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Article

Revitalizing Regional Industries through Public Innovation Intermediaries: A Multi-Stage Evaluation of the Maritime Open Lab Model

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Abstract

As regional industrial hubs face structural decline, the "Regional industrial resurrection (RIR)" model—utilizing Open Labs to integrate high-end infrastructure with customized corporate support—emerges as a critical solution to bridge the systemic "triple burden" of capital, talent, and infrastructure deficits. This study evaluates the Busan maritime Open Lab's performance (2021–2022) focusing on representative SMEs, with outcomes strictly verified by national authorities. Technical KPIs improved significantly: design lead times were reduced by 50–60%, and technology readiness advanced from TRL 5 to 9. High-fidelity results included 0.027% spatial precision and 91 FPS rendering stability, facilitating industrial-grade digital twin commercialization. Economically, these firms realized over 3.3 million USD in consolidated revenue, achieving a +66.4% organic growth rate based on a constant exchange rate to isolate macroeconomic volatility. Socially, the Open Lab's contribution resulted in 11.5 verified new employees, proving the model's capacity for regional job creation. Qualitative surveys revealed a 100% satisfaction rate for technical advisory, confirming the Open Lab's role as an essential "Innovation intermediary". Finally, the study proposes tailored expansion strategies for Taebaek/Samcheok, Gumi, and Gunsan across South Korea. These findings underscore the vital importance of public-led shared infrastructure and specialized human capital support in responding to declining regional industries.

Keywords: regional industrial resurrection (RIR); Open Lab; small and medium-sized enterprises (SMEs); customized corporate support; advanced technical KPIs; economic impact analysis; government-verified performance; user satisfaction analysis; innovation intermediary; tailored regional expansion strategies

1. Introduction

1.1. Background and Problem Statement

The traditional shipbuilding and maritime engineering cluster in Busan, long the indispensable backbone of the South Korean regional economy, is currently undergoing a profound structural erosion. This decline transcends transient economic fluctuations; it represents a systemic shift catalyzed by the global transition toward ultra-large, eco-friendly, and high-tech vessels, alongside intensifying price competition from emerging global followers. As the industry pivots toward a digitalization-driven paradigm, a critical decoupling has emerged between traditional manufacturing legacies and the sophisticated requirements of the modern global market [1]. Within this volatile landscape, regional small and medium-sized enterprises (SMEs) face an existential

survival crisis. These firms, which anchor the maritime supply chain's vital sub-layers, are immobilized by a "triple burden": prohibitive capital expenditure (CAPEX) for digital transformation, a chronic deficit of specialized technical talent, and the absence of advanced R&D infrastructure [2,3]. Indeed, recent literature highlights that the barriers to digital transformation in the global maritime transport and logistics sectors are systemic and universal, reinforcing the urgent need for targeted public interventions [4–6]. A notable example of this barrier is the adoption of high-precision 3D laser scanners—a prerequisite for digital engineering—which require an initial investment exceeding 87,367 USD. This substantial cost represents a prohibitive hurdle for SMEs already struggling with declining order volumes. This resource exhaustion triggers a destructive self-reinforcing cycle: technological obsolescence inevitably leads to the loss of global contracts, which in turn accelerates the socio-economic desolation of the region and the systemic hollowing out of local industrial talent.

1.2. The Open Lab as a Strategic Catalyst for Regional Industrial Resurrection

To break this cycle of decline, the Advanced Marine Industry Open Lab (hereafter, the Open Lab) model—spearheaded by public research institute, such as the Korea Institute of Ocean Science and Technology (KIOST)—has been introduced as a transformative regional innovation platform. Phase I of the regional innovation cluster project spanned from July 2018 to December 2022, and Phase II is currently underway (June 2023 – December 2027). Unlike conventional equipment-sharing facilities, the Open Lab functions as an "innovation intermediary" that bridges the technological gap by integrating high-end physical infrastructure with expert-led technical advisory services [7,8]. By providing a risk-free environment for SMEs to utilize advanced tools such as 3D laser scanning, virtual reality (VR), augmented reality (AR), and digital twin (DT) technologies, the Open Lab facilitates the transition from low-value traditional manufacturing to high-value emerging industries, including smart marine engineering and related technology-driven sectors.

The primary objective of this study is to provide a rigorous, evidence-based evaluation of the Open Lab's role in revitalizing these declining sectors. We analyze successful cases—including 3D scanning-based ship reverse engineering and XR-based maintenance training—to demonstrate how public R&D infrastructure enhances technological autonomy and market competitiveness. Crucially, to mitigate potential subjective bias in policy evaluation, this research employs a multi-stage verification framework. The reported economic outcomes, such as revenue growth and job creation, are strictly validated through official administrative records and audited by national authorities, including the Korea Institute for Advancement of Technology (KIAT). Through this approach, the study illustrates a sustainable model for regional innovation that can be extrapolated to other declining industrial hubs.

2. Materials and Methods

2.1 Infrastructure and Operational Framework of the Maritime Open Lab

The Open Lab was founded as a key initiative of the national regional innovation cluster project to serve as a strategic R&D infrastructure within the Busan regional innovation cluster. Managed by the Korea Institute of Ocean Science and Technology (KIOST), a national research institute specializing in ocean science and maritime technology, this innovation hub functions as a specialized unit providing a "one-stop innovation environment." While it leverages KIOST's institutional expertise, its dedicated infrastructure—including state-of-the-art equipment and a pool of specialized technical personnel—was established and is currently operated under the framework of the cluster project.

Its primary mission is to support local firms struggling amidst the structural decline of traditional regional core industries, such as conventional shipbuilding and maritime manufacturing. By providing access to high-cost hardware and expert knowledge, the center helps these firms overcome financial and personnel constraints that have intensified as regional industrial vitality diminishes [9]. Such a framework positions this collaborative platform as a critical open innovation

network that mitigates the inherent risks of R&D for resource-limited SMEs [10]. To operationalize this comprehensive support model, the platform is structured around two core pillars: specialized physical infrastructure for advanced technical testing and a versatile corporate support framework for knowledge transfer and consulting [11]. This dual-structure ensures that technological resources are effectively translated into commercial value for SMEs. The following sub-sections delineate these core components, detailing the integrated research assets—comprising both high-precision equipment and specialized human capital (Section 2.1.1)—and the strategic support activities (Section 2.1.2) designed to facilitate the digital transformation and sustainable growth of regional enterprises.

2.1.1. Integrated Research Assets: Specialized Equipment and Human Capital

To support the end-to-end lifecycle of maritime digital twin development—spanning from high-precision field data acquisition to immersive visualization—the Open Lab, a duplex facility spanning the 7th and 8th floors with a total area of approximately 400 m^2 , houses an extensive suite of state-of-the-art research infrastructure [12].

The spatial configuration and operational workflow of these integrated assets are illustrated in Figure 1. This includes a comprehensive main facility for large-scale visualization (Figure 1a) and a specialized workspace explicitly designed to support regional enterprises in their immersive content creation (Figure 1b). To facilitate high-fidelity user interaction within the virtual space, the lab utilizes advanced HTC VIVE Pro (Head-mounted display, HMD) and precision tracking systems (Figure 1c), enabling firms to seamlessly develop and conduct technical demonstrations of their customized VR/AR content (Figure 1d).

Furthermore, to provide readers with an interactive exploration of the actual facility—which features a 300-inch display system optimized for the development and demonstration of high-fidelity 2D/3D VR/AR immersive content—a comprehensive virtual tour generated via Matterport is accessible online (<https://www.vrstory.co.kr/panos//o-1>).

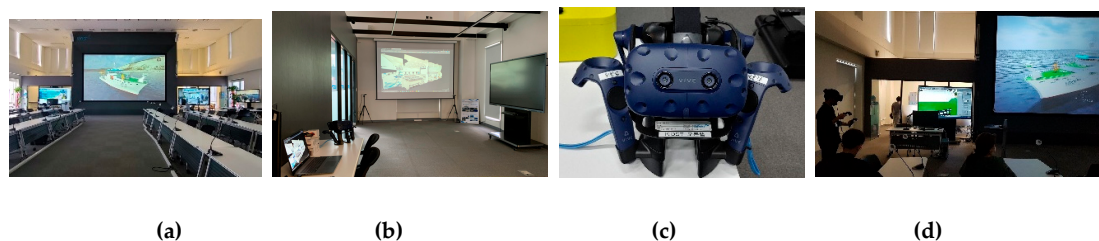


Figure 1. State-of-the-art infrastructure and immersive technology workflow of the KIOST Open Lab: (a) Panoramic view of the main research and training facility; (b) Dedicated workspace for regional enterprises to develop VR/AR content; (c) Head-mounted display (HMD) equipment and controllers for precision user interaction; and (d) Technical demonstration of the developed VR content.

While the lab maintains a vast array of facilities, the specific assets utilized in this study are categorized into the following four functional domains to ensure technical precision:

- **Precision Spatial Measurement and Surveying:** For high-fidelity reverse engineering and retrofitting, the lab utilizes terrestrial laser scanning (TLS) systems, primarily the FARO Focus M70 (Figure 2a). This system not only captures precise 3D spatial coordinates (x, y, z) of complex maritime structures with millimetric accuracy but also simultaneously acquires high-resolution photographic images. By mapping this RGB color data onto the spatial coordinates, it generates photorealistic 3D point clouds. This integration significantly enhances the visual clarity and precision of the subsequent modeling process, as demonstrated in various on-site surveying applications (Figure 2b,c). The utilization of high-precision 3D spatial coordinates in the modeling process enables the seamless integration of complex structural data into a unified virtual environment. This methodology facilitates high-fidelity reverse engineering by

providing a verified spatial framework that minimizes the margin of error in subsequent retrofitting simulations [13].



Figure 2. High-precision 3D laser scanning infrastructure and its on-site application: (a) FARO Focus M70 terrestrial laser scanner; (b,c) Data acquisition and spatial surveying within complex maritime structures.

- Immersive Content Creation and Visualization:** The Open Lab supports the full spectrum of extended reality (XR). For virtual reality (VR) workflows, the Insta360 Titan 11K enables ultra-high-definition 360-degree environment capture. By applying established methodologies of multi-directional image acquisition and omnidirectional video stitching—previously validated in marine environmental VR modeling [14]—this system provides highly accurate immersive content. The raw environmental data captured by this 8-lens specialized camera (Figure 3a,b) is seamlessly stitched and optimized for high-end simulations and interactive experiences via advanced HMDs, such as the Meta Quest 2 (Figure 3c, d).

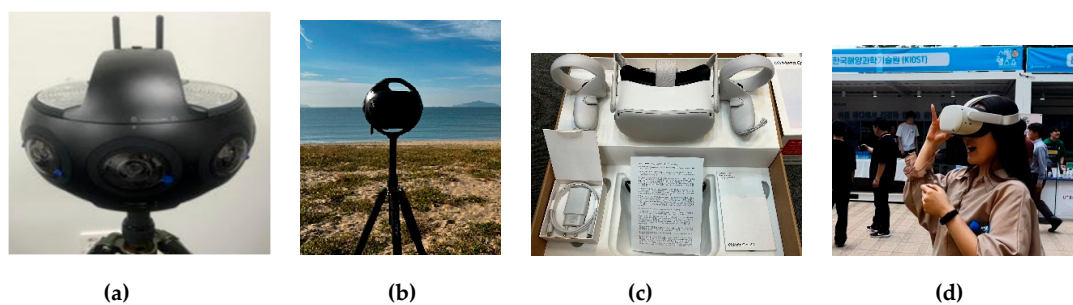


Figure 3. Infrastructure for immersive virtual reality (VR) content creation and experiential visualization: (a, b) Insta360 Titan 11K camera for 8-lens omnidirectional data acquisition; (c, d) Meta Quest 2 HMD and its on-site application for immersive VR experiences.

For sophisticated mixed reality (MR) applications, the Microsoft HoloLens 2 (Figure 4a) is utilized, enabling the real-time overlay of high-fidelity digital twin data directly onto physical maritime assets (Figure 4b), facilitating precise spatial alignment and interactive technical support. The effectiveness of this MR-based spatial alignment has been extensively validated in recent maritime studies, demonstrating its capability to significantly enhance on-site training and assembly assistance in modern shipyards [15,16].

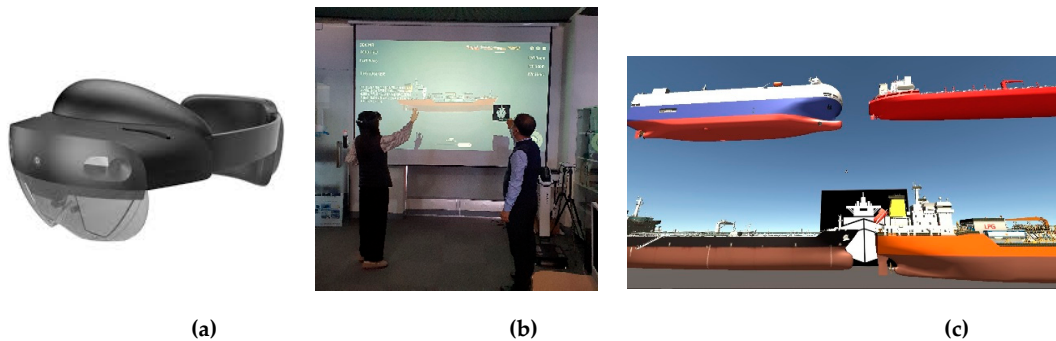


Figure 4. Advanced mixed reality (MR) visualization infrastructure: (a) Microsoft HoloLens 2 for high-fidelity data visualization; (b) Technical demonstration of interactive MR data overlay on a maritime model; (c) Augmented reality (AR) visualization of five distinct ship models triggered through holographic marker recognition.

- Coastal and Environmental Monitoring:** To support the specific technical needs of participating regional enterprises, the Open Lab utilizes a diverse array of specialized empirical monitoring equipment. This includes the GPS-based Aquadrift (Otronix Co., Ltd.) for tracking surface flow velocities and drift patterns (Figure 5a, b) [17]. Additionally, the Aquadopp profiler (Nortek) is deployed for long-term flow velocity measurements (Figure 5c) [18]. Specialized observation equipment, such as the YSI 650 MDS (Figure 5d), is also utilized for high-precision, real-time measurement of water quality parameters. These tools, supported by dedicated marine research teams, are instrumental in gathering the high-fidelity empirical data required to address the practical engineering challenges and technical validation needs of engineering firms specializing in the design and construction of hydraulic structures.

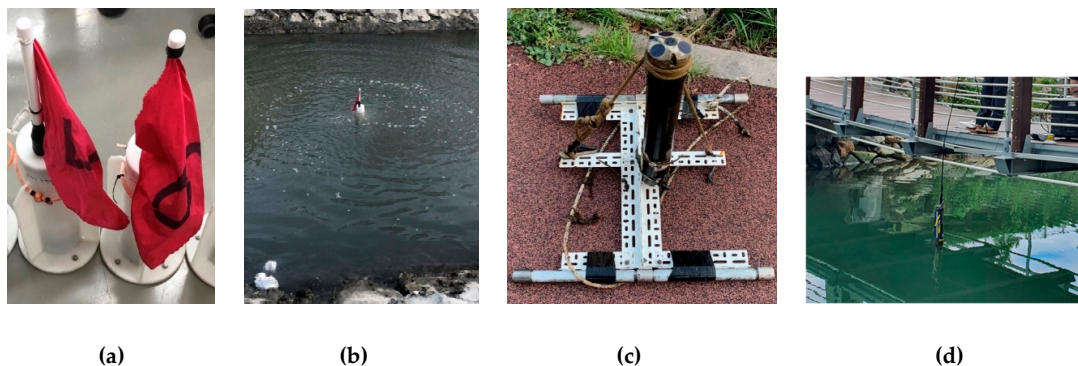


Figure 5. Specialized monitoring infrastructure for coastal and environmental data acquisition: (a, b) GPS-based Aquadrift system and its deployment for surface flow tracking; (c) Aquadopp profiler mounted on a bottom frame for long-term flow velocity measurements; (d) YSI 650 MDS specialized observation equipment utilized for high-precision, real-time water quality measurement and analysis.

- Computational and Processing Infrastructure:** To handle the significant data loads required for 3D point-cloud processing and real-time rendering, the lab provides high-performance Dell workstations and laptop computers optimized for engineering-grade simulations and digital twin integration.

Beyond this physical infrastructure, the Open Lab's capacity for high-level R&D and continuous corporate support is driven by a robust human capital framework. To effectively execute technology development and provide multidisciplinary corporate assistance across fields such as marine science, policy trends, ship design, ICT, IoT technologies, immersive content development (VR/AR), and digital twins, the lab operates a comprehensive expert pool structured into three distinct tiers:

- **Internal KIOST Researchers:** A core group of over 20 master's and doctoral-level experts (23 members) from KIOST, providing foundational scientific knowledge and R&D oversight in various marine, environmental, and spatial engineering disciplines.
- **Resident Support Staff:** A dedicated on-site team consisting of four resident researchers and one administrative staff member. They are stationed at the Open Lab to manage daily facility operations, facilitate continuous R&D, and provide immediate, hands-on technical troubleshooting for participating firms.
- **External Expert Network:** A collaborative pool of 22 external subject matter experts (SMEs) from academia and the maritime industry. This network actively engages with the lab to ensure comprehensive multidisciplinary consulting, specialized system validation, and strategic policy guidance.

2.1.2. Multidisciplinary Corporate Support and Engagement Activities

To maximize the utility of the integrated assets described in Section 2.1.1, the Open Lab operates a multifaceted support framework tailored to the specific needs of regional enterprises. To ensure operational efficiency and clarity, these activities are structured into three strategic pillars, addressing the entire lifecycle of industrial digital transformation:

1. Technical and Digital Infrastructure Support
 - **Engineering and technical advisory:** Providing hands-on assistance for 3D modeling, reverse engineering, and complex maritime simulations.
 - **Facility and equipment access:** Granting streamlined utilization of high-precision hardware (e.g., TLS scanners and XR devices) for independent R&D.
 - **Digital content creation:** Assisting in the development of high-fidelity digital assets, such as AR-based maintenance guides and digital twin visualizations.
2. Knowledge Sharing and R&D Capacity Building
 - **Technical education and seminars:** Organizing specialized training programs on emerging technologies (AR, VR, Digital Twin) to disseminate latest industrial trends.
 - **National R&D Project Planning:** Matching SMEs with experts to draft competitive proposals and navigate roadmaps to secure independent funding.
 - **Ad-hoc technical assistance:** Providing flexible, administrative, and technical support to resolve unforeseen hurdles during the transformation process.
3. Ecosystem Networking and Market Expansion
 - **Networking and collaborative hub:** Facilitating connections between SMEs, academia, and large-scale stakeholders within the Busan regional innovation cluster.
 - **Marketing and branding:** Enhancing the market visibility of developed technologies through promotional materials and strategic branding.
 - **Exhibition and global outreach:** Supporting corporate participation in international maritime exhibitions to showcase empirical research outcomes.

This comprehensive suite of services ensures that the Open Lab does not merely act as a passive equipment repository but as an active catalyst for industrial resilience, enabling regional firms to navigate the structural transition from traditional manufacturing to high-value-added digital engineering.

2.2. Definition of Technological Efficiency and Improvement Metrics

To evaluate the impact of the Open Lab infrastructure on SME performance, this study defines a comprehensive set of quantitative and qualitative metrics. These indicators measure both the optimization of internal technical processes and the strategic expansion of the firms' market presence.

2.2.1. Quantitative and Qualitative Metrics for Performance Evaluation

The performance of supported technologies is validated through a combination of field-captured data, simulation results, and expert-led evaluations, following established verification and validation (V&V) frameworks [19]. In alignment with the official outcome evaluation framework established by the KIAT, performance is assessed using multi-dimensional metrics—encompassing technical attainment, economic contribution, and social impact—rather than a single indicator to ensure a comprehensive evaluation across strategic dimensions [20,21].

- **Process Time Reduction Rate (Δt , %):** This metric quantifies technical efficiency by measuring the time saved in modeling, assembly, and maintenance lead times. It evaluates the productivity gained by replacing manual measurements or paper-based protocols with digital ICT tools (e.g., 3D scanning or AR guides).
- **Data Precision (Error Margin, mm):** This metric assesses precision and reliability by defining the spatial deviation between the scanned digital data and the actual physical dimensions of the ship or components.
- **Rework Cost and Rate Reduction (USD, %):** This evaluates the economic aspect of technical efficiency. It quantifies the reduction in frequency (%) and financial loss (USD) associated with re-performing tasks due to enhanced design and procedural accuracy.
- **Maintenance Training Error Metrics (%):** Specifically applied to XR-based training, these include:
 - **Tool Selection Error Rate (%):** Frequency of selecting incorrect tools during maintenance tasks.
 - **AR Spatial Mapping Error (mm):** The precision of holographic overlays on physical equipment.
 - **Procedure Deviation Rate (%):** The frequency of trainees diverging from standardized emergency or maintenance protocols.
 - **Evaluation Processing Time (s):** The time required to assess a trainee's performance (instantaneous in automated XR systems).
- **R&D Portfolio Expansion:** A qualitative and quantitative measure of strategic growth, evaluating the increase in academic and professional outputs, such as joint research publications and technical certifications acquired through the Lab's support.
- **Technology Readiness Level (TRL, Scale 1-9):** This metric tracks strategic growth by assessing the maturity of a technology as it progresses from conceptual prototypes to full commercialization, based on the standardized assessment framework established by NASA and further adopted by international innovation programs [22,23]. To provide a consistent assessment of technical maturity across various supported projects, the specific definitions and key milestones for each level are detailed in Table 1.

Table 1. Technology Readiness Level (TRL) definitions and classifications used in this study (Adapted from [22,23]).

TRL Level	Classification	Phase	Definition
TRL 1	Research	Basic Principles	Observation of basic principles
TRL 2	Research	Concept Formulation	Concept and application defined
TRL 3	Research	Proof of Concept	Analytical and experimental validation
TRL 4	Development	Lab Validation	Component validation in laboratory
TRL 5	Development	Relevant Environment	Testing in simulated environment
TRL 6	Development	Prototype Demo	System demonstration in relevant env.
TRL 7	Development	Operational Demo	System demonstration in operational env.
TRL 8	Deployment	System Completion	Final system testing and qualification

TRL 9	Deployment	Proven Success	Proven success in field operations
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2.2.2. Qualitative Metrics for Strategic and Market Expansion

Beyond numerical efficiency, the study monitors qualitative milestones that signify the long-term sustainability and market competitiveness of the SMEs.

- **Certifications and Awards:** Recognition of technical quality and corporate excellence through international certifications (e.g., KOLAS, KR, LR) and government honors.
- **Customer and Portfolio Diversification:** The expansion of the client base (from regional to global/public sectors) and the broadening of business areas, such as transitioning from traditional ship repair to high-value digital twin services.
- **Intellectual Property and R&D Engagement:** The increase in patent applications and the successful acquisition of national and local government R&D projects for immersive content development.
- **Overseas Market Entry:** The successful export or supply of digital maritime products and services to international shipping companies and global shipowners.

2.3. Methodology for Evaluating Economic Impacts: Revenue and Employment

To ensure the objectivity and transparency of the reported results, this study defines economic impacts through two primary indicators: verified revenue and employment performance. These data points were assessed and reported in strict accordance with the R&D performance guidelines established by the Ministry of Trade, Industry and Resources (MOTIR). The analytical scope of this research is specifically focused on the outcomes achieved in 2021 and 2022, a period reflecting the stage of "full-scale performance generation." While the initial years (2018–2020) were dedicated to the foundational establishment of the Open Lab—including infrastructure procurement, operating system formalization, and personnel recruitment—the subsequent 2021–2022 period represents the phase where active corporate support began to yield tangible and measurable results. These outcomes were formally evaluated and verified by an expert evaluation committee upon the successful completion of the project's first phase.

2.3.1. Calculation of Verified Revenue

The economic contribution to a firm's revenue is determined by applying the Infrastructure Attribution Rate (IAR)—or contribution rate—to the actual supply value of the projects supported by the Open Lab. For objective proof and data integrity, every reported revenue item required the submission of corresponding electronic tax invoices. The contribution rate was initially assessed by the participating firms based on the degree of infrastructure utilization and subsequently validated by the expert evaluation committee. During this official evaluation process, all reported performance metrics were rigorously cross-verified using original, unmasked administrative documents, including tax invoices for revenue validation and workplace subscriber lists for employment tracking.

Regarding corporate confidentiality and manuscript conciseness, this study refrains from disclosing the granular details of every individual commercial project. Instead, the revenue achievements presented in Section 3.3.1 represent the final consolidated figures for each firm, as officially audited and confirmed by the expert evaluation committee under the KIAT. Furthermore, while original documents were used for the internal verification, representative masked versions are provided in Appendix A for methodological reference to protect sensitive corporate and personal information.

For economic accuracy and to reflect specific market conditions during the data collection period, all financial outcomes were converted from Korean Won (KRW) to United States Dollars (USD) using the respective annual average exchange rates. Specifically, an exchange rate of 1,144.4 KRW/USD for 2021 and 1,292.0 KRW/USD for 2022 was applied, as sourced from the Bank of Korea

(BOK). All financial outcomes in this paper are presented exclusively in USD based on these defined rates, facilitating international comparison and ensuring clarity for a global audience.

The verified revenue (R_v) is calculated as follows:

$$R_v = \sum_{i=1}^n (V_i \times C_{R,i}) \quad (1)$$

- V_i : Supply value for i -th project ($i = 1, \dots, n$), excluding value added tax (VAT);
- $C_{R,i}$: Verified revenue contribution rate of the Open Lab for i -th project;

2.3.2. Calculation of Employment Performance

The impact on regional job creation was quantified by multiplying the number of newly hired employees by the Open Lab's contribution rate. In accordance with official employment performance regulations, only personnel who maintained their employment for a minimum of seven months post-hiring were included in this calculation; those employed for less than six months were strictly excluded. This metric reflects the extent to which the public infrastructure support facilitated the expansion of the firm's specialized workforce. The verified employment (E_v) is defined as:

$$E_v = \sum_{i=1}^n (N_i \times C_{E,i}) \quad (2)$$

where N_i is the number of new personnel officially registered during the support period, and $C_{E,i}$ is the employment contribution rate assigned based on the following criteria:

- **Direct Employment ($C_{E,i} = 1.0$):** If the firm is an official participating company in the KIAT regional innovation cluster project and the new personnel are registered as participating researchers, the employment is categorized as "Direct employment." In this case, a maximum weight of 1.0 (100%) is applied to the verified employment calculation.
- **Indirect Employment ($C_{E,i} < 1.0$):** For general enterprises not officially participating in the cluster project, new hiring is considered "Indirect employment" resulting from overall business expansion facilitated by the Open Lab's infrastructure and technical support. For these cases, $C_{E,i}$ is assigned a value of less than 1.0, representing the specific and proportional contribution of the Open Lab to the hiring decision as audited by national authorities.

2.4. Assessment Methodology for SME Satisfaction and Support Effectiveness

To comprehensively evaluate the qualitative impact of the Open Lab, a structured satisfaction and demand analysis survey was conducted among the participating small and medium-sized enterprises (SMEs). While the preceding sections outline the technical and economic metrics, this survey aimed to measure the practical effectiveness and service quality of the Open Lab's corporate support framework.

To support future research and practical applications, the comprehensive survey instrument used in this study is provided in Appendix B. By sharing this standardized questionnaire, this study aims to assist practitioners and researchers in similar innovation ecosystems in evaluating SME satisfaction and identifying critical areas for operational improvement, thereby fostering more effective open innovation environments. The questionnaire was meticulously designed using a 9-point Likert scale to ensure high discriminative power in the responses. The evaluation metrics were structured into the following core dimensions:

1. **Satisfaction by Support Type:** Assessing the perceived value of specific interventions, including immersive content creation, marketing support, technical consulting/engineering, facility/equipment utilization, and national project planning assistance.
2. **Service Quality Attributes:** Evaluating the operational excellence of the Open Lab across four specific criteria:
 - **Promptness:** The speed of processing support requests, responding to inquiries, and providing feedback.
 - **Reliability:** The technical expertise of the provided solutions and the transparency of administrative procedures.

- **Convenience:** Accessibility (including parking), space utilization for R&D, and the cost-effectiveness (time and economic) of utilizing the support services.
- **Staff Attitude:** The professionalism, proactiveness, and accuracy of the support personnel.

2.5. 3D Laser Scanning: Point-Cloud Based Virtualization and Engineering Optimization (VR)

This section examines 3D laser scanning technology through the operations of Company A, a specialized maritime engineering service provider. The company delivers comprehensive shipbuilding and ship repair engineering services by utilizing advanced laser scanners that simultaneously acquire high-precision 3D spatial coordinates and high-resolution imaging data.

By leveraging Company A's core expertise in modeling critical vessel spaces, the 3D laser scanning methodology implemented in the Open Lab focuses on translating complex physical maritime structures into high-precision digital assets. This approach is particularly essential given the intricate and non-standardized nature of ship interiors—such as engine rooms and ballast systems—where traditional manual measurement methods often result in significant cumulative errors and rework costs. To mitigate these issues, this study utilizes a terrestrial laser scanning (TLS) workflow to facilitate accurate reverse engineering and interference checking (clash detection).

The technical support process provided by the Open Lab and Company A is executed through the following three-phase operational framework:

1. **Field Data Acquisition:** Utilizing the FARO Focus M70, high-precision 3D point clouds are captured in complex environments. This stage eliminates the inaccuracies of manual measurement by documenting the exact "as-built" condition of the vessel.
2. **Data Processing and Registration:** Raw scan data are processed and aligned using the high-performance Dell workstations. This phase integrates individual scans into a unified, coordinate-accurate digital environment.
3. **Engineering Optimization and Modeling:** Based on the registered point cloud data, detailed 3D modeling and clash detection are performed. This allows for the precise verification of new equipment installation or structural retrofitting before physical execution.

To evaluate the practical impact of the technical support provided by the Open Lab, this study examines the following **technical indicators for Company A**:

- **Modeling Time Reduction Rate (%):** The rate of reduction in the time required for modeling critical interior spaces of vessels during retrofitting and repair processes compared to traditional methods.
- **Spatial Accuracy and Error Metrics (mm, %):** The error range (mm) and error rate (%) between the 3D scanned data and actual physical dimensions, specifically evaluated for chemical tankers and bulk carriers.
- **Reduction in Rework and Error Costs:** The quantified financial savings achieved by minimizing design errors and reducing the frequency of re-performing tasks (rework) due to enhanced spatial precision.

2.6. Augmented Reality and Digital Twin (AR & DT)

This section examines the integration of Augmented Reality (AR) and digital twin (DT) technologies within the Open Lab framework. The technical implementation was supported by the expertise of Company B, a specialist in ship repair training and vessel procurement support.

Company B develops sophisticated DT models that visualize both the exterior and critical interior features of vessels. These models incorporate advanced functionalities, such as transparency control, to enhance the intuitive understanding of complex structural layouts. These capabilities assist decision-makers in the vessel ordering process by providing clear and interactive visual data, thereby supporting shipyards and client representatives in finalizing construction specifications. Within the Open Lab, this expertise is further utilized to synchronize physical operational data with virtual models to provide real-time maintenance guidelines.

The technical support provided by the Open Lab for Company B's R&D process followed a systematic workflow:

1. **High-Fidelity DT Modeling:** Utilizing the Lab's high-performance workstations, complex vessel and engine structures were digitized. The "transparency control" feature was implemented to allow users to inspect internal components without physical disassembly.
2. **AR Maintenance Protocol Development:** Using Microsoft HoloLens 2, AR-based instructional overlays were developed for core maritime components, specifically focusing on the Caterpillar 3512 (high-speed) and Wärtsilä RT-flex50DF (low-speed) engines.
3. **Spatial Synchronization and Optimization:** Expert personnel from the Open Lab provided technical consulting on spatial registration to minimize the drift between digital overlays and physical engine parts, ensuring high operational reliability.

To evaluate the practical impact of the technical support provided by the Open Lab, this study examines the following **technical indicators for Company B:**

- **Process Efficiency (%):** The reduction rate of the assembly and disassembly process time for three core components of the Caterpillar 3512 engine when utilizing AR technology.
- **Spatial Registration Accuracy (mm):** The spatial registration error range between the AR system display and actual dimensions for both high-speed (Caterpillar 3512) and low-speed (Wärtsilä RT-flex50DF) engines.
- **Operational Reliability (%):** The reduction rate of procedural deviations (error rates) and rework costs resulting from enhanced design and procedural precision.
- **Technological Maturity (TRL):** The shift in Technology Readiness Level across technical domains before and after the Open Lab support.
- **Technical Standardization:** The acquisition of official technical certifications as a result of the standardized digital workflows.

2.7. Hydraulic Structure Design and Engineering Support

This section examines the technological advancement and business expansion of **Company C**, an engineering firm specializing in the design and construction of hydraulic structures for maritime and riverine environments. Through the technical consulting and analysis provided by the Open Lab, Company C has significantly expanded its technical capabilities, aligning with the strategic objectives of the "New maritime industry" sector.

A representative case involved an artificial coastal waterway, spanning 2.1 km, which faced critical water quality issues due to stagnant flow and sedimentation. To address these challenges, the Open Lab provided a comprehensive support framework consisting of the following three phases:

1. **CFD-based Design Optimization:** Utilizing the Lab's computational infrastructure, specialized computational fluid dynamics (CFD) analysis was performed to support the structural design of water quality improvement gates. This phase determined the optimal operation strategies and gate configurations to maximize flow circulation and minimize stagnant zones within the 2.1 km waterway.
2. **Field Performance Verification:** Following the physical installation of the gates, the Open Lab utilized its professional coastal monitoring equipment (e.g., Aquadopp profiler and GPS-based Aquadrift) and a collaborative research team from KIOST—consisting of the Coastal Disaster & Safety Research Department for flow velocity validation and the Environment Research Department for water quality assessment—to conduct high-precision measurements. This provided empirical evidence of the practical improvements in both hydraulic performance and environmental indicators.
3. **Joint R&D and Academic Expansion:** The collaboration extended beyond technical support to include joint research initiatives, facilitating the company's R&D growth and enhancing its academic presence in the hydraulic infrastructure sector. This partnership allowed the firm to transition from a construction-focused entity to a technology-driven engineering provider.

Furthermore, to evaluate the practical impact of the technical support provided by the Open Lab, this study examines the following **technical indicators for Company C**:

- **Design Support Efficiency:** The successful development and structural design of water quality improvement gates for the 2.1 km artificial coastal waterway.
- **Performance Verification Reliability:** The scientific validation of hydraulic and environmental improvements through cross-departmental field analysis, ensuring the empirical reliability and high data fidelity of the project outcomes.
- **R&D and Academic Output:** The number of joint research publications and the resulting academic contributions to the maritime infrastructure field.
- **Technological Maturity (TRL):** The shift in technology readiness level across technical domains before and after the Open Lab support.

2.8. Immersive VR Content Development

This section examines the development of immersive VR content utilizing the technical resources of **Company D**, a specialized content development firm and a direct participant in the regional innovation cluster project. To strengthen its production capabilities, Company D leveraged the cutting-edge technical infrastructure and expert consulting framework provided by the Open Lab.

1. **High-Definition Environment Capture:** To create realistic virtual representations of industrial sites, Company D utilized the Lab's professional video hardware, specifically the Insta360 Titan 11K. This enabled the acquisition of ultra-high-definition 360-degree environment data, providing the visual foundation for high-fidelity immersion.
2. **Immersive Visualization and Interaction Support:** For technical validation and user-testing, the Open Lab provided access to its large-scale 300-inch screen equipped with high-performance 2D and 3D projectors. Additionally, the Lab provided technical support to enable seamless user-to-content interaction using the HTC Vive Pro HMD, allowing for the evaluation of interactive features within the developed platforms.
3. **Strategic Consulting and Iterative Prototyping:** The Lab's expert pool provided intensive consulting on core content concepts, spatial layout optimization, and practical utilization strategies. Furthermore, the Lab provided critical feedback for the iterative improvement of prototypes, ensuring that the final output met the rigorous standards of industrial and safety applications.
4. **Business Networking and Project Identification:** Beyond technical assistance, the Open Lab acted as a strategic intermediary, connecting Company D with external organizations and public institutions. This networking support allowed the company to identify high-value projects and align its development goals with actual market demands within the maritime sector.
5. **Provision of Specialized Research Testbeds:** A defining characteristic of the Open Lab's support framework was the free-of-charge provision of specialized KIOST research infrastructures as field testbeds, which effectively removed the significant financial barriers often associated with high-end maritime R&D. This facilitated critical validation phases for diverse industrial projects; for instance, the Lab arranged access to an actual KIOST research vessel (RV) for the development of a VR-based shipboard fire response training program, enabling realistic simulations within a genuine maritime environment without the burden of chartering fees. Furthermore, for the creation of marine-based psychological healing VR content, the Lab provided the KIOST Korea South Pacific Ocean Research Center (KSPORC) in Chuuk, Micronesia, as a cost-free testbed. This enabled the acquisition of pristine terrestrial and underwater landscapes, ensuring the high-fidelity realism required for therapeutic efficacy while substantially reducing international field research expenditures.

To evaluate the practical impact of the technical support provided by the Open Lab, this study examines the following **technical indicators for Company D**:

- **Content Development Capability:** The number of immersive VR content projects successfully developed and the expansion of the firm's project portfolio through the Lab's networking and unique testbed provisions.

3. Results and Discussion

Based on the diverse technical and strategic supports provided by the Open Lab to foster corporate growth and self-sustainability, this chapter presents the tangible technical advancements and economic outcomes achieved by the participating firms. By analyzing the performance of four representative enterprises—Companies A, B, C, and D—this study evaluates the extent to which the integrated physical and human assets described in Section 2 facilitated operational excellence and long-term autonomy. The discussion focuses on the achievement of specific key performance indicators (KPIs) and analyzes how these individual outcomes collectively contribute to the resilience and sustainability of the regional maritime industry amidst its structural transition.

3.1. Framework for Performance Evaluation and Data Verification

To ensure a rigorous and objective assessment of the Open Lab's impact, this study employs a multi-tiered evaluation framework that strictly adheres to the R&D performance assessment guidelines established by the MOTIR. This framework aligns the technical outputs of each participating firm with the strategic objectives of the regional innovation cluster, focusing on the transition from immediate technical support to long-term corporate self-sustainability.

The primary focus of this assessment integrates the technical KPIs established in Section 2—such as operational efficiency, data precision, and strategic growth—with broader socio-economic outcomes, specifically verified revenue and job creation.

Regarding the technical performance metrics and supporting visual evidence (figures), the quantitative outcomes and representative images were evaluated and provided by the technical experts of the participating enterprises based on their internal assessment protocols. This approach ensures that both the reported engineering improvements and the demonstrated technological implementations reflect the professional evaluation and actual field-work of on-site specialists rather than speculative or unilateral estimations.

Crucially, to mitigate subjective bias and ensure data integrity, all economic outcomes reported in this chapter were finalized through a multi-stage auditing process. The values presented were initially calculated based on the Open Lab contribution rate (%) and administrative evidence (e.g., tax invoices and official employment records), then subsequently audited by expert evaluation committees under the KIAT.

The following sections are structured to provide a comprehensive analysis of these validated results:

Section 3.2 presents a detailed technical performance analysis for the four representative case studies, highlighting the specific engineering advancements facilitated by the Open Lab.

- Section 3.3 evaluates the consolidated socio-economic impacts, focusing on audited revenue generation and regional job creation during the 2021–2022 performance generation phase.
- Section 3.4 provides a qualitative validation of the support model through user satisfaction and needs analysis.
- Finally, Sections 3.5 and 3.6 derive strategic implications for regional industrial resurrection and propose a customized Open Lab construction model for other declining industrial hubs.

3.2. Technical Performance Analysis by Case Study

3.2.1. Company A: 3D Laser Scanning for Reverse Engineering

This section analyzes the performance of Company A, which utilized the Open Lab's high-precision 3D scanning infrastructure (FARO FOCUS M70) to innovate its reverse engineering and ship modification workflows. The assessment follows the quantitative and qualitative metrics defined in Section 2.2.1. The sequential workflow—transitioning from high-precision spatial data acquisition to virtual design validation and clash detection—is illustrated in Figure 6.

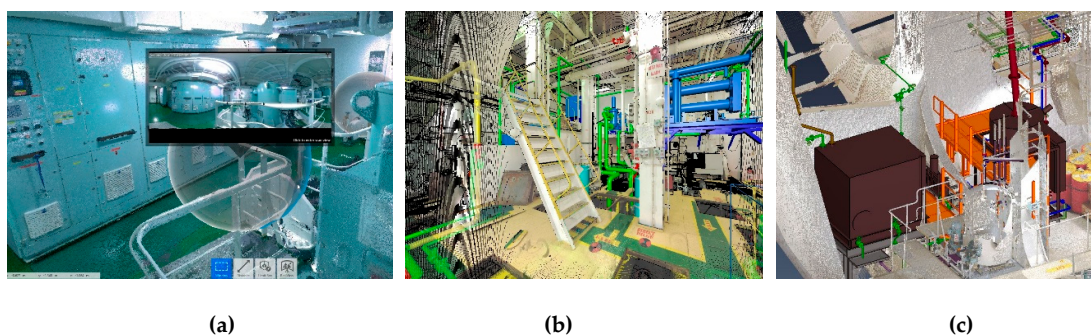


Figure 6. Application of 3D laser scanning for reverse engineering in complex vessel spaces: (a) High-precision point-cloud data acquired via 3D laser scanning; (b, c) Integration of newly designed 3D CAD models (colored pipes and equipment) for clash detection utilizing the acquired point-cloud data.

- **Technical Efficiency: Process Time Reduction**

The primary technical gain for Company A was the drastic reduction in data acquisition and design lead times. The fundamental driver of this operational optimization lies in the elimination of the conventional "physical templating" and its associated logistical loop. In traditional ship repair processes—such as replacing corroded seawater pipes—workers must physically dismantle the target pipe, transport it to an onshore facility to create a physical mold (templating), and temporarily reinstall the old pipe just to allow the vessel to continue its immediate voyage. This physical "mock-up" cycle incurs massive logistical costs, excessive manpower, and severe operational downtime.

- Conversely, the integration of 3D scanning completely bypasses this physical bottleneck. By capturing precise spatial coordinates of the target area within just 1 to 4 hours on-site, the vessel can depart immediately without any preliminary structural dismantling. The acquired point-cloud data serves as a highly accurate "virtual template" to generate detailed fabrication drawings (Figure 7d), enabling off-site manufacturing while the ship is sailing. The new component can then be seamlessly retrofitted during the vessel's subsequent port call, as empirically demonstrated in the sequential workflow in Figure 7.
- This paradigm shift from "physical templating" to "digital replication" is the core mechanism behind the efficiency gains, particularly in congested compartments like the engine room, pump room, and individual cabins where precise spatial data is critical for complex piping networks and interior outfitting. To empirically validate these gains, a comparative analysis of design time was conducted for a 13,000 DWT chemical tanker (LOA \approx 128 m). As shown in Table 2, the integration of 3D laser scanning resulted in significant time savings across all major compartments, achieving an average reduction of 50 hours (55.6%) compared to conventional manual methods.

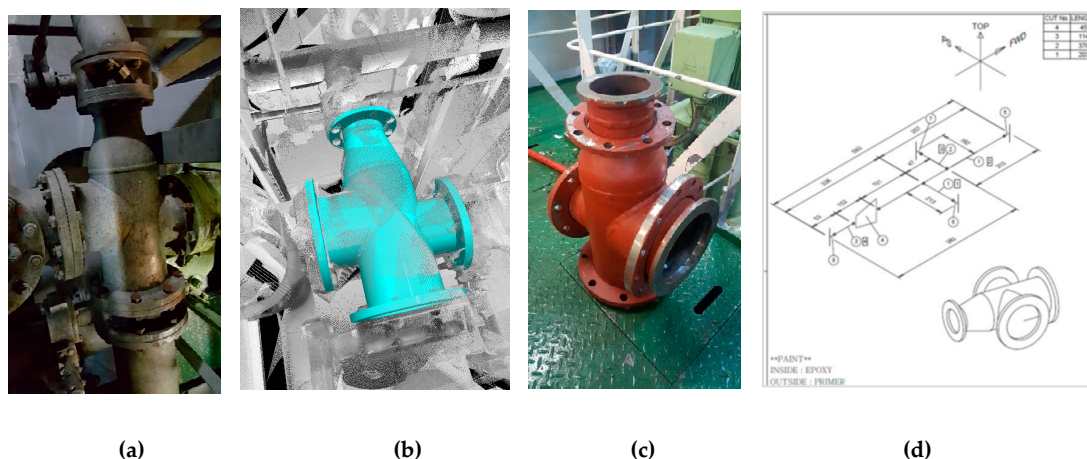


Figure 7. Empirical validation of the 3D scanning-based "virtual templating" workflow for pipe replacement: (a) Identification of the damaged seawater pipe on-site; (b) Acquisition of 3D point-cloud data and integration with virtual CAD design; and (c) Successful off-site fabrication and seamless on-site installation of the replicated component without preliminary dismantling; and (d) Generation of detailed fabrication drawings based on the virtual template for off-site manufacturing.

Table 2. Comparison of design time: Manual measurement vs. 3D scanning.

Compartment	Conventional (t_1) [hr]	3D Scanning (t_2) [hr]	Reduction (Δt) [hr (%)]
Engine Room	100	40	60 (60%)
Pump Room	160	80	80 (50%)
Cabin	50	20	30 (60%)
Forepeak Store	50	20	30 (60%)
Average	90	40	50 (55.6%)

- Precision and Reliability: Data Error Analysis**

To evaluate the reliability of the generated digital twins, the spatial deviation between scan data and actual physical dimensions was analyzed for a 13,000 DWT chemical tanker (128m) and a 250,000 DWT bulk carrier (329m). The relative error rate (E_r) was calculated as follows:

$$E_r(\%) = \left(\frac{|Scan\ data - Actual\ data|}{Actual\ data} \right) \times 100$$

Using this formula, the spatial accuracy and measurement reliability of the 3D scan data were evaluated across various compartments for two sample vessels. The resulting error metrics for the 13,000 DWT chemical tanker and the 250,000 DWT bulk carrier are summarized in Table 3 and Table 4, respectively.

Table 3. Scanning precision and relative error rates for a 13,000 DWT chemical tanker.

Compartment	Scan Data (d_s) [mm]	Actual Dim. (d_a) [mm]	Error (e) [mm (%)]
Engine Room	22,418	22,400	18 (0.080%)
Pump Room	2,814	2,800	14 (0.500%)
Cabin	15,312	15,300	12 (0.078%)
Forepeak Store	14,313	14,300	13 (0.091%)
Cargo Area	81,928	81,900	28 (0.034%)

Table 4. Scanning precision and relative error rates for a 250,000 DWT bulk carrier.

Compartment	Scan Data (d_s) [mm]	Actual Dim. (d_a) [mm]	Error (e) [mm (%)]
Engine Room	30,421	30,400	21 (0.069%)
Pump Room	18,214	18,200	14 (0.077%)
Cabin	15,213	15,200	13 (0.086%)

Forepeak Store	19,964	19,950	14 (0.070%)
Cargo Area	260,873	260,850	23 (0.009%)

As presented in Table 3 and Table 4, the precision of the 3D scanning-based digital twin was rigorously validated. Across both the chemical tanker and bulk carrier, the relative error rates remained significantly low, ranging from 0.009% to 0.500%. This level of accuracy ensures that the digital models can be reliably used for off-site pre-fabrication without the risk of on-site installation failures.

The results show that absolute errors were maintained below 30 mm even for massive structures. Notably, the relative error rate remained below 0.1% for most compartments. In the 260-meter cargo hold of the bulk carrier, an exceptional precision of 0.009% was achieved. Field practitioners reported that the perceived on-site error was consistently managed within 10 mm, ensuring a seamless fit during the pre-fabrication and assembly stages.

- **Economic Optimization: Rework Cost Reduction**

The high precision of 3D scanning significantly reduced the frequency and cost of rework (design-induced errors). For a standard modification project with a total construction cost of 77,400 USD (approx. 100 million KRW), the associated rework costs—including labor and materials—were limited to under 1,160 USD (approx. 1.5 million KRW). This establishes a rework cost rate of 1.5%, validating the technology's impact on minimizing financial risks in maritime engineering.

- **Strategic Growth: Market Expansion and Portfolio Diversification**

While Company A had already reached TRL 9, their growth was previously constrained by the high cost of equipment rental. The Open Lab's provision of FARO scanners enabled the company to scale its operations quantitatively and qualitatively:

- Quantitative growth: Successfully executed approximately 240 projects, including BWTS/Scrubber retrofits (~60 vessels), general repairs (~100 vessels), and eco-friendly modifications (~80 vessels).
- Market diversification: Leveraged accumulated spatial data to expand into non-maritime sectors, such as camper van modifications and reverse engineering for aging terrestrial industrial factories.
- This trajectory demonstrates that the Open Lab's support served as a catalyst for transitioning from technological maturity to autonomous industrial scalability, allowing the firm to secure new project contracts with major shipowners and industrial partners.

3.2.2. Company B: Advanced XR-Based Maintenance Training and Environment-Friendly Ship Simulators

This section evaluates the performance of Company B, an engineering firm specializing in maritime XR content. A critical differentiator in its success was the Lab's hybrid support model, which combined the provision of high-end physical infrastructure (tangible support) with specialized technical advisory and R&D planning (intangible support). By leveraging these comprehensive resources, Company B successfully developed a distinct portfolio of industrial XR and simulation applications. Specifically, AR-based content for maritime engine (e.g., Caterpillar 3512) repair education and training was created (Figure 8a), alongside a technical simulation platform for hydrogen fuel cell ships (Figure 8b). Furthermore, the initiative facilitated the practical implementation of a digital twin system across multiple devices (Figure 8c).

For Company B, independently acquiring high-end industrial 3D scanners—the cost of which was previously identified as a major industry barrier—or constructing specialized validation environments for XR devices presented prohibitive capital requirements. The initiative effectively removed these barriers by providing seamless access to these high-value assets alongside the necessary expert guidance, enabling the firm to focus its resources on core technology development and commercialization of next-generation green ship technology.

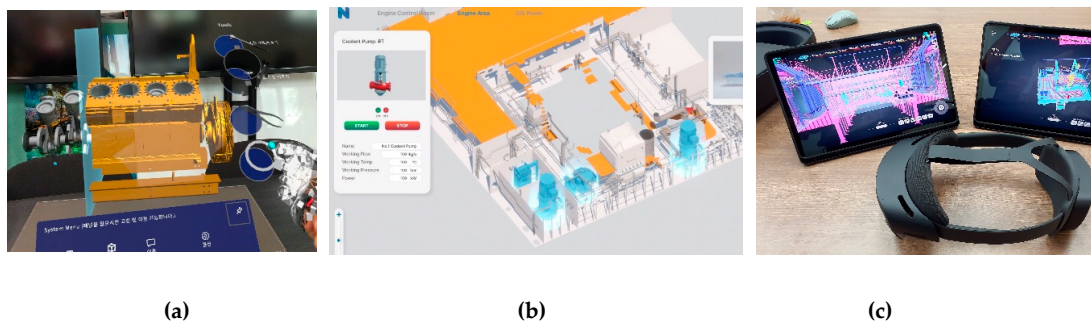


Figure 8. Multi-faceted XR and digital twin application development for maritime engineering firms through the Open Lab support framework: (a) Augmented Reality (AR)-based training content for marine engine (e.g., Caterpillar 3512) repair education; (b) Technical demonstration of a hydrogen fuel cell ship simulator interface; (c) Implementation of a digital twin system visualized across multiple devices (tablet, smartphone, and HMD).

- **Technical Efficiency: Process Time Reduction in Maintenance Training**

By leveraging the Open Lab's spatial computing devices (e.g., Microsoft HoloLens 2), Company B successfully transitioned from conventional paper-based training to immersive AR-guided engine maintenance systems. Table 5 compares the process times for a high-speed marine engine (Caterpillar 3512). The AR integration yielded an average time reduction of 60% for core tasks and up to 80% for preparatory procedures, drastically reducing the cognitive load on trainees.

Table 5. Comparison of process time: Manual vs. AR-based engine maintenance training.

Maintenance Protocol	Manual (t_1) [sec]	AR System (t_2) [sec]	Reduction (Δt) [sec (%)]
Cylinder Head Disassembly/Assembly	1,800	720	1,080 (60.0%)
Piston Disassembly/Assembly	1,500	630	870 (58.0%)
Crankshaft Disassembly/Assembly	2,400	960	1,440 (60.0%)
Tool Selection & Verification	400	120	280 (70.0%)
Consumables & Special Tool Check	300	60	240 (80.0%)
Average	1,280	498	782 (61.1%)

- **Precision and Reliability: Spatial Mapping and Technical Advisory**

Achieving industrial-grade precision in XR requires more than just high-end hardware. The Open Lab's technical experts directly intervened to optimize Company B's data processing pipelines. This included technical advisory on point-cloud to Unity conversion, polygon optimization (lightweighting), and spatial mapping error calibration.

Driven by the Open Lab's advisory on measurement reproducibility and error threshold management, the AR spatial mapping error was tightly constrained to $\pm 2.0\sim 3.0$ mm. The quantitative outcomes of these precision enhancements, categorized by engine type and specific target components, are summarized in Table 6.

Table 6. Spatial precision and AR hologram mapping accuracy by engine type.

Engine Type (Model)	Target Component	Reference Base	Error Margin [mm]
High-Speed (Caterpillar 3512)	Cylinder Head / Piston	Actual Physical Dim.	$\pm 0.8-1.5$
	HoloLens Spatial Mapping	Physical Position	$\pm 2.0-3.0$
Low-Speed	Pump / Blower / Lines	Actual Physical Dim.	$\pm 1.5-2.5$

(RT-flex50DF)

- **Operational Optimization: Error and Rework Reduction**

The combined hardware and advisory support directly translated into significant operational optimizations during training sessions. By providing step-by-step visual constraints and automated pass/fail assessment algorithms, the system preemptively blocked tool mis-selection and protocol deviations. A comparative analysis of these operational improvements against traditional training methods is summarized in Table 7. Notably, these enhancements reduced instructor dependency by 83% and enabled highly scalable training operations.

Table 7. Operational error and intervention reduction rates: Traditional vs. XR-integrated methods.

Performance Metric	Traditional Method	XR System Integration	Improvement [Rate (%)]
Tool Selection Error	3-5 instances / session	0-1 instance / session	≈80% Decrease
Procedural Deviation	2-3 instances / trainee	0-0.5 instances / trainee	≈75% Decrease
Instructor Intervention	20-30 min / session	3-5 min / session	≈83% Decrease
Evaluation Processing	10-15 min (Manual)	Instantaneous (Automated)	≈100% Decrease

- **Strategic Growth: Joint R&D Planning and Certification**

The most profound impact of the initiative was its role in strategic R&D planning and the formal validation of the firm's technological excellence. Through the Lab's structured support, Company B achieved several critical milestones that solidified its market position:

- **Certification and official honors:** The rigorous validation environment provided by the infrastructure enabled the firm to secure KOLAS testing certifications (December 2023) for its digital content, alongside the LR Statement of compliance and KR approval. Notably, in recognition of its pioneering contribution to the digital transformation of the maritime industry, Company B was formally honored with the Minister of Oceans and Fisheries (MOF) award. This ministerial commendation has served as a pivotal credential, significantly enhancing the firm's corporate credibility and facilitating its entry into high-barrier public sector markets.
- **National R&D Project Success:** The Lab acted as a strategic partner in R&D planning, successfully linking Company B to major national initiatives. These included the development of "LNG bunkering vessel digital twin contents" for the Korea Institute of Ocean Science and Technology (KIOST), 3D Metaverse scenarios for the Ministry of Science and ICT (MSIT), and domestic market revitalization projects for the MOF.
- **TRL Advancement:** Supported by these achievements, the technology maturity of Company B's core products progressed from a functional prototype (TRL 5) to a fully commercialized system (TRL 9), enabling the firm to secure long-term service contracts with major domestic shipping lines and offshore plant operators.

Ultimately, the Open Lab functioned not merely as an equipment rental facility, but as a strategic incubator that provided the technological methodologies and commercial pipelines necessary for an SME to achieve self-sustainability and market leadership.

3.2.3. Company C: Scientific Validation for Hydraulic Structures and Environmental Engineering

This section evaluates the performance of Company C, an engineering firm specializing in hydraulic structures. The firm developed and successfully installed bi-directional electric swing sluice gates to resolve severe water stagnation and pollution in the Dongsam Seawater Stream (Figure 9). Unlike previous cases focused primarily on equipment provision, the Open Lab supported Company C through rigorous scientific validation—combining computational fluid dynamics (CFD) modeling with the empirical field monitoring infrastructure described in Section 2.1.1 (e.g., Aquadrift and YSI 650 MDS).



Figure 9. Successful implementation and completion of the bi-directional electric swing sluice gate project at Dongsam Seawater Stream: The completion ceremony (February 2022) marks the successful execution of the hydraulic infrastructure project by Company C, facilitated by the Open Lab's scientific validation and field monitoring support (Photograph courtesy of Yeongdo-gu district office, 2022).

This integrated approach allowed for the precise verification of the system's engineering efficacy and its environmental impact prior to full-scale deployment. By providing high-fidelity data and technical assurance, the initiative enabled the firm to successfully secure and execute this large-scale public infrastructure project. The completion of the Dongsam Seawater Stream project serves as a representative case where the synergy between public research expertise and private sector engineering effectively addressed critical regional environmental challenges.

- Technical Efficiency: Analytical Proof of Concept (TRL 3)**

Prior to the actual construction, Company C required technical justification for the gate design and operational strategy. The Open Lab conducted 3D CFD simulations using the element-based finite volume method to analyze varying outflow scenarios. The analytical models verified that operating two sluice gates simultaneously, leveraging the maximum tidal range, would optimize the flow velocity across the entire stream. This simulation provided the crucial analytical and experimental proof of concept (TRL 3), ensuring that the structural design would meet the environmental objectives before manufacturing and installation commenced.
- Precision, Reliability, and Operational Optimization: Proactive Risk Mitigation via Scientific Evidence (TRL 8)**

Following installation, the Open Lab deployed high-precision measurement equipment to conduct a system prototype demonstration in an operational environment. Empirical data revealed a massive hydrodynamic improvement, demonstrating that bi-directional gate operation during maximum tidal ranges exponentially accelerated the previously stagnant flow. This amplified seawater exchange directly achieved the primary goal of environmental restoration. Continuous water quality monitoring confirmed that the increased velocity substantially enriched dissolved oxygen (DO) levels, rapidly elevating the stream's overall water quality and establishing a strong resilience and recovery capacity even following severe pollution events.

Furthermore, when a mass fish kill occurred in the stream, the Open Lab's digital twin-based IoT sensors and subsequent water quality analysis swiftly identified that the incident was driven by an external influx of pollutants coupled with a sudden spike in water temperature. By scientifically demonstrating that the mortality event was not caused by any structural or operational defects of the

sluice gates, this intervention proactively protected Company C from potential liability claims, thereby proving the overarching robustness and reliability of the installed infrastructure.

- **Strategic Growth: Market Expansion via Technical Reliability**

The Open Lab's support fundamentally transformed Company C's technological credibility. By co-authoring and publishing the validation results in peer-reviewed academic journals [24], the Open Lab provided Company C with objective, third-party verification of their engineering capabilities. Armed with these scientific outputs, Company C successfully executed technical promotions that led to tangible strategic growth. The firm secured new domestic and international contracts for hydraulic structures and successfully signed a memorandum of understanding (MOU) with a foreign specialized engineering company. This progression from TRL 3 to TRL 8—and subsequent commercial expansion—exemplifies how scientific validation through an Open Lab can drive the autonomous growth and global market entry of a regional SME.

3.2.4. Company D: Immersive Content Development for Marine Safety Training

Among various instances of immersive VR content development, this assessment focuses on the "Marine VR edu-entertainment and practical safety training immersive content platform (v1.0)"—previously introduced in Section 2.7—as a representative case. Notably, the platform incorporates high-fidelity immersive content specifically designed for crisis response training during ship fire emergencies. To facilitate high-precision 3D modeling of an actual vessel, the Open Lab provided KIOST's research vessel, *Isabu*, as a dedicated testbed for Company D.

As illustrated in Figure 10, the project encompasses an end-to-end workflow: from on-site spatial data acquisition and engine optimization to a role-based interactive simulation where trainees execute step-by-step fire suppression procedures. Developed using the Unity engine based on precise 3D modeling, this platform was successfully realized through intensive collaboration with the Open Lab, utilizing its high-end development infrastructure and expert feedback. To ensure immersive realism and operational stability, the platform was developed to meet rigorous technical requirements. The technological achievements were officially verified through an accredited third-party testing agency.

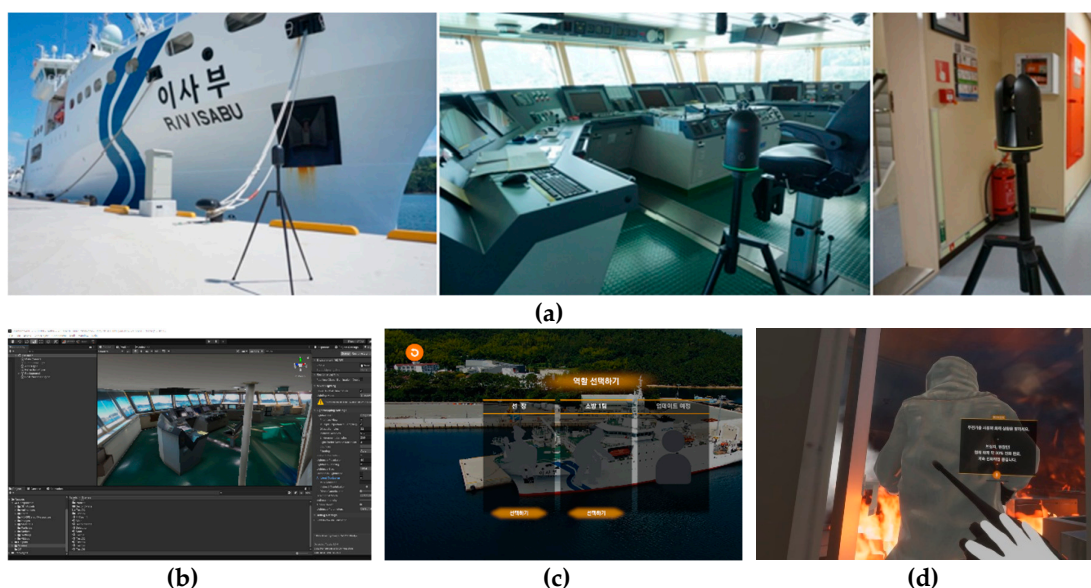


Figure 10. End-to-end development and execution workflow of the VR crisis response training platform: (a) On-site 3D LiDAR scanning of the RV *Isabu* to acquire high-precision spatial data; (b) Integration and optimization of the virtual environment within the Unity 3D engine; (c) Role selection interface assigning specific emergency

response duties (e.g., Captain, Fire squad) to trainees; and (d) Interactive step-by-step training phase for ship fire suppression and crisis management.

The key validated performance outcomes are summarized as follows:

- **Precision and Reliability (Spatial Fidelity)**
The platform successfully virtualized five distinct maritime compartments (e.g., bridge, engine control room, engine room, hallway, and steering gear room) based on Point Cloud data. The spatial deviation (dimensional error) between the virtualized 3D models and the actual physical spaces was strictly constrained to a remarkable average of 0.027%. This ultra-high precision was achieved alongside extensive graphical optimization, maintaining an average of 701,067 faces (polygons) and high-resolution texture details (averaging 7,372 pixels) per space, ensuring industrial-grade visual realism without compromising system load.
- **Technical Efficiency and Stability (System Performance)**
A critical factor in VR-based safety training is the prevention of cyber-sickness (motion sickness) and the provision of seamless user interaction. The official tests confirmed an average real-time rendering speed of 91 frames per second (FPS) during rapid viewpoint changes. Furthermore, the system demonstrated near-instantaneous interactivity, with UI menu button response times averaging 0.015 ms and movement button response times at 5.549 ms. The overall platform loading speed was also highly optimized to an average of 0.33 s.

These empirical results confirm that the Open Lab's infrastructure and technical advisory directly enabled Company D to overcome the traditional trade-off between high-fidelity 3D graphics and real-time system performance. By securing this officially certified technical reliability, Company D established a robust foundation for commercializing its interactive crisis response and VR training platforms in the highly demanding maritime education and safety sectors. Building upon these technological experiences—including the precise digital twin modeling of the research vessel *Isabu*—and continuous technical collaboration with the Open Lab, Company D successfully translated its certified capabilities into tangible market performance, achieving a substantial quantitative track record of developing and delivering 42 immersive content projects in 2021 and 19 projects in 2022.

3.3. Socio-Economic Impact Assessment: Verified Revenue and Employment

3.3.1. Verification of Revenue Generation

To provide a high-fidelity assessment of the Open Lab's economic impact, this study presents annual revenue figures and growth rates using two distinct valuation methods. Annual revenues for 2021 and 2022 are presented based on the actual exchange rate (AER) of each respective year to reflect the real-world purchasing power and the actual foreign exchange value earned by the firms during those periods. Conversely, the growth rates are calculated using a constant exchange rate (CER) based on the 2021 average. This dual approach is strategically employed to isolate the "organic growth" of the firms from external macroeconomic "noise"—specifically the significant depreciation of the Korean Won in 2022—thereby ensuring that the reported growth reflects true business performance rather than currency fluctuations. The verified revenue performance and the resulting organic growth rates for each participating firm are detailed in Table 8.

Table 8. Verified Revenue Performance and Organic Growth Rate (2021–2022).

Firm	2021 Revenue (AER, USD)	2022 Revenue (AER, USD)	Total (Sum, USD)	Organic Growth Rate (CER, %)
Company A	133,695	702,012	835,707	+492.8
Company B	3,495	58,050	61,545	+1775.0
Company C	774,205	669,505	1,443,710	-2.4
Company D	436,910	557,276	994,186	+44.0
Total (Sum)	1,348,305	1,986,843	3,335,148	+66.4

Note: AER (2021: 1,144.4 / 2022: 1,292.0). The Organic Growth Rate reflects pure revenue growth calculated based on the constant exchange rate (CER) of 2021 to exclude external currency depreciation effects; thus, the growth percentages are derived from KRW-denominated values and may not align directly with the change in the annual USD revenue totals.

- **Company A (3D Scanning-based Reverse Engineering):** Company A achieved an explosive organic growth rate of +492.8%. This economic leap is directly attributed to the technical efficiencies established in Section 3.2.1, where the firm achieved a 50–60% reduction in design lead times for complex ship modifications. The ability to rapidly acquire high-precision spatial data through Open Lab's infrastructure enabled the firm to secure high-volume contracts in the ship repair and eco-friendly modification markets, effectively translating technical time-savings into market share expansion.
- **Company B (XR-based Maintenance Training):** The most dramatic relative growth was observed in Company B, which recorded an organic growth rate of +1775.0%. As detailed in Section 3.2.2, Company B utilized the Open Lab to advance its technology from a laboratory prototype (TRL 5) to a certified commercial system (TRL 9). The significant reduction in training process times and the attainment of prestigious international certifications (KOLAS, LR, KR) served as the primary catalysts for this "J-curve" growth, showcasing how public infrastructure can bridge the "Death Valley" for software-oriented SMEs.
- **Company C (Scientific Validation for Hydraulic Structures):** Company C maintained the highest cumulative revenue of over 1.4 million USD. While the AER-based figures suggested a 13.5% decline, the CER-based analysis reveals a highly stable performance with only a -2.4% marginal fluctuation. This stability was underpinned by the scientific rigor discussed in Section 3.2.3, where Open Lab's CFD simulations verified the technical feasibility of the hydraulic gates. Crucially, when a mass fish kill incident occurred, the Open Lab utilized digital twin-based IoT sensors to prove that the event was caused by external environmental factors rather than structural defects. This proactive scientific defense protected the firm from liability claims, ensuring long-term project continuity and market trust.
- **Company D (Immersive VR Content Development):** Company D realized a steady organic growth of +44.0%, surpassing a cumulative revenue of nearly 1 million USD. This performance was driven by the successful delivery of 61 immersive content projects over two years. As analyzed in Section 3.2.4, the platform's 0.027% spatial precision and high-performance 91 FPS rendering stability were critical for its adoption in the maritime safety sector. The transformation of high-end technical validation into a high-volume delivery model highlights the Open Lab's role in scaling domestic technology for industrial-grade application.

In summary, the consolidated revenue of 3,335,148 USD and an overall organic growth rate of +66.4% validate the Open Lab as a high-performance economic engine. By mitigating external currency risks through CER analysis, this study proves that the synergy between public infrastructure and private enterprise leads to robust, self-sustaining industrial revitalization.

3.3.2. Social Impact: Regional Job Creation and Employment

Beyond direct economic revenue, the Open Lab model has functioned as a significant catalyst for regional job creation, contributing to the revitalization of the local maritime labor market. This social impact is quantified through verified employment (E_v), which adjusts the number of new hires by the Open Lab contribution rate ($C_{E,i}$), as summarized in Table 9. While Companies A and B focused on lean operational excellence and technical breakthroughs without immediate headcount expansion during the 2021–2022 period, Companies C and D demonstrated substantial employment growth driven by their respective scaling and R&D activities.

Table 9. Verified Employment Performance of Participating Firms (2021–2022).

Firm	2021			2022			Total (E_v)
	N_i	$C_{E,i}$	E_v	N_i	$C_{E,i}$	E_v	
Company C	1	0.8	0.8	1	0.7	0.7	3.5
	1	0.2	0.2	1	0.7	0.7	
Company D	1	0.4	0.4	1	0.7	0.7	8.0
	6	1.0	6.0	2	1.0	2.0	
Total (Sum)							11.5

- **Company C (Indirect Social Impact via Market Expansion):** As a non-participant in the direct Regional Innovation Cluster project, Company C's employment performance represents the indirect "spillover effect" of the Open Lab. The firm achieved a cumulative verified employment of 3.5 persons. This growth was fundamentally driven by the revenue stability and enhanced market trust established through the scientific validation of its hydraulic structures, as discussed in Section 3.2.3.

As Company C secured large-scale infrastructure projects and maintained a robust revenue stream—achieving a consolidated revenue exceeding 1.4 million USD over the 2021–2022 period—the demand for professional personnel in hydraulic design, construction management, and on-site technical support increased. The Open Lab's contribution to these hires reflects its role in strengthening the firm's project execution capacity, thereby enabling the firm to confidently expand its workforce to manage increasingly complex and high-value engineering contracts.

- **Company D (Direct R&D Scaling and Content Delivery):** In contrast, Company D's employment performance (total 8.0 persons) reflects a direct R&D-driven expansion as a core participant in the Regional Innovation Cluster project. The high volume of delivery—61 immersive content projects—was inherently labor-intensive, requiring a specialized workforce for 3D modeling, rendering optimization, and the operation of high-end Open Lab equipment. As analyzed in Section 3.2.4, maintaining ultra-high spatial precision (0.027% error) and high-performance rendering (91 FPS) necessitated the continuous involvement of dedicated research personnel. Consequently, Company D utilized the Open Lab's infrastructure as a platform for practical content development, leading to the recruitment of specialized developers and researchers to meet the rigorous technical standards of the maritime safety and education sectors.

The total verified employment of 11.5 persons within two years illustrates the diverse pathways through which public R&D infrastructure supports regional labor markets. While Company C represents the stabilization-led employment through market expansion, Company D exemplifies innovation-led employment through technical scaling. This collective impact proves that the Open Lab model does not merely provide temporary equipment access but acts as a foundational support system that allows regional SMEs to build sustainable human capital, ultimately contributing to the long-term resilience of the maritime industrial ecosystem.

3.4. Qualitative Validation: User Satisfaction and Needs Analysis of Regional Enterprises

To complement the quantitative technical and economic achievements discussed in the previous sections, a qualitative survey was conducted among 14 regional enterprises that actively utilized the Open Lab. The objective was to evaluate user satisfaction and analyze future operational needs. The survey results provided critical insights into why the Open Lab model was highly effective in generating the performance metrics outlined in Sections 3.2 and 3.3.

- **Verification of the Innovation Intermediary Role**

The overall satisfaction among the participating regional firms was exceptionally high, scoring a normalized 100 out of 100 points. Notably, while satisfaction with physical equipment utilization scored 98.2 points, satisfaction with expert-led "technical advisory services" attained

a perfect score of 100. When asked about the most significant contributions of the Open Lab (multiple responses allowed), 85.7% of the firms cited the "resolution of technical difficulties," followed by the "reduction in R&D costs" (57.1%) and "shortened product development periods" (28.6%). These results reaffirm the core hypothesis of this study: the Open Lab's true value lies not merely in functioning as an equipment rental facility, but in acting as an "innovation intermediary" that actively bridges the "Death Valley" of commercialization through specialized technical expertise.

- **Future Demands and the Necessity of Sustained Support**

Regarding future operational directions, the participating firms strongly requested "support for prototype production and commercialization" (71.4%), the "continuation of existing Open Lab support programs" (71.4%), and the "introduction of new and advanced equipment" (64.3%).

These demands highlight a critical structural vulnerability of regional industries. Regional enterprises frequently struggle with limited project budgets and chronic shortages of skilled professional manpower. For these regional SMEs to overcome such inherent limitations, scale up, and ultimately achieve self-sustainability (technological and economic independence), the provision of public-led infrastructure coupled with expert technical services—such as the Open Lab model—is essential. The survey results clearly demonstrate that these firms strongly desire the continuous and sustained support of the Open Lab to bridge the gap between initial R&D success and full-scale market dominance.

3.5. Strategic Expansion: Extrapolating the Open Lab Model to Other Declining Regions

The successful revitalization of Busan's maritime sector—driven by the synergy of high-end physical infrastructure and expert brainware—demonstrates that the Open Lab model can serve as a fundamental blueprint for reversing regional industrial decline. Building upon the qualitative validation from regional enterprises, this study proposes tailored Open Lab expansion strategies for three representative South Korean industrial hubs currently undergoing structural transitions.

- **Taebaek/Samcheok (Gangwon province): Digital twin-based smart farming in abandoned mines**

To mitigate the geographic isolation and economic stagnation of abandoned mine regions, the Open Lab model proposes a strategic pivot toward high-tech agriculture utilizing both subterranean spaces and underground thermal resources. By repurposing the natural constant-temperature (10–15 °C) environments and abundant subterranean mine water of these facilities, the region can foster high-value smart vertical farms. The significant cross-sectional dimensions of existing mine tunnels—such as those in the Hamtae Mine (averaging 6.0 m in width and 2.4 m in height)—provide superior spatial scalability for multi-tier vertical rack installations and the seamless deployment of autonomous logistics systems [25]. Building upon these inherent environmental advantages—particularly by harnessing the underground mine water and geothermal energy—the region recently established a world-class surface-level indoor smart farm at the abandoned Jangseong Mine site, successfully validating the commercial viability and scalability of repurposing mine resources [26].

The proposed Open Lab infrastructure focuses on unmanned ground vehicles (UGVs) equipped with LiDAR SLAM for underground spatial digitalization, alongside IoT sensor networks for real-time environmental monitoring. By establishing a digital twin of the underground farm, the Open Lab has the potential to facilitate data-driven, remote cultivation strategies. Crucially, the "Digital Proxy Support" model—where experts operate advanced systems on behalf of SMEs lacking specialized technical personnel—in collaboration with regional flagship universities, could establish a robust R&D talent pipeline, thereby holding the potential to transform a regional liability into a high-tech testbed for the future of agriculture.

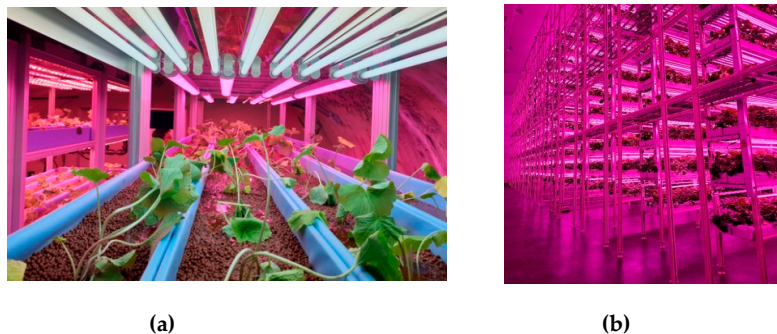


Figure 11. Representative cases of smart farm facilities utilizing abandoned mine infrastructure in Gangwon Province: (a) Subterranean smart farm for wasabi cultivation utilizing the internal tunnel space of the abandoned Hamtae Mine [25]; and (b) Large-scale, surface-level indoor smart farm for strawberry cultivation at the abandoned Jangseong Mine site, leveraging underground thermal resources [26].

- Gumi (Gyeongsangbuk province): Advanced defense and battery innovation hub**

Once a hub for mass electronics, Gumi is strategically transitioning toward K-defense and secondary batteries. This structural shift was significantly accelerated by the region's recent official designation as a 'Defense innovation cluster' by the national government [27], coupled with large-scale investments in the 'Secondary battery material industry hub center' and major battery cathode facilities [28]. To support this shift for local SMEs, the regional Open Lab should function as a "Security-cleared joint R&D hub" designed to meet the high-precision requirements of defense manufacturing and battery safety. Key infrastructure must include ultra-high-resolution 3D CT scanners for the non-destructive testing of legacy components, thermal runaway evaluation systems for battery cells, and EMI/EMC testing chambers for ensuring electronic reliability. By deploying experts in AI vision inspection and defense standard (MIL-STD) compliance, the Open Lab can facilitate the entry of regional SMEs into high-barrier defense procurement and battery supply chains without the burden of excessive upfront capital expenditure.
- Gunsan (Jeollabuk province): Offshore wind power & smart mobility transition**

Following the severe economic impacts of major automotive and shipbuilding plant closures, Gunsan is aggressively restructuring its industrial ecosystem around renewable energy and electric vehicles (EVs). This structural transition is strongly supported by the recent national designation of the Saemangeum area as a 'Secondary Battery specialized complex' [29] and the official selection of Gunsan Port (Pier 7) as a strategic support base for the offshore wind power batch rear complex [30]. To accelerate this shift, the regional Open Lab strategy centers on a "Prototyping-to-Certification" model. Necessary infrastructure must include advanced structural and material testing facilities for massive offshore wind components, alongside environmental reliability chambers for EV battery safety. By providing preemptive scientific validation for stringent international certifications (e.g., KOLAS, DNV), the Open Lab can effectively bridge the "Death Valley" for regional suppliers transitioning from traditional internal combustion engines and heavy manufacturing to the smart mobility and green energy sectors.
- Implications and Expected Effects**

The expansion of the Open Lab model to these regions is expected to yield significant socio-economic dividends, grounded in the empirical evidence observed in the Busan case. First, by lowering the entry barriers to high-tech sectors through shared public infrastructure, regions can anticipate a surge in organic growth similar to the +66.4% revenue increase achieved in this study. Second, the integration of regional universities into the Open Lab framework will create a stable "human capital anchor," preventing local brain drain and fostering Innovation-led Employment. Finally, this tailored approach ensures that regional industrial resurrection is not

a generic R&D effort but a highly customized strategic intervention. Ultimately, the Open Lab functions as a "Regional economic engine," enabling declining hubs to transition into self-sustaining innovation ecosystems through the efficient deployment of public-led technological assets.

4. Conclusions

4.1 Summary of Research Findings

This study has empirically verified the efficacy of the Open Lab model as a high-performance engine for regional industrial resurrection (RIR). By analyzing the performance of participating SMEs in Busan's maritime sector between 2021 and 2022, several key findings were established.

First, the technical intervention of the Open Lab enabled firms to bridge the critical "Death Valley" of innovation, facilitating TRL 9-level commercialization and the acquisition of international certifications through high-end infrastructure and specialized technical expertise. Second, the economic impact was substantial; the four representative firms achieved a consolidated revenue exceeding 3.3 million USD. By applying the constant exchange rate based on a CER to isolate macroeconomic volatility, this study revealed a robust +66.4% organic growth rate, demonstrating that the Open Lab directly enhances the market competitiveness and financial resilience of regional SMEs. Third, the social impact was evidenced by 11.5 verified new employees resulting from the Open Lab's contribution, illustrating a dual pathway of employment: "Innovation-led" growth through technical scaling and "Stabilization-led" growth through market expansion. Finally, qualitative analysis confirmed that regional enterprises prioritize expert-led technical advisory over simple equipment rental, underscoring the Open Lab's pivotal role as an essential "Innovation intermediary" that bridges the gap between high-tech infrastructure and local industrial needs.

4.2. Policy Implications and Recommendations

The results of this study offer several critical implications for regional development policy.

- **Transition from Hardware to Brainware:** Policy-makers must shift the focus from merely constructing physical facilities to providing "Expert-infused infrastructure." As seen in the 100% satisfaction rate for technical advisory, the success of regional SMEs depends on the availability of specialized human capital that can translate complex data into commercial value.
- **Necessity of Public-led Sustainability:** For regional SMEs facing chronic shortages in project budgets and professional manpower, sustained public-led support is not an option but a necessity. The Open Lab model ensures that technological and economic independence (Self-sustainability) is achieved through a long-term, stable support ecosystem rather than fragmented, short-term grants.
- **The Role of Regional University Anchors:** In many declining industrial regions where specialized public research institutes are absent, regional universities represent the unique and primary professional entities capable of fulfilling the technical and advisory roles required for Open Lab operations. Their integration into the framework is therefore vital, as they serve as a "Human capital anchor". By providing a steady pipeline of R&D talent and high-level expertise, these institutions prevent local brain drain and ensure the long-term technological resilience of the regional industrial cluster. This synergy allows the Open Lab to function not just as a facility, but as a sustainable knowledge hub that bridges the gap between academic research and industrial application.

4.3. Strategic Scaling for Regional Industrial Revitalization

Beyond the maritime sector of Busan, the Open Lab model offers a versatile blueprint for other declining industrial hubs in South Korea. Whether it is the digital twin-based underground clusters in Taebaek/Samcheok, the advanced defense hub in Gumi, or the renewable energy transition in Gunsan, the core principle remains the same: tailoring high-end public assets to the specific

technological needs of the region. By transforming local liabilities—such as abandoned mines or aging manufacturing sites—into specialized high-tech testbeds, the Open Lab can catalyze a self-sustaining innovation cycle across diverse geographic contexts. Such a tailored, cluster-based approach aligns with the European differentiation frameworks for maritime clusters, which emphasize that targeted institutional support is crucial for regional sustainability and global competitiveness [31].

4.4. Limitations and Future Research

While this study provides robust empirical evidence over a two-year performance generation phase, it is limited by its relatively small sample size of representative firms. Future research should involve a longitudinal study over a five-to-ten-year period to assess the long-term survival rates and global market entry of Open Lab-supported enterprises. Additionally, cross-border comparisons with international industrial innovation hubs (e.g., Germany’s Fraunhofer or UK’s Catapult centers) would provide further insights into optimizing the Open Lab model for the global stage. Moreover, as digital transformation in the shipping industry increasingly relies on complex, networked ecosystems, future studies must evaluate how regional Open Labs can integrate into global digital maritime networks [32].

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Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AER Actual Exchange Rate
 AR Augmented Reality
 BOK Bank of Korea
 BWTS Ballast Water Treatment System
 CAPEX Capital Expenditure
 CER Constant Exchange Rate
 CFD Computational Fluid Dynamics
 CT Computed Tomography
 DNV Det Norske Veritas

- DT Digital Twin
- EMI/EMC Electromagnetic Interference / Electromagnetic Compatibility
- FPS Frames Per Second
- HMD Head-Mounted Display
- ICT Information and Communication Technology
- IoT Internet of Things
- KIAT Korea Institute for Advancement of Technology
- KIOST Korea Institute of Ocean Science and Technology
- KOLAS Korea Laboratory Accreditation Scheme
- KOMSA Korea Maritime Transportation Safety Authority
- KPIs Key Performance Indicators
- KR Korean Register
- KSPORC Korea South Pacific Ocean Research Center
- LR Lloyd's Register
- MOF Ministry of Oceans and Fisheries
- MOTIR Ministry of Trade, Industry and Resources
- MOU Memorandum of Understanding
- MR Mixed Reality
- MSIT Ministry of Science and ICT
- R&D Research and Development
- RIIA Busan Regional Institute of Industrial Advancement
- RIR Regional Industrial Resurrection
- RV Research Vessel
- SLAM Simultaneous Localization and Mapping
- SMEs Small and Medium-sized Enterprises
- TLS Terrestrial Laser Scanning
- TRL Technology Readiness Level
- UGVs Autonomous Ground Vehicles
- VAT Value Added Tax
- VR Virtual Reality
- XR Extended Reality

Appendix A. Official Documents for Performance Verification

Electronic Tax Invoice				승인번호				
Supplier	등록번호		중사업장번호					
	상호(법인명)		성명					
	사업장주소							
	업태		종목					
	이메일							
Recipient	등록번호		중사업장번호					
	상호(법인명)		성명					
	사업장주소							
	업태		종목					
	이메일							
Date of Issue	Supply Value (V_i)	VAT	수정사유	비고				
2021-07-13	39,090,910	3,909,090	해당없음					
Month	일	Product	규격	수량	단가	Supply Value (V_i)	VAT	비고
07	13			1	43,000,000	39,090,910	3,909,090	
합계금액		현금	수표	어음	외상미수금	이 금액을 (청구) 함		
43,000,000		43,000,000						

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Figure A1. Representative masked electronic tax invoice utilized for the verification of corporate revenue performance (V_i).

Confirmation of Finalized Revenue (2021)

Company Information	
Name	BRN

R&D Project Information	
Project Name	Regional Innovation Cluster Development Program
Project No.	P0004797
Lead Inst.	KIOST
Project Title	Establishment of Advanced Marine Industry Open Laboratory and Development of Realistic Convergence Content

사업화매출액 세부내역						
Month	Product	Unit price	Quantity	Supply Value (V_i)	Contribution Rate(%), ($C_{R,i}$)	R&D-related Revenue ($R_{R,i}$)
07월		39,090,910	1	39090910	30	11,727,273
04월		509,090,910	1	509090910	50	254,545,455
04월		41,094,547	1	41094547	30	12,328,364
05월		99,772,728	1	99772728	40	39,909,091
06월		199,900,000	1	199900000	40	79,960,000
06월		103,777,091	1	103777091	40	41,510,836
08월		417,366,363	1	417366363	40	166,946,545
09월		17,193,636	1	17193636	30	5,158,091
10월		38,342,000	1	38342000	30	11,502,600
11월		15,810,000	1	15810000	30	4,743,000
12월		491,860,000	1	491860000	50	245,930,000
12월		28,538,710	1	28538710	40	11,415,484
Total				885,676,739		
Total Corp. Revenue for the Same Period				① 2,557,109,539		

* 과제기여율(%): 정부지원 과제가 해당 제품 사업화에 기여한 비중을 해당 기관이 1~100%의 범위에서 자율 선택

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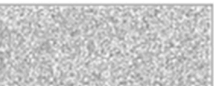
2022년 01월 05일

Company Name	Representative Name	Official Seal
②	②	③

* ①, ②은 수기 작성 ③은 인감 날인해주세요.

Figure A2. Representative masked confirmation document utilized for finalizing the verified revenue (R_v , referred to as R&D-related revenue in the document) based on the Open Lab contribution rate ($C_{R,i}$). (The red dashed border indicates the correspondence of the July supply value (V_i) from Figure A1 as it is reflected in this finalized statement.)

Certificate of 4 Major Social Insurance Subscription						
Issue No.		Date of Issue		Business Management No.		
Issue No.	National Pension	Health Insurance	Worker's Comp.	Employment Ins.		
BRN						
Company Name						
■ Subscription Details (As of the date of Issuance) 1 / 2						
No.	National ID No.	Name	Qualification Acquisition Date			
			National Pension	Health Insurance	Worker's Comp.	Employment Ins.
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11			2021.01.20	2021.01.20	2021.01.20	2021.01.20
12						
13						
14						

▷ 위 사업장 가입자 명부는 4대사회보험 정보연계시스템이 국민연금공단 국민건강보험공단 근로복지공단의 가입자 정보를 실시간 연계받아 제공하는 것이며, 발급사실 여부는 발급일로부터 90일까지 4대사회보험 포털사이트(www.4insure.or.kr)의 [발급사실확인] 메뉴에서 확인 가능합니다.
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Figure A3. Representative masked Workplace Subscriber List of the Four Major Social Insurances utilized for employment performance verification (N_i). (The red dashed border highlights the qualification acquisition dates (e.g., January 20, 2021) for a subset of the masked subscribers, which are used to verify the 7-month employment maintenance criterion for job creation calculation as described in Section 2.3.).

Appendix B. SME Satisfaction and Demand Survey

The following is the satisfaction survey administered to the SMEs utilizing the Open Lab's corporate support services. Respondents were asked to rate their satisfaction level on a scale from 1 (Lowest) to 9 (Highest).

Table B1. Satisfaction by Support Type (Evaluate only the services received).

Item	Satisfactory Level (1: Low ~ 9:High)								
1) Immersive Content Production Support (Funding and consulting for content creation)	1	2	3	4	5	6	7	8	9
2) Marketing Support (Creation of promotional immersive content for brochures, products, etc.)									
3) Technical Consulting & Engineering Support (Expert technical support for technological bottlenecks)									
4) Facility & Equipment Utilization Support (Rental of facilities/equipment for R&D and demonstration)									
5) National Project Planning Support (Assistance with proposal writing and evaluation for R&D projects)									
6) Exhibition Hosting Support (Support for exhibition activities to promote beneficiary companies)									
7) Other Support (Please specify: _____)									

Table B2. Promptness (Service Speed).

Item	Satisfactory Level (1: Low ~ 9:High)								
1) Time elapsed from the initial request to the actual provision of support	1	2	3	4	5	6	7	8	9
2) Speed of the representative's response to inquiries regarding corporate support									
3) Promptness of feedback on requested materials and data									

Table B3. Reliability.

Item	Satisfactory Level (1: Low ~ 9:High)								
1) Technical reliability (Expertise and accuracy of provided technology/information)	1	2	3	4	5	6	7	8	9
2) Administrative reliability (Adherence to funding schedules, clear sources of data)									
3) Institutional efforts to improve the service environment									

Table B4. Convenience.

Item	Satisfactory Level (1: Low ~ 9:High)								
1) Convenience of Open Lab utilization (Scheduling visits, using facilities/equipment)	1	2	3	4	5	6	7	8	9
2) Parking facilities and accessibility (Availability of sufficient parking space)									
3) Space utilization (Adequacy of space for R&D, consulting, and training)									
4) Required expenditure for support (Satisfaction regarding time and economic costs)									

Table B5. Staff Attitude.

Item	Satisfactory Level (1: Low ~ 9:High)								
1) Professional demeanor of the staff (Greetings, expressions, and attire)	1	2	3	4	5	6	7	8	9
2) Attitude during phone/email correspondence (Kindness, proactiveness, and accuracy)									

Table B6. Overall Service Evaluation.

Item	Evaluation								
1) Overall satisfaction with the Open Lab's corporate support services	1	2	3	4	5	6	7	8	9
2) Willingness to participate in future corporate support programs									

Table B7. Open-Ended Feedback.

Subject	Response
1) If subsequent follow-up or linked support programs are implemented, what specific types of corporate support would you like to receive?	
2) What were the most inconvenient or difficult aspects of using the corporate support services?	
3) What specific improvements are needed to better support the beneficiary SMEs?	
4) Other opinions and suggestions.	

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