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Article

Navigating the Future: Developing Smart Fairways for Enhanced Maritime Safety and Efficiency

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Abstract: The maritime industry is rapidly evolving with digital technologies, aiming to enhance efficiency, safety, and sustainability. Recent interest has focused on autonomous vessels and the digitalization of ports, yet fairway development has lagged behind. To effectively support the growing digital and autonomous marine traffic, it is essential that fairways are also upgraded and modernized. Addressing this need, this study examines key elements of Smart Fairways, with a particular focus on Finland's maritime infrastructure. This research contributes to the development of the Smart Fairways concept by identifying five foundational and ten advanced Smart Fairway service elements. The main finding highlights the foundational role of communication systems in the development of more advanced Smart Fairway services such as Enhanced Vessel Traffic Service, Port just-in-time Service, Remote Pilotage, and Digital Twin of the Physical Fairway.

Keywords: fairway; smart fairway; digitalization; communication; infrastructure; remote pilotage; VTS

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1. Introduction

> *"While listening to the visions on how autonomous vessels are sailing at our seas, I started thinking whether all these fancy ships would navigate towards the ports using the old fairway infrastructure with all those red and green buoys and other sea markings. Shouldn't also the future fairways be smarter?"* (Pilotage director)

About a decade ago, maritime communication for ships at sea was constrained, resorting to analogue radio or expensive satellite connections for only crucial data exchanges [1]. However, the last ten years have witnessed a transformation in maritime digitalization. The enhanced affordability and accessibility of satellite connectivity now permit ships to remain in constant communication with onshore operations [2]. This advancement, coupled with other progress in digital technologies and maritime regulation, has led to the advent of the first autonomous ships traversing global waters [3]. While these vessels currently still rely on onboard crews for safe navigation, there is a growing expectation that, in the foreseeable future, their reliability will reach a level where remote monitoring alone would suffice [4]. Similar advancement of digitalization is taking place in ports which are adopting new Industry 4.0 solutions and smart applications [5,6].

Still, vessels approaching the ports, autonomously or manually, navigate along traditional fairways. Typically, fairway infrastructure includes static waterway beacons with lateral and leading marks. Navigation is further assisted by pilotage, towage, icebreaking, and Vessel Traffic Service (VTS) to help safe navigation.

While the existing literature often concentrates on specific infrastructure elements or services, it tends to overlook the fairway as an integrated whole. To bridge this gap, our research is steered by a fundamental inquiry: *What are the key elements that constitute Smart Fairways, and how are these elements interrelated?* The urgency and importance of this research are highlighted by the worldwide movement towards safe, sustainable, and efficient transportation systems, facilitated by digitalization. This study identifies the key elements that constitute Smart Fairways, which are tailored to the unique maritime context of Finland, and analyzes the interdependencies of the elements. Given the country's substantial reliance on seaborne freight and its distinctive geographical features, including expansive archipelagos and shallow territorial waters, modern fairways are particularly vital for Finland [7].

We utilize the Delphi method [8] to leverage the collective expertise of a diverse panel, comprising experts from the R&D project 'S4V Fairway' [9]: maritime professionals, technologists, researchers, and authorities. We build on their insights to form a unified framework of a technologically advanced future Smart fairway. Such a framework will not only guide the technological and infrastructural development of maritime channels but will also provide valuable insights for shaping policy decisions and regulatory frameworks for traffic at seas.

This article contributes to the discourse on digitalization in general and smart technologies in the maritime sector in particular, i.e., on the evolution of potentially useful technologies and services for fairways. Rather than looking at separate technologies in isolation, the article emphasizes the synergy between technologies or elements that collectively form Smart Fairways. Furthermore, the study evidences the need for collaborative efforts and integrated solutions in realizing a more advanced, secure, and efficient maritime future.

The article unfolds across five chapters, each serving a distinct purpose. Section 1 introduces the maritime industry's current landscape and the concept of Smart Fairways. Section 2 provides a literature review on fairway development and digital technology in maritime operations. Section 3 outlines the research methodology, detailing the data collection and analysis techniques, and discusses the validity of the methods used. Section 4 presents the central findings of the study, highlighting communication systems as a critical element for Smart Fairway development. Finally, Section 5 discusses the implications and relevance of these findings and acknowledges the limitations of the study, offering avenues for future research.

2. Literature

A fairway is defined as the navigable part of waterway [10] or a channel in a body of water that is safe for the passage of ships [11]. It is essentially a designated path or corridor through water that is free of hazards such as shallow areas, reefs, or other obstacles that could impede safe navigation. The fairway ensures that vessels can travel safely to and from ports or through specific areas of a sea, lake, or river.

Fairways are often marked by navigational aids such as buoys, beacons, and lights, to guide ships [12]. These aids help mariners to stay within the safe boundaries of the channel. The precise dimensions and characteristics of a fairway can vary depending on the location, size and type of vessels expected to use it, and local geographical features. For example, in the design of fairways, the width required for safe navigation is an important consideration [13]. Ship movements in a fairway are recognized by Vessel Traffic Service (VTS), and the static and dynamic information of AIS data is collected for vessel traffic management [14,15]. In the design of new fairways and the redesign of existing fairways, the collision, allision and grounding probability, as well as vessel traffic, are considered [16,17]. The local pilots knowing local fairways, traffic patterns and weather conditions can provide guidance and relevant advice to avoid the hazards of navigating in unfamiliar or complex environments [18,19]. The potential risks concern not only human lives but also the environment. Thus, proper fairway management improves environmental sustainability, for example, by helping to reduce the maritime traffic-induced shore erosion in protected coastal fairways and preserving natural populations and habitats [20]. Overall, the design of a fairway considers various factors to ensure safe navigation for different types of vessels in specific locations [16].

There are only a few articles mentioning 'Smart Fairways' [7,21–26] or 'intelligent fairways' [7,27–31]. While these studies explore various aspects related to fairways, they do not provide a precise definition of a 'Smart Fairway'. However, they suggest that future fairways will utilize digital technologies and services to facilitate the safe navigation for all vessel types, from non-automated to fully autonomous [7]. These studies, instead, focus on different topics. These include risk management for smart shipping services [29,31]; network connectivity for communications ranging from low-priority entertainment to high-priority safety critical [22,32–34]; simulation of local wind conditions [23]; platforms [7]; and data-driven decision making in maritime transport and logistics [24]. They also analyze and develop methods for safeguarding systems against cyber threats [21,25,26,28]. Moreover, the aids to navigation are being modernized with the help of real-time data analytics and adaptive signaling systems; new and improved means of communication and weather-responsive navigational marks [12] are being developed. Also, advanced digital sea charts [35] and digital twins of fairways are in development [36]. Traditional VTS is being augmented with dynamic risk assessments and decision-making systems [37]. Initial trials of remote pilotage have begun, allowing pilots to offer navigation guidance without physically boarding the ships—for example, [27] discusses the potential of remote pilotage aided with emerging technologies as an alternative to pilotage exemptions granted to experienced captains. Additionally, methods are being developed to assess the environmental impact of marine traffic [38].

In summary, the literature emphasizes the significant role of digitalization in enhancing maritime operations, logistics capabilities, sustainability, and safety. The integration of modern information technologies and digital transformation has the potential to bring about substantial improvements in the maritime sector. Various approaches encompassing new technologies, safety audits, risk assessment methodologies, policy effectiveness, and data-driven solutions are being developed. These multifaceted efforts aim to ensure the safety, efficiency, and sustainability of maritime fairways. However, the focus is typically on individual infrastructure element or service, not the fairway as a whole. Therefore, this study aims to fill the gap in the literature by first defining what a Smart Fairway is and secondly by identifying a suite of fairway elements that create Smart Fairways, specifically tailored for Finnish coastal areas.

3. Method

We gather our empirical data using the Delphi method [8]. It involves a combination of workshops, questionnaires, interviews, and feedback sessions. Participants include a diverse range of stakeholders like regulating authorities, ICT and technology providers, shipping companies, fairway service providers and maritime educators and researchers from the S4V Fairway consortium. Additional experts were interviewed to broaden the scope, covering areas such as safety investigations, emergency response and naval operations.

The Delphi method is a prominent technique for technological forecasting and managerial decision making [39–41] initially developed for military technology forecasting and now also extensively used in business and social science for eliciting expert opinions (e.g., on port digitalization [42,43]). It aims to achieve a reliable consensus among experts, forming a solid basis for future action, though it may limit the exploration of innovative ideas [44].

We selected the Delphi method as our research approach over other methodologies due to its unique suitability for exploring emerging and complex topics, like Smart Fairways, which lack extensive prior research. The Delphi method is particularly adept at synthesizing expert opinions and achieving consensus in areas where empirical data may be sparse or evolving [44]. Its iterative approach allows for the refinement of ideas and opinions, fostering a deeper understanding among experts. This approach also mitigates the influence of dominant individuals, striving for a balanced representation of views [39]. These attributes make the Delphi method an ideal choice for our study, aimed at navigating the nuanced and forward-looking field of Smart Fairways.

Typically, Delphi data are collected from an expert group using several survey rounds, but other data collection methods, such as face-to-face workshops and interviews, can also be utilized as part of the Delphi method [40]. According to [45] and [41], the researchers first design the first data collection and select an appropriate group of experts who are qualified to answer the questions. The researchers then collect and evaluate the responses. Following this, they carry out a subsequent data collection phase informed by the initial responses, prompting participants to adjust their initial answers and/or respond to additional questions informed by collective feedback from the initial phase. This cycle is repeated by the researchers until a satisfactory level of agreement is achieved among the respondents. Our research design followed this generic process and consisted of four data collection phases; first was a survey, the second was an interview round, the third was an online workshop, and the fourth was again a survey. This research design enabled us to effectively combine multiple data collection methods, facilitating a comprehensive gathering of expert insights to reach a consensus.

The study was structured into four phases (see also Table 1):

1. Initial survey: The first stage of the study involved a Webropol questionnaire completed by 33 experts participating in a Business Finland-funded S4V Fairway project. The survey aimed to capture stakeholders' views on various aspects of the Smart Fairway, such as its operational timeline, primary users, and areas needing improvement. The survey also sought opinions on the expected benefits, target user groups, and service requirements of the Smart Fairway. Analyzed with Nvivo software, the collected data were subsequently presented and discussed at a consortium workshop, focusing on the survey findings and their potential implications;
2. In-depth Interviews of 23 participants were conducted to gain a deeper understanding of the current fairway system, its services, and related maritime transport developments. The interviews were conducted online over a two-year period, focusing on gathering diverse perspectives on the increased use of automation in maritime traffic, its impacts, and the corresponding needs for infrastructure and fairway services. Interviews were recorded and transcribed, with an option for respondents to decline recording. The data comprised detailed interview notes and recordings. Using Nvivo software, the first author coded the transcripts, summarizing the data, including interview quotes, in a document that was reviewed and approved by one of the co-authors. The main results were presented and discussed at a consortium workshop;
3. In the Delphi Workshop attended by 25 participants, a list of elements and categories, initially prepared by the Finnish Transport and Communications Agency, was reviewed and refined. This initial compilation was formulated by expanding upon existing fairway infrastructure and services, complemented by insights gleaned from earlier phases of the study. Additionally, its development was aligned with the strategic objectives of the Finnish Ministry of Transport and Communications [46], particularly focusing on enhancing infrastructure and services by digitalization in fairway systems. The interactive 2 h online workshop used a digital board to facilitate discussions, during which the participants assessed, modified, and expanded the list, focusing on the significance of each element and the challenges associated with them. The final list of Smart Fairway elements and their categories was compiled by the first author. It was emailed to the Delphi participants for feedback; small adjustments were made based on the feedback;
4. Survey on element characteristics: Thereafter, the researchers tailored the traditional Business Model Canvas [47] to better suit data collection about Fairway elements. The modified Canvas included questions on content, customer groups, delivery channels, partners, readiness level, financing, and requirements from the other elements (see Appendix A). The canvases for key elements were sent to the responsible parties, and

the researchers assisted them in completing the canvas. For example, the Finnish Meteorological Institute was responsible for filling out the canvases related to Weather Information elements. In contrast, the Finnish Transport and Communications Agency and the Finnish Transport Infrastructure Agency collaboratively completed the canvases for the Fairway Core Infrastructure elements. The collected data were presented and discussed at a public seminar. The authors of this article analyzed these canvases further to extract insights about the Fairway elements, especially their requirements from the other elements. Based on the results, the first author produced the first version of the paper and the related Figure 1, which were improved and validated by the other authors.

Table 1. Number of organizations and informants in each phase. A more detailed description of interviewees is in Appendix B.

	PHASE 1 Initial Survey		**PHASE 2 Interviewees**		**PHASE 3 Delphi Workshop**		**PHASE 4 Survey on Elements**	
	Organizations	Persons	Organizations	Persons	Organizations	Persons	Organizations	Persons
Regulating authorities	0	0	1	3	2	8	2	6
Technology and ICT providers	5	12	4	5	3	3	1	2
Shipping companies	2	2	3	3	2	2		
Fairway service providers	1	3	2	4	3	4	3	4
Maritime research and training	6	15	4	6	5	7	2	3
Military and safety authorities	1	1	2	2	0	1		
Total	15	33	16	23	15	25	8	15

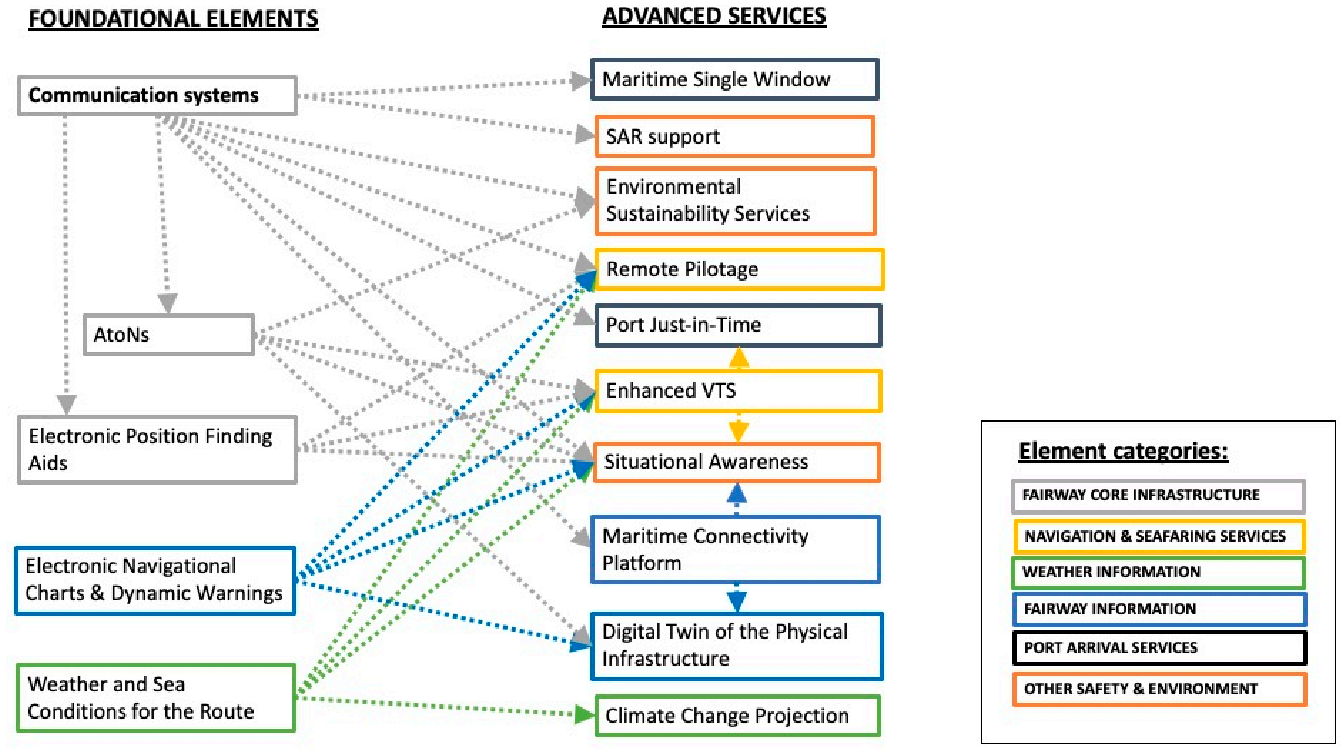

Figure 1. Smart Fairway elements and their interdependencies.

The Delphi method is not without its disadvantages, as highlighted by [48]. One such disadvantage is the potential limited expert input due to overly structured data collection. To mitigate this, our study incorporated in-depth interviews in the second round. This way, experts have more freedom to express their thoughts, thus enhancing the depth and diversity of the collected data. Another challenge is to ensure the relevance of the respondents' expertise to the study's topic. The respondents in our study are not only experts in their fields but also key stakeholders, some possessing decision-making authority regarding investments in various aspects of Smart Fairways. Hence, their insights are instrumental in strategically prioritizing development initiatives. The issue of self-rating of expertise was also considered against this backdrop: we did not ask for self-rating of expertise, because the respondents were selected and were known experts from organizations participating in an R&D project focused on Fairway. All in all, these designated experts can be expected to add credibility to the process. The last disadvantage of the Delphi method is that individual opinions can be influenced by the other experts: In a typical Delphi study, anonymity is maintained to prevent the influence of others' opinions. However, in our study, we waived respondent anonymization in the third online workshop round, because we believed more open and transparent discussion would enrich the overall quality of the data collected.

Validity

The trustworthiness of the study was advanced with multiple means. First, the researchers strive for transparency in reporting the research process [49] in multiple rounds. Second, both data collection and analysis benefited from investigator and informant triangulation [50]. Thirdly, the collaborative approach to the data analysis confirms the view built by researchers and brings a diversity of perspectives into the process [51].

The means of ensuring the validity of the inference drawn from the data are summarized in Table 2 [52].

Table 2. Validity of this study following [52].

Validity Criteria	**Explanation of Application in This Study**
Descriptive validity	The degree of accuracy of the collected data was ensured by recording the sessions and interviews. Where recording was not possible, detailed notes were taken. Notes from workshops were collaboratively created in Miro boards, and the summarized results were validated by the participants via email and shared between the researchers on the cloud with coding and bracketed comments.
Interpretive validity	To capture subjectivity in the informants' accounts, the researchers asked each informant about their background, position, and responsibilities in their organization. Interpretive validity was also improved by using several data collection methods to enhance the depth and diversity of the collected data.
Theoretical validity	To ensure that the concepts used to describe the phenomenon and the relationships between them are valid, the research included informants who are the most knowledgeable about the topic, but also represent different organizations and business areas. This way, it was possible to gain both breadth and depth of perspectives. Conventional qualitative content analysis was the primary analysis method, where coding categories are derived directly from the text data [53]. Coding frame (in Appendix C) was developed so that it met the requirements of unidimensionality, exclusiveness and exhaustiveness [54]. Data analysis proceeded from data reduction through data reorganization (coding) to data representation and conclusions [49].
External validity	Ensuring the external validity of the research findings means that the researchers acknowledge the special characteristics of the study context. We reflect the informants accounts and their descriptions against the contextual characteristics. The description of the context provided in the Introduction section gives the reader the possibility to evaluate generalizability to other contexts.
Evaluative validity	To improve the researchers' interpretations/evaluations, the research process included a discussion and debate between the researchers and informants exposing the inference to the examined phenomenon workshops and project seminars. In addition, this paper strives for describing the research process transparently.

4. Findings

4.1. Drivers and Definition of Smart Fairway

The study identified key trends through expert interviews and analysis of the literature. We highlight the main drivers for smarter fairways: (a) a trend towards increased digitalization in maritime transport, a wide spectrum of digital capabilities in vessels, ranging from none to fully autonomous; (b) increasingly inexperienced cargo ship seafarers, particularly in Nordic conditions; (c) increasing use of water areas for various recreational activities by individuals or groups, often with limited understanding on maritime traffic and experience on conditions; and (d) heightened environmental concerns leading to increased efforts to reduce emissions, wave erosion, and pollution, while also minimizing underwater noise and artificial light.

Against this backdrop, we derived a definition for Smart Fairway from expert opinions:

> *"Smart Fairway integrates information, new technologies, and automation to enhance traffic safety, efficiency, and to reduce environmental impacts."*

This implies the use of advanced, sensor-equipped maritime safety devices and better information and communication technology for improved traffic safety and efficiency [55]. Moreover, improved planning and optimization of routing can help in carbon footprint minimization, and vessels, for instance, can gather information on environmental effects en route.

In the foreseeable future, Smart Fairways should also support autonomous shipping, adapting to dynamic maritime conditions and traffic [46]. As the trials with autonomous vehicles [56] show, it does not suffice to automate vehicles only in relation to static road objects, but the autonomous vehicle must adapt dynamically to changing traffic by identifying and interacting with the other road users, moving objects, and adapting to changing weather and illumination conditions on roads. The experts pointed out that automated marine traffic will face similar requirements [57], but on a moving surface.

The respondents share the view that Smart Fairways classification should extended from present fairways, according to the physical and maintenance requirements:

> *"There will be several classes of Smart Fairways based on what levels of automation they support."*

There is an analogy to air traffic and runway classification [58,59], which provide different sets of navigation services, ranging from visual safety devices to an automated instrument landing system. Smarter fairways could eventually utilize and bundle additional key elements for improved efficiency, safety, and sustainability features.

Experts envision that a future Smart Fairway could cater also to a more diverse range of users, from merchant ships to leisure boats, and residents and recreational dwellers of summer cottages using the sea area. For the coexistence of vessels and seafarers with varying skills and technological capabilities on a Smart Fairway, experts suggest that enhanced situational awareness and communication are crucial. Some even suggested to separate traffic routes based on vessels' digital capabilities.

Hence, it would be practical to begin with safety-critical areas such as pilot entry/exit points, straits, shallow regions, fairway crossings, and harbors. Enhancing these parts of fairways will also improve activities such as Search and Rescue (SAR), customs, accident investigation and risk analysis.

4.2. The Identified Key Elements of Smart Fairway

The study identified the most crucial elements for safer and more efficient maritime traffic within the next 5–10 years. These elements were classified into a few categories:

A. Fairway Core Infrastructure elements enhance maritime safety, navigation accuracy, and operational efficiency through advanced technological integrations between communication systems, navigation aids and position finding and tracking. In maritime traffic, cyber security of integrated technical subsystems needs special attention.

   - Communication Systems will involve radios primarily for use in distress situations, communicating with Vessel Traffic Services (VTS) or Maritime Rescue Coordination Centers (MRCC) and between the vessels and seafarers. The use of advanced digital broadband systems—4G, 5G and satellite systems such as Iridium and Starlink—is expected to increase. VIRVE2, an advanced communication system for authorities and security operators, is integrated with the Global

  Maritime Distress and Safety System (GMDSS), which provides an internationally agreed-upon set of safety procedures, types of equipment, and communication protocols to enhance safety and facilitate the rescue of distressed vessels;
  - Aids to Navigation (AtoNs) will be equipped with advanced sensors for real-time monitoring of weather, traffic, and sea conditions; e.g., sea marks could also have capabilities for traffic control and can be connected to the power grid to share electricity. Their brightness will be adjusted to traffic conditions and visibility, and virtual AIS AtoNs will be used to alert mariners to new hazards, or to replace broken or moved physical AtoN's;
  - Electronic Position-Finding Aids will provide precise position data for electronic nautical charts. The current Global Navigation Satellite System (GNSS) is to be supplemented with VHF Data Exchange Ranging mode system (VDES R-mode). When there is a disruption to GNSS services onboard a ship, the VDES R-Mode system provides ranging measurements to an onboard navigation system so that the impact of the GNSS service outage on the ship's ability to navigate safely is minimized [60].

B. Fairway Information elements are geared towards digitizing and enhancing maritime navigation and safety through advanced digital platforms, creating digital twins of infrastructure, and improving electronic navigational charts and warning systems.
  - Maritime Connectivity Platform is providing the basic semantic standards and interoperability interface definitions for digital authentication service discovery and exchange of messages in maritime operations. This platform will facilitate secure and efficient digital operations in maritime contexts;
  - Digital Twin of the Physical Infrastructure: Future developments include creating digital real-time replicas of physical Aids to Navigation (AtoNs) and integrating high-resolution bathymetric data for key fairways and merchant routes. This transformation supports both automated navigation and remote shipping operations and includes comprehensive landscape data;
  - Electronic Navigational Chart and Dynamic Warnings. There will be an updated product specification introducing a machine-readable catalog system for Electronic Navigational Charts, simplifying updates and making the process more efficient. This includes digital delivery of navigational, meteorological, and safety warnings to ships, enhancing maritime safety and situational awareness.

C. Weather information elements focus on providing detailed, localized weather information and broader climate change projections to improve safety, navigation, and strategic planning in maritime operations.
  - Weather and Sea Conditions for the Route: This involves the use of advanced localized weather systems that utilize sensors in ports and on fairways. These systems integrate data from sensors and vessels en route to predict unexpected local weather conditions and traffic patterns, enhancing the safety and efficiency of maritime navigation;
  - Climate Change Projections provides maritime traffic entities, like shipping companies, with detailed climate change scenarios affecting seafaring conditions, including forecasted and observed changes in temperature, wind patterns, water levels, and ice conditions, for long-term planning and operational adjustments in the maritime industry.

D. Navigation and Seafaring Services enhance maritime navigation and operational efficiency through advanced VTS services, remote pilotage, icebreaking services for winter navigation, and improved tug services for vessel maneuvering.
  - Enhanced VTS Services could offer more advanced navigation assistance, including precise ship positioning and traffic management. The expansion of VTS to include private vessels like cruisers and yachts, along with multichannel announcements, aims to improve situational awareness for all seafarers;

- Remote Pilotage allows ships to be piloted remotely. It requires robust ship-shore communication, onboard automation, qualified masters, and approved ship equipment. Remote pilotage offers time savings and scheduling flexibility and is available for selected fairways;
- Icebreaking and Tugging Services assist in the sailing and maneuvering of vessels and keep waterways navigable and efficient during ice-covered conditions.

E. Port Arrival Services focus on optimizing port arrivals through efficient vessel berthing management and standardized maritime traffic notifications, enhancing the overall efficiency, safety, and security of port activities.

- Port Just-in-Time aims to enhance the real-time management of vessel berthing times and locations. It involves providing accurate Estimated Time of Arrival (ETA) and Departure (ETD) data to streamline coordination among various parties involved in port operations. The goal is to optimize routing, reduce wait times and expedite vessel turnaround;
- Maritime Single Window is a maritime traffic notification service, which will standardize territorial entry and port visit notifications. This standardization aids in various aspects of maritime and port operations, including border control, maritime search and rescue, oversight of hazardous material transport, collection of fairway dues, and monitoring of port safety and health.

F. Other Safety and Environment elements are improving maritime search and rescue operations, enhancing environmental sustainability through monitoring and data collection, and developing advanced tools for situational awareness for wider user groups.

- Search and Rescue (SAR) Support involves enhancing information exchange among Maritime Rescue Coordination Centers, first responders, emergency services, and authorities, thereby increasing the efficiency of SAR planning and missions;
- Environmental Sustainability Services includes deploying sensors on buoys and vessels to monitor and optimize emissions and erosion from maritime activities. It also encompasses crowdsourcing real-time data for eco-friendly routing and traffic timing, contributing to the reduction of the environmental impact of maritime operations;
- Situational Awareness involves the development of tools to aggregate and display relevant maritime data in a user-friendly format, potentially including predictive analytics for collision and hazard avoidance in regular traffic and on events at sea. The tools requirements will vary depending on the type of user (sailing boats, jet skiers, cottage owners, etc.) to ensure tailored and effective usage.

4.3. Dependencies and Priorities

It is essential to recognize the mutual reliance among the key Smart Fairway components. Consequently, the researchers conducted an analysis of the data pertaining to the requirements of each fairway element from other elements. Figure 1 summarizes the interconnectedness of different elements, highlighting the significance and complexities involved in the development of the Smart Fairway.

From this depiction, we can infer several insights: Firstly, the diagram illustrates that services shown on the right side are dependent on data and services from the five foundational elements on the left side, which include (1) Communication Systems, (2) AtoNs, (3) Electronic Position Finding Aids, (4) Electronic Navigational Chart and Dynamic Warnings, and (5) Weather and Sea Conditions for the Route. This suggests that the development and deployment of Smart Fairway elements must be carried out in a phased and systematic manner. Prioritizing the above-mentioned foundational elements is essential for laying a robust groundwork for the subsequent development of more sophisticated systems. This sequential approach ensures that the advanced elements of the Smart Fairway are built upon a tried, reliable, and efficient base.

Secondly, the reliance of the 10 advanced services—(1) Maritime Single Window, (2) SAR Support, (3) Environmental Support Services, (4) Remote Pilotage, (5) Port Just-in-time, (6) Enhanced VTS, (7) Situational Awareness, (8) Maritime Connectivity Platform, (9) Digital Twin of the Physical Infrastructure, and (10) Climate Change Projection—on other elements, as depicted in Figure 1, underscores a complex web of dependencies. These services, being at the forefront of the Smart Fairway initiative, necessitate a solid foundation in basic foundational elements to function optimally. Their complexity and reliance on other components mean that their development is not only more challenging but also dependent on the maturity and robustness of the related services and foundational fairway elements.

Thirdly, and of paramount importance, is the critical role of Communication Systems. The enhancement of Communication Systems is critical for the facilitation and advancement of other Smart Fairway elements. The high number of connections emanating from Communication Systems reflects their central role in information dissemination and coordination across various aspects of maritime operations. It implies the urgency of communication systems for Smart Fairways.

Given the complexities and interdependencies highlighted in the analysis, it becomes clear that strategic planning and coordinated development are imperative for the successful implementation of Smart Fairway systems. This would involve not only technological interoperability but also legal, regulatory, semantic, operational, and procedural adaptations to accommodate and leverage these new systems effectively.

As Smart Fairway development progresses, continuous monitoring and assessment will be crucial to address emerging challenges and integrate evolving technologies. This adaptive approach will ensure that the Smart Fairway system remains dynamic, responsive, and aligned with the ever-changing landscape of maritime navigation and safety.

5. Discussion and Conclusions

This study explores the concept and elements of future Smart Fairways to prepare for increasingly autonomous maritime traffic in Finland. Smart Fairway was defined as “Smart Fairway integrates information, new technologies, and automation to enhance traffic safety, efficiency, and to reduce environmental impacts”.

The study identified the Smart Fairway as consisting of five foundational and ten advanced service elements. Particularly, Communication Systems were found to be pivotal for the Smart Fairway initiative. Enhancing these communication systems is critical for facilitating the more advanced fairway elements, such as remote pilotage.

Similar to the classification systems for runways and air traffic control, Smart Maritime Fairways could also be differentiated into various classes. The classification could be based on the extent of automation and smart technologies they incorporate. Consequently, the fairways of the future are expected to demonstrate a continuum of automation capabilities, presenting a range of operational smartness levels. The regulatory and legal compliance is to be decided accordingly.

The holistic perspective taken in this study is crucial for understanding the complexity and interconnectivity of modern maritime traffic and operations. By examining how various elements come together to create Smart Fairway, the article sheds light on the broader implications of digital transformation in the maritime sector. This approach not only enhances our understanding of individual technological components but also provides insights into how they can be effectively combined to optimize the safety, efficiency, and sustainability of maritime transportation for various types of seafaring.

The employed Delphi method proved effective in exploring a topic that is both novel and not extensively researched. The Delphi method was chosen over other methods because it aims to bring together the diverse viewpoints of respondents, steering them towards a unified vision for the necessary future development. In comparison to simulation methods, which are valuable for testing specific scenarios or hypotheses under controlled conditions, the Delphi method provided a broader platform for gathering qualitative insights. However, moving forward, simulations, demonstrations, and further development work on the fairway elements is needed. Notably, Remote Pilotage, one of the advanced Smart Fairway services, has already been demonstrated, as seen in the successful test at the Port of Kokkola [61].

The study also revealed several domains that require additional research and development. This means that the Smart Fairways would combine together the elements studied in the literature ranging from mobile communication technology and satellites [32,33], AtoNs [12], improved VTS [37] to just-in-time arrivals [62], remote pilotage [27] and environmental protection [38]. These findings not only underscore the complexities involved in modernizing maritime infrastructure but also highlight the dynamic nature of technological advancements in this sector. The insights gained from this research are invaluable for shaping future strategies and policies, ensuring that they are well informed and effectively targeted. This provides a concrete basis for timing, ordering and dividing responsibilities of developing individual elements as building blocks for bundled maritime services.

The proposed solutions in this paper are relevant to the current state of technology but are not comprehensive. The dynamic and swift advancements in this sector call for an adaptable approach, capable of integrating emerging technologies. Take 6G technology as an example; it is anticipated to synergize with satellite systems, thereby becoming a crucial component of the forthcoming telecommunications network. 6G is set to go beyond earthbound networks by incorporating non-terrestrial networks (NTNs), including satellite communications, aiming for uninterrupted worldwide coverage [63]. This is particularly vital for areas where traditional maritime radio and mobile cellular networks fall short, such as maritime zones. As technological progress continues, particularly in equipment and navigation, a reassessment and possible enhancement of the fairway elements we have proposed will be essential. Further development can also open up possibilities for crowd-sourced services. However, this requires additional resources to guarantee the provision of open specifications and interfaces between the elements.

Moreover, it should be noted that our study did not delve specifically into the requirements necessary for a fairway to be fully prepared for autonomous shipping. Autonomous shipping represents a significant leap forward in maritime technology, requiring even more advanced systems for navigation, communication, and safety. These systems must function with a high reliability and precision, ensuring that vessels can operate without human intervention. Given the complexity of autonomous operations, a fairway equipped for such technology would need to meet stringent standards. In addition, at least enhanced AtoNs, precise electronic position-finding aids, and advanced VTS systems would be needed. The regulatory framework and safety protocols for autonomous shipping would also need to be defined to ensure seamless integration into the existing maritime infrastructure. This should include enforceable international agreements on communication channels, message formats, and maritime radio frequencies.

Moreover, our study offers an in-depth analysis specifically tailored to the unique context of Finland's maritime fairways. These are characterized by their extensive length, shallow waters, and challenging weather conditions. However, this specific focus does introduce certain limitations regarding the broader applicability of our study. The findings and recommendations are particularly relevant to Finland's maritime infrastructure and may not be directly applicable to other regions with differing topographical and hydrological characteristics. For instance, in Finland, fairways can extend a hundred kilometers out to sea, presenting unique challenges in implementing Remote Pilotage and Communication Systems. In contrast, regions with areas closer to the shorelines might not face similar challenges when establishing these services. Conversely, Finnish fairways are not impacted by tidal influences, a common challenge in other countries. Countries experiencing greater variability could benefit even more than Finland from elements like Dynamic Warnings and a Digital Twin of the fairway. Therefore, we suggest that although the components of a Smart Fairway may be similar, their significance can vary depending on the regional topographical and hydrological characteristics.

There are several areas needing further research. Future research should extend into examining the readiness for autonomous shipping, considering the technological underpinnings and infrastructural adaptations required. Also, the environmental repercussions of such technological implementations demand scrutiny. In tandem, the human aspect—ranging from cultural shifts to workforce transitions and education—calls for an investigation into the social implications of integrating advanced navigational technologies into traditional seafaring communities. As these intelligent systems begin to take shape, there is a pressing need to address the risk management and safety protocols for the more hazardous fairways, ensuring that increased traffic and automation do not compromise maritime safety. Furthermore, considering the scalability of these innovations, research must also delve into the economic implications, assessing the cost–benefit ratio and exploring potential returns on investments. Moreover, opening up a wider discussion on the urgency of implementing these elements and on developing bundled services for various user groups might prove beneficial.

Lastly, comparative analyses with other geographic regions could yield valuable insights, allowing for a nuanced understanding of Smart Fairway development that could inform both local and international maritime strategies. Through such multifaceted research endeavors, a comprehensive knowledge base can be built to navigate the future of smart maritime navigation.

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Institutional Review Board Statement: This study complies with the guidelines of the Finnish National Board on Research Integrity, which indicate an ethical review is not required for the following reasons: (a) The research respects the principle of informed consent, ensuring participants are fully aware and agree to their involvement. (b) All participants are adults, and the research does not compromise the participants' physical integrity. Furthermore, no intense stimuli are employed, and there is no potential for causing psychological distress or posing any danger to the safety of participants, researchers, or their close associates.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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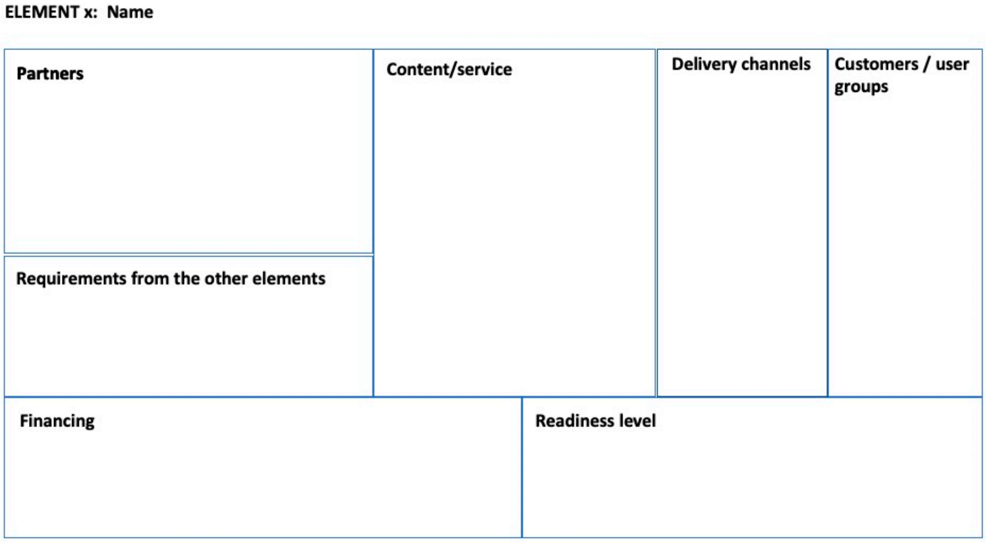
Appendix A



ELEMENT x: Name

Partners

Content/service

Delivery channels

Customers / user groups

Requirements from the other elements

Financing

Readiness level

Figure A1. Form for Describing a Fairway Element in Phase 4.

Appendix B

Table A1. List of Interviews in Phase 2.

Type	No	Industry	Interviewees	Duration (min), No. of Interviewers, Recording Method
Regulating Authorities	1	the Finnish Transport and Communications Agency	Chief Advisor, digital connections	50, 1, notes
	2	the Finnish Transport and Communications Agency	Head of Inspections and Surveys	51, 1, transcript
Technology and ICT providers	3	the Finnish Transport and Communications Agency	Chief Advisor, Ship technology and marine environment	53, 1, transcript
	4	Maritime digital Platforms	Senior project manager	58, 2, transcript
	5	Maritime digital Platforms	Senior project manager	35, 2, transcript
	6	Maritime technology and digital solutions	Managing director	83, 2, transcript
	7	telecommunication	Master researcher	65, 2, transcript
	8	Digital solutions, digital twins	Head of research operations	86, 2, transcript
Shipping companies	9	Shipping line	Operations director	53, 1, transcript
	10	Shipping line	Head of Group IT, hardware	45, 2, transcript
	11	Cargo shipping	COO	40, 1, notes
Fairway service providers	12	Vessel Traffic Service	Program manager	76, 2, transcript
	13	Piloting company	Chief Executive Officer	45, 2, transcript
	14	Piloting company	Pilotage director	64, 2, transcript
	15	Piloting company	Head of pilot dispatch center	45, 1, notes
Maritime Research and training	16	Maritime law	Dr., Head of research	55, 2, transcript
	17	Maritime Business and Policy	Assistant professor	25, 2, transcript
	18	Maritime management	Head of research	50, 2, transcript
	19	Maritime technology	Assistant professor	52, 2, transcript
	20	Logistics	Professor	45, 1, notes
	21	Maritime ecosystem	Senior Ecosystem Lead	59, 2, transcript
Military and safety authorities	22	Military	Chief of underwater warfare research branch	70,1, notes
	23	Safety investigation authority	Executive Director	70, 2, transcript

Appendix C Coding Framework

Current fairways

- Current fairway infrastructure
- User groups of fairways
- Operating and maintenance costs
- Safety and efficiency of fairways

Future fairways

- Description of Smart Fairway and expected benefits
- Stakeholders of the future fairway and their roles and responsibilities
- Improvements needed to current infrastructure
- Technology and data needed
- Other improvements needed
- Business benefits from Smart Fairways
- international potential

Fairway elements

- content
- customer groups
- delivery channels
- partners
- readiness level
- financing
- requirements from the other elements

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