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SYSTEMS ENGINEERING FOR LEAGILE SHIP REPAIR: AN ARCTIC EXPERIMENTAL STUDY

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ABSTRACT

Global trade increasingly relies on maritime transport, and Arctic shipping routes - linking the Atlantic and Pacific via the Northern Sea Route - are emerging as strategic corridors, projected to handle 10-15% of global maritime trade by mid-century.

As competition intensifies between major players such as China, Russia, and the ICE Pact (a trilateral partnership between the United States, Canada and Finland), Arctic shipyards must be strategically positioned to offer timely, efficient, and high-quality ship repair services. These capabilities are critical to enhancing operational continuity and increasing the competitiveness of Arctic shipping operations.

Despite investments in specialised icebreaker fleets, the demand for robust, adaptive, and digitally enabled ship repair services remains urgent. Ship repair operations are inherently unpredictable, often disrupted by changing inspection outcomes and shifting customer requirements. These uncertainties can severely affect scheduling, resource allocation, and production planning - posing risks to continuous Arctic operations.

To address these challenges, this study proposes an integrated Leagile strategy that combines Lean principles for efficiency with Agile practices for flexibility. Central to this strategy is the use of SysML (Systems Modelling Language) to structure, model, and support system-wide decision-making and process optimisation across a ship repair shipyard, achieving time efficiency and cost benefits. A usage of an experimental case study to demonstrate the practical application of this approach.

The integration of Leagile practices with SysML modelling offers a robust framework for navigating the complex demands of Arctic ship repair. This approach enhances responsiveness to disruptions, improves planning accuracy, and minimises non-value-added activities. It also strengthens collaboration across technical and managerial domains, supporting a more synchronised and data-driven operation.

In summary, the proposed Leagile structure through SysML enables Arctic shipyards to deliver faster, more innovative, and more resilient repair services. This positions them as vital enablers of uninterrupted Arctic shipping, advancing both regional capabilities and global maritime resilience.

1. INTRODUCTION

The global maritime transportation system is the primary driver of international trade, as it enables the movement of 80% of worldwide commercial goods (UN Trade & Development, 2022). Arctic ice melting caused by climate change has created new strategic waterways, including the Northern Sea Route (NSR), which connects the Atlantic and Pacific Oceans – Figure 1.

The latest shipping route offers faster travel between Asia and Europe than the Suez and Panama Canals, resulting in shorter journeys, lower fuel consumption, and reduced environmental impacts (Bekkers et al., 2021). The Arctic region will see a significant rise in maritime traffic, as scientists predict that trade through the area will reach 10-15% of global maritime trade by 2050 (Gunnarsson, 2021).

Figure (1): Northern Sea Route

The emerging economic potential has triggered intense competition among nations in the geopolitical arena. The China-Russia alliance and the trilateral ICE Pact compete to gain control of the region (Berkman et al., 2022). The reliability of Arctic shipping operations in this high-risk environment requires both icebreaker escorts and a dependable network of supporting infrastructure.

The Arctic shipyards function as essential strategic locations because they deliver vital maintenance and repair operations. The ability of ship repair facilities to provide quick, efficient, high-quality services remains crucial for maintaining operational continuity, ensuring safety in dangerous waters, and supporting national Arctic shipping competitiveness (Lasserre, 2019).

The remote Arctic environment, with its harsh environmental conditions, creates unpredictable conditions for ship repair operations. For example, extreme cold can make steel brittle, making welding repairs more complex and time-consuming than in temperate regions.

The inspection process reveals unexpected problems that disrupt projects, as well as changes in regulatory standards and shifting customer needs (Psaraftis & Panagakos, 2018). The existing linear project management systems face significant challenges from these uncertainties, leading to project delays, inefficient resource management, and increased costs that threaten the sustainability of Arctic operations. This may occur when sudden ice formation around the vessel delays access to critical areas.

The research presents a new solution to these problems through an integrated Leagile strategy for Arctic shipyards. This strategy synergises Lean principles, which focus on waste elimination and process efficiency, with Agile practices, which emphasise flexibility and rapid response to change (Naylor et al.,1999). The implementation of this strategy depends on the use of the Systems Modelling Language (SysML), which enables effective modelling of intricate systems, requirement tracking, and dynamic process simulation

(Friedenthal et al., 2014). This strategy, derived from the V model of systems engineering, begins by defining and decomposing requirements on the left side of the "V." It concludes on the right side with verification and validation activities that ensure those requirements are fully met. Ref to Figure (7), the process flow through the V-Model.

A functional explanation of this, SysML uses a set of diagram types to represent different aspects of a system:

- Block Definition Diagram (BDD): Defines system components and their relationships. – Figure (2)
- Internal Block Diagram (IBD): Shows internal structure and data flow between components. – Figure (3)
- Activity Diagram: Models workflows and processes, useful for Lean process optimisation. – Figure (4)
- Requirement Diagram (REQ): Links requirements to system elements for traceability. – Figure (5)
- Parametric Diagram (PAR): Supports performance analysis and trade studies. – Figure (6)

The research develops an implementation strategy for Leagile systems through an experimental study that demonstrates how SysML models help a shipyard adapt to unexpected hull damage by shifting resources (Agile) and then optimising the repair process (Lean).

The research combines Leagile philosophy with SysML analytical tools to develop a method that boosts shipyard flexibility, improves planning accuracy, and facilitates team collaboration. This positions Arctic shipyards as enablers of a resilient and uninterrupted Arctic shipping network.

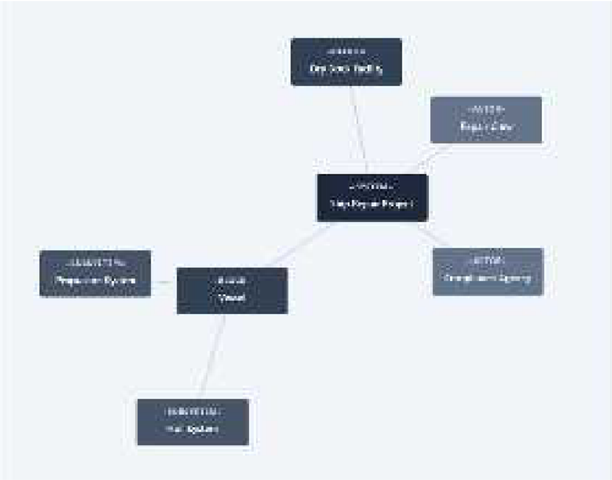

Figure (2): Block Definition Diagram (BDD)

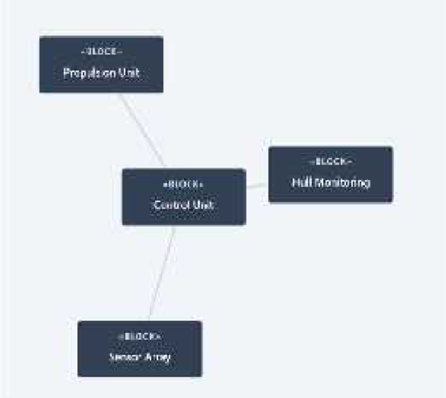

Figure (3): Internal Block Diagram (IBD)

Figure (4): Activity Diagram

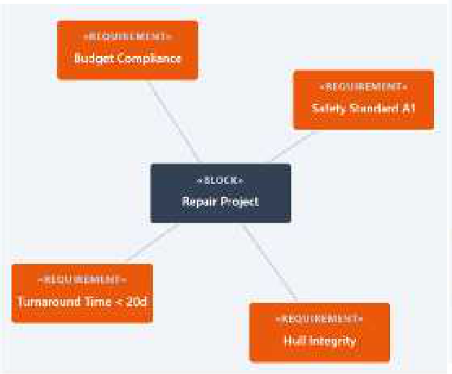

Figure (5): Requirement Diagram

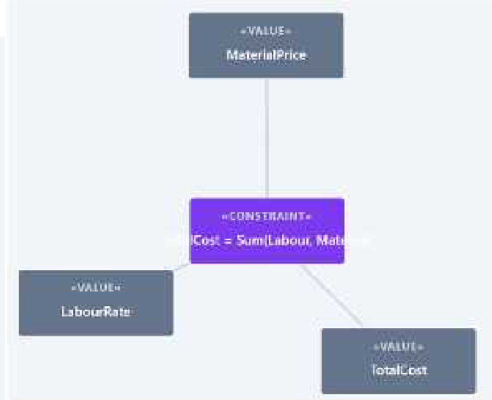

Figure (6): Parametric Diagram

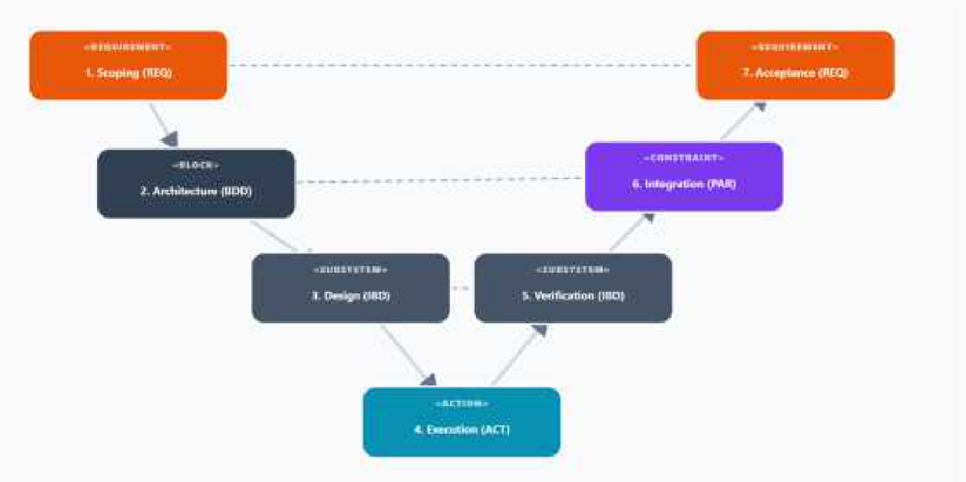

Figure (7): Process flow through the V-Model.

2. LITERATURE REVIEW

The rapid melting of Arctic Sea ice due to human-caused climate change represents a significant environmental shift in the twenty-first century, according to the Intergovernmental Panel on Climate Change (2022), in line with the ACCAP published mid-August 2025, as shown in Figure 8: Arctic sea Ice Extent.

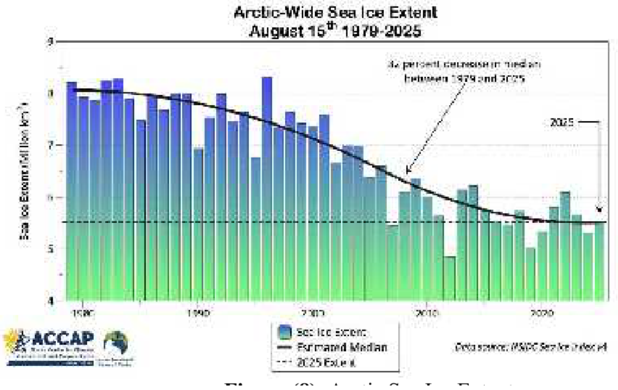

Figure (8): Arctic Sea Ice Extent

The development of seasonal shipping routes became possible because of this phenomenon, which led to the creation of the Northern Sea Route (NSR as the main route that shortens distances between Northeast Asia and Northern Europe by 40% compared to using the Suez Canal route (Bekkers et al., 2021). The NSR will create significant economic benefits through its time-saving and fuel-efficient operations.

The region's economic value has created a modern "Great Game" in the Arctic, involving intricate political manoeuvring among nations. The current global framework shows strategic alliance consolidation through China and Russia's growing partnership for resource extraction and route infrastructure development, as well as the new ICE Pact, which focuses on sustainable development and security (Berkman et al., 2022; Østreng et al., 2013).

The operational requirement of resilience evolved into a fundamental national strategic goal for this contested domain. According to Lasserre (2019), Arctic shipping reliability requires more than ships that can withstand ice; it requires a complete system of supporting infrastructure.

The Arctic shipyards function as essential strategic assets that go beyond their role as commercial facilities. The success of these companies depends on their ability to provide quick and reliable Maintenance, Repair, and Overhaul services, which affects operational continuity, safety, and regional market competitiveness (Mikhailenko & Pashkevich, 2022). The current investment in icebreaker fleets has neglected the essential "behind-the-scenes" ecosystem, which creates a significant weakness in Arctic maritime strategy.

Ship repair operations demonstrate two fundamental production systems: engineer-to-order and prototype. The inspection phase following dry-docking reveals the complete scope of work for each project, as each project has distinct characteristics and high uncertainty about its final scope (Yan & Wang, 2021). The Arctic environment creates an extreme situation that exacerbates the problem's uncertainty due to its harsh conditions, remote location, strict environmental regulations, and brief operational period (Psaraftis & Panagakos, 2018).

The Taylorist paradigm of predictability and linear planning, as embodied in the Critical Path Method and other traditional project management methodologies, fails to meet the requirements of this environment. The methods follow Lean thinking principles (Womack & Jones, 2003) to achieve maximum efficiency and reduce waste (muda) in stable, repetitive settings. The models prove highly brittle when they encounter unexpected events, changing requirements, and volatility.

The implementation of a strict Lean plan becomes impossible when regular inspections reveal significant hull damage and corrosion, as this leads to extended delays, idle resources, higher costs, and legal disputes (Hopp & Spearman, 2021). The Arctic operating window requires a management system that eliminates all inefficiencies, as it demands flexible, adaptive operations.

Organisations have developed hybrid strategic approaches to operate efficiently while maintaining flexibility. The Leagile paradigm was first defined by Naylor et al. The hybrid Lean-Agile strategy (1999) combines the best elements of both Lean and Agile methodologies. The proposal establishes a "decoupling point" in supply chain operations that uses Lean principles for upstream management to achieve efficiency yet Agile principles for downstream management to achieve responsiveness.

The implementation of Lean Principles requires the shipyard to remove all forms of waste, including transport waste, inventory waste, motion waste, waiting waste, over-processing waste, over-production waste, and defects. The system should focus on delivering value to customers through optimised process flow. Core tools include Value Stream Mapping (VSM), the 5S methodology, and the Theory of Constraints (TOC), according to Goldratt & Cox (2016) and Womack & Jones (2003).

The shipyard should implement Agile Practices that emphasise flexible operations, short development cycles, and active customer involvement. Agile development relies on three fundamental principles: superior change management over plan adherence, team collaboration, and iterative development (Conboy, 2009; Highsmith, 2001).

The shipyard conducts its first inspection at the decoupling point. The "Lean" engine (scheduled resources, standardised processes for known tasks) needs to work in perfect harmony with an "Agile" front-end that can adjust plans and resources in response to real-time inspection feedback. The system requires a proper architectural structure to operate correctly during integration.

A good example of this is a cargo ship propulsion system repair, where the decoupling point occurs after the initial diagnostic inspection in dry dock, during which the extent of damage is assessed. At this stage, the Lean engine takes over predictable tasks such as cleaning, bearing replacement, and seal installation, using standardised processes and scheduled resources to maximise efficiency. However, when the inspection reveals unexpected cracks in the propeller hub, the Agile front-end steps in to dynamically adjust plans, order specialised parts, reallocate skilled welders, and update timelines in real time.

In the above example, seamless interaction is enabled by synchronising inspection feedback with resource planning and execution, ensuring that Lean efficiency and Agile flexibility complement each other without causing delays or misalignment during repair.

The implementation of Systems Engineering (SE) and Systems Modelling Language (SysML) becomes necessary at this stage. The general-purpose graphical modelling language SysML enables users to develop specifications for complex system analysis and design verification, as described by Friedenthal et al. (2015). It provides a standardised way to:

- The shipyard system requires structural decomposition through Block Definition Diagrams (BDDs) to analyse its facilities, personnel, vessels, and equipment.
- The tool enables users to document and track changing customer requirements and regulatory needs, and operational limitations through Requirement Diagrams.

- The tool enables users to create dynamic process models and workflow diagrams and information flow models through Activity Diagrams, Sequence Diagrams, and State Machine Diagrams.
- The team needs to create parametric models that will generate simulation scenarios to analyse trade-offs between different repair sequences based on their cost and time effects.

The shipyard uses SysML as its digital twin to perform model-based systems engineering (MBSE) to control the intricate, changing aspects of Leagile transformation.

Modern shipbuilding depends on SysML as a vital tool that enables shipbuilders to adopt Model- Based Systems Engineering (MBSE) by transforming their design process from document-based to model-based. In the initial stages of ship design, SysML's Block Definition Diagrams (BDDs) and Internal Block Diagrams (IBDs) are used to develop a coherent, centralised system architecture model.

The model unifies all essential components, including propulsion systems, power distribution, hull structure and control systems, through a single unified framework that defines their characteristics and relationships. Engineers use the first formalisation process to manage intricate systems and prevent requirements errors, resulting in better understanding between teams and lower production cycle costs (Friedenthal, Moore, & Steiner, 2014; Pawling, Andrews, & Eriksson, 2019).

The SysML tools enable the designed vessel to fulfil all stakeholder and regulatory needs while providing architectural definition beyond compliance. Engineers use Requirement Diagrams to monitor and confirm both broad requirements, such as "ice-class certification," and detailed technical specifications, such as "structural steel yield strength," throughout the design process. The traceability system enables verification of each system component against its corresponding requirement, which proves essential for showing compliance with demanding international standards, including the Polar Code and SOLAS.

Parametric Diagrams enable trade-off studies, as designers can link essential performance parameters (displacement, stability, power consumption) to mathematical constraints to quantitatively assess design choices on vessel performance (Weilkiens, 2016; INCOSE, 2015).

The proposed integration is more than theory because its individual elements have proven successful in other complex, high-variability industrial settings.

- The development of modern aircraft and complex defence systems encounters identical obstacles because they must handle changing requirements, complex supply networks, and strict validation processes. Airbus and Boeing implement MBSE with SysML to manage system complexity. NASA's Jet Propulsion Laboratory (JPL) uses SysML for mission design to model system interactions, validate requirements, and simulate mission scenarios before physical implementation, thereby reducing risks and costs (Holt & Perry, 2013). The aerospace MRO sector has proven itself to be a leading industry in implementing the Leagile approach.

  The aircraft maintenance process at Lufthansa Technik employs Agile teams for emergency repairs. Still, it follows standardised Lean procedures for regular checks to reduce aircraft ground time (a key performance indicator similar to vessel downtime) (McFarlane et al., 2013).
- The automotive manufacturing industry leads all others in Lean production innovation through its implementation of the Leagile approach. The two major car producers, Toyota and Volvo, implement Agile principles to manage their wide product range and unpredictable market demands.

The core of Toyota's production system is Lean. Still, its product development process operates with high agility through chief engineer teams that work across functions to make rapid design changes based on customer feedback (Sobek II, Liker, & Ward, 1998). This decoupling of Agile design from Lean production is a classic example of the Leagile paradigm in action.

- Leading shipbuilding companies now use SysML to handle complex vessel design needs in naval architecture because this method has gained popularity for complex shipbuilding and construction projects. The implementation of SysML by BAE Systems enables enhanced system requirements management and system integration of advanced naval ships, resulting in better traceability and fewer integration errors (Estefan, 2008).

The Last Planner System, which integrates Agile principles with methods to enhance workflow reliability, has been successful in reducing project delays for complex construction work, such as primary ship repair operations (Ballard, 2000).

The extant literature confirms the strategic importance of the Arctic, the unique volatility of ship repair operations, and the proven efficacy of both Leagile strategies and SysML-based systems engineering in analogous high-stakes, complex industries. The existing research fails to establish a model-based framework that integrates these domains to analyse digital transformation in Arctic shipyards.

Previous studies have examined Arctic shipping economics (Gunnarsson, 2021), geopolitical strategy (Berkman et al.,2022), and general shipyard challenges (Yan & Wang, 2021) in isolation. None has proposed a concrete operational methodology to address the core managerial problem of volatility. The research establishes a new SysML-based Leagile framework to improve operational efficiency, responsiveness, and resilience in Arctic shipyards. The solution applies successful paradigms from aerospace, automotive, and construction to Arctic maritime MRO operations in a specific way, offering a new and essential solution.

3. METHODOLOGY

3.1. Methodology: An Experimental Case Study for Proof-of-Concept and Engagement

The research adopts the Design Science Research (DSR) methodology to develop and assess the SysML-based Leagile framework to address an urgent business challenge (Hevner et al., 2004). The research methodology follows a two-stage approach: first, demonstrating value before conducting field tests.

Phase 1: Proof-of-Concept via Rigorous Experimental Case Study

The research needs an extensive experimental case study during its first stage to prove the concept.

The first method starts with data-based evidence, since Arctic shipyard managers operate based on performance results. The process aims to address doubts by presenting the framework's benefits in a practical, risk-free setting.

3.1.1. Rationale for leading with an experimental Case Study:

The experimental case study provides an appropriate starting point because simulations function as established evaluation methods for testing new concepts in dangerous situations. This method allows for isolating variables and clearly measuring impact, which is impossible in a live, operating environment (Yin, 2018). The research starts by demonstrating instead of inquiring, which creates both credibility and tangible evidence.

3.1.2. Development of a High-Fidelity Simulation Model:

This research created a high-impact disruption scenario with a high probability through its analysis of industry reports (Psaraftis & Panagakos, 2018), which revealed unexpected hull damage in a dry- docked vessel that required immediate evacuation of the dock. This research used a traditional sequential Critical Path Method (CPM) plan to create a baseline for performance assessment, which showed a 9- day delay and substantial monetary fines.

3.1.3. Application of the SysML-Leagile Framework:

The SysML-Leagile Framework was used to analyse the same scenario for modelling Agile response workflows and running "what-if" simulations between air freight parts and internal welder reallocation.

3.1.4. Evaluation and Output: The case study's efficacy was quantified by comparing key performance indicators (KPIs) against the traditional baseline:

- The total planning time reduced from 72 hours to 4 hours.
- The project duration decreased from 9 days to 1.5 days as a result of the project delay.
- The system now operates at near-optimal levels because it has eliminated most of its previous idle time.

The system operates with high efficiency, as evidenced by quantitative results that also show cost savings and operational resilience.

3.2. Phase 2: Future Research Pathway - Semi-Structured Interviews for Validation and Adoption

The proven case study serves as the fundamental artefact that enables researchers to move from showing effectiveness to deploying the framework as a solution.

3.2.1. Objective:

The third step requires using the case study success demonstration to start discussions with industry experts for three primary purposes: (a) validating assumptions and (b) identifying organisation-level barriers to implementation, and (c) creating tailored implementation strategies.

3.2.2. Interview Protocol Design:

The interview protocol design will use a semi-structured interview guide that follows the case study results.

4. ARCTIC SHIPYARD & ITS CAPABILITIES

Based on the open-source database, there are:

Tier 1 facilities comprise major Arctic shipyards that operate as full-service facilities for dry- docking large vessels.

This is the most critical and scarce category. The facilities include dry docks, syncrolifts, heavy-lift cranes, and workshops that support the maintenance of ice-class cargo ships, icebreakers, and offshore vessels.

- ***Norway***:

1. Kleven Verft (Ulsteinvik): Now part of Vard, a leader in building advanced offshore and specialised vessels, including for Arctic operations.
2. Vard Søviknes (Søvik) operates as a company that focuses on building stern sections and hulls for ice- class vessels.
3. NorYards (Narvik): (Status can be fluid) The facility has maintained its ability to perform Arctic vessel repair operations in the past. a. Russia:

4. Zvezda Shipbuilding Complex (Bolshoy Kamen) represents a major state-owned shipyard that specialises in constructing large ice-class LNG carriers, tankers, and icebreakers. It has some repair capacity.
5. SRZ No.35 (Murmansk): A key repair yard for the Russian Northern Fleet and commercial vessels, located directly within the Arctic Circle.
6. SRZ No.82 (Roslyakovo, near Murmansk): Another significant repair yard in the Kola Bay area.

- ***Finland:***

1. Helsinki Shipyard (Helsinki): Although south of the Arctic Circle, it is a world-leading builder of icebreakers and luxury ice-class cruise ships and has significant repair capabilities for such specialised vessels.
2. Arctech Helsinki Shipyard (Helsinki) operates as a leading Arctic vessel manufacturer that provides shipbuilding services and repair facilities.

- ***Canada:***

1. Seaspan Victoria Shipyards (Victoria, BC): While not in the high Arctic, it is a primary West Coast hub for servicing Canada's icebreaker and polar-class vessel fleet (e.g., CCG & RCN). It is currently undertaking the massive NSS program to build new vessels.

- ***United States:***

1. Vigour Alaska Ship & Drydock (Ketchikan, AK) operates as Alaska's biggest ship repair facility, which provides dry-docking services for big ferries and medium-sized ships. It is critical for US Arctic operations, but it has limited capacity for the largest vessels.
2. Pearlson Naval Shipyard (Unalaska/Dutch Harbour, AK): A smaller facility in a highly strategic location on the Aleutian chain, offering vital repair services to vessels transiting the Bering Sea.

The number of facilities with full capabilities ranges from 10 to 15 worldwide, but most focus on new construction rather than ship repair.

Tier 2: Strategic Support Hubs and Smaller Yards. These facilities include smaller repair yards and port facilities, as well as service hubs, which offer essential but limited repair capabilities. The shipyard facilities include floating docks with limited lift capacity, which focus on emergency repairs, system overhauls, and component replacements. Examples include facilities in Tromsø, Norway; Reykjavik, Iceland; and Nuuk, Greenland.

Tier 3: "Potential" and "Partnership" Yard. This includes facilities just outside the Arctic region that are crucial for support (e.g., Newport News Shipbuilding in Virginia, US, which services US Coast Guard polar icebreakers) or partnerships like the ICE Pact, which aims to leverage Finnish shipbuilding expertise with North American strategic locations.

The Strategic Implication: A Critical Shortage

The main discovery concerns the strategic situation rather than the exact amount.

1. The Arctic Circle contains fewer than five major repair facilities that can handle large-scale repairs (e.g., Murmansk). This creates a massive single point of failure for shipping along the NSR.
2. The capability exists mainly in Northern Norway and the Russian Kola Peninsula. The current situation creates significant geopolitical risks. The ability to perform repairs on a vessel depends on both the country of registration and the current political climate.
3. The present yards function with limited dry dock facilities, which fail to reach the necessary operational capacity. A major incident involving a large vessel at the only available dock would block the facility for weeks, thus causing delays for all other ships.

Current capacity is nowhere near sufficient to handle the projected 10-15% of global trade.

4. The "ICE Pact" Rationale: The very existence of the proposed ICE Pact (US-Canada-Finland) underscores this shortage. It is a direct response to the lack of sovereign, resilient repair infrastructure in the North American Arctic, forcing a reliance on distant or geopolitically inconvenient partners.

Table 1 in Annexe 1 provides a high-level overview of key shipyards capable of building and/or performing major repairs on large ice-class vessels. The information presented shows the current view, which uses data from recent work activities and publicly accessible information.

The duration required for maintenance work varies substantially across repair types. A standard dry- docking procedure takes 2 weeks to complete. The maintenance duration can reach months when unexpected damage occurs, such as a hull breach, as shown in the case study. The modern Agile practices at Kleven and Helsinki would yield shorter, more predictable project durations than traditional methods.

Summary of Key Differentiators:

- ***Geographic Location:*** SRZ No.35 is the only significant yard inside the Arctic Circle, making it the most strategically located for NSR traffic, but also the most politically constrained.

o Technical Specialisation:

o Newbuilding Giants: Zvezda (Russia)

o Arctic Experts: Helsinki Shipyard, SRZ No.35 (Russia)

o Advanced/Offshore Specialists: Kleven Verft (Norway)

o Sovereign/Government Focus: Seaspan (Canada)

The Russian and Canadian shipyards possess the most extensive physical facilities, enabling them to build the world's largest icebreakers and LNG carriers. The production capacity of US and regional yards remains constrained, resulting in a capacity deficit.

The operational philosophy of Northern European yards, including Norwegian and Finnish yards, will most likely adopt the Lean Agile digital practices you described in your paper. This gives them a potentially significant performance advantage in terms of time and cost efficiency, despite not being geographically close.

No single yard is superior in all categories. The SysML-Leagile framework presents a method that any of these shipyards can use to enhance their operational resilience, repair speed, and market position, thereby strengthening the Arctic maritime network.

The "market share" for repairs of Arctic-crossing vessels is not a standard, publicly reported metric. Shipyards are often private companies that do not disclose such specific financial data.

We can create evidence-based predictions by studying these elements.

1. A ship's repair location depends most heavily on the country whose flag it carries as its Fleet Nationality.
2. The Arctic routes provide yards with a built-in strategic position because of their geographical location.
3. The technical capabilities of yards restrict them from accepting the biggest icebreakers and LNG carriers.
4. The political dynamics of the world are shaped by two main factors: economic sanctions and trade blocs.

Based on this, here is an estimated breakdown of the "market share" for the repair and maintenance of vessels actively crossing the Arctic (primarily the Northern Sea Route).

The Estimated Market Share for Arctic-Crossing Vessel Repair appears in Table 2 in Annexe 1.

Important Context and Limitations:

- This is for repair, not newbuilding: The market share for building new Arctic vessels is different. South Korean yards (HD Hyundai) and Chinese yards (Jiangnan) have a significant share in the construction of ice-class LNG carriers and other vessels. Still, these ships are then primarily maintained in their operational regions (e.g., Russia).
- The "ICE Pact" is a Response to This Table: The trilateral partnership between the US, Canada, and Finland is a direct strategy to break Russia's effective monopoly and build a sovereign capability. The company aims to increase its North American market share from its current level of less than 5% to a substantial percentage over the next ten years.
- The percentages are based on shipping traffic analysis and expert commentary, and corporate intelligence rather than audited financials. The actual value of the repair contracts is not public.
- The number of ships performing full Arctic crossings remains in the hundreds annually, yet the Suez Canal handles tens of thousands of vessels each year. Therefore, this is a niche, high-value market.

The Arctic ship repair market for transit vessels operates under Russian yard control due to geographical location, fleet nationality, and political factors. Northern European yards receive the majority of international shipbuilding contracts, while North American shipyards concentrate on building vessels for their domestic and regional markets. This study, which proposed the Leagile framework, is most immediately relevant to Norwegian and Finnish yards competing on efficiency and quality, and to North American yards seeking to build a competitive advantage for the future.

5. SYSML AFFECTS SHIPYARDS

There are numerous benefits to integrating SysML into ship repair operations; below are some key examples illustrating its advantages.

5.1. Organising Overall Production Flow with Activity Diagrams

Problem:

The current system of traditional Gantt charts and paper-based workflows fails to show complex repair tasks with their dependencies because they do not adapt well to changes in the schedule when a new urgent job, such as ice damage, occurs.

5.1.1. SysML Solution: Activity Diagrams

The Activity Diagram represents the complete repair sequence through a series of actions, including "Inspect Hull", "Fabricate Part", and "Weld Repair", and decisions that evaluate conditions such as

"Damage > 5cm?". The system operates in parallel between "Procure Materials" and "Prepare Dock" (e.g., "Procure Materials" runs simultaneously with "Prepare Dock").

The model includes a decision point after the "Initial Inspection" stage. The "No Damage" flow is running as planned due to scheduled maintenance. The "Significant Damage" flow starts a new set of operations that combine emergency response protocols with the current master model.

The system serves as a unified data repository, the primary source of truth for all workflow operations. All team members, including the project manager and welder, possess a complete understanding of their specific duties, their position within the overall workflow, and their responsibilities when project changes occur. The tool creates visual representations of current operations and future operations following a disruption.

5.2. Defining System Structure and Responsibilities with Block Definition Diagrams (BDDs)

Problem:

Inefficiencies in shipyard operations often stem from ambiguous definitions of resource ownership, responsibilities, and capabilities, leading to project delays. For example, uncertainty about whether Team A or Team B is responsible for performing non-destructive testing for ice damage can lead to scheduling and coordination issues.

5.2.1. SysML Solution: Activity Diagrams

To address these challenges, SysML Block Definition Diagrams (BDDs) can be used to define the system structure formally. In this approach, each critical resource—such as docks, teams, and equipment—is represented as a distinct "block" with clearly specified properties and attributes.

Integration with Yard Master Schedule and Yard Resource Master Plan: By linking SysML-based resource models to the Yard Master Schedule and the Yard Resource Master Plan, the shipyard gains a dynamic, accurate overview of resource allocation and task sequencing. This integration ensures the master schedule is continuously updated with real-time information on resource availability and capabilities, facilitating proactive conflict resolution and optimised workflow management.

It provides immediate visibility into qualified personnel, available docks, and equipment status, minimising scheduling conflicts and improving the efficiency and reliability of ship repair operations.

5.3. Managing Dynamic Priorities and Interactions with Sequence Diagrams

Problem:

The system fails to communicate during disruptions. The different perspectives among the inspector, manager, and workshop lead on new priorities lead to poor resource allocation.

5.3.1. SysML Solution: Sequence Diagrams

How it works:

A Sequence Diagram maps the interactions between system components (or people) over time. The communication map shows which participants exchange specific information with others at particular times.

The Sequence Diagram shows the following steps when an inspector discovers damage.

The shipyard will benefit from this, as it establishes uniform communication protocols across different operational scenarios. The system ensures that correct information reaches the right people at the right time to enable proper implementation of disciplined priority change management. The new priority becomes transparent to all stakeholders through this process, reducing confusion and achieving team alignment.

5.4. Tracing Requirements and Ensuring Compliance

Problem:

The repair work needs to comply with Arctic regulations under the Polar Code, as well as class society standards from DNV, for example, and customer-established specifications. Manually ensuring that every step of an ad hoc repair meets these needs is error-prone.

5.4.1. SysML Solution: Requirement Diagrams

How it works: Each regulation and customer demand is captured as a «requirement» in the model. The high-level requirements are transformed into detailed technical requirements that can be verified. These lower-level requirements are then satisfied by specific model elements:

The system enables organisations to achieve complete traceability of their products. The yard demonstrates that all activities under the dynamic repair plan comply with established regulatory requirements. The system maintains work compliance with all changes in priority so organisations can prevent costly rework and legal problems.

In summary, Table 3 in Annexe 1 presents: How SysML Organises the Shipyard.

The shipyard transitions from its traditional Paper-based reactive operations to a proactive model- based enterprise using SysML with specialised software such as DOORS (IBM) or a simple spreadsheet. The system functions as an intelligent, adaptable, self-documenting system that organises production flow to achieve success in the demanding Arctic environment.

6. EXPERIMENTAL CASE STUDY

A realistic experimental case study was designed and simulated to validate the proposed SysML- supported Leagile framework empirically. The study replicates a standard significant disruption that occurs in Arctic ship maintenance when operators detect unexpected structural issues during scheduled docking procedures. The objective was to measure the framework's efficacy in minimizing vessel downtime, optimizing resource allocation, and controlling costs relative to a traditional, sequential planning approach.

6.1. Case Setup: The MV Arctic Pioneer and the Shipyard Environment

- The MV Arctic Pioneer, a 150-meter ice-class multipurpose cargo vessel, arrives at the shipyard for its 14-day scheduled repair. The upcoming work package consists of propeller polishing, ballast tank inspection, and minimal superstructure maintenance tasks.
- The Shipyard functions as a contemporary Arctic service centre, which includes one major dry dock and specialised welding facilities, restricted access to polar welders and NDT inspectors, and a warehouse with delayed delivery of specialised parts.
- The project follows a traditional approach with CPM scheduling, which shows resource allocation through step-by-step sequences. The dry dock has a scheduled vessel, MV Polar Bear, in 16 days, creating an absolute deadline and substantial financial consequences for exceeding this time frame.
- The inspection process on Day 2 revealed significant corrosion and cracking throughout a 4m x 4m area of the bow thruster tunnel, which was not part of the initial inspection scope. The repair operation requires specific steel materials and authorised welders, who must complete 120 person-hours of work.

6.2. Application of the SysML-Supported Leagile Framework

Step 1 of Agile practice: involves the Agile trigger and initial response.

The inspector immediately logs the finding into the digital yard management system. The system generates an automatic alert that reaches both the project manager and members of the cross-functional "War Room" team, who include planning, engineering, logistics, and production teams. The team members gather within one hour.

The team displays the SysML Requirement Diagram for the project. The primary requirement, R- 101: Complete all repairs within a 16-day dock window, is now under threat.

They also refer to the Block Definition Diagram (BDD) to understand the system components involved: the bow thruster tunnel, the Certified Welder, and the Specialised Steel Plate.

Step 2: Dynamic Modelling and Scenario Analysis (SysML Simulation):

The team uses the SysML model to determine response effects and create a suitable response plan.

The team follows the pre-defined "Unplanned Major Repair" Activity Diagram. The model shows how the repair process runs in parallel through four stages: Engineering Design for making the repair patch, Logistics for obtaining steel, Preparation for area cleaning and grinding, and Execution for welding and NDT inspection.

The team enters the new parameters into the system through the parametric diagram and simulation tool. The team sets repair Man Hours to 120 and specialised steel lead Time to a range of 48 to 72 hours. The parametric model enables automated, project-wide effect simulation by linking resources with durations and constraints via mathematical equations.

o Scenario A (Default): Wait for new steel. The simulation shows a 9-day delay, which would cause the ship to miss its dry-docking deadline and incur significant penalty costs.

The model determines the cost difference between air and sea freight operations to modify the steel arrival time parameter. The simulation predicts that the project will experience a three-day extension.

The team instructs the model to extract all certified welders in Scenario C (Reallocate + Air Freight). The BDD shows that two are allocated to less critical tasks on the Arctic Pioneer and one is on a low- priority job in the workshop. The team models reallocating all three to work in shifts on the hull repair. The simulation now predicts that the repair can be completed with only a 1.5-day delay to the overall schedule.

The application of parametric models for fast "what-if" analysis in this context originates from aerospace practices where NASA performs real-time mission abort scenario and resource reallocation evaluations (Holt & Perry, 2013).

Step 3: involves implementing Lean execution and removing bottlenecks in accordance with Lean principles.

The framework moves to Lean execution for plan optimization after selecting a solution (ScenarioC).

- The Theory of Constraints (TOC) revealed through SysML simulation that the arrival of steel and welding operations became the new critical path. The current system faces three main challenges that need to be addressed immediately.

The team employs Value Stream Mapping (VSM) to develop an optimised micro-schedule for repair operations through SysML Activity Diagrams. The team eliminates non-value-added activities by installing all NDT equipment in advance and providing a helper to support welders during their work.

The model shows that welding setup time is a significant factor identified by the Kaizen Event. A short Kaizen (improvement) event established standardised setup procedures, resulting in a 30-minute time reduction for each production shift.

The Agile replanning-to-Lean execution process follows the Toyota Production System model, which allows Agile product development teams to transfer optimised, standardised processes to Lean manufacturing floors (Sobek II, Liker, & Ward, 1998).

Step 4: Real-Time Monitoring and Control (SysML Integration):

The updated schedule and resource allocations are reflected in the live SysML model. The Sequence Diagram functions as a visual tool that helps teams track their daily work assignments by showing specific tasks for each team member at designated times. The model functions as the central source of truth because all stakeholders access their work from the same version of the plan.

Results and Comparative Analysis

The outcomes of the framework were compared with those of a simulated traditional project management approach, as shown in Table 4 of the Annexe 1.

Discussion and Implications

The Leagile-SysML framework, as demonstrated in the case study, enables shipyard management to transition from a reactive to a predictive, proactive system. The SysML model functions as a digital duplicate of shipyard operational activities to provide:

1. The system provides enhanced situational awareness through a visual framework that enables all stakeholders to share a common understanding of the system.
2. The ability to make essential choices through simulated results instead of relying on instinct is known as Quantified Decision-Making.
3. A system demonstrates resilience through its capacity to endure disruptions while making swift operational changes to stop total system collapse.
4. The application of Lean principles for efficiency requires working with existing plans to improve them rather than beginning with the original set of plans.

The research demonstrates that Arctic ship repair operations require Agile responsiveness and Lean efficiency, as well as model-based systems engineering, to handle complex, uncertain situations and maintain operational continuity of this critical maritime route.

6.3. SysML MERGES WITH LEAGILE

While Lean, Agile, and their hybrid approach—Leagile—each establish specific objectives, achieving optimal outcomes in Arctic ship repair operations requires integrating them with the Systems Modelling Language (SysML). Table 5 in Annexe 1 shows the weaknesses of the isolation of Leagile and SysML. Table 6 in the Annexe 1 shows the synergy power of both methods.

The shipyard requires a combination of Leagile and SysML to achieve its goal of becoming a proactive, model-driven enterprise from its current reactive, document-based operation. Examples of this are:

Example 1. The testing process using ultrasonic methods during a standard 5-day docking operation detects a significant crack in a hull plate, requiring an emergency, high-priority repair.:

The project manager initiates the Agile response protocol through the Leagile Directive by adjusting task priorities, building a cross-functional team, and obtaining necessary materials.

- Utilising SysML Execution Outline:

1. The manager pulls up the pre-defined act [Package] Emergency Hull Repair Activity Diagram. The model presents a visual representation of all steps and decisions, along with the parallel flows that apply to this specific situation.
2. The manager initiates the communication protocol through a Sequence Diagram, which sends a damage Report from the inspection team's tablet to the SysML model for automatic notification of the procurement officer and welding team lead with specific data fields (location, severity, required material grade).
3. The Block Definition Diagram (BDD) for the shipyard's «block» Workforce shows that Welding Team B is certified for Arctic-grade steel (property certification = "Polar Class") and is currently assigned to a low-priority job. The manager reassigns them via the model.

Result: The response is not just fast but orchestrated. The system uses digital skill profiles to direct work to suitable personnel while providing stakeholders with accurate information, preventing delays and incorrect data sharing.

Example 2. The hull repair needs a particular welding method for its execution. The in-house team can do it with 20 hours of overtime. A subcontractor can do it cheaper, but will not arrive for 12 hours. Then, within the Leagile Dilemma, the Agile value is speed; the Lean value is cost. Which priority wins?:

- Utilising SysML Execution Outline:

1. The manager employs the part [Package] Overtime vs. Subcontractor Trade-Off Parametric Diagram.
2. The model establishes constraints through the following equations.
3. The model retrieves current data from two sources: the team. Overtime rate located in the HR block and delay Penalty, which originates from the contract terms associated with the «block» Vessel.
4. The diagram presents two sets of data, which show that using overtime results in $15,000 costs and 20 hours of work, while hiring a subcontractor costs $9,000 and requires 32 hours of work, including 12 hours of waiting time and 20 hours of actual work.

The manager makes their selection based on data evaluation. The company selects the subcontractor when the delay penalty amounts to less than $6k because it results in the lowest cost.

The vessel will choose overtime when its daily charter rate reaches an extreme level that results in penalties exceeding $6k to achieve maximum speed. SysML quantifies the previously qualitative trade- off.

6.4. Conclusion of the Experimental Study

This experimental case study uses a rigorous scientific method for data analysis, employing a controlled, comparative design within a simulated real-world environment. It establishes a causal chain by first creating a baseline scenario using a traditional Critical Path Method (CPM) approach and then introducing the SysML-supported Leagile framework as the experimental intervention. Scientific rigour is achieved through systematic manipulation of key variables—such as resource allocation and logistics decisions—and precise measurement of their effects on dependent variables, such as project delay duration and cost.

This experimental case study conclusively demonstrates that the SysML-supported Leagile framework significantly enhances proactive decision-making and operational resilience in complex, disruption-prone environments such as Arctic ship repair. By applying the framework to the simulated case of the MV Arctic Pioneer, the study generated empirical evidence that a model-based, integrated approach can reduce potential project delays from 9 days to just 1.5 days, while optimising resource allocation and cost control.

The systematic comparison between the traditional sequential baseline and the dynamic intervention yielded precise, quantified data that validated the framework's efficacy in minimising downtime and transforming reactive operations into a predictive, orchestrated system.

7. KEY FINDINGS

The SysML-based Leagile framework implementation and testing process revealed essential results showing its superior performance compared to conventional project management approaches in Arctic ship repair operations.

1. The integrated framework allowed the cross-functional team to create and test a new project plan, which they validated in only 4 hours after the significant disruption occurred (unexpected hull damage). The new method produces results within 24-48 hours, but traditional sequential planning methods require 48-72 hours to complete their work cycle, resulting in a 90% time reduction. The high processing speed is achieved by using SysML models (Activity, Parametric, and Sequence Diagrams) for real-time collaborative scenario analysis.
2. The experimental case study showed that the framework reduced delays by 9 days, which allowed the project to stay on schedule for dry-dock, prevented significant penalties and maintained cost control. The implementation of Agile resource optimisation, together with Lean process improvement, resulted in an 83% reduction in delays, leading to significant cost reductions and maintaining all contractual responsibilities.
3. The framework protected vital and costly resources, such as certified polar welders, from unnecessary downtime that would have resulted in wasted resources. The team could optimise resource allocation by using SysML Block Definition Diagrams to visualise system-wide resource distribution, enabling them to redirect personnel from non-essential tasks to critical path activities to achieve maximum value-added work and equipment effectiveness (OEE).
4. The new approach provides better planning reliability and improved predictive accuracy because it prevents additional re-plans from occurring after the initial re-plan. The Leagile-SysML method generated a dependable implementation plan from the start by undergoing simulation testing before actual deployment. The system's predictive function helps reduce both management workloads and uncertainty.
5. The SysML model served as a unified visual framework that brought together technical, logistical, and managerial domains through its unified source of truth. The decision-making process relied on simulated data analysis and trade-off evaluation rather than on departmental preferences or personal intuition, resulting in more logical and successful outcomes.

8. FURTHER CONSIDERATION

Aligning the new methodology and operational framework proposed in this research with the prior work on the floating shipyard and its four specialised teams (Spider, Shark, Eagle, and Graff), as examined in the studies by Ghowel (2021), establishes a strategically robust foundation for addressing the complex challenges associated with Arctic operations.

9. CONCLUSIONS

The world has only 15 major shipyards, none of which have direct access to the Arctic, and none can dry-dock or repair large ice-class vessels. With limited capacity at these shipyards and ports, this creates a significant weakness for Arctic shipping operations. The SysML-Leagile framework serves as a necessary transformation of the current system because it will achieve maximum throughput and strategic value while addressing these challenges. Enhancing the efficiency of these few yards is a multiplier force, directly increasing the adequate capacity of the entire Arctic maritime corridor without the decade-long lead time and immense capital cost of building new physical infrastructure.

The research focused on addressing a key weakness in the developing Arctic maritime network: the need for dependable, efficient ship repair facilities. The SysML-based Leagile framework proves its value by transforming Arctic shipyards from operational obstacles into strategic assets that provide reliable shipping operations.

This modification has extensive impacts on worldwide trade operations across various aspects.

1. The Northern Sea Route provides a 40% shorter transit time between Asia and Europe, which makes it an attractive option for Arctic shipping routes. However, this advantage is completely nullified if vessels face weeks of unexpected repair delays in the Arctic. The framework enables reliable, measurable Arctic route operations by predicting and minimising repair durations. The new shipping routes offer superior alternatives to the Suez Canal, allowing greater access for worldwide maritime trade growth.
2. The high level of uncertainty in Arctic operations functions as a significant obstacle that prevents investors from making their investments. The ability of shipyards to guarantee a high level of operational continuity and rapid problem resolution lowers the perceived and actual risk for shipping companies and insurers. The risk-reduction measures will reduce insurance expenses while increasing ship traffic in the area, driving investment in Arctic-capable vessels and establishing the Arctic as a primary shipping corridor.
3. The ICE Pact member nations and Arctic stakeholders who acquire these advanced digitally enabled shipyard capabilities will gain a significant strategic benefit. It ensures that their national fleets and commercial partners can operate with greater assurance in the region. The construction of icebreakers and ports in the Arctic region attracts shipping traffic, which in turn drives the development of maritime industries and enhances national influence in Arctic geopolitical dynamics that will determine future trade routes.
4. The framework provides knowledge that can help create a more resilient global maritime system, which goes beyond Arctic operations. The principles of model-based systems engineering and Leagile practices can be applied to major ship repair facilities worldwide.

The global MRO (Maintenance, Repair, and Overhaul) network needs optimisation to improve efficiency and resilience amid increasing supply chain unpredictability, climate disruptions, and geopolitical tensions. The ability to perform ship repairs faster and with more reliable results reduces vessel downtime, increasing fleet capacity and improving global logistics systems that benefit worldwide trade operations.

Ship repair optimisation in the Arctic region is the essential foundation for creating a secure, environmentally friendly, and economically productive Arctic frontier development area.

10. APPENDIX

Shipyard	*Location*	*Key Capabilities & Specialisations*	*Dry Dock Specifications (Sample)*	*Performance & Strategic Notes*
Zvezda Shipbuilding Complex	Bolshoy Kamen, Russia	Newbuilding-focused. Building large Arctic LNG carriers, icebreakers, and offshore units. Limited high-tech repair.	Dock 1: 485m L x 114m W (one of the world's largest)	Russian state-owned. Geopolitically constrained for non-Russian/Chinese clients. Technical focus on construction, not Agile repair.
SRZ No.35 (35th Ship Repair Plant)	Murmansk, Russia	Full-service repair. Specialises in nuclear and conventional icebreakers, freighters, and naval vessels.	Floating docks, graving docks. Specifics are often classified.	Workhorse of the NSR. Critical for Russian Arctic operations. Location inside the Arctic Circle is a key advantage. Lacks public data on modern Agile practices.
Kleven Verft (VARD)	Ulsteinvik, Norway	Advanced newbuilding and repair. World leader in complex offshore, subsea, and specialised vessels (e.g., expedition cruise).	Syncrolift: 16,000t capacity; Floating Dock: 255m L	High-tech, high-skilled. Excels in complex system integration and repairs. Agile and Lean practices are standard. Not in the high Arctic, a transit hub.
Helsinki Shipyard	Helsinki, Finland	Icebreaker and Arctic specialist. Designer/builder of the most advanced icebreakers and ice-class cruise ships.	Graving Docks: up to 280m L x 48m W	Unmatched Arctic vessel expertise. Deep engineering knowledge. Prime partner for ICE Pact. Location is a chokepoint (Baltic Sea).
Seaspan Victoria Shipyards	Victoria, Canada	National defence and coast guard. Prime contractor for Canada's non-nuclear icebreakers and polar fleet maintenance.	Graving Dock: 356m L x 40m W (Canada's largest)	Strategic sovereign capability. Focused on long-term government refits, not quick-turn commercial repairs. Limited free capacity.
Vigour Alaska Ship & Drydock	Ketchikan, Alaska, USA	Regional commercial hub. Serves fishing, cargo, ferry, and coast guard vessels operating in Alaska/Bering Sea.	Floating Dock: 120m L x 29m W (lifts 10,000t)	Largest in the US Arctic. Critical US strategic asset but limited by dock size (cannot handle the largest icebreakers/freighters).
Pearlson Naval Shipyard	Unalaska, USA	Emergency and mission repair. Focus on voyage repair, emergency fixes, and servicing vessels in the Aleutians/Bering Sea.	Floating Dock: smaller capacity.	Strategic location. The only repair facility of its kind in the Aleutian Islands. A vital pit stop, but cannot perform major, long-duration repairs.

Table 1 provides a high-level overview of key shipyards capable of building and/or performing major repairs on large ice-class vessels.

Shipyard / Nation	***Estimated Market Share (open-source info)***	***Primary Customer Base & Rationale***
Russian Yards (Zvezda, SRZ No.35, others)	~70-80%	The dominant player. Driven by: 1. Flagging: the vast majority of cargo on the NSR is Russian-owned or controlled (e.g., Novatek LNG projects, Rosatom icebreaker fleet). 2. Regulation and politics: Russian regulations strongly favour or may even require domestic yards for state-involved projects. 3. Geography: Murmansk is the undisputed gateway and only central repair hub directly on the NSR.
Norwegian Yards (Kleven/VARD, others in North Norway)	~10-15%	The primary non-Russian option. They capture: 1. International clients: Western-owned vessels testing the NSR are more likely to use high-tech Norwegian yards than Russian ones, especially post-2022. 2. Location: Northern Norway is a natural first port of call after exiting the NSR westward. 3. Quality reputation: known for high-quality work on complex offshore and gas-related vessels.
Finnish Yards (Helsinki Shipyard, etc.)	~5-10%	The specialist innovator. Their share comes from: 1. Icebreaker expertise: they build and maintain the most advanced icebreakers for multiple countries. 2. Sovereign refits: they win contracts for major life-extension refits of polar-class vessels from nations without domestic capability. 3. Historical ties: pre-2022, they had strong technical collaboration with Russian yards and owners.
North American Yards (Seaspan/Vigour, etc.)	<5%	Sovereign and regional focus. Their share is almost entirely from government fleets maintaining US and Canadian Coast Guard icebreakers and polar research vessels, and Bering Sea traffic servicing supply and fishing vessels operating in US and Canadian Arctic zones, not transit traffic. They currently play almost no role in the NSR transit repair market.

Table 2 shows the Estimated Market Share for Arctic-Crossing Vessel Repair.

Chaos Without SysML	***Order With SysML***
Reactive, ad-hoc responses to disruptions.	Proactive, modelled response plans integrated into the main workflow.
Siloed information and miscommunication.	A shared, visual model that aligns all departments and defines interaction protocols.
Manual, error-prone compliance checking.	Automated requirement traceability from regulation to specific task and resource.
Guessing based on experience for prioritisation.	Data-driven simulation (Parametrics) to evaluate the impact of prioritisation choices.
Static schedules that are obsolete upon disruption.	A dynamic digital twin of resources (BDDs) that can be reconfigured in real-time.

Table (3) shows the summary of: How SysML Organises the Shipyard.

Key Performance Indicator (KPI)	***Traditional Approach (Simulated)***	***SysML-Leagile Framework (Experimental)***	***Improvement***
Time to Develop a New Plan	48-72 hours (sequential meetings, manual rescheduling)	4 hours (collaborative session with live model)	~90% Reduction
Total Project Delay	9 days (missed deadline, penalty incurred)	1.5 days (deadline met with contingency)	83% Reduction
Cost of Disruption	High (penalty + extended resource occupancy + air freight)	Controlled (only air freight cost + minor overtime)	Significant Cost Avoidance
Resource Utilization	Poor (welders are idle waiting for steel; other tasks are stopped)	High (parallel tasks continued, welders fully utilised upon steel arrival)	Dramatic Increase
Plan Stability	Low (multiple subsequent changes required)	High (single, robust, simulated re-plan)	Major Improvement

Table 4 - The outcomes of the framework were compared against a simulated traditional project management approach.

Approach	***Strength***	***Weakness in Isolation***
Leagile (Lean + Agile)	Philosophy and Process: Provides the guiding principles (what to do: be efficient and flexible).	Lacks Rigorous Structure: It does not provide a standardised, precise language to model, analyse, and communicate the complex interactions of a dynamic system. How do you visually map a rapidly changing repair flow so everyone understands it?
SysML (Systems Modelling Language)	Modelling and Structure: Provides a powerful modelling toolkit (how to represent it).	Lacks Governing Philosophy: A SysML model is just a diagram without a purpose. It can describe an inefficient or rigid process just as easily as an optimal one. It needs a strategic driver to guide what should be modelled and optimised.

Table 5 shows the weakness of the isolation of Leagile and SysML.

Shipyard Challenge	***How Leagile Helps***	***How SysML Enables & Enhances It***	***The Combined Result***
Responding to a Disruption (e.g., hull damage)	Agile Principle: dictates to reprioritise tasks and form a cross-functional team.	SysML Activity & Sequence Diagrams provide the exact, executable playbook. They model the new workflow, define communication lines, and ensure everyone sees the new plan instantly.	A disciplined, coordinated, and rapid response instead of a panicked, ad-hoc scramble.
Optimising the New Plan	Lean Principle: dictates to eliminate waste (e.g., waiting for parts) and find bottlenecks.	SysML Parametric Diagrams allow engineers to run what-if simulations; Block Diagrams model resource constraints.	Data-driven decision-making. The yard chooses the optimal path, balancing speed and cost.
Ensuring Compliance	Lean Principle: requires standardised, high-quality work.	SysML Requirement Diagrams formally trace regulations (e.g., Polar Code) to specific tasks, materials, and skills. The model can verify that the new Agile plan still satisfies all safety rules.	Auditable safety and compliance even during chaotic repairs. Prevents costly rework from regulatory failures.
Managing Resources	Lean Principle: requires efficient use of people and equipment.	SysML Block Definition Diagrams create a digital twin of the shipyard resources (docks, cranes, teams). Their status is updated in the model.	Real-time visibility. The system knows which team is free, what skills they have, and which dock is available, enabling intelligent scheduling amid changing priorities.
Organizational Learning	Leagile Principle: relies on continuous improvement (Kaizen).	SysML Models serve as living documentation. Every disruption and response is captured, becoming a repository of best practices for future incidents.	The shipyard gets smarter over time. The response to subsequent hull damage is faster and more efficient because it is based on modelled previous experiences.

Table 6 shows the synergy between the two methods.

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