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ARTIFICIAL AND COMPUTATIONAL INTELLIGENCE

Parametric design for sustainable marine infrastructure

Hassan ABDOLPOUR [1] * and **Maciej MARUT** [2]

[1] Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
[2] COWI A/S, Wrocław, Poland

Abstract. As coastal cities expand and confront the challenges posed by climate change, the imperative for sustainable infrastructure is becoming increasingly urgent. Marine infrastructure such as ports, quays, and ferry terminals are vital to urban ecosystems; however, they significantly impact the environment due to substantial material consumption and high energy requirements. Innovative solutions are essential to enhance design efficiency, reduce carbon emissions, and ensure long-term durability. Digital methodologies, including parametric design, building information modeling (BIM) and remote monitoring, present promising avenues toward sustainable marine infrastructure. By leveraging intelligent design processes and real-time data integration, these approaches can minimize material waste, extend structural lifespan, and promote eco-friendly urban development. This paper explores how the integration of these digital tools can contribute to the advancement of sustainable urban systems, aligning with contemporary development trends in urban infrastructure.

Keywords: sustainable infrastructure; parametric design; marine infrastructure; digital transformation; BIM.

1. INTRODUCTION

The building and construction industry is experiencing substantial digital transformation in order to meet the challenges of climate change, resource limitation and evolving performance requirements [1]. This is especially relevant for marine infrastructure, such as ports, quays (Fig. 1) and ferry terminals, which must all effectively balance operational efficiency with sustainability and resilience [2]. Traditionally, these structures have utilized "heavy" concrete or steel constructions, that are often overengineered and not optimized for material usage or ecological considerations [3]. In many cases, environmental impacts (e.g. carbon emissions, underwater habitat disruption) have not been sufficiently addressed [4]. Today, however, the industry is embracing more sophisticated tools – most notably, parametric design, building information modeling (BIM) and digital twins, to tackle sustainability imperatives and complexity in design [5]. At the same time, the latest advances show that parametric methods, coupled with real-time sensor data and digital twin platforms, can strengthen lifecycle management of marine infrastructure and enhance resilience against future climate uncertainties [6].

Fig. 1. Norwegian ferry quay – existing view of the ramp and platform

*e-mail: hassan.abdolpour@pwr.edu.pl

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1.1. Recent advances in urban digitalization

Recent calls for greener, more adaptable infrastructure have fueled interest in parametric design – an algorithmic approach that uses adjustable parameters to generate multiple design solutions rapidly. Rather than producing a single "static" design, parametric workflows consider a wide range of possibilities, automatically updating the 3D geometry when parameters change. This technique has already proven transformative in building architecture, enabling fluid forms and optimized facades that adapt to climate data. In civil and structural engineering, parametric modeling significantly reduces the labor of iterating through load cases and geometry adjustments, while also unlocking multi-objective optimization (e.g. minimizing material volume while maximizing structural safety). Such computational tools can discover solutions that balance cost, carbon footprint and also resiliency in ways that a single-iteration, manual design rarely could. Recent research indicates that integrative frameworks combining parametric modeling with environmental data are especially effective in reducing both material and energy demands, aligning with the goals of sustainable infrastructure [7]. Digitalization of construction further amplifies these gains. When parametric models connect seamlessly to BIM platforms and finite element analysis (FEA) software, teams can synchronize geometry, analysis and documentation in near real time. This reduces human error, eliminating hand modeling of geometry, and supports clash free design coordination [8]. It also facilitates collaboration between disciplines (e.g. in structural, geotechnical and mechanical engineering), when the same digital models can be reviewed. Subsequently, these models can be integrated as digital twins, enabling owners and operators to perform predictive maintenance and asset management while gaining operational insights. By monitoring real-time sensor data, a digital twin can proactively schedule repairs or optimize energy consumption, thereby enhancing sustainability throughout the asset's lifecycle [4, 9].

1.2. Digital methods and sustainability

Sustainability considerations – particularly reducing embodied carbon – have become a top priority in new infrastructure. Concrete and steel are significant contributors to greenhouse gas emissions, so refining a design to use less material (without compromising performance) is a direct environmental benefit [2]. Parametric optimization can systematically trim excess dimensions, reposition elements and shift loads to minimize total material volume [3]. It can also incorporate ecological enhancements, such as textured or "bio-receptive" surfaces that encourage habitat growth by automatically adjusting shapes or openings to support biodiversity in coastal environments [4]. Hence, the primary advantage of the parametric approach is its capacity to simultaneously integrate multiple criteria, including environmental, structural and operational factors. Several recent studies underscore these benefits. Tao *et al.* (2024) demonstrated that a genetic algorithm could optimize seawall cross-sections to halve wave overtopping with only a marginal increase in cost [10]. Similarly, Ajtayné Károlyfi and Szép (2023) observed that parametric BIM frameworks facilitate rapid assessment of embodied environmental impact, providing designers with immediate feedback on how each geometric tweak changes a project's sustainability metrics [8]. Together, these findings confirm that computational design workflows often lead to better results in cost, carbon emission or functionality. Even with these developments, the maritime sector has often been slower to adopt parametric or BIM methods. Ferry quays, breakwaters and pier foundations still commonly use older, standard engineering approaches. This can cause overly heavy designs and missed chances to improve habitats or make the structures more flexible once they are built [3]. However, ports worldwide now face increasing pressures from the need to accommodate higher shipping volumes, as well as from stringent emission and environmental protection regulations. In Norway, the planned transition to electric ferries mandates the modernization of quay infrastructure, requiring minimized rework, accelerated project delivery and resilience under evolving climate conditions. The Norwegian ferry terminal case study analyzed here demonstrates how parametric design can simultaneously improve structural efficiency, reduce resource use and yield environmental benefits.

1.3. Research gap

Despite the extensive use of parametric approaches in architectural design, applications of such methods in maritime infrastructure – particularly for modernizing ferry terminals – remain relatively uncommon, which creates a knowledge gap in both academic research and practical engineering [2–4, 8, 10]. Although some studies have demonstrated the potential of advanced modeling tools, most have focused on specific elements (e.g. seawall cross-sections or steel-intensive solutions) rather than on holistically integrating parametric design, building information modeling and real-time data feedback. To address this gap, the present study develops and applies a parametric methodology for sustainable marine infrastructure, combining Grasshopper, Tekla Structures and SOFiSTiK in a Norwegian ferry terminal context. Through this case, the paper offers a more comprehensive workflow than is typically documented in maritime practice and lays out a replicable framework for bridging parametric design with digital twin creation. In particular, it builds upon and extends previous work by the authors [11] to validate the proposed approach in a real-world modernization scenario. The results highlight how parametric modeling can streamline design iterations, reduce material consumption and lower carbon emissions – contributing to the growing body of knowledge on resilient and eco-friendly waterfront development.

2. CASE STUDY: NORWEGIAN FERRY QUAY

2.1. Background

Norway relies substantially on sea transport due to its extensive coastline and numerous fjords. Around 150 ferry routes connect important roads. Many ferry terminals in Norway are old and face problems such as aging structures, increasing numbers of vehicles, and new "green" ferries that need modern facilities. Designing these terminals is challenging because they must withstand heavy vehicle loads, ferry impacts, wave forces and seawater corrosion. Traditional methods can be slow and include many repeated steps, requiring close teamwork between structural and geotechnical engineers. As projects get more complex, digital methods like parametric modeling become very important.

2.2. Methodology

The case study focused on the application of parametric modeling in designing a sustainable ferry terminal in Norway. The primary objectives were to accommodate heavy ferry loads, address site-specific geotechnical constraints and achieve ambitious sustainability targets. Parametric modeling enables a digital model to be controlled by adjustable parameters – such as platform dimensions, pile spacing and construction materials – so that any change in a parameter automatically updates the entire design. This capability allows for rapid testing of numerous configurations without time-consuming manual redrafting. All essential data for the model originated from the project's design-basis documentation, including ferry dimensions, geotechnical strata and performance criteria, thereby ensuring that every design variant generated in Grasshopper complied with real-world constraints.

To optimize the quay structure and foundations, the project implemented a fully digital, parametric workflow integrating three closely connected tools (Table 1). Rhinoceros 3D with Grasshopper enabled automatic updates of the 3D model whenever parameters such as pile spacing, slab thickness or deck geometry were adjusted. This approach significantly streamlined the iteration process as compared with conventional drafting methods. Tekla Structures served as the central BIM environment, capturing geometry, material properties and reinforcement layouts while providing real-time synchronization with ongoing model changes. Meanwhile, SOFiSTiK performed structural analysis for each variant, including stability checks, stress calculations and deformation assessments under dynamic ferry impacts [7, 11]. Any change made in Grasshopper – such as altering steel pile diameter from 800 mm to 600 mm or modifying slab thickness within a 500–1100 mm range – instantly triggered regeneration of both the 3D geometry and the updated finite element model. The integration of these tools ensured seamless and dynamic workflow. Grasshopper was directly linked to Tekla via a live connection, so every adjustment in design parameters was immediately reflected in the BIM model. Structural elements – including piles, concrete slabs, reinforcements and docking equipment – were all updated in real time. Concurrently, Grasshopper generated analysis models in SOFiSTiK, accurately representing pile foundations anchored in bedrock (see Fig. 3). The complete model was exported in IFC format, facilitating data sharing among stakeholders, improving communication, and reducing potential conflicts early in the design phase. This continuous feedback loop enabled the design team to evaluate configurations not only against structural requirements (e.g. Eurocode deflection limits), but also in terms of material usage, construction cost and approximate carbon footprint, using standard emission factors.

Table 1
Main digital tools

Tool	Role in the project
Rhinoceros + Grasshopper	Parametric modeling of the quay, rapid generation of design variants, real-time feedback.
Tekla Structures (BIM)	Detailed 3D modeling, integration of parametric elements, central data repository.
SOFiSTiK (FEA)	Structural analysis and optimization of the quay under static and dynamic loads [7, 11].

Figure 2 presents a conceptual overview of the parametric design process, illustrating how parameter input, geometry generation, multi-objective optimization, BIM integration and digital twin creation are connected. The iterative nature of parametric modeling allowed for quick testing of alternative layouts and pile arrangements. For example, more densely spaced piles at 8 m intervals could compensate for smaller diameters, while a sparser 12 m grid was feasible if the diameter remained at 800 mm. These real-time trade-offs were easily visualized, supporting data-driven decisions that balance geotechnical conditions, docking loads and sustainability goals. A key project objective was to optimize the foundation layout, limiting excessive piling and minimizing underwater disturbance. Previous research shows that significant performance gains can be achieved in parametric seawall cross-sections with minimal cost increases [9, 10]. In this project, variables such as pile spacing, slab thickness and foundation arrangement were iteratively refined in Grasshopper, with each variant undergoing structural checks in SOFiSTiK. Systematic comparison allowed the team to converge on a final configuration that required fewer piles than conventional approaches, with pile positions strategically defined by load demand (see Fig. 4). This reduced both construction expenses and environmental impact. Throughout the process, material volumes (steel and concrete) and design-hour metrics were tracked, with in-house benchmarks from previous quay projects helping to gauge efficiency gains. This multi-criteria approach demonstrated that parametric modeling could ensure structural safety, lower embodied carbon and shorten design timelines. During these iterations, the BIM model in Tekla Structures was continuously updated to reflect all changes, facilitating coordination among structural, mechanical and electrical disciplines. By the end of the design phase, the team was confident in the solution's accuracy and durability. As a result of this methodology, a highly detailed digital twin of the ferry terminal was established, serving both construction and future

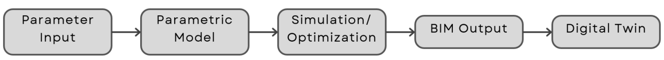


Fig. 2. Conceptual workflow of a parametric design process, from parameter input through geometry generation and optimization, to BIM integration and digital twin deployment

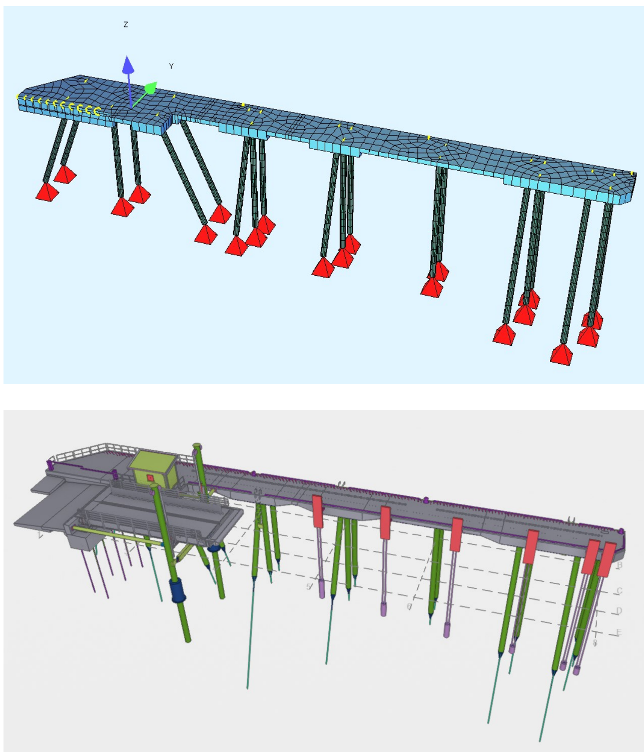
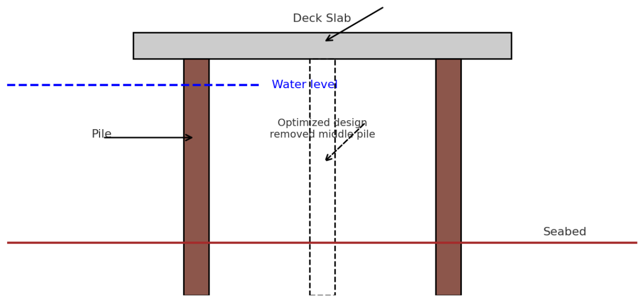


Fig. 3. Upper image: structural analysis model created in SOFiSTiK used for load and deformation evaluation; Lower image: parametric geometry model of the ferry quay structure



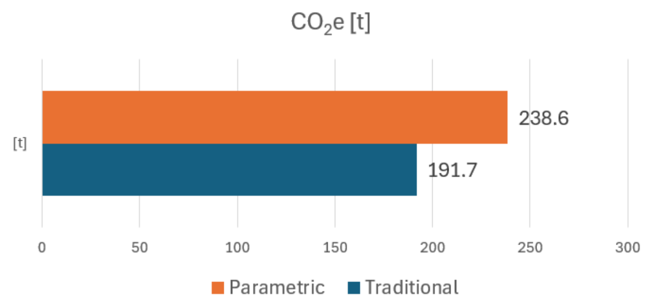


Fig. 4. Upper image: scheme of the optimized quay foundation showing efficient pile layout and reduced material usage while maintaining safety; Lower image: sustainability impact – differences in carbon emission

operational management needs. Later sections discuss how this integrated approach led to tangible reductions: in pile counts (~ 10%), concrete consumption (~ 12%), and overall project timeline (~ 25%) as compared with conventional engineering workflows, confirming the wider value of parametric design in sustainable marine infrastructure.

2.3. Mathematical modeling in the parametric workflow

The structural behavior of the quay foundation elements (piles, beams, slab) under the loads applied is represented using the finite element method (FEM). In this parametric approach, the global equilibrium of the structure is described by the stiffness matrix equation (1):

$$[K]\{u\} = \{F\}, \tag{1}$$

where K is the global stiffness matrix, u is the displacement vector, and F is the external load vector [12]. Solving this matrix equation provides the structural displacements and internal forces, essential for verifying limit-state criteria as per Eurocode. Structural design verification follows Eurocode rules [13–15]. For the ultimate limit state (ULS), structural safety is confirmed by ensuring that the design effects do not exceed resistances (2):

$$M_{Ed} \le M_{Rd} \wedge N_{Ed} \le N_{Rd}\,. \tag{2}$$

For the serviceability limit state (SLS), deflections must remain within permissible limits (3):

$$\delta_{\max} \le \delta_{\text{allowable}}\,. \tag{3}$$

Typically, allowable deflections are governed by ratios recommended in EN 1990 [13], often between length divided by 250 or 300. The parametric workflow incorporates automated optimization pseudo-code loops, as an example:

for each variant in design_space:
  update_model(*pile_spacing = variant*)
  results = run_FEA()
  compute M_Ed, N_Ed, δ_max from results
  check_limits = (*M_Ed <= M_Rd*) *AND* (*N_Ed <= N_Rd*) *AND* (*δ_max <= δ_allowable*)
  if check_limits:
    store(*metric* = { *material_volume, δ_max, variant*})
  select_best = variant with minimum material or deflection among stored

The algorithm systematically evaluates different design variants, recalculates equilibrium, performs Eurocode checks (ULS and SLS), and records performance metrics, allowing for rapid convergence to optimal designs.

2.4. Analysis of results

The analyzed ferry terminal consisted of a reinforced concrete slab supported by steel piles directly fixed into the bedrock. The platform was designed to accommodate typical ferry loads and provided two-way vehicle traffic. The slab thickness varied between 500 mm and 1100 mm in critical areas, ensuring adequate strength and minimal deformation. Steel tube piles filled with concrete provided structural stability and corrosion resistance. Elastomeric fenders were installed for safe docking.

Finite element analysis confirmed the piles effectively resisted dynamic loads during ferry docking, with manageable horizontal deflections (5–8 cm) and significant safety margins.

Geotechnical assessments showed variable soil conditions above the bedrock, mainly sand and clay with average strength parameters [16]. The bedrock was close to the surface, enabling direct fixation of piles into rock, simplifying the foundation design [11]. Parametric modeling allowed designers to explore and optimize numerous configurations at a considerably faster pace. Conventional methods often produce only a few manually drafted options and involve separate steps for geometry and analysis. By contrast, parametric design integrates these tasks in almost real time – updating geometry, documentation, and load evaluations automatically. Although it demands specialized expertise, higher initial effort and robust computing resources, this approach substantially improves design accuracy, reduces overengineering and shortens overall project timelines.

2.5. Numerical comparison

Numerical results comparing a conventional design with the proposed parametric design are presented below. Table 2 summarizes structural outcomes: number of piles, concrete volume, steel consumption and required design effort.

These results indicate notable improvements with the parametric design due to more design iterations and geometry control. The number of piles is reduced by ~ 10%, concrete volume by ~ 12%, and steel mass by ~ 27%. Design time is reduced by ~ 25%. Together, these savings demonstrate the material and efficiency gains of the parametric approach over the conventional method.

Table 2
Comparison of design outcomes

Parameter	Traditional	Parametric
Number of piles reduction [–]	20	18
Slab concrete volume – thickness reduction [m^3]	344.3	302.42
Steel mass – pile pipes diameter reduction [t]	69.47	50.52
Design time – overall [h]	400	300

2.6. Sustainability impact

Sustainability of the optimized quay design was assessed based on life-cycle environmental performance, focusing on embodied carbon associated with material use. As marine infrastructure relies heavily on resource-intensive materials, particularly concrete and steel, minimizing their use is essential for sustainable development. Here, the embodied CO_2 emissions were calculated following relevant standards and codes [17, 18]:

$$CO_2e = V_c * EF_c + M_s * EF_s\,, \tag{4}$$

where V_c – total volume of concrete (m^2), M_s – mass of steel (t), EF_c, EF_s – emission factors for concrete (kg CO_2e/m^2) and steel (kg CO_2e/t), respectively. The conventional design produced approximately 238.6 tCO_2e, while the parametric design yielded about 191.7 tCO_2e – representing a 20% reduction in embodied carbon (Fig. 4). This significant decrease is consistent with recent studies, which demonstrate that digitally optimized and steel-intensive solutions can reduce life-cycle carbon as compared with conventional approaches [8]. Similar trends are observed globally, where ports are adopting digital methods, innovative materials and nature-based solutions to achieve aggressive decarbonization targets [19]. For instance, recent case studies report 8–15% reductions in energy use following process digitalization, and some large European ports have documented up to a 67% reduction in CO_2 emissions within just a few years [20, 21].

2.7. Summary and recommendations

The ferry terminal outcomes confirm that parametric design substantially reduces resource consumption (~ 10% fewer piles) and lowers embodied carbon (~ 20% cut). Such findings indicate that adopting parametric tools (e.g. Grasshopper, Tekla, SOFiSTiK) in marine infrastructure can deliver significant benefits in cost, schedule and sustainability.

3. DISCUSSION

3.1. Improvements in design and construction efficiency

The adoption of parametric modeling and digital workflows brought several clear improvements to the ferry terminal project. As shown in Table 3, first and foremost was the speed and number of design iterations possible. Using traditional methods, exploring even a handful of different structural layouts could take weeks of drafting and calculation. In this project, however, the team was able to test dozens of configurations in a fraction of that time, thanks to automation. As noted by Ajtayné Károlyfi and Szép (2023), manual creation and evaluation of design alternatives is very time-consuming, whereas "parametric design can serve as an effective tool" to develop and analyze many options rapidly [8]. Rapid iteration also allowed incorporating feedback from stakeholders in almost real time. If the port authorities required a design modification (e.g. increased clearance for vehicles), the parametric model could be promptly updated, allowing a revised solution to be produced within hours rather than days. Secondly, the parametric approach led to an optimized structural design with tangible material savings. By using computation to balance the load distribution, the design minimized over-engineering. In conventional designs, engineers

Table 3
Key improvements from parametric digital design (as observed in the Ferry Quay Project)

Aspect	Conventional approach	Parametric digital approach
Design iterations	Limited number of options due to time-consuming manual re-design. Potential 2–3 alternatives.	Rapid generation of dozens of alternatives [8]. Enables thorough exploration of the design space before finalizing.
Structural efficiency	Frequent over-engineering for safety; surplus materials in some elements.	Optimization of member dimensions and layout; material use restricted to what is strictly necessary [10]. No compromise on safety, yet reduced waste.
Error reduction	Separate models/drawings can lead to inconsistencies and human errors.	A single, integrated model for design and documentation – ensures consistency and minimizes errors [8].
Design coordination	Sequential workflow, risk of late clashes or design changes (costly).	Concurrent coordination in BIM; issues resolved digitally at early stages. Smooth collaboration across disciplines.
Project cost & time	Longer design phase, more uncertainty; potential for rework during construction.	Shorter design cycle; optimized design reduces material/construction costs. Fewer onsite changes help keep the project on schedule and within budget [4].
Sustainability	Environmental aspects considered later (if at all); no full optimization.	Sustainability integrated from the outset (e.g. minimizing material use, considering future energy consumption). More climate-resilient and low-carbon design [2].

often apply large safety factors and standard spacings "just in case", which can inadvertently waste material. Here, the optimization ensured materials were used only where needed.

Notably, the final design's concrete volume was reduced as compared with a similar terminal designed without parametric tools (the design avoided redundant members by fine-tuning the structural grid). This contributes to sustainability by reducing embodied carbon in construction. A broad literature review found that parametric design in the built environment tends to evolve towards climate-responsive and resource-efficient solutions [2]. In this case, the terminal's foundation and frame were refined to use the minimum acceptable quantities of concrete and steel while meeting Eurocode criteria. In a related coastal infrastructure project, parametric optimization achieved a ~ 28% improvement in an objective function (combining performance and cost) as compared with the original design [10]. Such improvements underscore how parametric design can increase structural efficiency beyond what manual methods typically attain. Thirdly, the integration of BIM and parametric tools improved accuracy and reduced errors in the design documentation. Because the Grasshopper model fed directly into Tekla BIM, there was little need for re-modeling or translating drawings, which is often where human errors occur. The approach ensured consistency – the structural plans and schedules were all derived from the same coordinated model. This dramatically reduces the chance of discrepancies (for example, a column location mismatch between architectural and structural drawings, a common error in fragmented workflows). As a result, the construction team can trust that the plans are correct, preventing costly rework in the field. Károlyfi and Szép highlight that ensuring "intelligent computer support that decreases possible sources of errors" is a major goal of integrating parametric design with BIM [8]. The project described herein achieved that by maintaining one data-rich model through all the stages. Additionally, clash detection was performed on the BIM model to catch any interdisciplinary conflicts early on. Very few clashes were found, confirming efficacy of the coordinated design. Another important benefit was its cost-effectiveness. Although innovative, the parametric process it is not merely a technological experiment; rather, it delivers tangible financial benefits by optimizing resource use and minimizing project delays. Material savings directly translate to cost savings. Moreover, the time saved in design (due to faster iterations and fewer coordination errors) compresses the project schedule, which can lower overhead costs. Moreover, the robust design process mitigates risks that often lead to budget overruns. For example, by thoroughly exploring the design space, the team ensured there were no major design changes later (change orders during construction can be very expensive). Also, potential problems were solved digitally in advance. A case in point is the foundation: the parametric model tested the foundation against various load cases, so the risk of encountering an under-designed foundation (and having to retrofit it later) was virtually eliminated. Research on digital twins and AI in maritime sectors notes that data-driven design can improve efficiency and reduce operational costs [4, 22]. While that reference deals more with shipping, the principle applied here in construction – better upfront design leads to fewer costly issues down the line.

Beyond the design and build phase, an unexpected advantage of the digital approach is its impact on future operations and maintenance of the terminal. The rich BIM model prepared the ground for creating a digital twin of the facility that can be used by operators. In fact, the project team delivered the as-built BIM model (updated during construction to reflect any minor changes) to the port authority as a starting point for an operational digital twin. This model can be linked with sensor data and maintenance databases to support the terminal's management over its lifespan (Fig. 5). Compared to traditional ports where asset information is fragmented, a BIM-driven asset management approach offers substantial improvements. It enables real-time monitoring of structural conditions, predictive maintenance and efficient asset management. For example, if the ferry terminal has strain gauges or settlement markers, their readings can be fed into the digital twin to continuously assess structural health. This facilitates predictive maintenance, addressing issues before they escalate. In contrast, conventional maintenance might be purely periodic or reactive. By utilizing continuous data, a digital twin enables more proactive management, as presented in Table 4.

Table 4
Comparison of traditional asset management and digital twin-based management for port infrastructure (based on [4])

Criteria	Traditional asset management	Digital twin-based management
Cost efficiency	High costs because problems are fixed after they happen, which is often expensive.	Reduced costs thanks to predictive maintenance (fixing issues before they fail), which limits emergency repairs.
Real-time adaptability	Low adaptability; depends on set schedules for inspections and maintenance.	High adaptability with continuous monitoring of the infrastructure, allowing changes to maintenance plans in real time.
Data integration	Data are spread out in different places or departments (silos).	Central data integration using BIM/GIS and IoT sensors, giving a complete view in one system.
Predictive maintenance	Scheduled preventive maintenance; inability to predict failures in advance.	Predictive maintenance driven by AI, allowing proactive management (issues to be spotted early with sensor data).
Scalability	Hard to expand to many locations; each terminal is managed separately.	Easy to expand to many terminals (the same digital twin system can be copied for other assets).
Sustainability impact	Few environmental measures in operation and maintenance; may waste energy.	Supports energy savings and less material waste by improving how each asset is used (for example, controlling energy use).

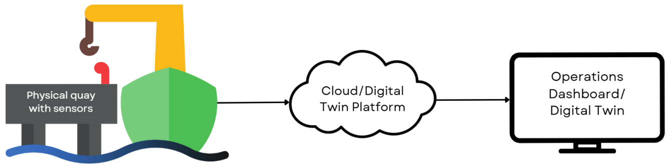


Fig. 5. Digital twin data ecosystem: real-time sensor data flow into a cloud-based platform and monitoring dashboard, enabling predictive maintenance and efficient operation

3.2. Toward sustainable asset management (digital twin)

The advantages of digital changes do not end when construction finishes. They continue when the terminal is in operation.

By using the BIM model as a digital twin, the operators can manage their assets in a smarter and more eco-friendly way. In many ports, asset management is often split between different departments, and maintenance is mostly reactive (fixing problems after they happen). Connecting BIM with maintenance systems helped to overcome these issues.

Using a digital twin has many benefits for the environment and for efficiency. For example, instead of waiting for a ferry ramp to break (and then fixing it), sensors can warn the team that the ramp is likely to fail soon. They are able to plan repairs before a more serious issue arises because of this proactive strategy. This approach lowers operational costs and minimizes the likelihood of unplanned service interruptions. The old approach might use fixed maintenance plans or rely on sight checks, which can miss smaller warning signs. With a digital twin, data is collected all the time. Kaklis *et al*. (2023) say that in shipping, a digital twin can greatly improve efficiency and help follow rules by using data to make decisions [1]. The same idea works for port infrastructure: for example, energy use (lighting, air conditioning, etc.) can be checked and improved through the digital model. It is also important to note that future changes or unknowns can be managed better with these digital systems. Ports and terminals need to adjust to changes in climate, rising sea levels, and shifts in how the terminal is used. A static design cannot account for all future contingencies, whereas a digital twin allows for continuous data integration, facilitating well-informed decisions under uncertainty. Methods for making decisions under "deep uncertainty" are being used more often with digital tools. For example, if sea levels rise faster than expected, the digital model can help test potential solutions, such as raising a seawall or changing the docks. This type of planning renders the infrastructure stronger and more ready for challenges. In summary, the use of parametric design with a digital twin enhances the value of the structure not only during construction but also over the course of its lifetime.

4. CONCLUSIONS

This study applied a holistic parametric design workflow – integrating Grasshopper for geometry creation, Tekla Structures for BIM coordination, and SOFiSTiK for structural analysis – to modernize a ferry terminal in Norway under demanding load and sustainability requirements. The results demonstrate that, by systematically testing multiple configurations, the project team reduced the number of foundation piles by approximately 10%, concrete volume by around 12%, and embodied carbon by about 20% as compared with a conventional baseline. These outcomes confirm that parametric modeling can significantly enhance both structural and environmental performance, fulfilling the project's original objectives of accommodating heavy ferry loads and improving sustainability.

The findings also validate the efficiency and versatility of the parametric approach, corroborating prior research [2, 3, 8, 10], while extending those insights to a comprehensive ferry terminal retrofit. This indicates that a complete digital workflow – encompassing automated geometry updates, real-time structural verification and emission tracking – can be successfully implemented for complex maritime infrastructure projects.

However, the study has several limitations. The geotechnical assumptions were somewhat simplified, relying on averaged soil parameters and idealized bedrock profiles; future work could benefit from incorporating more detailed geotechnical data or dynamic soil-structure interaction models. Material behavior was analyzed under standard design assumptions without advanced nonlinear modeling or experimental validation, suggesting a need for further laboratory testing or in-situ monitoring. In addition, the operational data used were limited to design-basis load cases, providing only engineering estimates for scenarios such as actual ferry docking conditions, future increases in traffic, or extreme weather events, rather than real-time feedback from the structure itself.

Directions for future research include broadening the applicability of the presented methodology to other types of maritime infrastructure, such as piers, breakwaters or offshore platforms, and adapting it to diverse site-specific constraints. The use of advanced algorithmic optimization, for example with genetic algorithms or other solvers within Grasshopper, could automate parameter selection and enable deeper, multi-objective optimization – balancing cost, carbon footprint and structural performance. Real-time digital twin development, through integration of IoT sensor networks into the BIM environment, could allow for live, reactive modeling that would enhance predictive maintenance and operational verification of parametric predictions throughout the structure's lifespan. Additionally, advancing parametric scripting to automate code compliance checks, reinforcement detailing, and geotechnical verifications within Grasshopper could further streamline iterative design processes, minimizing manual work and potential human error.

In summary, the findings from this project reinforce the substantial potential of parametric design in shaping a more sustainable and efficient future for maritime infrastructure. As the sector adapts to green ferry technologies, stricter emissions regulations and an increasingly digitized construction environment, this workflow offers a replicable and practical example of how parametric modeling can deliver measurable improvements in both project delivery and long-term asset management.

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