Next Level of Water Infrastructure Management Using High-Definition Digital Twins

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1. SUMMARY

The paper presents "InfraCloud", a partially government-funded German project aimed at more efficiently managing aging harbor and waterway infrastructure (e.g., quay walls, locks, and barrages). In Germany, approximately 70% of the 2,500 such structures have the lowest or second-lowest condition rating, with 20% older than 100 years and 80% older than 50 years (expected lifespan: 80–100 years). A similar situation exists for bridges. InfraCloud combines an innovative measurement platform with a web-based digital twin solution capable of handling and streaming terabytes of data, including point clouds, meshes, high-definition images, and documents. Custom-developed AI tools enable precise damage detection, classification, and automated workflows for repair planning, tendering, and construction verification. This paper demonstrates, through real-world renovation projects by HydroMapper, how ultra-high-resolution digital as-built twins and AI-assisted processes can extend the lifespan of critical port infrastructure by 5–10 years. It highlights efficiency gains and quantifiable KPIs related to time and cost savings for operators, engineering firms, and construction companies.

Das Paper stellt das Projekt „InfraCloud“ vor – ein teilweise vom deutschen Staat finanziertes System zur effizienteren Bewirtschaftung alternder Hafen- und Wasserstraßeninfrastruktur (z. B. Kaimauern, Schleusen, Wehre). In Deutschland sind 70 % der rund 2.500 entsprechenden Bauwerke in einem schlechten oder sehr schlechten Zustand, 20 % älter als 100 Jahre und 80 % älter als 50 Jahre (bei einer erwarteten Lebensdauer von 80–100 Jahren). Eine ähnliche Situation besteht bei Brücken. InfraCloud basiert auf einer innovativen Messplattform und einer webbasierten Digital-Twin-Lösung, die große Datenmengen (Punktwolken, Meshes, HD-Bilder, Dokumente) verarbeiten und streamen kann. Ergänzt wird dies durch eigens entwickelte KI-Tools, die Schäden automatisch erkennen, klassifizieren und Workflows für Instandsetzung, Ausschreibung und Bauüberwachung unterstützen.
Das Paper demonstriert anhand realer Sanierungsprojekte von HydroMapper, wie durch den Einsatz ultrahochauflösender digitaler Zwillinge und KI-gestützter Prozesse die Lebensdauer kritischer Infrastruktur um 5–10 Jahre verlängert werden kann. Es werden konkrete

Effizienzgewinne sowie messbare KPIs zu Zeit- und Kosteneinsparungen für Betreiber, Ingenieurbüros und Bauunternehmen vorgestellt.

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2. CURRENT SITUATION WITH WATER AND ROAD INFRASTRUCTURE

German ports, like in many other European countries, secure purchasing power and prosperity throughout the world's 3rd largest economy.

In 2022, German seaports handled a cargo throughput of approximately 280 million tons along roughly 140 km of quay wall length. The network of federal waterways in Germany comprises about 7,500 km of inland waterways. Federal waterways also include around 23,000 km² of maritime waterways, such as the German Bight.

Operators must manage waterways, infrastructure structures, and superstructure despite increasing age and demographic changes with ever fewer personnel. Aging infrastructure requires greater deployment of personnel and technical resources in the coming years to ensure operations. According to the Federal Transport Infrastructure Plan, €16.2 billion should flow into maintenance and replacement measures for federal waterways by 2030 (BMDV 2016).

Neither the form nor the quality of available information allows dynamic and innovative use of structure data in ongoing operations with efficient involvement of port personnel.
Over the lifespan of infrastructure, questions repeatedly arise that must be answered in the context of structure condition, intended use, and remaining service life. In recent years, the IT side addressed this issue by developing various lifespan or infrastructure asset management systems (IMS). IMS primarily serve damage documentation during regular structure inspections. Damages are catalogued exemplarily and illustrated with photos, then summarized in an inspection report with a recommendation for measures.

These processes have not been fully digitized or automated, resulting in media discontinuities and inconsistencies from structure inspection through budget planning, rehabilitation planning, to construction execution.

The HydroMapper measurement system and the InfraCloud management platform address this gap (HESSE et.al. 2020; HESSE et.al. 2021). HydroMapper focuses on high-quality sensory data acquisition and automated data processing steps. InfraCloud handles data management and processing using AI methods, mainly through process automation for operators and AI-based evaluation of captured measurement data.

This also promotes integration of existing analog data sources (data mining) and improvement/completion of digital measurement data.

The goal of both the HydroMapper system and the InfraCloud management platform was to develop AI-supported evaluation automations that enable personnel-independent preprocessing of infrastructure data and more efficient utilization of existing human resources (HOLSTE et.al. 2022).

3. DEVELOPMENT OF HYDROMAPPER AND INFRACLOUD

The realization of the forementioned developments has been carried out in three major research projects since 2018, as Figure 1 shows, funded by the German Federal Ministry of Transport and Digital Infrastructure (BMDV).

Figure 1: Phases of HydroMapper and InfraCloud development

Stage 01 (HydroMapper, 2018–2021) focused on sensor technology, inspection workflows, point cloud platforms, and BIM modeling to enable high-quality hybrid 3D data acquisition and initial digital processing for waterway structures.

Stage 02 (port_AI, 2021–2024) advanced AI-driven solutions, including data centers, model-based inspection, Inspect-App, and IoT monitoring, emphasizing automated damage detection and real-time condition assessment.

Stage 03 (Port:Evolution, 2025–2027) targets advanced integration, such as 5D data integration, data mining, FEM-based analysis, and IAM systems, to achieve comprehensive lifecycle management and further automation.

These staged projects progressively build a fully digital, AI-supported ecosystem for sustainable port infrastructure management, reducing personnel dependency while enhancing efficiency and asset longevity.

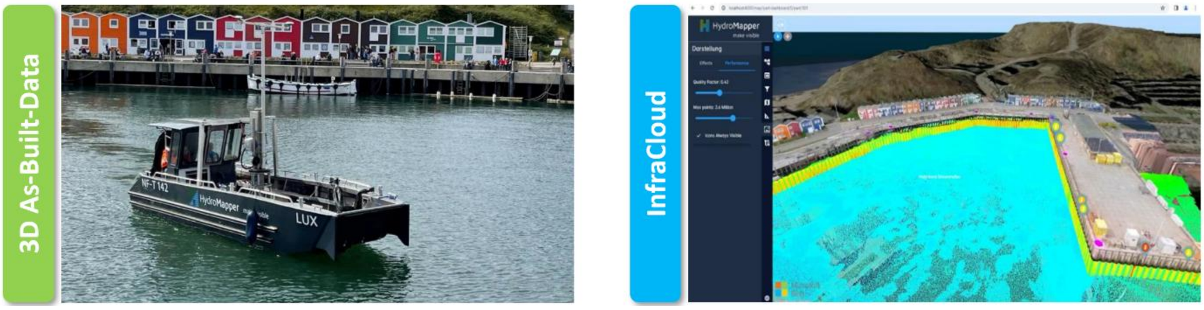

Figure 2: Synergies between HydroMapper and InfraCloud

Figure 2 shows an as-built-survey at the port of Helgoland in Germanys North Sea and the provisioning of the data via the InfraCloud platform. It illustrates the two core components of the InfraCloud product ecosystem (HESSE 2022).

1. The HydroMapper hybrid measurement system, designed for high-resolution data acquisition both above and above water. By combining terrestrial LiDAR scanners with underwater acoustic profiler systems, HydroMapper delivers exceptionally detailed 3D point clouds and meshes, achieving sub-centimeter accuracy even in challenging aquatic environments.
2. The InfraCloud SaaS platform, which provides clients with direct, browser-based access to the resulting ultra-high-resolution 3D as-built digital twins.

Drone surveyingdata, for example, is a cost effective and widely available data acquisition tool (HESSE and LUEKEN 2022). The InfraCloud platform supports seamless integration of multiple data sources to create a comprehensive initial dataset:

- Terrestrial and mobile 3D laser scans
- Aerial drone photogrammetry and LiDAR surveys
- HydroMapper HD underwater and above-water measurements
- Existing 3D BIM or CAD models
- 360-degree panoramic images
- Publicly available geospatial data (e.g., orthophotos, digital elevation models – DEM)

During routine inspections, field personnel can instantly upload high-resolution mobile phone images directly into the platform, providing additional close-up views of detected damages and enhancing visual documentation.

The asset object structure strictly adheres to established national standards and damage assessment catalogues, such as the WSVPruf guidelines for water-bound infrastructure (quay walls, locks, weirs) and the ASB-Ing standard for bridge assets. This ensures full compatibility with regulatory requirements and enables consistent, interoperable data management.

Figure 3 further demonstrates how diverse data sources are imported into the unified InfraCloud platform, creating a single common database accessible to all stakeholders – from asset owners and civil engineers to construction companies and maintenance teams.

Figure 3: Fully digital workflow using the InfraCloud platform

This integrated approach delivers multiple key benefits for infrastructure owners:

1. Recurring asset inspections are performed entirely digitally on a high-resolution up-to-date 3D as-built model
2. Eliminating the need for repeated on-site surveys
3. Significantly reduced field time.

After damage assessment, precise metric measurements (e.g., crack lengths, spalling areas, corrosion depths) can be combined with standardized price tables from negotiated framework contracts, enabling rapid budget estimation within minutes.

The same comprehensive dataset supports the automatic generation of tender documents for subcontractors and the creation of preliminary time schedules.

Upon completion of repair or construction works, the platform allows exact verification of repaired volumes and dimensions – particularly valuable when contracts are based on an "as-is" payment model.

For specific structure types, such as steel sheet pile walls along waterways, the precise knowledge of the outer geometry and bending moments derived from the 3D model enables reliable calculation of the remaining service life of quay walls, supporting proactive maintenance planning and long-term asset optimization.

4. DIGITAL TWIN FOR INFRASTRUCTURE ASSET MANAGEMENT

4.1 Digital damage assessment on the InfraCloud platform

The damage assessment process on the InfraCloud platform is intuitive and straightforward, requiring only a standard PC or laptop with a modern web browser—no additional software installation is necessary.

An example of such an assessment, based on combined HydroMapper and drone survey data, is shown in Figure 4. In this case, 13 damages were detected, georeferenced, labeled, and categorized according to their severity. Each damage record is stored in the platform's internal database, from which it can subsequently be retrieved, exported, or deleted following repair.

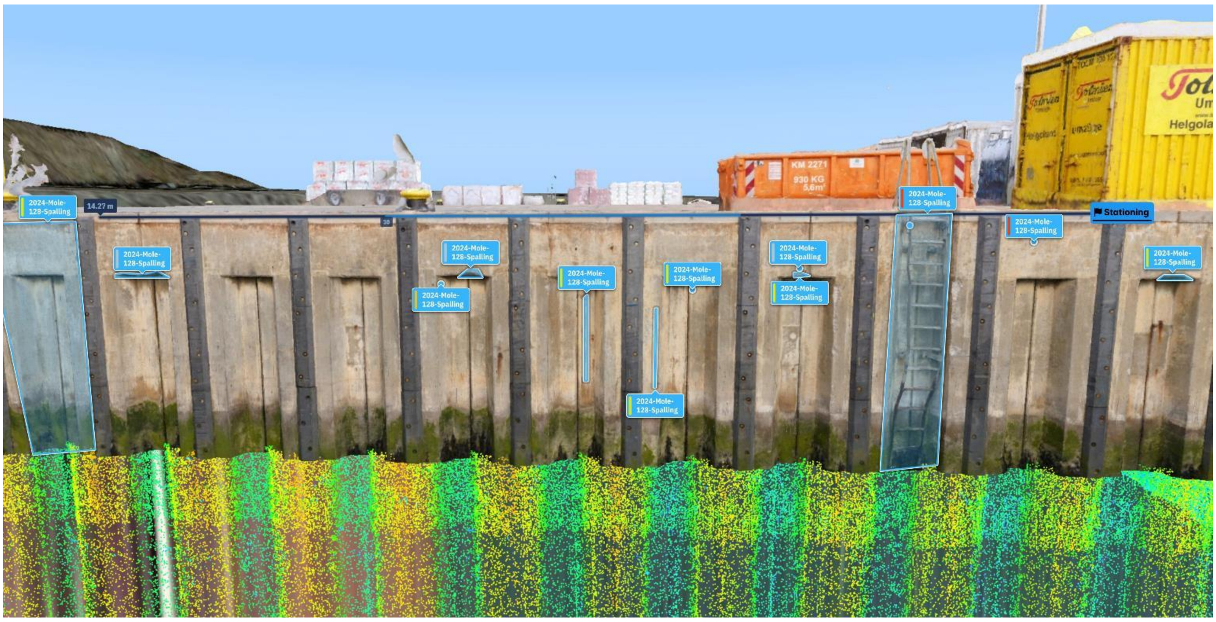

Figure 4: Assessed, labeled and categorized as-built damage

4.2 InfraCloud touch point with the building lifecycle

The graphic (Figure 5) illustrates the multiple integration points of InfraCloud within the building lifecycle process.

The workflow begins with fully digital, high-resolution as-built inspections, enabling pre-assessment of damages in the office prior to on-site verification. This approach significantly reduces fieldwork requirements, as locating and accessing potential damage sites typically accounts for the majority of inspection time and costs. Empirical results from deployed projects indicate time savings of approximately 50 % for the overall inspection process, while simultaneously improving the accuracy and consistency of damage classification.

Once all damages have been identified and categorized – including severity levels and precise metric quantification – the dataset can be exported as parametric IFC (Industry Foundation

Classes). This standardized format allows seamless integration into Building Information Modeling (BIM) environments, facilitating further design and simulation tasks.

The comprehensive damage inventory, including classification, severity, and geometric parameters, directly supports the subsequent repair planning phase. The primary advantage of the InfraCloud solution lies in its end-to-end integration: it not only provides ultra-high-resolution as-built data but also accompanies the entire rehabilitation workflow from damage detection through to construction verification.

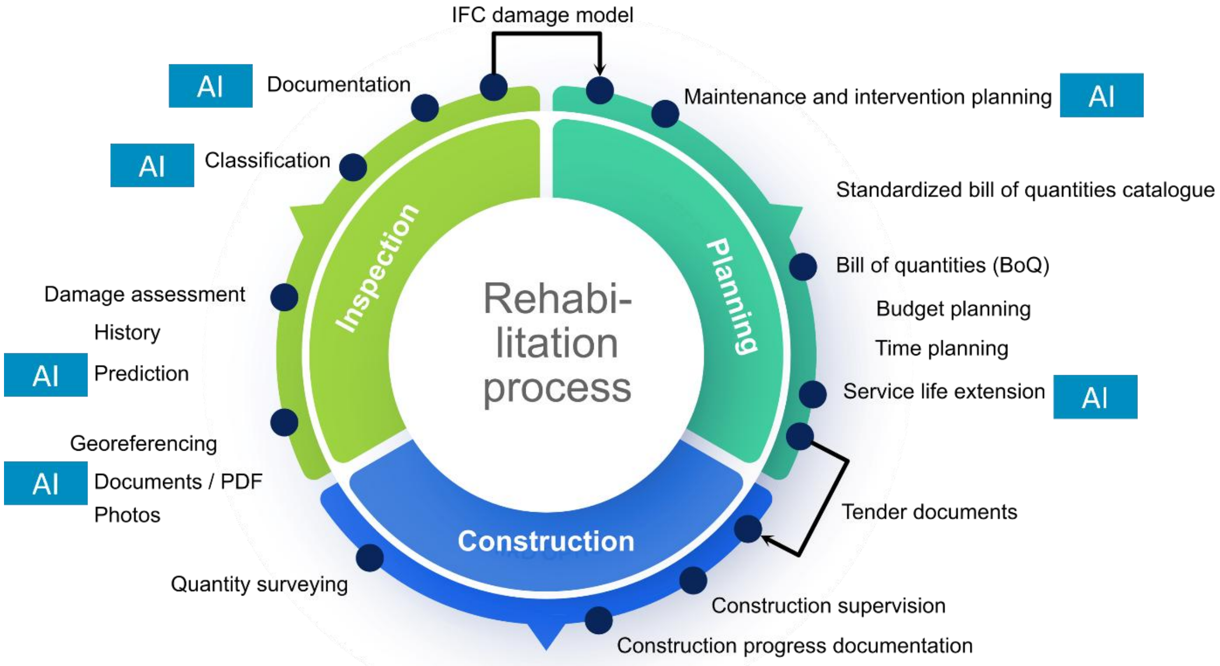

Figure 5: Touch points of the InfraCloud digital workflow with the rehabilitation process

A key operational benefit is the ability to generate tender documents directly from the validated damage dataset – either in full or selectively for specific subsets. These documents can be exported in industry-standard formats such as GAEB (Gemeinsamer Ausschuss Elektronik im Bauwesen), ensuring immediate compatibility with established tendering and cost-estimation software used by contractors and public authorities.

This streamlined digital chain minimizes media discontinuities, reduces error sources, and accelerates the transition from inspection to procurement and execution, ultimately contributing to more efficient infrastructure asset management.

5. USING AI AND DIGITAL TOOLS FOR AUTOMATING THE BUILDING LIFECYLE WORKFLOW

5.1 AI based recognition of damages like cracks and rust

In the context of AI -based recognition and detection we refer to the joint research project port AI. Within this project, a methodology for a damage recognition was developed to detect the presence of cracks and spalling using high-resolution orthoimages (Alamouri et al. 2024). The proposed methodology involves two steps: training the damage detection model and extracting the geometric characteristics of the detected cracks.

The damage detection model is a deep learning (DL) architecture based on a U-Net (Ronneberger et al. 2015) with VGG19 (Simonyan & Zisserman 2014) as the backbone or feature extractor. A total of 20 orthophotos (Figure 6a) with their corresponding labels (Figure 6b, classes: cracks (red) and spalling (orange)) were employed, where 15 were used for training and 5 for testing. Each image was split into patches of 300×300 pixels without overlapping, and different augmentation techniques were applied to reduce overfitting, such as rotations, horizontal/vertical flips, and random variations of contrast and brightness. The trained model achieved a mean Intersection over Union (mIoU) (a metric that measures the level of agreement between the detected damage and the label) of 62% in the test set (a set of images never seen during training). Figure 6c shows the model's prediction overlaid on the input image, where we can see how the model successfully detected both classes, including very thin cracks (red) with a slight confusion with spalling (orange).

The geometric characteristics of the detected cracks, such as their width and slope, were extracted using digital image processing techniques to inspect each detected crack individually. As a crack might be continuous with varying width and slope, the detected crack is divided into a grid, where the geometric features are almost constant in each cell. The computed geometric features are displayed in each cell of the grid. Figure 6d illustrates a detected crack (red) and its corresponding geometric features, where the width is in millimeters and the slope varies from -90° to 90° (from the positive x-axis). In this way, it is possible to identify cracks and the exact position where the crack represents a potential risk (e.g., a very thick crack with a slope of approximately 90°).

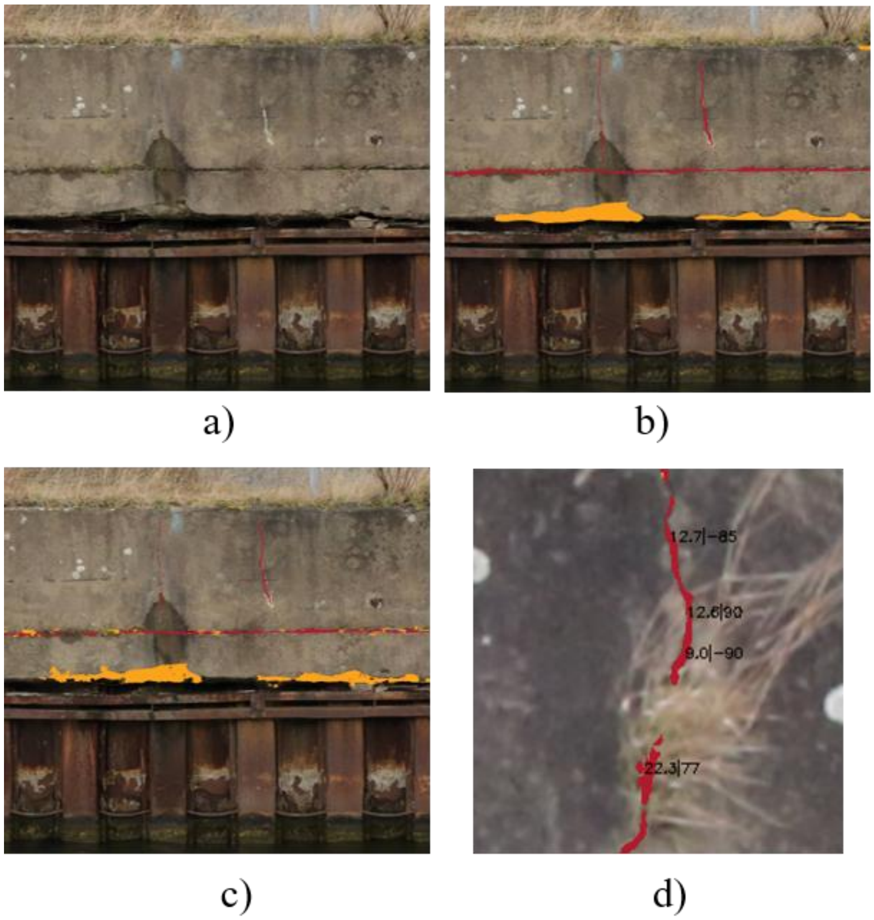

Figure 6: Results obtained using the AI-based damage recognition model: a) original orthoimage, b) manually annotated image (cracks: red, spalling: orange), c) model's prediction, and d) geometric features extracted from detected cracks (width and slope)

5.2 AI assisted data mining from analogue construction drawings

Currently, a large number of 2D construction plans of harbor facilities in Germany exist as scanned analogue documents. These documents include hand drawn, as well as, handwritten plans from the early twentieth century to the present day. The plans describe the planned construction of the harbor facilities like the ground plan of the site, the side views and cross section views of the port objects along with their dimensions. The automated extraction of relevant data from these plans is crucial for efficient digitization of the harbor plans and also for their seamless integration into larger pipelines like damage monitoring or Digital Twins.

For automating the data extraction process from the scanned plans, image processing and AI methods as well as further data sources like cadastral data (ALKIS) are utilized (Figure 7).

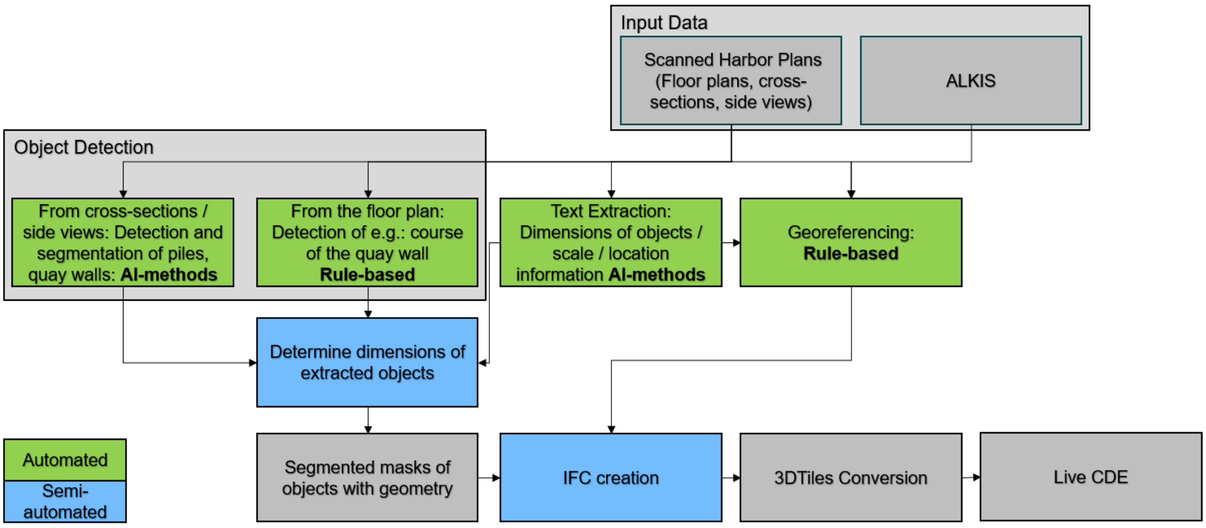

Figure 7: Data transformation pipeline of the AI assisted document referencing

The plans contain mainly geometric and additional related textual information about the harbor facility. Textual information (e.g., the name of the harbor and the scale of the plan) can be extracted from the scanned documents using Optical Character Recognition (OCR) (Smith 2007). Geometric information (e.g., construction lines) can be analyzed by utilizing modern AI methods. A deep learning-based algorithm is applied to automatically detect relevant objects such as quay walls and pillars on the plans through 2D bounding boxes. This is achieved by taking a pre-trained YOLO model (Tian et al. 2025) and performing transfer learning on it using labelled images of harbor plans.

The objects located on the plans with the 2D bounding boxes can then be extracted using semantic segmentation at the pixel level. This is implemented by applying transfer learning on a Segformer (Xie et al. 2021) deep learning model pre-trained on a large dataset to obtain a precise pixel-wise extraction of the relevant objects. Once the objects are extracted from the plans as segmentation masks, their dimensions can be determined by converting the lengths of the mask edges in pixels to meters using the scale of the plan.

Rule based georeferencing the scanned documents using additional data like ALKIS helps in bringing the plans to a common coordinate reference system (CRS) (e.g., ETRS89/UTM) and also has the added advantage of determining the depth (or extrusion) of larger harbor structures like quay walls and steel sheet pile walls. The segmentation masks with their dimensions and the text information can be used to create BIM-compliant Industry Foundation Classes (IFC) files suitable for further tasks like Common Data Environments (CDE).

5.3 Connecting BIM models to the InfraCloud Live-CDE

To ensure consistent and interoperable use of inspection-derived as-built information within a CDE, the InfraCloud platform integrates a dedicated data-transformation pipeline that connects the previously created IFC models (see chapter 5.2) with its cloud-native visualization and data management environment. This integration enables a continuous and traceable digital workflow throughout all stages of infrastructure maintenance.

Central to the pipeline is an IFC-to-3D-Tiles1 conversion framework optimized for IFC 4.32. It extracts geometry, semantic attributes, and unique identifiers while placing strong emphasis on correct georeferencing, critical for linear infrastructure spanning large geographic areas. The system supports both automatic CRS resolution using IFC 4.3 geospatial entities (e.g., IfcGeographicCRS, IfcMapConversionScaled) and manual CRS definition when such metadata is absent, ensuring accurate spatial placement regardless of upstream export quality. The processed geometry is converted into GL Transmission Format Binary (.glb) file and a 3D-Tiles-compliant tileset.json, enabling efficient streaming in the InfraCloud Web Viewer.

The resulting hierarchical structure mirrors the semantic and spatial organization of the original IFC model and is exposed as an interactive tree. This supports advanced inspection and planning workflows, including selective visualization of defects, extraction of repair-relevant subsets, and comparison of as-is and as-designed conditions.

6. Summary and conclusion

The InfraCloud project—developed through BMDV-funded research phases 3D HydroMapper (2018–2021), port_AI (2021–2024), and Port:Evolution (2025–2027)—establishes an AI-supported, cloud-based ecosystem for sustainable management of aging harbor and waterway infrastructure. With around 70% of Germany's approximately 2,500 quay walls, locks, and barrages in poor or very poor condition and many significantly exceeding their original 80–100-year design life, the solution integrates the high-resolution HydroMapper measurement platform (terrestrial/mobile LiDAR, underwater acoustic profiling, drone photogrammetry) with the web-based InfraCloud digital twin platform, which streams and processes terabyte-scale data (point clouds, meshes, HD images, historical plans). Custom AI modules (U-Net-based crack/spalling detection achieving ~62% mIoU, YOLO/SegFormer-assisted data mining from analog drawings) automate damage recognition, classification, quantification, and georeferencing; the fully digital workflow delivers up to 50% time savings in inspections, rapid budget estimation, automated tender documents (GAEB-compatible), and precise construction verification. Real-world renovation projects demonstrate service-life extensions of 5–10 years as well as substantial cost and time savings for operators, engineers, and contractors. InfraCloud thus marks a paradigm shift from

[1] https://www.ogc.org/standards/3dtiles/
[2] https://ifc43-docs.standards.buildingsmart.org/

reactive, personnel-intensive processes to proactive, largely automated lifecycle management—a scalable model for critical infrastructure in Germany and Europe that enhances safety, cost-efficiency, and resource conservation, with ongoing advancements (5D integration, FEM analysis, deeper automation) unlocking even greater potential.

REFERENCES

A. Alamouri, J. Backhaus, V. De Arriba López, P. M. Achanccaray Diaz, M. Gerke. High-Resolution Data Capture and Interpretation in Support of Port Infrastructure Maintenance, DGPF-Jahrestagung, 2024, 269-278.

Hesse, C., Holste, K., Neumann, I. 2020: 3D Hydromapper, ein innovatives Mobile-Mapping-System zur Erfassung von Verkehrswasserbauwerken. In: Wunderlich (Hrsg.), Ingenieurvermessung 20, Beiträge zum 19. Internationalen Ingenieurvermessungskurs München, Wichmann Verlag, Berlin, 2020.

Hesse, C., Holste, K., Neumann, I., Esser, R., Geist, M. 2021: 3D HydroMapper – Ein innovatives Messsystem für die Erfassung, Prüfung und das Management von Wasser-Infrastrukturbauwerken, zfv – Zeitschrift für Geodäsie, Geoinformation und Landmanagement, 4/2021: 259-265.

Holste, K., Hesse, C., Esser, R. 2022: Digitalisierung von Wasserbauwerken – Anwendungen, Chancen und Herausforderungen in der Praxis. In: DVW e.V. (Hrsg.): UAV 2022 – Innovation und Praxis. Beiträge zum 195. DVW-Seminar am 28. und 29. März 2022. DVW-Schriftenreihe Band 100/2022, Wißner-Verlag, Augsburg, 2022.

Hesse, C., Lüken, S. 2022: Schadensmodellierung der Staustufe Geesthacht. Erzeugung georeferenzierter Orthophotos und digitaler Geländemodelle durch den Einsatz von UAS und terrestrischen Laserscannern, IWSV Magazin, Zeitschrift des Ingenieurverbands Wasser- und Schifffahrtsverwaltung e.V., 62. Jahrgang, Ausgabe 3- 2022, Seite 15-19, ISSN 1614-2144, Magdeburg 2022.

Hesse, C. 2022: Digitalisierung von Wasserbauwerken - Anwendungen, Chancen und Herausforderungen in der Praxis. In: DVW e. V. (Hrsg.): Hydrographie – Messen mit allen Sinnen. Beiträge zum 204. DVW-Seminar und 35. Hydrographentag vom 14. bis 16. Juni 2022 in Bremerhaven. DVW-Schriftenreihe Band 102/2022, Wißner-Verlag, Augsburg, 2022.

Ronneberger, O., Fischer, P., & Brox, T., 2015: U-net: Convolutional networks for biomedical image segmentation. In Medical Image Computing and Computer-Assisted Intervention–MICCAI 2015: 18th International Conference, Munich, Germany, October 5-9, 2015, Proceedings, Part III 18 (pp. 234-241). Springer International Publishing.

Simonyan, K. & Zisserman, A. 2014: Very deep convolutional networks for large-scale image recognition. arXiv preprint arXiv:1409.1556.

Smith, R. 2007: An overview of the Tesseract OCR engine. Proceedings of the Ninth International Conference on Document Analysis and Recognition (ICDAR), Vol. 2, pp. 629–633, 2007

Tian, Y., Ye, Q., & Doermann, D. 2025: YOLOv12: Attention-Centric Real-Time Object Detectors: arXiv preprint arXiv:2502.12524, 2025

E. Xie, W. Wang, Z. Yu, A. Anandkumar, J. M. Alvarez and P. Luo. 2021: "SegFormer: Simple and Efficient Design for Semantic Segmentation with Transformers," in NeurIPS 2021, 2021.

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