downstream correction toward upstream prevention.

4.6.2. Fragmented cross-enterprise coordination baselines

The upstream weakness identified above is increased by the fragmented nature of cross-enterprise coordination baselines in the wind industry. Chapter 4 showed that APQP and ICE requirements and early process rules are clearly visible in the wind industry. However, the same findings also show that these baselines do not yet extend far enough across firms to create a sufficiently shared coordination foundation. The core A1 problem is therefore whether these technical standards function as inter-firm compatibility baselines rather than as company level structures that lose coherence once design intent moves across organizational boundaries.

This problem becomes particularly visible in the current wind industry production model, where one blade design of an OEM often has to be industrialized across several manufacturing organizations in different regions each with different routines, process assumptions and ways of handling issues. At the same time, because the number of blade suppliers is limited, the same supplier may manufacture blades for more than one OEM, each with different development processes, expectations and decision logics. Under such conditions, judgments about manufacturability, what constitutes a deviation and how change requests should be prioritized can diverge significantly across firms. What is acceptable or feasible in one plant may be treated as problematic in another, while a process that aligns with one OEM's way of working may conflict with another company's. As the findings on design rules (4.4.3) also suggest variation in what is considered acceptable design practice across firms can create misunderstandings, coordination overload and avoidable instability during manufacturing.

Compared with the literature review findings of Chapter 2 the wind industry appears to have adopted selected standardization practices without yet establishing an equally strong shared cross enterprise baseline. In mature-industry terms, A1 is meant to reduce ambiguity early by allowing different actors to work from a common interface definition. In the wind blade context, by contrast the findings suggest that standardization remains more bounded within firms than across the wider network.

The findings also help explain why this fragmentation persists as several interviewees pointed to a sector that remains less mature than industries such as automotive, with weaker shared routines across the wider industry and a stronger tendency for firms to protect what they know rather than build broader common structures (4.3.1). The issue is therefore not only technical complexity but also the commercial and organizational condition of the sector itself. Firms are operating under scale-up pressure, narrow margins and intense competition and therefore hesitating to standardize coordination more broadly across competitors and partners. This makes it more difficult to build stronger partnerships, shared routines and common ways of working that extend beyond the boundaries of one firm and its immediate suppliers.

The limited number of blade suppliers intensifies this challenge further, because different OEMs are often indirectly tied together through overlapping dependence on the same manufacturers, yet that interdependence is not managed through a strong shared coordination structure. What follows from the findings is therefore not a call for sharing proprietary design knowledge but for stronger standardization of the sector's non-proprietary coordination structure. This concerns, for example, how feedback is handled across design and manufacturing boundaries, how manufacturing issues are escalated and resolved, how engineering changes are prioritized, and how routines for communication, supplier collaboration and capability development are organized across firms. The wind industry appears to lack a pre-competitive coordination environment, one that gives firms a more common direction in how they coordinate while still leaving room for competition at product and technology level.

This matters because if concept development and early design work begin without a sufficiently shared cross-enterprise baseline later DMI mechanisms must absorb more ambiguity than they should. Reviews, manufacturing interface roles and site-level support are then forced to compensate downstream for upstream coordination that was never fully stabilized across firms. This helps explain why earlier sections identified a meaningful later stage coordination base in the wind industry while still showing that upstream manufacturability integration remains weaker and more in need of strengthening. In that sense, A1 shapes whether the rest of the DMI can build on a common foundation or whether later phases must continue correcting for fragmentation that should have been addressed earlier.

4.6.3. Weak supplier development and participation

The weaknesses identified in Sections 4.6.1 and 4.6.2 also extend into how the wind industry works with its manufacturing base (suppliers). The findings suggest that weak supplier development and participation represent one of the main upstream weaknesses of the wind blade DMI. Chapter 4 showed that coordination mechanisms related to suppliers are not sufficiently developed. In particular, recurring supplier meetings and supplier quality structures indicate that some supplier learning logic is present yet the findings do not show strong evidence of direct supplier development interventions comparable to those described in mature industry practice (2.5.3 & 2.5.4). Framework C therefore treats D1 primarily as a strengthening direction rather than as an already established mechanism, while B1 and C1 remain relevant but underdeveloped because readiness logic, supplier learning and broader shared support structures appear weaker than would be needed to create a stronger upstream coordination base.

The interview data also point to a broader structural problem behind this weakness. The number of blade manufacturers is limited, margins are low and when one supplier appears promising several OEMs may concentrate demand on it at the same time. This can generate rapid growth in production volume and cash flow but also immediate pressure to scale capacity, workforce and process maturity. Under such conditions, the kinds of coordination weaknesses identified earlier in the thesis, such as weak early supplier involvement, fragmented inter-firm baselines and insufficiently robust design embedding become more likely to surface during industrialization. The issue is therefore that key suppliers they may be pushed into rapid scale-up before the necessary capability base has been built progressively.

Compared with the mature-industry pattern described in Chapter 2, the wind industry therefore appears weaker at treating supplier capability as something to be actively built over time rather than assumed at the point of execution. As highlighted previously, C1 (4.3.6) is visible in a partial form through recurring supplier development meetings, but not yet at the level of maturity described in automotive examples, while D1 (4.3.7) lacks clear evidence of dedicated customer teams providing direct on site operational support to raise supplier performance. B1 (4.3.5) is present, but the pre-project summary also notes that it remains vulnerable to bottlenecks and fragmented planning. Taken together, this suggests that supplier participation in wind is still closer to periodic coordination than to a more stable capability building relationship.

The consequence extends beyond a simple sourcing problem as when manufacturers are repeatedly overloaded, weakened, or replaced, capability is not accumulated and retained in a stable way. Learning is interrupted, improvement trajectories are reset and OEMs continue moving between fragile partners instead of building a stronger manufacturing base over time. As a result, the DMI becomes unstable not only because blade products and processes are technically complex but also because the supplier base itself is insufficiently stabilized. Under such conditions, manufacturability learning is harder to carry from one industrialization effort to the next, and similar coordination and production problems are more likely to recur.

The findings therefore point toward a practical shift in how the industry works with its key manufacturers. Rather than treating blade manufacturers mainly as interchangeable, price driven suppliers, the evidence suggests a need to treat them more as longer-term business partners whose capability must be actively supported and improved. This implies more stable coordination arrangements with manufacturers, including better handling of feedback and recurring issues, stronger involvement in early development and decision making and more deliberate support for capability growth over time.

This also implies that strengthening the upstream DMI requires action across several connected mechanisms rather than through D1 alone. Suppliers need earlier involvement in development (D2), so that manufacturing realities can shape design before major decisions are fixed. Supplier development (D1) should take the form of more direct capability building support between OEMs and key manufacturers, including closer involvement of process and manufacturing specialists, structured support for recurring production problem solving and shared improvement efforts at supplier sites. Capability development schedules and readiness logic (B1) need to be built more progressively, so that capacity, process maturity, and workforce capability are developed before suppliers are pushed into rapid industrialization under high demand. In parallel, broader supplier learning and coordination forums (C1) could help create continuity in how recurring issues, lessons and improvement priorities are shared across the relationship. In this sense, the comparison with mature industries is useful because those industries generally combine earlier supplier involvement, more active supplier development and more deliberate readiness building over time (2.5.3,2.5.4).

Weak supplier development in the wind industry is therefore not an isolated purchasing issue, but part of a wider upstream coordination weakness. A1, D2, D1, B1, and C1 are connected rather than separate: if firms begin from weak common baselines, involve suppliers too late, develop them too weakly, and build readiness under pressure rather than progressively, the supplier base remains fragile and the design–manufacturing interface remains reactive rather than stable.

4.6.4. Compressed prototype learning and validation

Chapter 4.5.1 showed that production prototypes, trial builds, and fit-build-test cycles are clearly present in the wind industry. In that sense, B4 is not a missing mechanism but one of the more established later phase coordination practices. The main weakness lies less in whether prototypes are used and more in how fully they are allowed to function as learning and stabilization mechanisms before commercialization and scale-up.

The findings suggest that the prototype learning cycle is increasingly compressed by commercial and deployment pressure. Prototypes are intended not only to validate the product, but also to generate structured learning about manufacturability, process stability and recurring issues before serial production begins. However, the evidence indicates concern that newer turbines may move toward commercialization before enough time has been allowed for prototype learning, field validation and track record development. In this sense, the mechanism remains present, but its learning value is weakened in use. This matters because when prototype learning and validation discipline are compressed, mechanisms such as engineering changes, site support, and launch-phase problem-solving must absorb issues that should have been reduced earlier. In that sense, weak use of B4 reinforces the broader pattern discussed in this chapter that coordination becomes more reactive when upstream and pre-commercialization learning is shortened. The consequence is not only more pressure on later mechanisms, but also greater risk that recurring design–manufacturing problems are discovered only after scale-up has already begun.

Strengthening B4 therefore requires better protection of prototypes as learning tools rather than treating them primarily as schedule gates. This means tracking findings more carefully, preserving enough time for structural, production, and manufacturing engineers to learn from prototype performance and ensuring that commercialization occurs only after sufficient full-system validation has taken place. In this respect, one interviewee argued that engineers need enough time to learn from the prototype and suggested a minimum two year gap between prototype and commercialization. Whether that exact interval applies universally is less important than the underlying point which is that prototype value depends on the industry allowing enough time for learning before mass industrialization begins.

4.6.5. Shop-floor capability

The interview findings highlight that a further strengthening direction should be added alongside designers' tacit manufacturing knowledge (A5), namely the capability of the workers and technicians who physically translate blade design into the manufactured product. This issue goes beyond A5 as currently defined, because it is not limited to whether designers understand manufacturing from direct exposure but also concerns whether the shop floor has the stable capability required to realize complex blade designs consistently under scale-up conditions. While A5 was identified as one of the clearest weak points in the design phase (4.4.1), the interview material also suggested that the knowledge problem extends beyond designers to workers and technicians on the shop floor.

What the interviews show is that blade production remains highly dependent on manual work and execution skill in key stages. This becomes especially consequential when factories are ramped quickly, when new products are introduced into existing plants or when new sites are expected to industrialize increasingly complex and larger blades under schedule and cost pressure. Under such conditions, worker capability becomes a direct source of interface instability. Several interviewees described a context in which manual operations remain extensive, while skill formation has not always kept pace with growth in production demand. The issue is therefore not only that blade manufacturing contains manual tasks, but that the industry is often trying to scale a highly execution sensitive process faster than worker capability can be built and stabilized.

This matters because composite blade manufacturing is not simply a matter of assembling a fully pre defined product. Production outcomes are highly sensitive to environmental conditions, tools, equipment, fabrics and execution practice, and the final result can vary significantly when the same process is carried out under different conditions. In that setting, manufacturing does not just execute design intent but on the contrary it partly determines how that design is realized in practice. Worker capability and process discipline therefore become part of the interface itself rather than a separate factory issue. A design may be formally correct and still prove difficult to realize robustly if the required tolerances, sequencing, placement accuracy or process controls exceed what can be reproduced consistently in practice.

Compared with the mature industry framework used in this thesis, this is an important extension rather than a direct reuse of an existing mechanism. Framework B captures designers' tacit manufacturing knowledge through A5, but the wind blade context suggests that this alone is not sufficient. In manual composite manufacturing, the capability of the shop floor directly shapes whether design intent can be translated into a stable production outcome. That is why Framework C adds A5* as a distinct strengthening direction as it captures a blade specific capability issue that emerged inductively from the interviews and that was not fully covered by the original mature industry typology.

The findings therefore suggest that A5* should be understood as a capability mechanism concerned with the qualification, stability, and operational readiness of the shop floor in manual composite manufacturing. The strengthening direction implied by the interviews is not a single intervention, but a combination of measures. More structured worker and technician capability development appears necessary, especially around composite specific training, qualification and the disciplined handling of critical manual operations. Stronger shop-floor exposure for designers remains important, because direct contact with manufacturing reality helps design teams understand what stable execution actually requires and where nominal digital design assumptions may be too optimistic. More robust closed loop feedback from production problems into design is also needed so that recurring execution difficulties are not treated only as local factory issues, but are used to improve design robustness, tolerances, and manufacturability assumptions. Finally, selective automation was repeatedly suggested as a longer term way to reduce dependence on craftsmanship where manual variability is most damaging, while still recognizing that human capability will remain important in many parts of blade production.

Taken together, these findings show that worker capability should not be treated only as an operational background condition. In the wind blade case, it is a direct part of whether the DMI functions reliably under scale-up. Where manufacturing remains manual, materially sensitive, and exposed to execution variability, the shop floor becomes a decisive part of how design intent is interpreted and realized. That is why A5* adds something important beyond designers' tacit manufacturing knowledge alone as it captures the fact that stronger DMI in wind requires not only better informed designers, but also a more capable, stable and systematically supported manufacturing workforce to carry complex blade designs into production with consistency.

4.7. Framework C Synthesis for strengthening the DMI in the wind industry

Framework C was developed by translating the findings of Sections 4.3 to 4.6 into explicit framework decisions. The preceding analysis showed, first, how the coordination mechanisms in Framework B appeared across the pre-project, design, and manufacturing and launch phases of the wind turbine blade context and, second, which broader coordination patterns recurred across these findings. On that basis, Framework C does not simply reproduce Framework B. It retains the mechanisms that already form an important coordination base in the wind context, strengthens or adjusts those that remain weak, fragmented, or too late acting, and adds wind-specific directions where the interview findings showed that Framework B did not fully capture the coordination problem. The following stages explain how these decisions were made in order to develop a framework better suited to strengthening the DMI interface in wind turbine blade manufacturing under scale-up pressure.

The first stage concerns the parts of the DMI that are already sufficiently developed to remain central in the refined framework. These include the digital exchange of product-definition information across firms (A2/A3), sign-off and acceptance routines (B3), producibility design reviews (C3), joint product/process design teams (D3), manufacturing/producibility interface roles (C4), site-level engineering support (C7), and continuity across launch and startup (D4). Taken together, these mechanisms show that the wind context already contains a meaningful later-stage coordination base. In the refined framework, they therefore remain central because they already support design review, technical release, launch continuity and cross-functional design process coordination at a level that is important for the DMI. At the same time, the findings also show that these mechanisms are concentrated more strongly in the later phases of the process than in the earlier embedding of manufacturability. Their role in Framework C is therefore not to show that coordination in DMI is already mature, but to define the current coordination base, on which a stronger one must be built.

The second stage concerns the mechanisms that must be strengthened if the DMI is to improve in a more preventive rather than corrective way. The findings show that this need is strongest in the earlier parts of the process. D2 joint development is central here. In the refined framework, D2 must be positioned as a priority mechanism for strengthening earlier manufacturing involvement, because the findings repeatedly show that manufacturing is still brought in too late to shape key design decisions before they become harder to reverse. If the wind DMI is going to become stronger upstream, manufacturing and process knowledge must be involved earlier and in a more structured way during concept and early design work. Basically, what Framework C is suggesting for closing this gap is to bring mechanisms such as C4 and C5 also at an earlier stage. A5 designers' tacit manufacturing knowledge must also be strengthened more explicitly in Framework C. The findings show that designers do not yet have sufficient exposure to manufacturing realities and the expert views point directly to stronger plant exposure, closer shop-floor contact and rotation or early attention to factory practice as ways to rebuild that knowledge. In this sense, Framework C should treat A5 both as a deficiency in current practice and as a strengthening requirement for earlier manufacturability understanding inside the design function. A6 design rules must be developed in a similar way, as the findings show that such rules exist but remain fragmented, insufficiently formalised and too weakly supported by software checks. In the refined framework, A6 should therefore be strengthened toward clearer manufacturability rules, tolerances and acceptance criteria and toward stronger software supported checking of design-for-manufacturing and design-for-assembly requirements during design rather than after problems appear downstream. Together, D2, A5, and A6 define the central strengthening core of Framework C, because they address the part of the DMI that is currently least sufficiently developed and most in need of improvement.

The same strengthening logic applies to the upstream coordination environment within which design and manufacturing begin to interact across firms. In Framework C, A1 compatibility standards remains important, but it must be positioned more explicitly as a cross-enterprise standardisation issue rather than only as an internal early process standard. The findings show that company level APQP routines are already used, but that the wider supply chain baseline remains too fragmented. A4 early cost visibility should also be broadened in the refined framework, as the issue is not simply that early cost awareness exists, but that early evaluation still does not include manufacturability and cycle-time implications strongly enough. B1 capability development schedules likewise remains relevant but should be strengthened toward better alignment of readiness, supplier capability and schedule coordination across multiple projects and firms. C1 supplier development committees should also remain visible in the refined framework but not only as recurring meetings. The findings and expert views suggest that the real strengthening need lies in more institutionalised shared learning and stronger shared coordination definitions across firms. In this sense, A1, A4, B1 and C1 should be positioned in Framework C as mechanisms whose relevance remains high but whose current form is not yet sufficiently developed to support a stronger upstream DMI.

Part of this stage also includes mechanisms in the end-product phase, such as prototype and fit-build-test cycles (B4) and engineering change routines (C6). Although the interview data support the strong validation and change-handling processes of the wind industry in the manufacturing stage, room for improvement has nonetheless been identified through the interview data. More specifically, C6 is already sufficiently developed as a formal mechanism but urgency pathways can still create challenges for clear traceability and create competing instructions in practice. Additionally, the B4 findings show clearly that prototype and validation mechanisms exist but that their effectiveness is repeatedly weakened when the industry moves faster than the learning cycle can support.

The third stage concerns additional strengthening areas that are not yet developed in current wind practice but are still important enough to be carried into Framework C as targeted directions for improvement. One such case is C5 guest engineers. The findings do not clearly evidence a resident or semi resident supplier engineer role in the Toyota sense and the absence of such a role is important because it highlights the gap of a more embedded and continuous supplier contribution that could strengthen the DMI through earlier integration of OEM and supplier knowledge. A similar logic applies to C8 product support and warranty feedback roles where the lack of a stronger reciprocal supplier side support loop suggests a weakness in learning across manufacturing, assembly and early field use. Framework C also adds B2 Relationship assessment programmes as an upstream strengthening direction since a more formalized routine for assessing supplier relationships and coordination capability could help identify weaknesses earlier and support more targeted supplier development and schedule alignment. D1 supplier development teams can also be treated in this way as the findings suggest that more intervention support to suppliers could become a useful upstream strengthening capability for the wind interface. Another important challenge pointed out by the interview data that affects the DMI concerns training and composite manufacturing capability. The findings show that the capability issue is not limited to designers' tacit knowledge alone but extends to worker and technician know-how on the shop floor, especially in composite manufacturing where process sensitivity, material behaviour and execution skill matter strongly. In Framework C, these areas should therefore not be treated as central existing mechanisms but as strengthening directions or new mechanisms that extend the framework beyond what is already sufficiently developed in current practice.

Overall, these decisions show that Framework C does more than reproduce Framework B in a new setting. It keeps the mechanisms that already provide a meaningful coordination base in the wind industry, strengthens those that remain weak, fragmented or too late acting, and adds targeted directions where the interview findings showed that the original framework did not capture the wind context sufficiently. Figure 4.4 and Table 4.2 show that the overall mechanism structure of Framework B is maintained, but refined more explicitly for the wind industry context. The main strengthening emphasis lies in building a stronger upstream coordination base through earlier joint development (D2), stronger tacit manufacturing knowledge and plant exposure for designers (A5), more formalised design rules supported by DfM and DfA checks (A6), and stronger cross-enterprise coordination baselines and supplier-support structures across firms. At the same time, later-phase mechanisms such as prototype and validation cycles (B4) and engineering change routines (C6) remain important, but are refined to protect learning and handle urgency without loss of traceability. Framework C also incorporates added strengthening directions such as shop-floor capability (A5*), guest-engineer type support (C5), supplier development support (D1), relationship assessment (B2) and stronger supplier-side feedback roles (C8). In this way, Framework C makes visible both the current coordination base of the wind industry and the targeted improvements needed to strengthen the design–manufacturing interface more effectively across phases.

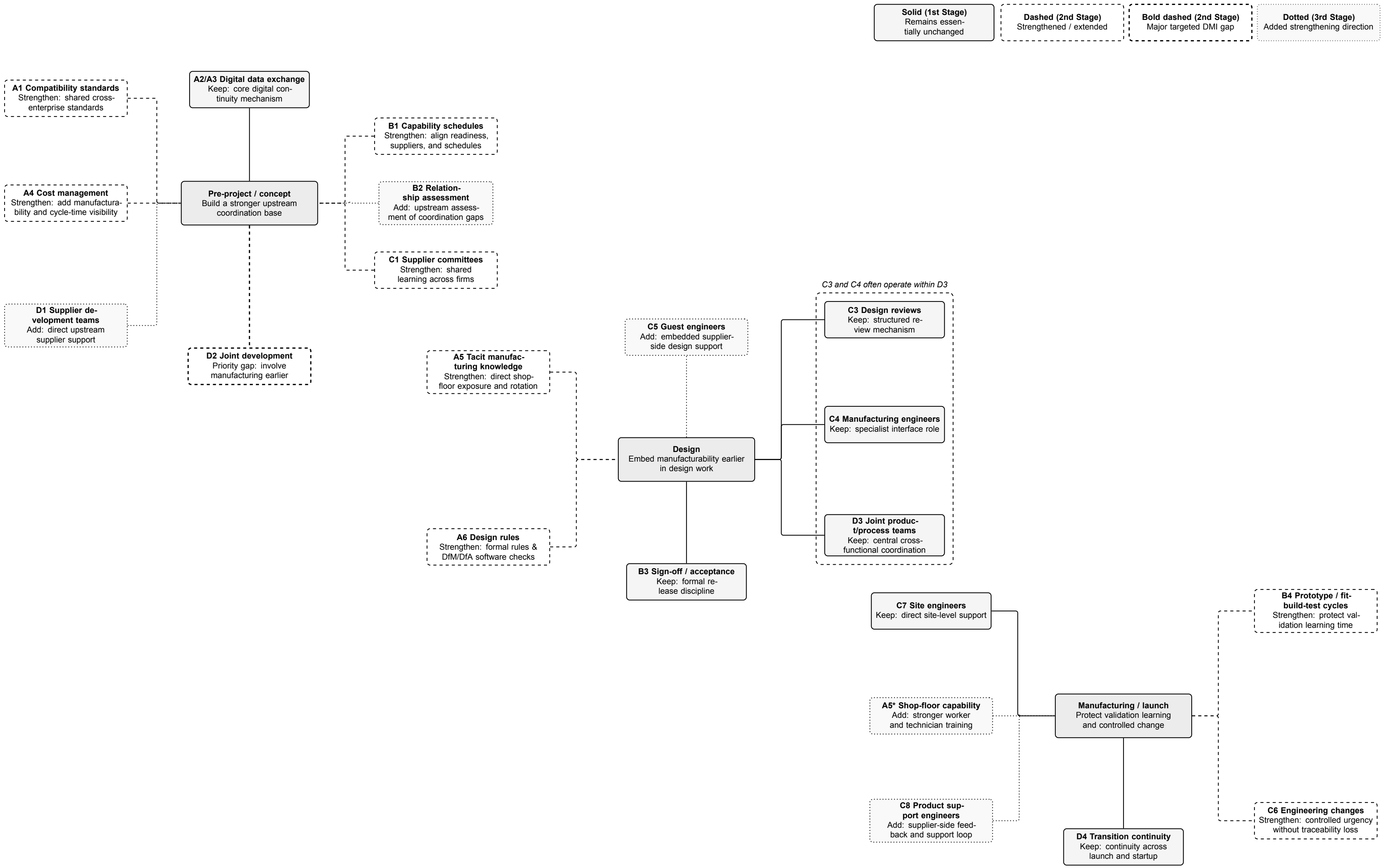

Figure 4.4: Framework C: refined framework for strengthening wind industry's DMI

Table 4.2 complements Figure 4.4 by showing, mechanism by mechanism, how Framework C responds to the current wind industry situation.

Table 4.2: Framework C for strengthening the DMI in the wind industry

Mechanism	Mechanism in Wind Currently	Framework C response	DMI strengthening implication
Pre-project / concept phase			
A1 Compatibility standards	Present, but incomplete across firms and stages.	**Strengthened**	Stronger cross-enterprise standardisation, shared specifications, and clearer interface definitions across OEMs, suppliers, and stages.
A2/A3 Digital inter-firm data exchange and interoperability	Clearly present and already supporting inter-firm product-definition exchange, though uneven across firms.	**Remains essentially unchanged**	Maintain as a core digital coordination mechanism and deepen consistency across firms.
A4 Cost management	Present, but still too narrow because early evaluation does not include manufacturability and cycle-time implications strongly enough.	**Strengthened**	Broaden early evaluation from cost visibility alone to cost, manufacturability and cycle time visibility.
B1 Capability development schedules	Present in planning and readiness logic, but vulnerable to bottlenecks, fragmented schedules, and weak coordination across projects.	**Strengthened**	Better alignment of readiness, supplier capability, and schedule coordination across firms and projects.
C1 Supplier-development committees	Present, but less mature and less institutionalised than in mature industry examples.	**Strengthened**	Move beyond recurring meetings toward stronger shared learning, broader inter-firm knowledge structures, and more mature supplier development support.
D1 Supplier development teams	Not clearly evidenced in current wind practice, but identified as a useful improvement direction.	**Added as strengthening direction**	More direct, intervention oriented upstream supplier support where capability is insufficient.
D2 Joint development	Major current DMI gap, manufacturing is still brought in too late to shape early design choices.	**Major strengthening priority**	Earlier and more structured manufacturing involvement in concept and early design before decisions become harder to change.
Design phase			
A5 Designers' tacit manufacturing knowledge	Not sufficiently embedded in everyday design work. Designers are too distant from shop-floor realities.	**Strengthened**	Stronger designer plant exposure and shop-floor rotation to build manufacturability understanding.
A6 Design rules	Present, but fragmented, insufficiently formalised, and weakly supported by tool based checks.	**Strengthened**	Clearer tolerances, acceptance criteria, and manufacturability rules, supported by software DfM/DfA checking during design.
B3 Sign-off / acceptance	Already sufficiently developed and widely embedded in broader review and release routines.	**Remains essentially unchanged**	Maintain as a core formal readiness and release mechanism.

Mechanism	**Wind situation today**	**Framework C response**	**DMI strengthening implication**
C3 Producibility design reviews	Already sufficiently developed and clearly used in wind design work.	**Remains essentially unchanged**	Maintain structured manufacturability review logic, recognising that it often operates within broader D3 coordination.
C4 Producibility / manufacturing engineers	Already sufficiently developed as a specialist interface role connecting design with factory realities.	**Remains essentially unchanged**	Maintain specialist manufacturing interface support in design, recognising that it often operates within broader D3 coordination.
C5 Guest engineers	Not clearly evidenced in current practice, but analytically important as a possible strengthening direction.	**Added as strengthening direction**	More embedded supplier-side technical contribution during design, beyond meetings and reviews only.
D3 Joint product / process design teams	Already sufficiently developed and one of the clearest design-phase coordination mechanisms.	**Remains essentially unchanged**	Maintain as the broader cross-functional coordination arrangement within which C3 and C4 often operate.
Manufacturing / launch phase			
A5* Composite manufacturing know-how and shop-floor capability	The findings show that the capability problem extends beyond designers to workers and technicians, especially in composite manufacturing.	**Added from wind findings**	Stronger composite specific training, worker capability, and plant manufacturing know-how.
B4 Production prototypes / fit-build-test cycles	Clearly present, but their learning function is compressed by scale-up and commercialisation pressure.	**Strengthened**	Protect prototype and validation learning time before serial production and commercialisation.
C6 Engineering change routines	Clearly present and mature, but urgency can weaken traceability and create temporary confusion.	**Strengthened**	Create controlled urgency paths without bypassing formal change discipline and traceability.
C7 Site engineers	Already sufficiently developed and clearly used, though often in hybrid or temporary form.	**Remains essentially unchanged**	Maintain direct site level technical support during startup and production.
C8 Product support engineers	Not clearly evidenced in current wind practice, but important as a missing reciprocal supplier side support loop.	**Added as strengthening direction**	Stronger supplier side support and early field feedback loops into manufacturing and design.
D4 Transition teams	Already sufficiently developed as continuity across launch and startup, even if achieved through project based forms.	**Remains essentially unchanged**	Maintain continuity between design, launch, startup, and early production.

Together Figure 4.4 and Table 4.2 show that Framework C remains grounded in the original mechanism logic of Framework B but refines it in order to make it more fit for purpose for the wind industry context. The main change lies in making explicit where the wind industry already provides sufficient support to the DMI, where mechanisms require strengthening and where additional strengthening directions are needed.

4.8. Chapter summary

This chapter examined how the coordination mechanisms in Framework B appear in the wind turbine blade context by using the interview data as the empirical basis for interpretation. The findings showed that these mechanisms do not appear with equal strength across the development process. The wind context appears stronger in the later design and manufacturing related phases, where mechanisms for review, sign off, problem solving, engineering changes, site support and transition into launch are more clearly visible, than in the earlier stages where manufacturability should already be embedded before major decisions become harder to change.

The cross phase synthesis showed five broader patterns across these findings. First, early integration of design and manufacturing remains weak, especially where earlier manufacturing involvement, stronger manufacturability knowledge in design and more stable upstream alignment would be needed. Second, coordination baselines across firms remain fragmented, which limits the extent to which standards, rules and shared expectations operate across the wider interface rather than within individual organizations. Third, supplier development and participation appear weaker than in mature industry examples, especially in the upstream phases where capability building and structured joint development would be expected. Fourth, prototype learning and validation remain under pressure, as the findings point to tension between the need for stronger track record building and the commercial pressure to move quickly toward industrialization. Fifth, the interview material showed that shop floor capability should be treated as an added strengthening direction, since execution quality in blade manufacturing remains highly dependent on manual work, operator capability and the handling of sensitive composite processes.

On that basis, Framework C was developed as a refinement of Framework B for the wind industry context. The framework retains the mechanisms that already form an important part of the current coordination base, strengthens or adjusts mechanisms that appear weak, fragmented or too late acting and introduces additional directions where the interview findings showed that Framework B did not capture the coordination problem sufficiently. In this way, Chapter 4 moves from the literature based reference framework, through the interpretation of the interview findings, to a refined framework aimed at strengthening the DMI in wind turbine blade manufacturing under scale up pressure.

Chapter 5 builds on these findings by discussing what this means for the literature on inter-firm design manufacturing coordination and for the wind industry more broadly.

5
Discussion

5.1. Introduction

This chapter discusses the meaning of the findings presented in Chapter 4 by relating them back to the mature industry literature and the wind industry context. Section 5.2 interprets the findings. Section 5.2.1 discusses the usefulness of a mature industry lens for analysing inter-firm design–manufacturing coordination in the wind turbine blade context. Section 5.2.2 explains what the wind case supports about inter-firm DMI coordination, while Section 5.2.3 discusses where the wind case differs from mature industry literature and why adaptation is needed. Section 5.3 discusses the validation of Framework C and clarifies how the framework should be interpreted given the limited empirical validation within this thesis. Section 5.4 then sets out the theoretical contribution of the study. Finally, Section 5.5 explains the contribution of the study to the wind industry. Overall, this chapter moves from the empirical findings to their broader interpretation and contribution.

5.2. Interpreting the findings

5.2.1. Usefulness of a mature-industry lens

Applying a well established coordination typology from mature industries proved useful for examining the wind blade context. This was particularly relevant because the wind industry has been studied far less from an integration and coordination perspective than more established industrial settings, while research has more often focused on technical development and component performance. In that sense, Framework B provided a structured and theoretically grounded way to examine a field in which inter-firm coordination is still less clearly conceptualised. This is consistent with the role Framework B was given earlier in the thesis that was as an intermediate framework derived from mature industry evidence and used to examine how coordination mechanisms appear in the wind blade context in order to enhance DMI and not as a final model of the wind industry.

At the same time, the findings show that Framework B was useful as an analytical lens rather than as a ready made template. Many of the mechanisms identified in mature industries were visible in the wind blade context, which supports the relevance of the framework but they appeared in adapted, partial, uneven, or underdeveloped forms. Chapter 4 showed this clearly. Some mechanisms provided a meaningful coordination base, especially in the later phases, while others remained weak, fragmented or only partly developed. The value of the mature industry lens therefore lies not in offering a set of mechanisms to be copied directly into wind, but in providing a structured basis for identifying what already exists, what remains weak and where refinement is needed.

This is also why the findings justify the refinement from Framework B into Framework C. The empirical material did not simply confirm or reject the mature industry typology. Instead, it showed which mechanisms were sufficiently visible to remain central, which required strengthening and which wind industry's specific conditions had to be recognised more explicitly in order to explain how the interface operates in practice. In that sense, Framework C is not a rejection of the mature industry lens, but its adaptation to a sector in which coordination problems are shaped by global outsourcing, scale-up pressure, fragmented cross-enterprise baselines and blade specific production realities.

The usefulness of the mature industry lens therefore lies in the fact that it made it possible to study the wind blade context with a clearer coordination vocabulary and to identify more precisely where the wind case diverges from the mature industry pattern and thus provide a better view of how to strengthen wind industry's DMI. Framework B made those distinctions visible, while Framework C translates them into a framework that is better suited to the wind industry context.

5.2.2. What the wind case supports about inter-firm DMI coordination

The findings are consistent with the broader literature that treats design and manufacturing as strongly interdependent rather than as separate stages linked only by a downstream handoff. Within NPD, manufacturability and industrialization depend on how well product and process decisions are aligned before serial production begins (Mishra & Shah, 2009; Swink, 1999; Terwiesch et al., 2001; Thomé & Sousa, 2016; Wlazlak et al., 2019). The wind case supports this view as across the findings, the main issue was not the absence of later stage coordination but the unevenness of coordination across phases. The stronger mechanisms appeared mainly in the design and manufacturing or launch phases, where the industry relies on reviews, sign-off, prototype cycles, engineering changes, site support and transition continuity. This suggests that the core problem is not whether design and manufacturing need to be coordinated, but how early and how consistently that coordination is built into the development process. In that sense, the wind case supports the literature's argument that later production problems often reflect earlier failures to align product and process decisions.

The findings are also consistent with coordination theory in showing that inter-firm DMI cannot be managed through a single mechanism. Once work is distributed across firms, coordination must combine more programmed forms, such as standards, formal checkpoints and codified guidance, with more adjustment based forms that allow interpretation, feedback and joint problem solving under uncertainty (Malone & Crowston, 1994; Tai, 2017; Twigg, 2002; Van de Ven et al., 1976). The wind case supports this logic. The empirical material did not point to one dominant mechanism that explained coordination performance on its own. Instead, the interface was managed through a combination of mechanisms, some aimed at pre-specifying information and responsibility, others aimed at handling uncertainty, interpretation and exceptions during development and industrialization. This reinforces the literature's view that inter-firm DMI requires a portfolio of complementary arrangements rather than a single coordination solution.

Finally, the findings support the literature's argument that once design and manufacturing are separated across firms, the issue is not only technical transfer but also coordination across knowledge boundaries, responsibilities and interpretations. Inter-firm DMI problems are not solved simply by transmitting drawings, specifications or design data downstream. They also depend on whether firms can translate design intent into manufacturable requirements, obtain usable feedback from production and resolve ambiguity across organizational boundaries (Carlile, 2002; Olausson et al., 2009; Tai, 2017; Takeishi, 2001). The wind case supports this point clearly as the recurring need for reviews, interface roles, site support, engineering change routines and later-phase correction mechanisms as well as the emphasis on the development of ”cross-enterprise” coordination standards, indicates that the challenge is not merely to transmit technical information but to align different actors around shared understanding and workable decisions. This supports the broader DMI and coordination theory view that cross-firm industrialization depends on managing dependencies, interpretations and feedback across the interface, not only on technical design quality in isolation.

5.2.3. Where the wind case differs from mature-industry literature

Although the mature industry lens proved useful, the wind case does not fully fit in this pattern. The findings suggest a more uneven coordination base in which later-phase mechanisms are more visible than upstream ones. Reviews, sign-off, engineering changes, site support and transition continuity are present, but earlier integration remains weaker and less consistently embedded across firms. In that sense, the wind case suggests that coordination is weighted too much toward later correction and too little toward earlier alignment.

A clear difference concerns the strength of cross-enterprise coordination baselines. In mature industry terms, mechanisms such as compatibility standards, shared interface rules, and common approval structures are intended to reduce ambiguity early and allow different actors to work from a stable common baseline (Twigg, 2002). The wind case suggests a weaker version of that condition. Although selected standards and structured processes are visible, they do not yet appear to extend strongly enough across firms to create a sufficiently shared coordination foundation. Instead, the findings point to a setting in which different OEMs, plants, and suppliers may work with different routines, assumptions, and decision logics, even where they are indirectly tied together through overlapping supply arrangements.

Another difference concerns supplier development and participation as mature industry literature does not treat suppliers only as external production capacity but as partners whose readiness, capability and development are supported through more structured forms of interaction, assessment and joint development (Dyer & Nobeoka, 2000; Reed & Walsh, 2002; Twigg, 2002). The wind case suggests a weaker and less institutionalized version of this logic as supplier meetings and some planning structures are present but the broader development logic seen in mature industry examples (2.5.3, 2.5.4) appears less developed. This matters because the findings suggest that manufacturing capability is often expected to absorb scale-up pressure without equally strong upstream capability building structures across firms. In this respect, the wind case differs from the mature industry pattern not because supplier participation is absent but because it appears less deliberate, less systematic and less deeply embedded in the wider coordination architecture.

A related difference concerns the role of prototypes and validation. Mature-industry literature treats pilot builds, prototype runs and fit-build-test cycles as learning mechanisms that help surface problems before full industrialization begins (Adler et al., 1999; Cohee et al., 2019; Twigg, 2002). In the wind case, such mechanisms are clearly present but their learning function appears more compressed. The findings suggest that commercialization pressure can reduce the time available for structural, manufacturing and production teams to learn fully from prototype outcomes before scale-up begins. As a result, prototypes remain formally present but may function more as compressed validation checkpoints than as fully protected learning phases. This is important because it pushes more problem absorption into later mechanisms such as engineering changes, site support and launch-phase correction.

5.3. Validation of Framework C

Framework C was shared with the interview participants after its development. The purpose of this step was to ask whether the final framework and the main strengthening directions were recognizable, relevant and useful for the wind turbine blade industry, and whether important coordination mechanisms or practical issues had not been sufficiently captured. However, due to time limitations, no additional feedback was received from the interviewees before finalizing the thesis. Therefore, Framework C should be understood as an analytically grounded framework rather than as a fully externally validated sector wide model.

The credibility of Framework C comes from the structured way in which it was developed. First, Framework B was derived from mature industry literature and used as the analytical reference for the empirical work. Second, the interview material was analysed through directed qualitative content analysis, using Framework B as the initial coding structure while still allowing non-fitting and repeated wind-specific material to remain visible. Third, the findings were reduced into mechanism summaries, compared across mechanisms and phases, and translated into Framework C through explicit framework decisions. This means that Framework C was not developed from isolated interview statements, but from repeated patterns in the interview material and from the comparison between mature industry mechanisms and the wind blade context.

At the same time, the validation of Framework C remains limited. The empirical basis consists of seven expert interviews, which is suitable for exploratory qualitative research but not sufficient for a definitive assessment of the whole wind industry. The framework should therefore be interpreted as a qualitative mapping of coordination patterns and improvement directions in the wind turbine blade context. Some mechanisms are strongly supported by repeated interview evidence, while others are included as analytically relevant strengthening directions that require further empirical testing.

Further validation could be done in three ways. First, Framework C could be reviewed by additional

OEM, supplier and manufacturing experts to assess whether the mechanisms are recognizable, complete and useful. Second, it could be applied to one or more real blade development or industrialization programmes to examine whether it helps identify coordination weaknesses in practice. Third, the framework could be compared with company documents, such as design review records, quality planning documents, engineering change records, launch reports and supplier interface documentation. In this way, future validation can test whether Framework C is also practically useful for strengthening inter-firm DMI coordination in wind turbine blade manufacturing.

5.4. Theoretical contribution

In mature industry research, processes within NPD are understood as strongly interdependent processes in which product design, manufacturing knowledge and production readiness must be aligned if industrialization is to remain stable (Mishra & Shah, 2009; Swink, 1999). Within that broader problem, the DMI is critical because it is the point where design intent and manufacturing realities must be brought into alignment (Thomé & Sousa, 2016). Existing wind industry research, however, has rarely examined wind turbine blade industrialization through the DMI and coordination theory, even though offshore wind has been identified as an underexplored but promising setting for testing and extending organizational and interorganizational theories in complex project based environments (Johnsen et al., 2019; Neri, 2016). Instead, offshore wind has more often been studied through technical, techno-economic, and adjacent supply chain lenses than through inter-firm coordination at the DMI (D'Amico et al., 2017; Neri, 2016; Skjølsvold et al., 2024). The first theoretical contribution of this thesis is therefore to show that the wind blade context can be studied productively through the DMI lens, and that doing so makes visible coordination problems that are not sufficiently captured by more technical or purely logistical perspectives.

The second theoretical contribution is that the thesis applies coordination theory to explain how the inter-firm DMI is actually supported in the wind blade context, where that support remains weak and why those weaknesses matter for industrialization and scale-up. Rather than treating coordination problems only as general communication failures or supply chain inefficiencies, the thesis shows them more specifically as problems of dependency management across firms, phases and knowledge boundaries (Carlile, 2002; Malone & Crowston, 1994; Okhuysen & Bechky, 2009). This helps explain why the wind blade DMI depends not on one mechanism, but on a combination of standards, reviews, specialist roles, sign-off routines, prototype learning, engineering change processes and cross phase support. In that sense, the thesis contributes a more explicit coordination explanation for wind blade industrialization problems than much of the current wind literature provides.

The third theoretical contribution is that the thesis shows that mature industry coordination mechanisms are transferable to the wind blade context only selectively. Framework B proved useful as a reference structure for identifying and organising inter-firm DMI mechanisms but the empirical findings showed that these mechanisms do not appear in wind in the same form or with the same balance as in mature industry examples. Their appearance is more uneven, more partial and more shaped by wind-specific conditions such as global outsourcing, scale-up pressure, fragmented cross-enterprise baselines and the manual and materially sensitive nature of blade manufacturing. The refinement from Framework B to Framework C is therefore not only an empirical adjustment, but also a theoretical one. It shows how the mature industry DMI logic changes when applied to the wind blade context and why both selective transfer and context specific adaptation are needed when inter-firm coordination theory is brought into this sector.

5.5. Contribution to the wind industry

The value of this thesis for the wind industry lies in showing more clearly that stronger blade industrialization depends not only on technical design but also on how coordination is organised across firms. The findings indicate that OEMs and manufacturers need to work together earlier and more deliberately so that manufacturing realities shape concept choices, design rules, readiness planning and industrialization decisions before major problems are locked in. In that sense, the study points to the need for a stronger upstream coordination base rather than continued reliance on later correction.

The findings also suggest that blade suppliers should not be treated mainly as external production capacity, but as industrialization partners whose capability, readiness and learning need to be developed progressively over time. This is especially important in a context where manual composite manufacturing still makes execution quality highly sensitive to worker capability, process discipline and variation in how production is actually carried out. A more deliberate supplier development logic is therefore needed if industrialization is to become more reliable under scale-up pressure.

At the same time, the study shows that more reliable scale-up cannot be achieved only through improvements inside individual OEM–supplier relationships. The industry also needs stronger shared coordination structures across firms, including clearer interface definitions, better escalation and feedback routines more consistent change handling practices and stronger common expectations around supplier development and readiness. Without a stronger cross-enterprise coordination base, even well developed mechanisms inside single firms are likely to remain limited in their effect.

Finally, the thesis shows that commercialization pressure has itself become part of the coordination problem. Prototype and validation mechanisms are present but their learning value weakens when new turbines are pushed toward market introduction before enough track record and industrialization learning have been built. This suggests that more reliable scale-up depends not only on having prototype and validation structures in place, but also on protecting them from being compressed by commercial pressure.

The study also contributes to the wind industry by moving beyond diagnosis alone. It does not only show where coordination at the DMI remains weak or uneven but also translates these findings into a more concrete strengthening framework through Framework C. In this way, the research identifies not only the broader areas in which coordination needs to improve, but also which existing mechanisms provide a useful base and should remain central which require stronger implementation in the wind blade context and where additional directions are needed to address conditions that the mature industry framework did not capture sufficiently. This is important because it gives the industry not only a clearer explanation of the current coordination problem, but also a more structured basis for strengthening the interface in practice.

Overall, the contribution of this thesis to the wind industry lies in making the DMI more visible as a practical coordination problem rather than treating failures mainly as technical or isolated operational issues. By identifying which coordination mechanisms already provide a base in the wind blade context, which remain weak or fragmented, and where additional strengthening directions are needed, the study offers a more structured basis for improving blade industrialization under scale-up pressure. In that sense, its value for the industry lies not only in diagnosing where coordination is failing but also in clarifying where improvement efforts should be focused if more reliable turbine scale-up is to be achieved.

6

Conclusion

6.1. Introduction

This chapter concludes the thesis by answering the research questions of the study. Section 6.2 answers Sub-question 1, Section 6.3 answers Sub-question 2, and Section 6.4 answers Sub-question 3. Section 6.5 then answers the main research question by bringing these results together. Section 6.6 discusses the limitations of the study, while Section 6.7 presents recommendations for industry practice and future research.

6.2. Answer to SQ1

Which coordination mechanisms are identified in mature industries for managing the design– manufacturing interface across firms?

The literature review showed that mature industries manage the inter-firm DMI through a structured set of coordination mechanisms rather than through one single practice. Using coordination theory as the analytical lens and Twigg's inter-organizational DMI typology as the main organizing structure, these mechanisms were identified and organized in two complementary ways. They can be grouped into four coordination families which reflect different coordination logic and across the main phases of product development. In the pre-project phase, coordination is oriented more toward defining common rules and aligning expectations. In the design phase, the emphasis shifts toward integrating manufacturability knowledge into developing designs. In the manufacturing phase, coordination becomes more focused on handling remaining uncertainty and solving production problems.

On that basis, Chapter 2 developed Framework A as the reference framework fully based on the literature and Framework B as an intermediate framework derived from Framework A and aligned more closely with mature industry practices. In this thesis, Framework B serves as the literature based analytical reference structure for examining how these coordination mechanisms appear in the wind blade context and for supporting the later refinement into Framework C. SQ1 therefore showed that mature industry DMI coordination is systematic, multi mechanism and phase dependent rather than ad hoc or limited to isolated practices.

6.3. Answer to SQ2

To what extent do these coordination mechanisms appear in wind turbine blade manufacturing and how are they adapted, absent or underdeveloped?

The interview findings showed that many of the coordination mechanisms identified in mature industries are also visible in wind turbine blade manufacturing, but they do not appear as a fully developed or coherent inter-firm DMI system. Using Framework B as the analytical reference structure, Chapter 4 showed that the wind context contains a mix of clear matches, adapted forms, partial practices and important gaps.

A first important finding was that the overall coordination base is uneven across phases. Chapter 4 explicitly showed stronger mechanisms later in the process and weaker coordination earlier, where manufacturability and cross firm alignment should ideally be embedded upstream. In the pre-project phase, formal starting structures are visible and some mechanisms from Framework B are clearly present, such as digital inter-firm data exchange (4.3.2) and elements of standards based coordination (4.3.1). At the same time, this phase also showed some of the clearest weaknesses: shared standards across firms remain incomplete, readiness and planning structures appear in adapted rather than robust form (4.3.5), supplier development forums exist but are less developed than in the mature-industry model (4.3.6), and early joint development remains an important gap (4.3.8). This means that the early coordination base exists, but it is not yet strong enough to systematically bring manufacturing influence into design-shaping decisions from the beginning.

The findings from the later phases showed a stronger coordination picture, but not a fully mature one. The chapter was structured by development phase precisely because multiple mechanisms operate together in practice and this phase based reading showed that design and manufacturing/launch contain a more visible coordination base than the upstream phase. Across these later stages, the data point to more established use of design review (4.4.4), technical support (4.4.5, 4.5.3), engineering response (4.5.2), and launch related continuity structures (4.5.5). However, these mechanisms also do not appear in the wind context exactly as described in mature industry literature. They often appear in partial, adapted, or uneven forms rather than as stable, highly institutionalized arrangements.

Taken together, the answer to SQ2 is that mature industry coordination mechanisms do appear in wind turbine blade manufacturing, but unevenly and with significant contextual variation. Some are clearly visible, some are adapted to the wind context and others remain weak, fragmented or underdeveloped. The main empirical pattern is therefore not simple absence, but incomplete and uneven development. A partial coordination base exists, yet the mechanisms that would embed manufacturability earlier, strengthen supplier side participation, and create stronger upstream inter-firm alignment remain the weakest parts of the current wind blade DMI.

6.4. Answer to SQ3

How should these coordination mechanisms be adjusted to better fit the wind turbine blade context and strengthen inter-firm design–manufacturing coordination in support of more reliable scale-up?

The findings indicate that the coordination mechanisms identified in mature industries should not be transferred directly to the wind turbine blade context as fixed templates. Instead, they need to be adjusted in a way that reflects both the existing coordination base of the wind industry and the specific weaknesses that emerged from the empirical findings. Framework C therefore does not replace Framework B, but refines it. More specifically, it distinguishes between mechanisms that already provide sufficiently developed support to the DMI, mechanisms that remain relevant but require strengthening and additional strengthening directions that emerged from the interview data as important in the wind blade context.

The main adjustment required is a stronger earlier embedding of manufacturability in inter-firm design work. In the current wind context, coordination is still stronger at reviewing, correcting and stabilizing problems later in the process than at preventing them upstream. Framework C therefore gives priority to earlier joint development between design and manufacturing (D2), stronger tacit manufacturing knowledge and plant exposure for designers (A5) and more explicit and formalized design rules supported by manufacturability oriented software checks (A6). Together, these mechanisms form the central strengthening core of the refined framework because they address the part of the DMI that the findings showed to be least sufficiently developed and most in need of improvement.

A second adjustment concerns the wider upstream coordination environment across firms. The findings suggest that stronger DMI coordination in wind requires more than improving the design phase alone. It also requires a more stable cross enterprise base through stronger compatibility standards across firms (A1), broader early evaluation of cost together with manufacturability and cycle time implications (A4), better alignment of readiness, supplier capability and schedules (B1), and more institutionalised shared learning across firms (C1). In the same logic, Framework C adds strengthening directions such as relationship assessment programmes (B2), supplier development teams (D1) and guest engineers (C5), because the wind blade context appears weaker than mature industries in building supplier capability progressively and in embedding supplier side knowledge early enough in the coordination process.

The later phases also require adjustment, but not because they are absent. Rather, they need to function less as compensation mechanisms for earlier weaknesses. Framework C therefore keeps mechanisms such as sign-off (C6), design reviews (C3), manufacturing interface roles (C4), joint product/process teams (D3, D4), site engineers (C7) and transition continuity as central parts of the coordination base, while refining prototype and validation cycles (B4) and engineering change routines (C6) to better fit the pressures of compressed learning and urgency in the wind industry. This means protecting prototype learning time more explicitly and handling urgent engineering changes without loss of traceability. Finally, the findings also justify wind-specific additions beyond the original mature industry typology, especially stronger product support feedback loops (C8) and shop floor capability as an added strengthening direction (A5*). This last point is particularly important in blade manufacturing, where manual composite work, process sensitivity and execution skill mean that reliable DMI coordination depends not only on better informed designers, but also on a more capable and stable manufacturing workforce. SQ3 therefore showed that stronger inter-firm DMI coordination in wind requires a refined framework that both strengthens weak mature industry mechanisms and extends the framework where blade specific production realities demand it.

6.5. Answer to the main research question

How can the design–manufacturing interface across firms in wind turbine blade manufactur- ing be strengthened to support more reliable turbine scale-up under increasing deployment pressure, using coordination mechanisms identified in mature industries?

The findings of this thesis indicate that the DMI across firms in wind turbine blade manufacturing can be strengthened not by transferring mature industry coordination mechanisms directly as fixed templates, but by using them as a structured reference and refining them to the wind blade context. The literature review showed that mature industries rely on a systematic set of inter-firm DMI coordination mechanisms, while the empirical findings showed that the wind industry already contains part of such a coordination base but in an uneven form. More specifically, the current wind industry pattern appears stronger in later review, validation, engineering response and launch support than in the earlier embedding of manufacturability and supplier side coordination. As a result, strengthening the DMI requires shifting a greater share of coordination effort upstream, so that manufacturing knowledge influences design before key decisions harden and before later mechanisms are forced to compensate for earlier weaknesses.

In this thesis, that answer is expressed through Framework C. Framework C shows that more reliable turbine scale-up depends on a stronger earlier integration of design and manufacturing, stronger cross-firm standardization and shared learning, clearer and more explicit manufacturability guidance, protected prototype learning, and more robust handling of engineering change and production feedback. At the same time, the findings also show that the wind blade context requires additions beyond the original mature industry template, especially where manual composite manufacturing, shop-floor capability and wider cross-enterprise fragmentation shape whether design intent can be translated into stable production outcomes.

The main research question is therefore answered as follows: the inter-firm DMI in wind turbine blade manufacturing can be strengthened by refining mature industry coordination mechanisms into a wind-specific framework that both reinforces weak upstream mechanisms and adjusts the coordination structure to the realities of blade industrialization and wind industry's unique conditions under scale-up pressure. This need for adaptation is important because wind turbine blade manufacturing differs from mature industries such as automotive. Both industries work with several components and suppliers, but wind blades are very large composite structures with manual-intensive production, rapid increases in product size and strong pressure to commercialize new platforms quickly. Compared with automotive, wind blade production has more variation between manufacturing sites and stronger dependence on supplier and shop-floor capability.

6.6. Limitations

This study has several limitations that should be considered when interpreting its findings. First, the study was developed in a context where research on inter-firm design–manufacturing coordination in the wind industry is still limited. Because of this, the literature review could not build on an extensive body of literature from the wind industry on this topic. Instead, the thesis used literature from mature industries as the main analytical point in order to identify coordination mechanisms and develop Framework A and Framework B before examining how these appear in the wind blade industry. This was necessary, but it also means that the initial analytical basis came from other industrial settings and was then adjusted to wind, rather than being built from an extensive wind-specific literature base from the beginning.

Second, the empirical part of the study was based on semi-structured expert interviews. This was because the aim was to understand how coordination mechanisms appear in practice, how they are adapted or underdeveloped and how the empirical findings could be used to refine the framework which was based on the literature. At the same time, the study did not include internal company documents or a formal company case study that could provide additional triangulation. As a result, the findings offer a detailed picture based on experts' insights into the DMI, but they do not include the same level of evidence from company documents or company processes that a case study within one company might have provided.

Third, the number of interviewees was relatively limited. The final sample included seven experts with backgrounds in OEM, supplier manufacturing or in both contexts. The interviewees provided useful insights from both perspectives into how design and manufacturing are coordinated across firms in the wind blade context. However, the sample remains small. For this reason, the findings should not be read as an assessment of the whole wind industry but instead be understood as an exploratory qualitative mapping of how selected coordination mechanisms appear, where they seem weak or underdeveloped, and where improvement directions can be identified.

Finally, as discussed in Section 5.3, Framework C was not fully validated through implementation in a live industrial setting. The study shows how Framework C can be analytically derived from the literature review and interview findings, but it does not yet show how its use would affect coordination performance in practice over time. Therefore, Framework C should be understood as a grounded but still developing framework that requires further validation in real blade development or industrialization settings.

6.7. Recommendations

6.7.1. Recommendations for industry practice

Based on the findings of this study, several practical recommendations can be made for the wind industry. First, OEMs and blade manufacturers should work together earlier and more deliberately during concept development and design. The findings showed that manufacturability is still brought in too late and that later coordination mechanisms are often forced to correct problems that should have been addressed earlier. Earlier involvement of manufacturing would allow production realities to shape concept choices, design rules, readiness planning and industrialization decisions before major design choices are fixed. More systematic joint development, stronger designer exposure to manufacturing environments and more formalized manufacturability rules and checks would help shift coordination from downstream correction toward upstream prevention.

Second, the industry should work toward a more stable supplier base and a more active way of developing suppliers. OEMs should rely less on treating blade manufacturers as suppliers that can easily be replaced and should instead build more stable long-term relationships with key manufacturers. This means involving suppliers earlier in development, supporting their growth more directly and building readiness more gradually before they are pushed into rapid industrialization. In particular, production capacity, workforce capability and process maturity should be built before too much demand is placed on one supplier during scale-up. The aim should be to build and keep capability over time, instead of repeatedly moving between weak manufacturing partners.

Third, the industry should move toward stronger shared non-proprietary coordination structures across firms. The findings suggest that the current problem is not the absence of standards as such but the incomplete reach of those standards across organizational boundaries. Because the number of blade suppliers is limited, the same manufacturers may work with more than one OEM, each with different routines, expectations, and decision logics. Under these conditions, firms are indirectly tied together through overlapping dependence on the same supplier base, yet this interdependence is not managed through a stronger shared coordination structure. What is needed is therefore not the sharing of proprietary design knowledge, but greater standardization of the sector's non-proprietary coordination environment, such as clearer interface definitions, better escalation and feedback routines, more consistent change handling practices and stronger common expectations around supplier collaboration and readiness as well as development.

Finally, stronger discipline is needed around prototype learning, validation and commercialization timing. The findings showed that prototypes and validation mechanisms are present in the wind industry but their learning value weakens when turbine programs are pushed toward commercialization too quickly. This suggests that the issue cannot be left only to the short term commercial pressures of individual firms. In addition to better tracking of prototype findings and stronger learning before serial production, there is also a need for a firmer sector or policy level discipline around how much validation and track record should exist before new turbines move into full commercialization and scale-up.

6.7.2. Recommendations for future research

Future research should build on this study in several more focused ways. First, Framework C should be examined through application in practice. This thesis showed how the framework can be developed from the literature review and interview findings but it did not test how its use would affect coordination in live industrial settings. A next step would therefore be to apply Framework C in real blade development and industrialization settings and examine how it functions in practice over time.

Second, future research should examine the cross-enterprise coordination problem more directly. This study showed that one of the main weaknesses of the current wind blade DMI is the fragmented nature of coordination baselines across firms, especially in a sector where different OEMs may depend on the same limited supplier base while using different routines, expectations and decision logics. Further research could therefore look more closely at how overlapping OEM–supplier relationships affect manufacturability judgments, engineering changes, escalation routines and coordination stability across the wider network.

Finally, future research could examine the DMI through richer case based evidence. This study relied mainly on expert interviews. Further research could build on this by using internal company documents, engineering change records, meeting material, readiness documents or observations from one or more blade programs. This would make it possible to examine coordination not only through expert's perspective but also through how coordination is formally organized and how issues are handled in practice.

References

A220 suppliers quality requirements (Rev. 2) [Previously known as ASQR 4.6; internal quality management document]. (2024, January 12). Airbus Canada.

Adient. (2019, April). *Global supplier standards manual - quality* (Revision 3.0) [Document ID: AE-PSOS-ST-12-E].

Adler, P. S. (1995). Interdepartmental interdependence and coordination: The case of the design/manufacturing interface. *Organization Science*, *6*(2), 147–167. https://doi.org/10.1287/orsc.6.2.147

Adler, P. S., Goldoftas, B., & Levine, D. I. (1999). Flexibility versus efficiency? A case study of model changeovers in the Toyota production system. *Organization Science*, *10*(1), 43–68. https://doi.org/10.1287/orsc.10.1.43

Andersson, P., Wolgast, A., & Isaksson, O. (2008). Current industrial practices for re-use of manufacturing experience in a multidisciplinary design perspective. *International Design Conference - DESIGN 2008*.

Aoki, K., & Wilhelm, M. (2017). The role of ambidexterity in managing buyer-supplier relationships: The Toyota case. *Organization Science*, *28*(6), 1080–1097. https://doi.org/10.1287/orsc.2017.1156

Ashwill, T. D., Ogilvie, A., & Paquette, J. (2013, April). *Blade reliability collaborative: Collection of defect, damage and repair data* (tech. rep. No. SAND2013-3197) (Unlimited Release. Approved for public release; further dissemination unlimited). Sandia National Laboratories. Albuquerque, New Mexico, Livermore, California.

Bayne, L. (2010, May). *Supplier development practices in the South African motor industry* [Master's thesis, University of Cape Town].

Carlile, P. R. (2002). A pragmatic view of knowledge and boundaries: Boundary objects in new product development. *Organization Science*, *13*(4), 442–455. https://doi.org/10.1287/orsc.13.4.442.2953

Cohee, G. L., Barrows, J., & Handfield, R. (2019). Early supplier integration in the us defense industry. *Journal of Defense Analytics and Logistics*, *3*(1), 2–28. https://doi.org/10.1108/JDAL-03-2018-0007

DaimlerChrysler Corporation. (2004, December). *Process sign-off (pso)* (Fifth Edition). DaimlerChrysler Corporation.

D'Amico, F., Mogre, R., Clarke, S., Lindgreen, A., & Hingley, M. (2017). How purchasing and supply management practices affect key success factors: The case of the offshore-wind supply chain. *Journal of Business & Industrial Marketing*, *32*(2), 218–226. https://doi.org/10.1108/JBIM-10-2014-0210

David, A. (2021, May). The evolution of global onshore wind turbine blade production and trade [Executive Briefings on Trade]. https://www.usitc.gov/publications/332/ID-032_final.pdf

Dekkers, R., Chang, C. M., & Kreutzfeldt, J. (2013). The interface between "product design and engineering" and manufacturing: A review of the literature and empirical evidence. *International Journal of Production Economics*, *144*, 316–333. https://doi.org/10.1016/j.ijpe.2013.02.020

Delaunay, J.-Y. (2019). Use of ISO 10303 STEP AP242 ed1 for configured MBD interoperability. *Global Product Data Interoperability Summit (GPDIS)*.

Dyer, J. H., & Nobeoka, K. (2000). Creating and managing a high-performance knowledge-sharing network: The toyota case. *Strategic Management Journal*, *21*, 345–367.

European Bank for Reconstruction and Development. (2023). *Wind-sector supply chain guidance* (tech. rep.) (Environmental and social risk management toolkit for financial intermediaries). EBRD. London, United Kingdom. https://www.ebrd.com/content/dam/ebrd_dxp/assets/pdfs/financial-institution/sustainable-finance/environmental-and-social-risk-management/issues/Wind-sector-supply-chain-guidance.pdf

European Commission. (2025). *Focus: Wind energy – powering the clean transition* [Accessed: 2025-07-05]. European Commission. https://energy.ec.europa.eu/news/focus-wind-energy-powering-clean-transition-2025-03-17_en

Fife, S. T., & Gossner, J. D. (2024). Deductive qualitative analysis: Evaluating, expanding, and refining theory. *International Journal of Qualitative Methods*, *23*, 1–12. https://doi.org/10.1177/16094069241244856

Flankegård, F., Granlund, A., & Johansson, G. (2021). Supplier involvement in product development: Challenges and mitigating mechanisms from a supplier perspective. *Journal of Engineering and Technology Management*, *60*, 101628.

Ford Motor Company. (2006, September). *Electronic supplier communication with ford: Edi brochure (en)* (Version 1.94) [Date Revised: 20.09.2006. Originator: GSEC]. Global Supplier Electronic Communications (GSEC). https://portal.covisint.com

Forman, H. (2001). Supplier development at deere & company [Case study. Reprinted with permission from the Institute for Supply Management, 2001 Case Writing Workshop].

Garcia, F., Grabot, B., & Paché, G. (2019). Adoption mechanisms of a supplier portal: A case study in the european aerospace industry. *Computers & Industrial Engineering*, *137*, 106105. https://doi.org/10.1016/j.caie.2019.106105

Gittell, J. H. (2006). Relational coordination: Coordinating work through relationships of shared goals, shared knowledge and mutual respect. In O. Kyriakidou & M. Özbilgin (Eds.), *Relational perspectives in organizational studies: A research companion* (pp. 74–94). Edward Elgar Publishing.

Global Wind Energy Council & Boston Consulting Group. (2023, December). *Mission critical: Building the global wind energy supply chain for a 1.5°c world* (Co-authored with Boston Consulting Group). Global Wind Energy Council (GWEC). Brussels, Belgium. https://gwec.net

Hallinan, D. (2025, July). *Strategic supply chain issues & ireland's energy transition* (Secretariat Paper No. 37) (NESC Secretariat Paper). National Economic & Social Council. Dublin, Ireland. https://www.nesc.ie

Hastings, S. E., & Gardner, C. (2011, June). *Supplier risk evaluation and control* (tech. rep. No. TOR-2011(8591)-18). The Aerospace Corporation. El Segundo, CA.

Hilletofth, P., & Eriksson, D. (2011). Coordinating new product development with supply chain management. *Industrial Management + Data Systems*, *111*(2), 264–281. https://doi.org/10.1108/02635571111115173

Hong, Y., Pearson, J. N., & Carr, A. S. (2009). A typology of coordination strategy in multi-organizational product development. *International Journal of Operations & Production Management*, *29*(10), 1000–1024. https://doi.org/10.1108/01443570910993465

Hsieh, H.-F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research*, *15*(9), 1277–1288. https://doi.org/10.1177/1049732305276687

Huang, G. Q., & Mak, K. L. (1999). Current practices of engineering change management in uk manufacturing industries. *International Journal of Operations & Production Management*, *19*(1), 21–37. https://doi.org/10.1108/01443579910244205

James, T., & Goodrich, A. (2013, December). *Supply chain and blade manufacturing considerations in the global wind industry* (NREL/TP-6A20-60063) (Prepared for the U.S. Department of Energy Clean Energy Manufacturing Initiative). National Renewable Energy Laboratory. Golden, CO, USA. https://www.nrel.gov/docs/fy14osti/60063.pdf

Johnsen, T. E., Mikkelsen, O. S., & Wong, C. Y. (2019). Strategies for complex supply networks: Findings from the offshore wind power industry. *Supply Chain Management: An International Journal*, *24*(6), 872–886. https://doi.org/10.1108/SCM-11-2018-0410

Kidd, M. W., & Thompson, G. (2000). Engineering design change management. *Integrated Manufacturing Systems*, *11*(1), 74–77.

Kim, H. J., & Cho, J.-R. (2025). Numerical analysis of fatigue life of wind turbine blades reinforced with graphene platelets. *Applied Sciences*, *15*(4), 1866. https://doi.org/10.3390/app15041866

Knackstedt, S., Sutton, M., & Summers, J. D. (2023). Part change management: A case study on automotive engineering and production. *ASME Open Journal of Engineering*. https://doi.org/10.1115/1.4056813

Kong, K., Dyer, K., Payne, C., Hamerton, I., & Weaver, P. M. (2023). Progress and trends in damage detection methods, maintenance, and data-driven monitoring of wind turbine blades – a review. *Renewable Energy Focus*, *44*, 390–412. https://doi.org/10.1016/j.ref.2022.08.005

Kongsberg Defence & Aerospace. (2024, November). *Supplier quality assurance requirements (SQAR)* (Revision L) [Document ID: P10098].

Kramer, K. J., & Schmidt, M. (2022). Circular supply chain management for the wind energy industry: Conceptional ideas towards more circularity. *Wirtschaftsgraphische Arbeiten und Berichte (WGAB)*, *2022*(4), 61–77. https://doi.org/10.30844/wgab_2022_4

Liker, J. K., Kamath, R. R., Wasti, S. N., & Nagamachi, M. (1996). Supplier involvement in automotive component design: Are there really large us-japan differences? *Research Policy*, *25*, 59–89.

Liu, M., Qin, J., Lu, D.-G., Zhang, W.-H., Zhu, J.-S., & Faber, M. H. (2022). Towards resilience of offshore wind farms: A framework and application to asset integrity management. *Applied Energy*, *322*. https://doi.org/10.1016/j.apenergy.2022.119429

Majeske, K. D., Lynch-Caris, T., & Herrin, G. (1997). Evaluating product and process design changes with warranty data. *International Journal of Production Economics*, *50*, 79–89.

Malone, T. W., & Crowston, K. (1994). The interdisciplinary study of coordination. *ACM Computing Surveys*, *26*(1), 87–119. https://doi.org/10.1145/174666.174668

Miltenburg, P. R. (2003). *Effects of modular sourcing on manufacturing flexibility in the automotive industry: A study among German OEMs* [Doctoral dissertation, Erasmus University Rotterdam] [ERIM PhD Series Research in Management, 30].

Mishnaevsky, L. (2022). Root causes and mechanisms of failure of wind turbine blades: Overview. *Materials*, *15*(9), 2959. https://doi.org/10.3390/ma15092959

Mishra, A. A., & Shah, R. (2009). In union lies strength: Collaborative competence in new product development and its performance effects. *Journal of Operations Management*, *27*(4), 324–338. https://doi.org/10.1016/j.jom.2008.10.001

Modine Manufacturing Company. (2019, November). *Modine global supplier manual* (Version 6). Modine Manufacturing Company.

Musial, W., Stefek, J., Oteri, F., Kreider, M., Gill, E., & Maniak, S. (2023). *A supply chain road map for offshore wind energy in the united states* (tech. rep. No. NREL/TP-5000-84710). National Renewable Energy Laboratory (NREL). https://docs.nrel.gov/docs/fy23osti/84710.pdf

Neri, I. F. M. (2016). Supply chain integration opportunities for the offshore wind industry: A literature review. *International Journal of Energy Sector Management*, *10*(2), 191–220. https://doi.org/10.1108/IJESM-04-2015-0007

Office of the Under Secretary of Defense (Acquisition and Technology). (1998, August). *DOD integrated product and process development handbook*. Department of Defense. Washington, DC.

Office of the Under Secretary of Defense for Research and Engineering. (2024, May). *DoD producibility and manufacturability engineering guide*. Department of Defense. Washington, DC.

Okhuysen, G. A., & Bechky, B. A. (2009). Coordination in organizations: An integrative perspective. *Academy of Management Annals*, *3*(1), 463–502. https://doi.org/10.1080/19416520903047533

Olausson, D., Magnusson, T., & Lakemond, N. (2009). Preserving the link between R&D and manufacturing: Exploring challenges related to vertical integration and product/process newness. *Journal of Purchasing and Supply Management*, *15*(2), 79–88. https://doi.org/10.1016/j.pursup.2008.12.004

Onukwulu, E. C., Agho, M. O., & Eyo-Udo, N. L. (2023). Developing a framework for supply chain resilience in renewable energy operations. *Global Journal of Research in Science and Technology*, *1*(2), 1–18. https://doi.org/10.58175/gjrst.2023.1.2.0048

Özer, Ö., & Uncu, O. (2013). Competing on time: An integrated framework to optimize dynamic time-to-market and production decisions. *Production and Operations Management*, *22*(3), 473–488. https://doi.org/10.1111/j.1937-5956.2012.01413.x

Petersen, K. J., Handfield, R. B., & Ragatz, G. L. (2003). A model of supplier integration into new product development. *Journal of Product Innovation Management*, *20*, 284–299.

Pourzarei, H., Ghnaya, O., Rivest, L., & Boton, C. (2024). Engineering change management: Comparing theory to a case study from aerospace. *International Journal of Product Lifecycle Management*, *15*(4), 318–342.

Power Technology. (2024). *European wind power expansion targets: Can they be met?* [Accessed: 2025-07-05]. Power Technology. https://www.power-technology.com/news/european-wind-power-expansion/

Primo, M. A., & Amundson, S. D. (2002). An exploratory study of the effects of supplier relationships on new product development outcomes. *Journal of Operations Management*, *20*(1), 33–52. https://doi.org/10.1016/S0272-6963(01)00080-6

Prostean, G., Badea, A., Vasar, C., & Prostean, O. (2014). Risk variables in wind power supply chain [Presented at SIM 2013 / 12th International Symposium in Management]. *Procedia - Social and Behavioral Sciences*, *124*, 124–132. https://doi.org/10.1016/j.sbspro.2014.02.468

Radhakrishnan, R., Amsalu, A., Kamran, M., & Nnaji, B. O. (1996). Design rule checker for sheet metal components using medial axis transformation and geometric reasoning. *Journal of Manufacturing Systems*, *15*(3), 179–189. https://doi.org/10.1016/S0278-6125(96)85040-4

Reed, F. M., & Walsh, K. (2002). Enhancing technological capability through supplier development: A study of the U.K. aerospace industry. *IEEE Transactions on Engineering Management*, *49*(3), 231–242. https://doi.org/10.1109/TEM.2002.803868

Rudolf, Ł., & Roszak, M. T. (2022). Tools of product quality planning in the production part approval process. *Archives of Materials Science and Engineering*, *118*(2), 67–74. https://doi.org/10.5604/01.3001.0016.2591

Safran Cabin. (2025, September). *Supplier quality requirements* (Revision W) [Document ID: SQR-1].

SCRA. (2006, June). *STEP application handbook ISO 10303 version 3*. SCRA. North Charleston, SC.

Siemens Gamesa Renewable Energy. (2021). *Sg 14-236 dd offshore wind turbine brochure*.

Skjølsvold, T. M., Heidenreich, S., Henriksen, I. M., Oliveira, R. V., Dankel, D. J., Lahuerta, J., Linnerud, K., Moe, E., Nygaard, B., Richter, I., Skjærseth, J. B., Suboticki, I., & Vasstrøm, M. (2024). Conditions for just offshore wind energy: Addressing the societal challenges of the north sea wind industry. *Energy Research & Social Science*, *107*, 103334. https://doi.org/10.1016/j.erss.2023.103334

Son, C. E. (2018). Supply chain risk management: A review of thirteen years of research [Published: December 10, 2018]. *American Journal of Industrial and Business Management*, *8*, 2294–2320. https://doi.org/10.4236/ajibm.2018.812154

Stanev, S., Krappe, H., Ola, H. A., Georgoulias, K., Papakostas, N., Chryssolouris, G., & Ovtcharova, J. (2008). Efficient change management for the flexible production of the future. *Journal of Manufacturing Technology Management*, *19*(6), 712–726. https://doi.org/10.1108/17410380810888102

Supplier quality assurance manual (sqam) [Supplier Quality Assurance Manual]. (2014). Mercedes-Benz U.S. International, Inc.

Supplier requirements manual (Issue 10) [Supplier requirements manual]. (2018, May). Faurecia.

Suurmond, R., Wynstra, F., & Dul, J. (2020a). Unraveling the dimensions of supplier involvement and their effects on npd performance: A meta-analysis. *Journal of Supply Chain Management*, *56*(3), 26–46. https://doi.org/10.1111/jscm.12221

Suurmond, R., Wynstra, F., & Dul, J. (2020b). Unraveling the dimensions of supplier involvement and their effects on NPD performance: A meta-analysis. *Journal of Supply Chain Management*, *56*(3), 26–46. https://doi.org/10.1111/jscm.12221

Swink, M. (1999). Threats to new product manufacturability and the effects of development team integration processes. *Journal of Operations Management*, *17*(6), 691–709. https://doi.org/10.1016/S0272-6963(99)00027-3

Tai, Y.-M. (2017). Effects of product lifecycle management systems on new product development performance. *Journal of Engineering and Technology Management*, *46*, 67–83. https://doi.org/10.1016/j.jengtecman.2017.06.001

Takeishi, A. (2001). Bridging inter- and intra-firm boundaries: Management of supplier involvement in automobile product development. *Strategic Management Journal*, *22*(5), 403–433. https://doi.org/10.1002/smj.164

Terwiesch, C., Bohn, R. E., & Chea, K. S. (2001). International product transfer and production ramp-up: A case study from the data storage industry. *R&D Management*, *31*(4), 435–451. https://doi.org/10.1111/1467-9310.00230

Terwiesch, C., Loch, C. H., & Meyer, A. D. (1997). *A framework for exchanging preliminary information in concurrent development processes* (Working Paper No. 97/117/TM). INSEAD.

Thomé, M., & Sousa, R. (2016). Design-manufacturing integration and manufacturing complexity: A contingency investigation of job rotation and co-location. *International Journal of Operations & Production Management*, *36*(10), 1090–1114. https://doi.org/10.1108/IJOPM-07-2015-0453

Twigg, D. (1998). Managing product development within a design chain. *International Journal of Operations & Production Management*, *18*(5), 508–524. https://doi.org/10.1108/01443579810206361

Twigg, D. (2002). Managing the design–manufacturing interface across firms. *Journal of Manufacturing Technology Management*, *13*(4), 212–222. https://doi.org/10.1108/09576060210426912

U.S. Department of Energy, Wind Energy Technologies Office. (2023, August). *Wind energy supply chain progress report* (tech. rep.) (Prepared by the Wind Energy Technologies Office (WETO)). U.S. Department of Energy. Washington, D.C. https://www.energy.gov/eere/wind/wind-energy-supply-chain-progress-report

Van de Ven, A. H., Delbecq, A. L., & Koenig, R. J. (1976). Determinants of coordination modes within organizations. *American Sociological Review*, *41*(2), 322–338. https://www.jstor.org/stable/2094477

Veers, P., Dykes, K., Basu, S., Bianchini, A., Clifton, A., Green, P., Holttinen, H., Kitzing, L., Kosovic, B., Lundquist, J. K., Meyers, J., O'Malley, M., Shaw, W. J., & Straw, B. (2022). Grand challenges: Wind energy research needs for a global energy transition. *Wind Energy Science*, *7*, 2491–2496. https://doi.org/10.5194/wes-7-2491-2022

Volvo Group. (2022). *Supply partner quality assurance manual* (Sixth edition). Volvo Group Purchasing.

Wind Turbine Models. (2024). *Vestas v164-8.0 wind turbine*. https://en.wind-turbine-models.com/turbines/318-vestas-v164-8.0

WindEurope. (2024). *Wind energy in europe: 2024 statistics and the outlook for 2025–2028* (Accessed June 2025). WindEurope. Brussels, Belgium. https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2024-statistics-and-the-outlook-for-2025-2030/

Wlazlak, P., Säfsten, K., & Hilletofth, P. (2019). Original equipment manufacturer (OEM)-supplier integration to prepare for production ramp-up. *Journal of Manufacturing Technology Management*, *30*(2), 506–530. https://doi.org/10.1108/JMTM-05-2018-0156

World Forum Offshore Wind. (2024). *Global offshore wind report 2024* (Accessed June 2025). World Forum Offshore Wind (WFO). Hamburg, Germany. https://wfo-global.org/wp-content/uploads/2025/04/WFO_Global-Offshore-Wind-Report-2024_final.pdf

Yu, H., Zhu, S., & Yang, J. (2021). The quality control system of green composite wind turbine blade supply chain based on blockchain technology. *Sustainability*, *13*(15), 8331. https://doi.org/10.3390/su13158331

Zhou, B., Yu, F., Li, H., & Xin, W. (2020). A quantitative study on the void defects evolving into damage in wind turbine blade based on internal energy storage. *Applied Sciences*, *10*(2), 491. https://doi.org/10.3390/app10020491

A

Interview Materials

A.1. Introduction

The interviews were conducted using a semi-structured interview guide that provided a common structure across the study, but it was not treated as a fixed questionnaire. Questions were adjusted in wording, order, and emphasis depending on the participant's role, background, and involvement in the DMI. The guide also developed during the research process. Earlier interviews were broader and exploratory, helping to identify how coordination problems were experienced in practice. Later interviews became more focused and were used to examine specific coordination mechanisms, investigate where gaps or weak points appeared, and test the researcher's developing interpretations. In this way, the interviews combined consistency in overall direction with enough flexibility to follow role specific insights and relevant emerging themes.

A.2. Interview protocol

Before each interview, participants were informed about the purpose of the study, the voluntary nature of participation, and the intended use of the interview data. They were told that the research examined coordination at the design–manufacturing interface in wind turbine blade development and manufacturing, and that the interview aimed to gather expert insights on how this interface was managed in practice. Participants were informed that the interview would take approximately 45–60 minutes, that they could decline to answer any question, and that they could withdraw from the interview at any time. Permission for audio recording was requested before the interview started. The recordings were used only for transcription and analysis. All interview data were anonymized during transcription, and the analysis and reporting were based only on anonymized material. Follow-up questions were used where relevant in order to clarify role specific practices, examples, and interpretations.

A.3. Adaptation across interviews

The interview guides presented in this appendix were used as structured but flexible guides rather than as fixed scripts. Not all interviewees were asked the same questions, and not all mechanisms were discussed in every interview. The wording, order, and emphasis of questions were adjusted depending on the participant's role, experience, and involvement in different parts of the design–manufacturing interface. Some interviewees were better placed to discuss design-phase mechanisms, while others were better placed to discuss industrialization, factory coordination, startup, supplier support, or downstream feedback.

The interview process also developed over time. Earlier interviews were broader and exploratory and were used mainly to understand how the interface was experienced in practice and where the main breakdowns, tensions, and weaknesses appeared. Later interviews became more focused and were used to examine specific coordination mechanisms in greater detail. In this later phase, follow-up questions were used where needed to clarify whether a mechanism existed in practice, whether it was strong enough, where important gaps remained, and what changes interviewees considered most useful.

As the analysis progressed, some later interviews were also used to probe patterns and preliminary interpretations that had started to emerge from the earlier interviews and the coding process. This was done through selective follow-up questions adapted to the interviewee's background, rather than through one identical validation script. In this way, the interviews remained semi-structured and adaptive throughout the study, while still following a common analytical direction.

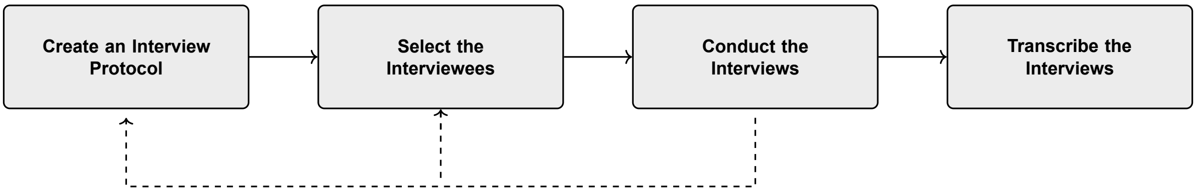

Figure A.1: Overview of the interview process

A.4. Exploratory interview guide

The following guide reconstructs the broader exploratory interview approach used in the earlier stage of the study. At this stage, the interviews were used to understand how coordination across the design–manufacturing interface was experienced in practice, where breakdowns and bottlenecks appeared and which themes seemed most important for later investigation. The guide was used flexibly and was not followed as a fixed script. Not all questions were asked in every interview, and the exact wording depended on the participant's role and experience.

A. Participant background and role

1. Could you briefly describe your role and experience in wind turbine blade development or manufacturing?
2. Which part of the process were you most directly involved in?
3. Which company interfaces or cross-functional interfaces did you deal with most often?

B. Coordination across design and manufacturing

4. Could you explain how coordination typically works across the different stages from design to production?
5. Who usually leads the different stages, and how are responsibilities divided between design, manufacturing, and quality related actors?
6. How are handovers between stages or between organizations usually managed in practice?
7. Are coordination roles generally clear, or do overlap and confusion also occur?

C. Information exchange and handovers

8. How is technical information exchanged between design and manufacturing in practice?
9. How are changes, clarifications, or manufacturing related concerns communicated across interfaces?
10. Do design teams and manufacturing teams work from the same information base, or do translations and reinterpretations occur during handover?

D. Bottlenecks and disconnects

11. From your experience, where do design and manufacturing most often disconnect in blade development?
12. At which stage do coordination bottlenecks usually appear: during design, industrialization, startup, production, or later in operation?
13. Do different actors tend to interpret coordination responsibilities differently?
14. Where do misunderstandings or misalignments most often arise?

E. Disruptions, breakdowns, and problem handling

15. What kinds of disruptions or breakdowns typically occur in wind turbine blade development and manufacturing?
16. What usually causes these problems?
17. When problems occur, how are they typically identified and addressed?
18. Are there formal routines that work well, or does recovery often depend on informal workarounds and individual initiative?

F. Practices that work well or fail

19. Are there coordination practices or routines that you have seen work particularly well?
20. Are there practices that tend to fail or create repeated difficulties?
21. Have you seen important differences in how companies, plants, or regions approach coordination?

G. Closing reflections and improvement suggestions

22. If you could strengthen one part of the coordination between design and manufacturing, what would you change?
23. Which change do you think would make the biggest difference in reducing later problems?
24. Based on your experience, which issues at the interface deserve the most attention?

A.5. Focused interview guide

The following guide reconstructs the more focused interview approach used in the later stage of the study. At this stage, the literature framework had already been developed. The interviews were therefore used more directly to examine specific coordination mechanisms, explore where they appeared strong, weak, adapted, or absent in practice, and test the researcher's developing interpretations. As with the earlier guide, this version was used flexibly rather than as a fixed script. Not all questions were asked in every interview, and the exact emphasis depended on the participant's role, expertise, and relevance to particular mechanisms. In addition to the main prompts listed below, follow-up questions were used where needed. These were used to clarify whether a mechanism existed in practice, whether it was strong enough, where gaps or weak points remained and what interviewees saw as the main possibilities for improvement. As a result, the guide was used not only to identify mechanisms, but also to probe their adequacy, limitations, and possible strengthening directions.

Opening and interview framing

- Brief explanation of the study focus on the design–manufacturing interface in wind turbine blade development and manufacturing.
- Clarification that the interview focuses on coordination across organizational boundaries rather than on technical blade design itself.
- Short explanation that the interview draws on a literature based framework of coordination mechanisms identified in mature industries.
- Clarification that the purpose is not only to ask whether such mechanisms exist in principle, but also whether they are robust enough in practice, where the main gaps appear, and what changes could strengthen the interface.

General opening question on the main disconnects

- From your experience, where do design and manufacturing most often disconnect in blade development?
- At which stage do these disconnects usually become visible: detailed design, industrialization, startup, serial production, or later in operation?
- When problems appear in startup or in the field, where do they usually trace back to?

Pre-project and upstream coordination mechanisms

- **A1 Compatibility standards:** Do shared coordination standards or common working baselines exist across OEMs, suppliers, and plants? If so, how do they work in practice? Would you say they are sufficiently robust across firms, or do important gaps remain?
- **A2/A3 Digital data exchange and product-definition interoperability:** Is engineering and manufacturing information exchanged in a sufficiently robust digital way, or does the receiving side still need to reinterpret and reconstruct important information?
- **B1 Capability development schedules:** Before a new blade program or major change begins, is there a formal mechanism that aligns readiness, capability development, resources, and timing across design and manufacturing?
- **B2 Relationship assessment programmes:** Are supplier or relationship assessment routines used to evaluate how well coordination across firms is working before execution problems appear?
- **C1 Supplier development committees:** Are there recurring formal forums or committees used to discuss supplier capability, recurring interface issues, or manufacturability concerns?
- **D1 Supplier development teams:** Do OEMs or lead firms ever provide direct supplier development support aimed at improving capability, manufacturability readiness, or quality performance before launch?
- **D2 Joint development:** How early does manufacturing or supplier knowledge influence design decisions before key choices become difficult to reverse?

Design-phase coordination mechanisms

- **A4 Cost management:** How visible are manufacturing cost implications during design, and are they integrated into design decisions in a robust way?
- **A5 Designers' tacit manufacturing knowledge:** Do design engineers understand manufacturing realities well enough in practice, or do manufacturability issues still appear too late?
- **A6 Design rules:** Are manufacturability constraints translated into explicit design rules, standards, or tools, or do they still depend heavily on the experience of individuals?
- **B3 Sign-off / acceptance:** Is there a formal manufacturability sign-off or acceptance step before moving forward, and how robust is it in practice?
- **C3 Producibility design reviews:** Are there structured producibility or manufacturability reviews during design, and do they meaningfully influence decisions?

- **C4 Producibility / manufacturing engineer role:** Is there a specific role or function that acts as the interface between design and manufacturing during development?
- **C5 Guest engineers:** Do engineers from suppliers, factories, or partner organizations spend time directly embedded with the other side during development or industrialization?
- **D3 Joint product/process design teams:** Are there real cross-functional teams in which design and manufacturing work together early enough to shape both the product and the production process?

Manufacturing, launch, and downstream feedback mechanisms

- **B4 Production prototypes / fit-build-test cycles:** Are prototype builds, trial runs or validation cycles used as a structured mechanism before serial production or commercialization? If yes, how are they used?
- **C6 Engineering changes:** In practice, how structured and robust is the engineering change process during industrialization and manufacturing?
- **C7 Site engineers:** Do dedicated technical people provide direct on-site support during startup, launch or early manufacturing? If yes, what role do they play in practice?
- **C8 Product support engineers / downstream feedback:** Is there a formal support or feedback role that captures recurring issues from startup, manufacturing, service, or early operation and translates them back into design and manufacturing improvements?
- **D4 Transition teams:** After design release, do design and process people remain involved during startup and early industrialization, or does a handover mentality still dominate?

Closing reflections and strengthening directions

- If you could strengthen one coordination mechanism at the design–manufacturing interface, which one would make the biggest difference?
- Which changes would most improve the reliability of industrialization, startup, and later field performance?
- Are there important interface issues or mechanisms that have not yet been covered by the discussion?

B

Coding and analytical materials

This appendix presents the analytical material that supported the empirical part of the study. Table B.1 provides the full coding framework used to operationalize Framework B before coding began. Table B.2 then presents an extended coding trail showing how selected interview segments were linked to mechanisms, interpretive notes and framework implications.

Tables B.3–B.7 present the main analytical displays used in the later stages of the analysis. These include the mechanism summary, the pattern matrix and the final Framework C decision sheet. Together, they show how the analysis moved from coded interview material to cross-mechanism interpretation and finally to the refinement of Framework B into Framework C.

B.1. Full coding framework / codebook

Table B.1 presents the full coding framework used in the empirical analysis. The codebook translated Framework B into operational coding categories and clarified what counted as relevant evidence during coding.

Table B.1: Full coding framework used in the interview analysis

Phase	Mechanism	Working definition used in coding	What counted as evidence in interviews	What did not count	Mature-industry anchor example
Pre-project / concept	**A1** Compatibility standards	Shared technical, procedural, or coordination baselines that create a common cross-firm starting point for development and handover.	Statements about common interface definitions, shared specifications, aligned release logic, APQP like structures, or lack of such common baselines across firms.	Digital file exchange only, formal sign-off decisions, or general coordination without a shared baseline element.	APQP common platform standards
Pre-project / concept	**A2/A3** Digital inter-firm data exchange and interoperability	Structured digital exchange of engineering and product definition data across firms through shared models, CAD/CAM transfer, or interoperable source files.	Statements about CAD or model exchange, STEP like transfer, shared source files, common digital product definition data, or interoperability between engineering and manufacturing systems.	General meetings, informal communication, or manual clarification without a digital exchange mechanism.	STEP AP242 / shared CAD source
Pre-project / concept	**A4** Cost management systems	Visibility of design, development, and production cost implications so that trade-offs can be discussed across the interface.	Statements about cost targets, cost visibility, manufacturing cost implications, labour or tooling cost implications, or cost informed design trade-offs.	General timing or manufacturability issues where cost was not part of the discussion.	Rover RG2000 / joint cost reduction work
Pre-project / concept	**B1** Capability development schedules	Structured alignment of capability building, plant readiness, and development timing before project progression.	Statements about manufacturing baseline packages, readiness milestones, capability schedules, plant preparation timing, or misalignment between readiness and development pace.	End-of-design sign-off decisions or downstream prototype validation.	MRR / PRR readiness reviews
Pre-project / concept	**B2** Relationship assessment programmes	Formal routines used to assess supplier relationships or interface readiness before execution problems appear.	Statements about supplier assessment, relationship appraisal, formal upstream evaluation of coordination quality, or structured review of interface readiness.	Normal supplier meetings or recurring forums without a clear assessment logic.	Supplier assessment programme
Pre-project / concept	**C1** Supplier-development committees	Recurring cross firm forums in which OEMs and suppliers discuss capability, interface issues, and improvement priorities.	Statements about supplier forums, recurring cross firm committees, supplier conferences, or structured discussion forums addressing interface issues.	Hands-on support teams working directly with suppliers.	Toyota *Kyohokai* supplier forum
Pre-project / concept	**D1** Supplier development teams	Teams working directly with suppliers to improve capability, quality, or recurring design/manufacturing problems.	Statements about direct OEM support teams, supplier development teams, capability building support, or hands-on supplier improvement activity.	Annual forums, committee arrangements, or assessment only routines.	Supplier technical support / SQD teams
Pre-project / concept	**D2** Joint development	Early manufacturing or supplier involvement before major specifications are fixed.	Statements about concept stage manufacturing involvement, early supplier integration, early manufacturability shaping, or lack of involvement before design freeze.	Later detailed coordination after major design choices were already fixed.	Early supplier involvement / concept-stage obeya
Design	**A5** Designers' tacit manufacturing knowledge	Manufacturing understanding carried by designers through plant exposure, rotation, or previous production experience.	Statements about factory exposure, shop-floor experience, job rotation, practical manufacturing knowledge, or dependence on experienced individuals with such backgrounds.	Explicit formal rules, software checks, or dedicated specialist interface roles.	Job rotation / plant exposure
Design	**A6** Design rules	Explicit codification of manufacturability constraints into formal design guidance, tolerances, or software supported checks.	Statements about DfM rules, acceptance criteria, tolerances, design handbooks, checklists, software checks, or formal rule based manufacturability controls.	Tacit know-how only, without explicit rule based guidance.	DFX rules / rule-check tools

Phase	Mechanism	Working definition used in coding	What counted as evidence in interviews	What did not count	Mature-industry anchor example
Design	**B3** Sign-off / acceptance	Formal acceptance of design or manufacturability conditions before progression to the next step.	Statements about manufacturability sign-off, manufacturing feasibility approval, formal acceptance gates, or explicit accept/reject decisions before build.	Broader readiness planning without a clear acceptance decision.	PPAP manufacturing feasibility sign-off
Design	**C3** Producibility design reviews	Structured review moments in which designs are checked against manufacturability or producibility constraints.	Statements about producibility reviews, manufacturability review meetings, formal design review events, or structured checks during design.	Ongoing team arrangements or dedicated specialist roles when no review event was central.	DRBFM / manufacturability review
Design	**C4** Producibility / manufacturing engineer role	Dedicated interface role linking design and manufacturing during development.	Statements about manufacturing engineers, producibility engineers, interface engineers, or named specialists bridging design and manufacturing decisions.	Resident external engineers or one-off review events.	Manufacturing engineer / gemba support
Design	**C5** Guest engineers	Engineers from suppliers or partner organizations spending sustained time embedded with the other side during development.	Statements about resident engineers, embedded external engineers, or near full-time co-location across firm boundaries.	Occasional visits, meetings, or short-term technical contact only.	Toyota guest engineer
Design	**D3** Joint product / process design teams	Cross-functional teams jointly coordinating product and process development during design and industrialization.	Statements about joint teams, cross-functional design/manufacturing teams, industrialization teams, or bundled arrangements combining design, reviews, and interface roles.	One-off reviews or isolated specialist roles without a continuing team arrangement.	IPPD / IPT / obeya during development
Manufacturing / launch	**B4** Production prototypes / fit-build-test cycles	Prototype builds, pilot runs, or validation cycles used to test product–process fit before serial production.	Statements about mock-up blades, design prototypes, process prototypes, pilot builds, trial runs, or structured validation before commercialization.	Review meetings or simulations without an actual build or validation cycle.	Pilot build / significant production run
Manufacturing / launch	**C6** Engineering change routines	Formal routines for requesting, checking, approving, and implementing engineering changes after release.	Statements about engineering changes, technical notes, ECOs, formal approvals, change requests, or urgent change handling routines.	General troubleshooting where no formal change routine was central.	ECO / technical note process
Manufacturing / launch	**C7** Site engineers	Site-level technical support roles that connect design/manufacturing knowledge to startup or production problems.	Statements about on-site engineering support, launch support, factory-side troubleshooting, resident technical support, or direct technical presence during startup.	Remote support only, without a site-level presence.	Resident representative / on-site support
Manufacturing / launch	**C8** Post-launch support and warranty feedback roles	Roles or routines that feed launch, field, or warranty learning back into design and process improvement.	Statements about launch support, field feedback loops, warranty review, service-to-engineering feedback, or recurring issue feedback into design and manufacturing.	Change-control routines where feedback or learning was not the main point.	Launch support / warranty feedback
Manufacturing / launch	**D4** Transition teams	Cross-functional arrangements that maintain continuity from design release into startup and early industrialization.	Statements about design, process, OEM, or launch teams staying involved during startup, manufacturing preparation, or early production to solve handover problems jointly.	Site-level troubleshooting only or ongoing design-phase product/process teams.	Transition team / launch continuity team

B.2. Extended coding trail

Table B.2 presents an extended set of coding examples from the interview analysis. Whereas Table 3.3 in the main text provides only a small number of illustrative examples, this appendix table shows a broader audit trail across interviewees, phases, and mechanism types, including a number of repeated non-fitting segments that were carried forward into the later refinement of Framework C.

Table B.2: Sample of coding trail from interview segment to framework implication

Interviewee	Phase	Interview segment	Primary	Secondary	Practice status	Interpretive note	Framework implication
SBE-01	Design / development	“This CAD can be used as a source for FEA, but also as a source for manufacturing …these files can be shared by suppliers and feed downstream to manufacturing, though not every company uses it.”	A2/A3	—	Partial practice	Shared digital source files do exist, but use is uneven across firms.	Present in wind, but not yet fully consistent across companies.
SBE-01	Design / development	“We do not do drawings anymore …people are exchanging STEP files and all.”	A2/A3	—	Present practice	Standard digital product-definition exchange is now normal in at least part of the industry.	Supports retention of digital data exchange as an existing mechanism.
SBE-01	Pre-project / concept	“If we can standardize our processes, even between OEMs of turbines, this will maybe reduce the supply-chain bottlenecks.”	A1	—	Recommendation	Cross-OEM common baselines are still weak, stronger compatibility standards are seen as a strengthening direction.	Supports the interpretation that A1 is underdeveloped across firms.
SBE-01	Design / development	“My first weeks on the job were literally in manufacturing …nowadays, you do not see this anymore.”	A5	—	Partial practice	Earlier plant exposure created tacit manufacturing knowledge, but this is weakening.	Supports A5 as present but eroding rather than strongly institutionalised.
SBE-01	Design / development	“Nothing beats standing there and looking at it …the first month should always be on the shop floor.”	A5	—	Recommendation	Strong endorsement of structured factory exposure for designers.	Supports strengthening A5 in Framework C.
SBE-01	Design / development	“All companies have guidelines on what to do and what not to do …they take into account manufacturing capabilities, but they differ from company to company.”	A6	—	Partial practice	Design rules exist, but vary between firms and appear less robust than rule based systems in mature industries.	Supports A6 as present but adapted and uneven.
SBE-01	Design / development	“The structural engineers are very aware of the cost …you get very strict budgets and key metrics for that.”	A4	—	Present practice	Cost is visible in design work, although not all shop-floor implications are equally visible.	Supports retention of A4 as an existing mechanism.
SBE-01	Design / development	“I think the idea of the tool is actually quite interesting …if we can actually create a tool that can flag when we are designing things and tell us that this is not allowed, I think that is a very nice idea.”	A6	—	Recommendation	The respondent explicitly supports stronger formalised and tool supported manufacturability rules rather than relying only on experience or manual checking.	Supports strengthening A6 through more explicit and software-supported rule enforcement.
SBE-01	Manufacturing / ramp-up	“And not only for engineers …the workers that you currently have today in the production, they do not get composite training …previously anybody who wanted to work needed to have a composite technician certificate …this knowledge gap is maybe not covered enough.”	—	—	Repeated non-fitting material	The segment points to workforce qualification and shop-floor capability rather than to designers’ manufacturing knowledge.	Possible strengthening direction (A5*): shop-floor capability and workforce qualification.
SBE-01	Manufacturing / ramp-up	“Bigger companies definitely have this implemented …I think this is very mature and it is there.”	C6	—	Present practice	Formal engineering-change handling is well established in larger firms.	Supports C6 as a clear match in later-phase coordination.
SBE-01	Pre-project / concept	“they are not very involved in the early phase…but I think it is something to improve on… they see something that we don’t.”	D2	—	Gap / absent	Early manufacturing involvement is weak and often delayed until later phases.	Supports the finding of weak early integration.
SBE-01	Pre-project / concept	“Yes, it is quite mature …a lot of suppliers do that …it is always required that we follow this.”	B3	—	Present practice	Formal sign-off / acceptance appears well established.	Supports B3 as a clear later gate type mechanism.
MIS-02	Design / development	“All these departments sit together …designers, process people, equipment experts …they discuss these issues together.”	D3	C3	Present practice	Product and process are coordinated through joint cross-functional team arrangements.	Supports D3 as a clear match in the design phase.

Interviewee	Phase	Interview segment	Primary	Secondary	Practice status	Interpretive note	Framework implication
MIS-02	Design / development	“There are risks …learning from other products …what are the changes against that product? That is how we do the evaluation.”	C3	D3	Present practice	Manufacturability is checked through structured review logic drawing on prior cases.	Supports C3 as present through review based evaluation.
MIS-02	Design / development	“There is a process and equipment team …they are the middle layer who interfaces both the factories and the engineering team.”	C4	D3	Present practice	A dedicated interface role bridges engineering and factory realities.	Supports C4 as a clear match.
MIS-02	Manufacturing / ramp-up	“They try a small proto …feasibility studies on the process …design, process, plant, and equipment people all participate.”	B4	D3	Present practice	Trial builds are used jointly to validate both design and process.	Supports B4 as a clear structured mechanism.
MIS-02	Manufacturing / ramp-up	“They will be part of the launch …the design guys will be part of the launch …before that, these small trials keep happening.”	D4	B4	Present practice	Design and process people stay involved through startup rather than disappearing after release.	Supports D4 as a clear continuity mechanism.
MIS-02	Manufacturing / ramp-up	“There is a proto set …then they validate the set and approve the set, and then they go for serial production.”	B4	B3	Present practice	Prototype sets are tied to validation and approval before serial production.	Supports the structured use of B4 linked to B3.
MIS-02	Manufacturing / ramp-up	“Engineering change is an evolving process …every month there are a few changes …it is a continuous phase.”	C6	—	Present practice	Change handling is routine and continuous during execution.	Reinforces C6 as a later-phase mechanism.
BME-06	Pre-project / concept	“Coordination typically follows APQP requirements …design development, interface transitions, and communication are carried out accordingly.”	A1	—	Present practice	APQP like structures function as coordination baselines in some settings.	Supports A1 as present, though not necessarily cross enterprise in a strong sense.
BME-06	Design / development	“Design planning …includes structural design, load calculations, and manufacturability reviews.”	C3	—	Present practice	Manufacturability review is built into design planning.	Supports C3 as a direct match.
BME-06	Manufacturing / ramp-up	“Technical handover is jointly led …technical meetings focus on process feasibility and quality acceptance standards for review and confirmation.”	C3	B3	Present practice	Technical handover combines review and acceptance elements.	Supports C3 and B3 as linked design-to-manufacturing mechanisms.
BME-06	Manufacturing / ramp-up	“Issues arise during design change implementation across time zones …stakeholders have different definitions of what counts as an urgent change.”	C6	—	Partial practice	Formal change routines exist, but urgency and coordination across actors remain uneven.	Supports C6 as present but variably robust in cross firm settings.
BME-06	Manufacturing / ramp-up	“Robustness …conducting trial validations for critical processes in advance and setting up backup plans.”	B4	B1	Present practice	Trial validation is explicitly linked to process robustness and preparation.	Supports B4 as present and linked to readiness logic.
BME-06	Manufacturing / ramp-up	“Clear escalation paths …quality issues are reviewed according to severity, root causes are analysed, and corrective actions are quickly formulated.”	C6	—	Present practice	Escalation and corrective action logic support structured change and issue response.	Reinforces C6 as a strong later-phase mechanism.
BME-06	Pre-project / concept	“Review meetings are organised by the OEM with all blade manufacturers, with joint risk assessments and collaborative identification of disruption points.”	C1	—	Present practice	Recurring OEM-led forums bring multiple manufacturers together to discuss shared risks and interface issues.	Supports C1 as present in adapted form.
BME-06	Pre-project / concept	“There is a general lack of systematic definitions for cross-enterprise coordination processes …a collaborative standard system across the supply chain would help eliminate fragmented rules.”	A1	—	Gap / absent	Existing standards are fragmented and do not yet create a true common cross-enterprise baseline.	Supports the fragmented-baseline finding for A1.
LSBM-03	Manufacturing / ramp-up	“If externals manufacture according to our design, we also support the process during startup …we would send a crew of company’s people …it is never just handing over the paper.”	D4	C7	Present practice	OEM support continues into outsourced startup through direct launch involvement.	Supports D4 and also illustrates C7-type support.

Interviewee	Phase	Interview segment	Primary	Secondary	Practice status	Interpretive note	Framework implication
CCE-04	Manufacturing / ramp-up	“Designers should not design only something nominal …they should indicate robustness and tolerance …manufacturing must always comply with these acceptance criteria.”	A6	A1	Recommendation	Stronger explicit tolerances and manufacturability discipline are needed.	Supports strengthening A6 within the existing mechanism family.
CCE-04	Manufacturing / ramp-up	“…you could see technicians sitting on the balsa sheets and using a knife to make it all fit …”	—	—	Repeated non-fitting material	The segment highlights execution quality at operator level in a manual composite process.	Possible strengthening direction (A5*): shop-floor execution capability.
CCE-04	Pre-project / concept	“The whole market would not get an insurance contract without proper track record …now turbines are sold without having been properly validated.”	B4	—	Gap / absent	Commercialisation pressure weakens the validation value of prototypes and track record.	Supports the compressed-learning finding for B4.
SEM-05	Manufacturing / ramp-up	“It is really important to go through a prototype …allow engineers the time to learn …allow a minimum of two years between prototype and commercialisation.”	B4	—	Recommendation	Prototype learning needs protected time before scale-up.	Supports strengthening B4 within the existing mechanism.
SEM-05	Manufacturing / ramp-up	“There is a lot of manual work …it is pretty much craftsmanship so it depends on skills …so you have to start a factory almost from scratch or really ramp up, scale up drastically from what you had …and make a way more complex blade, or you have to bring a new product to a factory, then you need a lot more people …and then maybe half of them are brand new coming from unrelated jobs into a factory. So this is where it breaks …”	—	—	Repeated non-fitting material	The segment points to workforce skill, factory stability, and ramp-up execution capability.	Possible strengthening direction (A5*): workforce capability and execution stability.
SEM-05	Manufacturing / ramp-up	“If you do not do this, you will end up having troubles and pay the price quite heavily …you will lose money.”	B4	—	Gap / absent	Insufficient prototype learning creates later quality and financial losses.	Reinforces the B4 gap under commercial pressure.
PEM-07	Pre-project / concept	“The diligence process from the OEMs to find suppliers …there are not so many suppliers …the first small issue you have in the field, you just lost all your margins …a lot of companies start, grow fast, then get first issues in the field and start to go down …most of the companies just get bankrupted.”	B1	—	Gap / absent	The issue is not only project readiness, but the fragility of the supplier base itself under scale-up pressure.	Supports the pattern of weak supplier capability development and unstable upstream readiness.
PEM-07	Pre-project / concept	“When you do partnership with your supplier, you need to treat them not as your supplier, but as your business partner …in the wind industry, they do not treat the suppliers as partners …if you bring your supplier close to you, make them your partner, maybe you can start getting better suppliers and better blades to produce.”	D1	C1	Recommendation	Supplier development is validated as useful, but described more as something wind should do more seriously than as a strong existing practice.	Supports strengthening D1 and moving toward longer term supplier partnership rather than price-driven transactional sourcing.

B.3. Selected analytical displays

This section presents the main analytical displays used in the later stages of the analysis. Table B.3 summarizes how the mechanisms in Framework B appeared in the wind interview data at mechanism level. Tables B.4, B.5, and B.6 then present the pattern matrix used to compare recurring cross mechanism findings, repeated improvement directions within existing mechanisms, and possible extension signals that were kept visible during the refinement process. Finally, Table B.7 presents the decision sheet used to move from Framework B to Framework C by recording how each relevant mechanism or strengthening direction was treated in the final synthesis.

Table B.3: Mechanism summary of Framework B in the wind interview data

Mechanism	Status in wind	Main summary	Main issue	Main improvement idea
A1 Compatibility standards	Partial practice	Wind uses mature-industry type baselines, especially APQP-like setups, but shared cross-firm coordination baselines remain fragmented.	Company-level standards do exist, but common responsibility and specification baselines across firms are still weak.	Strengthen shared coordination standards and set clearer common responsibility baselines across firms.
A2/A3 Digital inter-firm data exchange and interoperability	Present practice	Digital product-definition exchange is one of the clearest direct matches, with shared CAD, STEP, and model based transfer feeding manufacturing.	The main issue is uneven uptake across firms rather than absence of the mechanism itself.	Wider and more consistent use across firms.
A4 Cost management systems	Present practice	Cost visibility is present, mainly through design-side budget and cost-model awareness.	Manufacturability and cycle-time implications appear less visible than cost.	Strengthen the link between cost, cycle time, and manufacturability visibility.
A5 Designers’ tacit manufacturing knowledge	Gap / absent	Evidence points to weak or declining shop-floor exposure and to physical separation between design offices and plants.	Tacit manufacturing familiarity is difficult to sustain when direct factory exposure is weak.	Reintroduce plant exposure, station rotation, and stronger tacit know-how transfer to designers.
A6 Design rules	Gap / absent	Wind evidence highlights the need for robustness, tolerances, and manufacturability constraints, but mostly in fragmented or weakly formalized form.	The gap lies between the need for explicit producibility rules and the reality of company-specific and sometimes ad hoc practice.	Make robustness and tolerance rules more explicit and support them with tool based manufacturability checks.
B1 Capability development schedules	Gap / absent	Wind evidence combines readiness-check logic with repeated warnings about supplier bottlenecks, fragmented schedules, and wave-effect delays.	Readiness and capability logic exist, but cross-project alignment and supplier capability remain weak.	Strengthen supplier capability alignment, readiness integration, and schedule coordination before execution.
B2 Relationship assessment programmes	No coded primary evidence yet	No direct wind evidence was coded for formal relationship assessment programmes in the narrow mature-industry sense.	Supplier coordination evidence exists, but not clear formal relationship-appraisal routines as the main mechanism.	
B3 Sign-off / acceptance	Present practice	Acceptance and sign-off logic is clearly present through PPAP-like approval, prototype-set approval, and review based confirmation.	Some supplier–OEM acceptance interactions still combine formal and informal routines and uneven expectations.	Improve expectation alignment across firms.
B4 Production prototypes / fit-build-test cycles	Present practice	Wind clearly uses prototypes, validation sets, and launch-stage trials, and the evidence strongly links them to learning before scale-up.	The issue is not absence of validation logic, but whether enough protected learning time exists before commercialization.	Allow stronger prototype learning loops, root-cause analysis, and meaningful time between prototype and commercialization.
C1 Supplier-development committees	Present practice	Recurring cross-firm forums are visible through supplier meetings, OEM-led review meetings, and joint risk discussions.	Some signals go beyond committees toward broader shared-learning arrangements that are not yet clearly institutionalized.	Expand OEM-led review and risk forums toward stronger shared learning across firms.
C3 Producibility design reviews	Present practice	Manufacturability and producibility reviews are clearly present through formal design planning, technical handover reviews, and feasibility discussions.	The issue is less their absence than how they sit inside broader team arrangements.	
C4 Producibility / manufacturing engineer role	Present practice	Manufacturing-engineering interface roles are clearly evidenced, especially where a middle layer bridges factory reality and design decisions.	Evidence is strong	

Mechanism	Status in wind	Main summary	Main issue	Main improvement idea
C5 Guest engineers	No coded primary evidence yet	No direct wind evidence was coded for resident or semi-permanent guest engineers embedded with the customer design team.	Current evidence covers meetings, reviews, and site support, but not the stronger resident guest-engineer form.	Addition as strengthening mechanism
C6 Engineering change routines	Present practice	Engineering change routines are strongly visible through formal change handling, escalation paths, technical notes, urgent paths, and continuous ramp-up changes.	The issue is delay, urgency definition, and cross-time-zone implementation rather than absence of the mechanism.	Clarify urgency definitions and fast paths without losing formal traceability.
C7 Site engineers	Present practice	OEM or expert-team site support is clearly evidenced through on-site supervision, startup support, quality verification, and technical intervention.	Support is often temporary or hybrid rather than permanently resident.	Strengthen clearer hybrid remote/on-site support models.
C8 Post-launch support and warranty feedback roles	Partial practice	Closed-loop production and launch feedback is present, but less richly evidenced than site support or change-control routines.	Feedback is sometimes informal or aspirational rather than strongly institutionalized.	Build more structured closed loop learning and post-launch feedback capture.
D1 Supplier development teams	Present practice	Hands-on supplier-development support is evidenced, but the dataset remains relatively thin compared with other mechanisms.	It is difficult to separate active supplier-development teams from broader supplier forums and meetings.	Addition as strengthening mechanism.
D2 Joint development	Gap / absent	Early concept-stage joint development with manufacturing input remains one of the clearest weak points compared with mature-industry expectations.	Respondents do see value in earlier involvement, but current practice is described as limited or not deep enough.	Bring manufacturing and supplier knowledge into concept and early design earlier and more deeply.
D3 Joint product / process design teams	Present practice	Cross-functional product/process coordination is clearly seen through liaison project teams and joint design–manufacturing–equipment setups.	Team based coordination often bundles reviews and specialist roles inside it rather than operating as a pure standalone mechanism.	Improve role clarity inside cross-functional teams.
D4 Transition teams	Present practice	Continuity across handover into manufacturing is positively evidenced through launch participation, startup crews, and supervision during manufacturing preparation.	Evidence is stronger around launch continuity than around fully formalized standing transition teams.	Strengthen continuity structures into launch and early industrialization.

Table B.4: Recurring cross-mechanism patterns in the wind interview data

Pattern ID	Recurring pattern seen in wind data	Mechanisms involved	Analytical meaning	Handling in thesis
P1	Later-stage formalization (acceptance, validation, escalation/change routines, launch/startup continuity, and on-site support) is stronger and better evidenced than early-stage standardization across companies.	B3, B4, C6, C7, D4 vs. A1, D2	Wind translates several later-stage mature-industry control mechanisms more clearly than early concept-stage coordination basics.	Treated as a maturity pattern inside Framework B, no new mechanism added.
P2	Design-phase coordination often appears as a bundle of team, review, and interface-role mechanisms rather than one isolated device.	D3, C3, C4	Supports keeping these mature-industry mechanisms separate while allowing overlap in coding and interpretation.	Retained inside the framework, overlap made explicit rather than collapsed into one new mechanism.
P3	Tacit manufacturing knowledge and early concept-stage manufacturing involvement remain clear weak points even where later formal controls are stronger.	A5, D2	These are gap findings: the mechanisms exist in the framework, but wind evidence shows them as weak, fading, or mainly recommended rather than built into practice.	Treated as a gap match result inside the existing framework.
P4	APQP-style setup is present, but respondents still describe fragmented rules across companies, incomplete written baselines, and missing systematic coordination standards across the supply chain.	A1	Suggests wind borrows some mature-industry structures without truly standardizing coordination across firms at sector level.	Treated mainly as a context/refinement note rather than grounds for building a new framework from scratch.
P5	Several respondents point to process robustness, inspection discipline, automation/AI support, and shared knowledge infrastructures as important, but these do not map neatly and repeatedly enough to justify adding a new mechanism yet.	B1, C1/C8 boundary notes	Useful as a cautious observation and as repeated non-fitting material to keep visible.	Retained as a possible future extension.
P6	Different outsourcing/interface setups (such as build-to-print versus design-for-spec) appear to shape where misunderstandings arise, but this currently looks like a context issue rather than a separate coordination mechanism.	A1 boundary condition	Helps explain why the same mature-industry mechanism may work differently depending on how design responsibility is split across firms.	Treated as a boundary note only.
P7	Prototype/track-record validation is not only similar to a mature-industry coordination mechanism but also one of the clearest wind-industry gaps when serial commercialization moves faster than prototype learning.	B4	Strongly supports the thesis aim: the mechanism is present and understood in wind, but repeated interviews show it may still not be used enough during rapid scale-up.	Retained as a strong match with a major gap result inside the existing framework.
P8	Physical distance and large hierarchies can weaken both design-side manufacturing understanding and the translation of calculated technical risk into commercial decisions.	A5, A6, C2	A boundary/context issue around existing mechanisms rather than a replacement framework. Mature-industry mechanisms may work poorly when tacit know-how and expert risk translation are structurally weak.	Treated as a boundary note only..
P9	Fragmented contractual/interface management appears as a recurring wind-industry coordination problem, and one interview explicitly contrasts this with EPC/EPCI-style top-level integration used in mature project industries.	Boundary across A1/B1 and extension candidate X5	May point to a controlled Framework C extension around lead-systems integration or contract-interface consolidation, but evidence is still too thin to adopt as a full mechanism.	Retained as a possible extension candidate.

Table B.5: Repeated improvement directions within existing Framework B mechanisms

Mechanism / cluster	Repeated interviewee suggestion	Why it stays inside the existing framework	Handling in thesis
A6	Tool-supported design rules, stronger robustness/tolerance definition, and clearer acceptance criteria.	This is described as stronger explicit design-for-manufacturing rules, not as a separate mechanism.	Used under A6 as an enhancement / gap discussion, Framework C reads A6 more strongly rather than adding a new mechanism.
D2	Earlier and deeper manufacturing involvement during concept and design shaping.	This is directly D2 logic, so it is treated as a gap plus improvement direction rather than as a new mechanism.	Used as a major gap finding under D2, D2 is retained and marked as underdeveloped in wind.
B4	Stricter prototype and track-record validation before commercialization and scale-up, with enough time for learning from prototypes.	The interview evidence strengthens the validation mechanism rather than pointing to a different one.	Used as a B4 match-with-gaps narrative, B4 is retained and treated as underused.
A5	Designer exposure to factories and shop-floor experience to improve tacit manufacturability understanding.	This directly strengthens A5 rather than creating a new category.	Used under A5 as gap and enhancement discussion, A5 is retained as weakly built into normal practice.
A5.1	Workers training.	Repeated evidence points to workforce capability and training as important, but this no longer sits fully inside the original A5 definition.	Carried forward as repeated non-fitting material and considered further in Framework C refinement.
C6	Faster urgency paths with clear definitions, without bypassing traceability.	This is an adaptation inside engineering-change routines, not a separate new mechanism.	Used under C6 tension discussion, C6 is retained with urgency-path refinement.
A1/B1/C1 cluster	Stronger cross-company standards, checkpoints, and recurring coordination forums.	These suggestions intensify existing mechanisms across the framework rather than replacing them.	Used as a cross-cutting enhancement bundle, may support Framework C wording refinement, but not a new mechanism.

Table B.6: Possible extension or new mechanism candidates tracked during the analysis

Candidate ID	Potential addition / extension	Current basis in interviews	Why not fully adopted yet	Current handling in thesis
X1	Shared learning and disruption knowledge infrastructure across firms	Comes up through industry-wide shared knowledge-base ideas and broader supplier–OEM learning discussions.	So far it appears in too few interviews and still partly overlaps with C1 and C8.	Recorded as a possible Framework C extension and discussed in the findings and discussion, but not adopted.
X2	Technical risk translation and decision-escalation capability across large hierarchies	Comes up in the CCE-04 interview as failure to carry calculated technical risk into managerial and commercial decisions.	At present this is mainly one strong interview and still overlaps with A5, A6, and C2 as a context issue.	Retained as a candidate extension and context note and added in A6 strengthening.
X4	Cross-enterprise coordination standard system spanning supply-chain stages	Appears clearly in the BME-06 response as missing systematic coordination definition across firms.	It can still be read as a stronger A1/B1 cluster rather than as a fully distinct new mechanism.	Integrated in A1 strengthening.
X5	Lead systems integrator and EPC-style contractual interface management	Appears strongly in the SEM-05 material and is also indirectly supported by earlier complaints about too many interfaces and fragmented responsibilities.	At present it is still one strong interview plus indirect support, and can still be read as an A1/B1 extension rather than a fully separate mechanism.	Tracked as a serious candidate extension in Framework C, but not adopted.

B.4. Framework C decision sheet

Table B.7 presents the final mechanism level decisions used to move from Framework B to Framework C. The table combines the decision logic recorded in the analytical workbook with the final synthesis stated in Chapter 4.7. It therefore reflects not only whether a mechanism was evidenced in wind, but also how the findings justified keeping it unchanged, strengthening it, treating it as a major gap, or carrying it into Framework C as an added strengthening direction.

The Framework C decision sheet presents the final interpretive step of the analysis. While the coding framework and coding trail showed how interview material was linked to individual mechanisms in Framework B, this table shows how those mechanism-level findings were carried forward into the final refinement of the framework. Its purpose is to make explicit how the study moved from empirical mapping to framework adjustment. More specifically, it records how each relevant mechanism was treated after the cross-case comparison: whether it was retained largely unchanged, strengthened, treated as a major gap, or added as a strengthening direction where the wind data pointed beyond the initial mature-industry structure. In this way, the table functions as the bridge between the findings in Sections 4.3–4.6 and the final Framework C synthesis in Section 4.7.

The table was produced through the analytical process described in Chapter 3. After the interview material had been coded against Framework B, the coded segments were compared across mechanisms, interviews, and phases through the mechanism summaries, pattern matrices, and iterative review of repeated matches, gaps, and non-fitting material. On that basis, each mechanism was assessed in relation to two questions: first, how it currently appeared in the wind context, and second, what this implied for the final framework used to answer the third sub-question. The resulting decisions were then recorded in a structured way so that the move from Framework B to Framework C would remain visible and traceable rather than appearing only as a final summary at the end of the chapter.

Unlike the earlier analytical displays, this table does not simply summarize evidence. It consolidates it into a framework level judgment. For that reason, the rows reflect the final interpretation adopted in the thesis rather than the full range of intermediate notes that appeared in the workbook during analysis. The table therefore mirrors the final findings: mechanisms that were already clearly present in wind were retained as part of the existing coordination base, mechanisms that appeared weak, fragmented, or underdeveloped were carried forward as strengthening priorities, and repeated wind-specific issues that were not fully captured by the original mechanism set were represented as added strengthening directions in Framework C.

Table B.7: Framework C decisions based on the wind interview findings

Mechanism	Wind situation today	Framework C response	Why this response was chosen	DMI strengthening implication
Pre-project / concept phase				
A1 Compatibility standards	Present, but incomplete across firms and stages.	Strengthened	The findings show that APQP-like and similar structures exist, but they do not yet function as a sufficiently shared cross-enterprise coordination baseline.	Stronger cross-enterprise standardisation, shared specifications, and clearer interface definitions across OEMs, suppliers, and stages.
A2/A3 Digital inter-firm data exchange and interoperability	Clearly present and already supporting inter-firm product-definition exchange, though uneven across firms.	Remains essentially unchanged	This is one of the clearest direct matches between the mature-industry reference and wind practice.	Maintain as a core digital coordination mechanism and deepen consistency across firms.
A4 Cost management	Present, but still too narrow because early evaluation does not include manufacturability and cycle-time implications strongly enough.	Strengthened	Cost visibility exists, but the findings show that manufacturability and cycle-time effects are still not brought into early evaluation strongly enough.	Broaden early evaluation from cost visibility alone to cost, manufacturability, and cycle-time visibility.
B1 Capability development schedules	Present in planning and readiness logic, but vulnerable to bottlenecks, fragmented schedules, and weak coordination across projects.	Strengthened	The mechanism exists in adapted form, but repeated evidence shows supplier capability immaturity and weak schedule integration across fragmented execution settings.	Better alignment of readiness, supplier capability, and schedule coordination across firms and projects.
B2 Relationship assessment programmes	Not clearly evidenced in current wind practice, but analytically useful as an upstream strengthening direction.	Added as strengthening direction	The findings suggest that a more formal routine for assessing relationship and coordination quality could help identify weaknesses earlier.	Add upstream assessment of coordination gaps and relationship quality before execution problems emerge.
C1 Supplier-development committees	Present, but less mature and less institutionalised than in mature-industry examples.	Strengthened	Recurring forums are visible, but the findings suggest the real need is stronger shared learning and more systematic inter-firm coordination routines.	Move beyond recurring meetings toward stronger shared learning, broader inter-firm knowledge structures, and more mature supplier-development support.
D1 Supplier development teams	Not clearly evidenced in current wind practice, but identified as a useful improvement direction.	Added as strengthening direction	The interview findings suggest that more direct intervention-oriented supplier support could strengthen upstream coordination where capability is weak.	More direct upstream supplier support where capability, readiness, or manufacturability alignment is insufficient.
D2 Joint development	Major current DMI gap, manufacturing is still brought in too late to shape early design choices.	Major strengthening priority	This is one of the clearest gap findings against the mature-industry reference and sits at the centre of the weak early-integration problem.	Earlier and more structured manufacturing involvement in concept and early design before decisions become harder to change.
Design phase				
A5 Designers' tacit manufacturing knowledge	Not sufficiently embedded in everyday design work, designers remain too distant from shop-floor realities.	Strengthened	The findings repeatedly show weak plant exposure, weak direct manufacturing familiarity, and excessive distance between design and factory practice.	Stronger designer plant exposure and shop-floor rotation to build manufacturability understanding.
A6 Design rules	Present, but fragmented, insufficiently formalised, and weakly supported by tool based checks.	Strengthened	The findings show that robustness, tolerances, and manufacturability constraints are needed, but are still not formalised strongly enough in practice.	Clearer tolerances, acceptance criteria, and manufacturability rules, supported by software DfM/DfA checking during design.
B3 Sign-off / acceptance	Already sufficiently developed and widely embedded in broader review and release routines.	Remains essentially unchanged	The findings show this as a clear mature-industry match and part of the current later-stage coordination base.	Maintain as a core formal readiness and release mechanism.

Mechanism	Wind situation today	Framework C response	Why this response was chosen	DMI strengthening implication
C3 Producibility design reviews	Already sufficiently developed and clearly used in wind design work.	Remains essentially unchanged	The findings show structured manufacturability review logic already operating in wind, often inside broader team arrangements.	Maintain structured manufacturability review logic, recognising that it often operates within broader D3 coordination.
C4 Producibility / manufacturing engineers	Already sufficiently developed as a specialist interface role connecting design with factory realities.	Remains essentially unchanged	The specialist interface role is one of the clearest design-phase matches in the interview data.	Maintain specialist manufacturing-interface support in design, recognising that it often operates within broader D3 coordination.
C5 Guest engineers	Not clearly evidenced in current practice, but analytically important as a strengthening direction.	Added as strengthening direction	The absence of a more embedded supplier-side engineering presence highlights a gap in continuous cross-firm technical integration.	More embedded supplier-side technical contribution during design, beyond meetings and reviews only.
D3 Joint product / process design teams	Already sufficiently developed and one of the clearest design-phase coordination mechanisms.	Remains essentially unchanged	Cross-functional team coordination already forms an important part of the wind DMI base, even though other mechanisms often sit inside it.	Maintain as the broader cross-functional coordination arrangement within which C3 and C4 often operate.
Manufacturing / launch phase				
A5* Composite manufacturing know-how and shop-floor capability	The findings show that the capability problem extends beyond designers to workers and technicians, especially in composite manufacturing.	Added from wind findings	Repeated non-fitting material showed that Framework B did not capture the importance of worker capability, plant know-how, and execution stability strongly enough.	Stronger composite-specific training, worker capability, and plant manufacturing know-how.
B4 Prototype / fit-build-test cycles	Clearly present, but their learning value is weakened when commercialization moves faster than prototype validation and field learning.	Strengthened	The findings show a strong mature-industry match, but also one of the clearest current wind gaps under scale-up pressure.	Protect validation learning time, root-cause learning, and meaningful time between prototype and commercialization.
C6 Engineering changes	Already sufficiently developed as a formal mechanism, but urgency pathways can still weaken traceability and create competing instructions.	Strengthened	The mechanism is clearly present, but the findings show a recurring tension between speed and controlled traceability.	Controlled urgency without loss of traceability and clearer fast-path definitions.
C7 Site engineers	Already sufficiently developed as direct site-level support, though often in adapted rather than permanently resident form.	Remains essentially unchanged	The findings show that direct technical support during startup and launch is already part of the current coordination base.	Maintain direct site-level support, while improving continuity between remote and on-site forms where needed.
C8 Product support engineers / supplier-side feedback roles	Only partly developed, stronger reciprocal supplier-side feedback and support loops remain weak.	Added as strengthening direction	The findings show that learning from startup, manufacturing, and early field use is still not fed back strongly enough through supplier-side roles.	Add a stronger supplier-side feedback and support loop linking downstream issues back into design and manufacturing improvement.
D4 Transition continuity	Already sufficiently developed as launch and startup continuity across the handover into manufacturing.	Remains essentially unchanged	The findings show meaningful continuity across design release, launch, and early manufacturing, even if not always through a formal standing team.	Maintain continuity across launch and startup.