Analyzing the impact of Canal Istanbul on ship traffic dynamics in the Turkish straits: a maritime traffic flow simulation model

Sis Ozgun Yamak Ormeci[1]*, Murat Ozkok[1], Sercan Erol[2], Ercan Kose[1], Ersan Basar[2]

[1] Naval Architecture and Marine Engineering Department, Surmene Faculty of Marine Sciences, Karadeniz Technical University, Trabzon, Turkey
[2] Maritime Transportation and Management Engineering Department, Surmene Faculty of Marine Sciences, Karadeniz Technical University, Trabzon, Turkey

ARTICLE INFO

ABSTRACT

The Turkish Straits System (TSS) is one of the world's busiest maritime corridors, facing congestion challenges due to larger ships, increased transit demand, and regulatory constraints. To address these issues, the Canal Istanbul Project (CIP) has been proposed as an alternative route to improve traffic efficiency and navigational safety. This study develops a maritime traffic system and queuing model based on the Vessel Traffic Flow Problem (VTFP) framework to evaluate the potential impact of CIP on TSS ship traffic. Two traffic models, namely one-way and two-way transit configurations, are simulated using Simio software, integrating historical AIS data and traffic constraints. Scenario analyses indicate that redirecting 90 % of transit ships to Canal Istanbul and 10 % to the Istanbul Strait results in a 36 % reduction in ship density and a 50 % decrease in waiting times. These findings demonstrate that Canal Istanbul has the potential to enhance efficiency and safety in the TSS, offering a data-driven basis for optimizing ship traffic flow in constrained waterways.

1. Introduction

Spanning 164 nautical miles, the Turkish Straits System (TSS) connects the Black Sea to the Aegean Sea and serves as one of the world's busiest maritime corridors [1]. Strategically located between Asia and Europe, the TSS holds significant geopolitical and economic importance. It comprises two straits, namely the Istanbul Strait and the Canakkale Strait, characterized by narrow, S-shaped curves, as well as the Marmara Sea. These straits facilitate global trade by linking the Black Sea to the Mediterranean while serving as key transit points for vessels from the Danube-Rhine and Volga-Don River systems [2, 3]. Despite its critical role in maritime transport, the TSS faces growing congestion driven by larger ships, increased transit demand, and operational challenges. Meteorological, geographical, and hydrodynamic factors, together with local traffic regulations, contribute to bottlenecks [4-6]. Narrow, high-risk waterways experience significant bottlenecks due to their unique geographical, meteorological, and oceanographic conditions, combined with increasing ship traffic density [7]. Similar concerns have been reported in other congested maritime regions, where the placement of

emergency facilities and the analysis of accident risk are crucial for navigational safety [8-9]. Existing canals and waterways often prove insufficient to alleviate congestion, necessitating new navigational solutions. Additionally, advancements in shipbuilding have introduced new challenges, as larger, faster vessels increase the risk of maritime accidents [10]. Consequently, accident rates in constrained waterways have risen, particularly in the Istanbul and Canakkale Straits [11, 12].

Maritime accident studies indicate that the highest-risk zones in the Istanbul Strait are at the entry and exit points, where human error, adverse weather, and technical failures frequently lead to collisions and groundings [13-15]. Similarly, the Canakkale Strait experiences collisions, navigational conflicts, and fires, particularly at its narrowest section, the Kilitbahir region [16, 17]. To mitigate risks, Rules and Regulations (R&R) have been implemented. However, the TSS remains prone to periodic closures due to traffic restrictions, maintenance, and accidents, causing extended waiting times and shipping delays [18-24]. Vessels on standby create bottlenecks in maritime traffic, disrupting international shipping and causing significant delays in global trade logistics. Statistical data indicate that the number of ships transiting the Turkish Straits peaked at 56,600 in 2007 but declined by 38 % to 35,146 in 2022 [25]. Despite this decrease, the average gross tonnage and the number of ships exceeding 200 meters in length have increased, reflecting shifts in ship design and cargo capacity [25-29]. This trend indicates changes in ship design parameters, increased cargo-carrying capacity, and proportional growth in vessel length [30]. Consequently, congestion in the Istanbul and Canakkale Straits has intensified [14, 31, 32].

To mitigate this issue, the Canal Istanbul Project (CIP) has been proposed as an alternative route to enhance navigational efficiency and safety. Spanning 45 km, this artificial canal connects the Black Sea to the Sea of Marmara via the European side of Istanbul. It operates under specific legal regulations [33]. By reducing ship density in the Istanbul Strait, Canal Istanbul is expected to alleviate congestion and mitigate accident risks in the TSS.

Building on these considerations, this study aims to develop a simulation-based model to assess the potential impact of Canal Istanbul on the efficiency of existing TSS ship traffic. The current queuing dynamics and system structures of the TSS are modelled through simulation. Subsequently, Canal Istanbul is incorporated into the model, yielding a new simulation framework that evaluates the performance of both structures. To the best of the authors' knowledge, this study is the first in the literature to analyse the impact of the Canal Istanbul on the efficiency of TSS ship traffic using a simulation-based approach. Unlike previous studies, which primarily focus on traffic regulations and risk assessments within the TSS, this study incorporates a newly proposed maritime route into a simulation framework to evaluate its potential effects on navigational efficiency, congestion reduction, and transit times. In line with this objective, the study seeks to address the following research questions by analysing the proposed simulation model.

RQ-1: Which simulation model (Model 1 or Model 2) yields better performance outcomes?

RQ-2: How do one-way and two-way ship traffic configurations influence system performance?

RQ-3: What is the impact of different model scenarios on system performance?

RQ-4: How do transit and non-transit ships affect ship density and waiting times in the TSS?

RQ-5: How does Canal Istanbul impact the queue structure of the Istanbul Strait based on key performance metrics such as the number of ships in the queue and waiting times?

The key contributions of this paper are highlighted from various aspects as follows.

(i) First Simulation-Based Analysis of Canal Istanbul's Impact on the TSS: To the best of the authors' knowledge, this study is the first to develop a simulation-based framework that models ship traffic flow through Canal Istanbul and integrates it into the TSS. Unlike previous studies, which predominantly focus on regulatory aspects and risk assessments, this research quantitatively evaluates the effects of Canal Istanbul on maritime traffic flow, congestion, and queue structures.

(ii) Integration of Real Automatic Identification System AIS Data and Navigational Constraints into the Simulation Model: This study incorporates historical AIS data, ensuring realistic vessel movement patterns and operational constraints. Additionally, it adheres to the navigational Rules and Regulations (R&R) of the Turkish Straits, enabling a flexible and adaptable modelling framework in which regulatory conditions and dataset parameters can be dynamically modified.

(iii) Quantitative Assessment of Canal Istanbul's Influence on Queue Dynamics and Ship Traffic Density: This study evaluates the impact of Canal Istanbul on queueing structures, waiting times, and vessel densities under various transit configurations. The results provide empirical insights into how traffic redistribution can alleviate congestion in the Istanbul Strait while maintaining system-wide efficiency.

(iv) Comparative Scenario Analysis of TSS with and without Canal Istanbul Integration: A comprehensive comparative analysis is conducted between the existing TSS model and the Canal Istanbul–integrated model. The study simulates ten traffic redistribution scenarios to determine the optimal transit configuration that minimizes delays and maximizes navigational efficiency. The findings indicate that Scenario 10, in which 90 % of transit ships are allocated to Canal Istanbul, results in a 36 % reduction in ship density and a 50 % decrease in waiting times compared to the current system.

(v) Practical Implications for Maritime Traffic Optimization and Policy Development: The findings provide critical insights for maritime authorities, policymakers, and transportation planners seeking to improve vessel traffic management in constrained waterways.

The rest of the paper is organized as follows. Section 2 presents a literature review that highlights the differences between this study and previous research. Section 3 explains the methodology, including the development of the simulation model and the integration of data. Section 4 presents the simulation results, evaluating the impact of Canal Istanbul under different scenarios. Section 5 discusses the findings in relation to maritime traffic management. Finally, Section 6 concludes the study by summarizing key insights and offering directions for future research.

2. Literature Review

Research on ship transit, scheduling, and traffic management in international waterways has grown steadily over the past two decades, employing diverse methodologies, including heuristic approaches, mathematical programming, and simulation-based models. While this body of literature has offered valuable insights into congestion control and operational efficiency, a critical synthesis reveals specific thematic patterns, methodological trends, and areas where existing studies fall short in addressing emerging navigational challenges. Table 1 provides a comparative summary of the reviewed studies, including their methodologies, problem types, and geographical focus (e.g., straits versus canals), thereby supporting the synthesis presented in this section.

Early works primarily focused on congestion analysis and traffic flow modelling in key maritime corridors. Merrick et al. [19] examined ferry density and accident risks in San Francisco Bay, while Kose et al. [34] employed AweSim to assess oil transport risks. Franzese et al. [35] developed a simulation model for the Panama Canal, emphasizing queue structures and system dynamics. In the context of the TSS, Almaz et al. [36] developed a scenario-based simulation model that incorporates meteorological conditions and regulatory constraints. This model was further refined by Or et al. [5], who introduced navigational transition regimes, and by Ozbas and Or [20], who considered tugboat logistics and geographical constraints. Building on this work, Mavrakis and Kontinakis [24] enhanced the structural modelling of the Istanbul Strait, while Uluscu et al. [3] proposed a queuing model analysing system bottlenecks and vessel waiting times.

Parallel research explored ship traffic in other critical straits and rivers. Almaz and Altiok [37] modeled congestion in the Delaware River, and Qu and Meng [38] applied discrete-event simulation to the Singapore Strait. Mandalaki and Manesis [39] leveraged Simio to optimize port scheduling, whereas Dong et al. [40] explored queuing structures in the Yangtze River under navigational constraints. Fang et al. [23] proposed a one-way scheduling model that improves upon the first-come, first-served (FCFS) rule. Sluiman [41] extended

ship scheduling logic to major straits, including the Istanbul Strait. Lalla-Ruiz et al. [42] and Rahimikelarijani et al. [21] optimized waiting times and emissions in the Yangtze Delta and the Houston Canal, respectively. Meisel and Fagerholt [43] presented bidirectional transit optimization for the Kiel Canal, a structure closely comparable to the Istanbul Strait in terms of navigational constraints.

Further contributions include Liu et al. [18], who studied LNG traffic in restricted waterways, and Andersen et al. [44], who developed a scheduling model for the Kiel Canal. Li et al. [45] proposed a multi-objective optimization framework for constrained waterways. Bolat and Kayisoglu [46] employed ARMA models for traffic prediction in the Istanbul Strait, while Ozlem et al. [7] proposed heuristic scheduling algorithms. Zhang et al. [47] applied entropy-based methods for complexity analysis, and Wen et al. [48] developed network models capturing behavioural dynamics in dense traffic. Tonoglu et al. [31] utilized FAHP and PRAT methods for sector-based risk analysis. Chen et al. [49] incorporated cellular automata and navigational rules into traffic modelling, and Zhang et al. [50] proposed a metaheuristic framework to reduce delays and energy consumption simultaneously.

Despite the breadth of these studies, a clear research gap persists in integrating newly proposed infrastructures, such as Canal Istanbul, into maritime traffic simulations. Existing models predominantly emphasize static regulatory constraints or historical bottlenecks, with limited focus on assessing the system-wide impacts of alternative transit routes. Moreover, while simulation approaches are well established, only a limited number of studies leverage real AIS data or dynamically incorporate navigational rules into adaptable modelling frameworks. This study aims to address these limitations by presenting a simulation-based framework that integrates Canal Istanbul into the TSS network. Unlike previous models, it emphasizes queue dynamics, vessel density, and operational performance under different traffic configurations. The use of real AIS data and flexible regulatory parameters positions this work as a novel and practically relevant contribution to maritime traffic management in constrained waterways.

3. Methodology

The dynamic modelling framework presented in Figure 1 illustrates Canal Istanbul's impact on ship traffic within the TSS. This study comprises four main components: input definition, model parameter specification, model structure development, and output analysis.
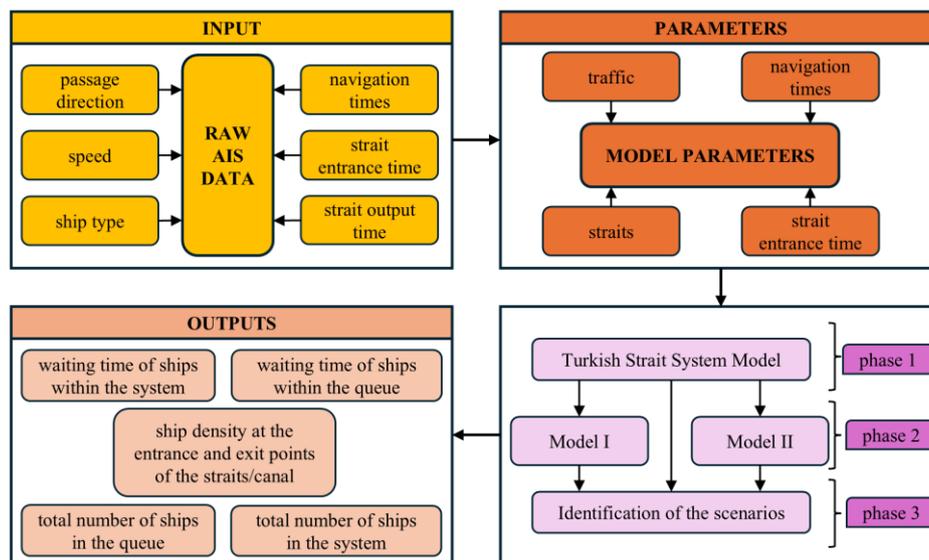

Fig. 1 Flowchart of the research methodology

3.1 Inputs of the simulation model

The input data includes straight entry direction, ship type, speed, entry and exit times, and total navigation duration. Historical ship traffic records obtained from the General Directorate of Coastal Safety provide 12 months of AIS-based navigational data for both the Istanbul and Canakkale Straits. These records include

vessel length, breadth, draft, tonnage, International Maritime Organization (IMO) number, flag, and departure and arrival ports. Rather than using the raw data directly, the study statistically analyses them to derive representative distributions for ship arrivals, transit durations, and entry–exit times. This approach ensures that the simulation model reflects realistic variations in maritime traffic intensity and temporal dynamics.

On an annual basis, vessel traffic in the Turkish Straits System comprises 42,979 ships transiting the Istanbul Strait and 44,613 vessels transiting the Canakkale Strait. Among these, 50.18 % and 50.24 %, respectively, proceed northbound, indicating an approximately symmetrical directional distribution. To align with real-world maritime operations, the model defines six principal transit routes that represent all possible directional connections among the Aegean Sea, the Sea of Marmara, the Black Sea, and the Canal Istanbul. These routes capture the complete navigation network of the Turkish Straits System, encompassing both single-strait passages and full-transit movements. Their spatial distribution and interconnections are presented in Figure 2, which illustrates the modelled ship traffic configuration across the system.
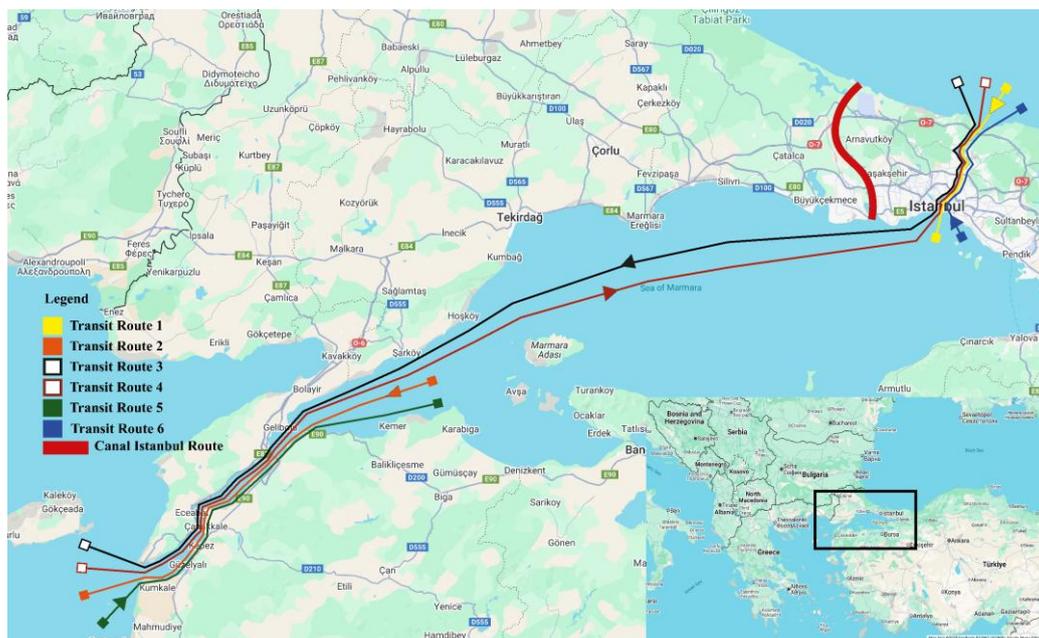

Fig. 2 Modelled ship transit routes across the Turkish Straits System and Canal Istanbul.

Table 2 presents the total number of non-transit, transit, and overall ship passages, which serve as key validation references for the simulation model. In line with these inputs, the simulation software ensures that the entities generated at the *OutputBuffer* of the Source module correspond to those recorded at the *InputBuffer* of the *Sink* module. The Source module marks the entry of ships into the system, while the *Sink* module marks their exit. Any discrepancy between these values indicates an inconsistency in entity generation and signals a modelling error that must be corrected.

Table 1 The relevant studies in the existing academic literature

Authors		Köse et al. 2003 [34]	Merrick et al., 2003 [19]	Franzese et al., 2004 [35]	Almaz et al., 2006[36]	Özbaş and Or, 2007 [20]	Or et al., 2007 [5]	Uluscu et al., 2009 [3]	Kundak and Baypinar, 2011[51]	Qu and Meng, 2012 [38]	Almaz and Altiok, 2012[35]	Mandalaki and Manesis, 2013 [39]	Eldemir et al., 2013 [52]	Zhang et al., 2015 [53]	Fang et al., 2015 [23]	Sluiman, 2017 [41]	Liu et al., 2017 [54]
Canal/Strait		IS	OW	OW	IS	IS	IS	IS	CI	OW	OW	IS	IS	OW	OW	IS	OW
Problem type		VTFP	VTFP	VTFP	VTFP	VTFP	VTFP	VTFP	E	VTFP	VTFP	VTFP	MTM	VTSP	VTFP	VTSP	VTFP
Solution Approaches	SM	•	•	•	•	•	•			•	•	•	•		•		
	HM/MHM																•
	OM							•						•		•	

Authors		Tütüncü, 2017 [55]	Sözer and Ozsoy, 2017 [56]	Nigussie and Altunkaynak, 2017a [57]	Nigussie and Altunkaynak, 2017b [58]	Lalla-Ruiz et al., 2018 [42]	Rahimikelarijani et al., 2018 [21]	Xin et al., 2019 [59]	Meisel and Fagerholt, 2019 [43]	Liu et al., 2019 [18]	Zhang et al., 2019 [60]	Nigussie and Altunkaynak, 2019 [61]	Baba, 2020 [62]	Balcıoğlu, 2020 [63]	Ahmed and Altunkaynak, 2020 [64]	Saçu et al., 2020a [65]	Saçu et al., 2020b [66]
Canal/Strait		CI	CI	CI	CI	OW	OW	OW	OW	OW	OW	CI	CI	CI	CI	CI	CI
Problem type		ED	HM	UP	UP	VTSP	VTSP	VTFP	VTSP	VTFP	VTFP	UP	RF	P	GM	SD	SD
Solution Approaches	SM						•	•		•	•						
	HM/MHM					•			•								
	OM		•	•	•								•	•		•	•

Authors		Andersen et al., 2021 [44]	Li et al., 2021 [45]	Bolat and Kayisoglu, 2021 [46]	Özlem et al., 2021 [7]	Menteşe and Tezer, 2021 [67]	Zhang et al., 2022 [45]	Wen et al., 2022 [47]	Tonoğlu et al., 2022 [31]	Şen et al., 2022 [68]	Enlil and Dinçer, 2022 [69]	Uluengin et al., 2022 [70]	Chen et al., 2023 [49]	Zhang et al., 2023 [50]	Mersin et al., 2024 [71]	Xu et al 2025[72]	**This Study**
Canal/Strait		OW	OW	IS	IS	CI	OW	OW	IS/CS/MS	CI	CI	CI	OW	OW	CI	OW	MS/CI/IS/CS/
Problem type		VTSP	VTSP	TSM	VTSP	EI	VTFP	SFM	MAP	WFE	UP	UP	VTFP	VTSP	P	TSM	VTFP
Solution Approaches	SM																•
	HM/MHM	•	•		•								•	•			
	OM			•		•	•								•		

OM (Other Methods): Optimization Model, Social Force Model, FAHP and PRAT, Autoregressive Moving Average Model (ARMA), Exact Methods, Vessel Traffic Scheduling Algortihm, Empirical Review, Research Methods, Hydrodynamic Model, Matric Model, Numerical Model, Dynamic Model, Urban Growth Model-VTFP: Vessel Traffic Flow Problem-VTSP:Vessel Traffic Scheduling Problem-SFM:Social Force Model-MAP:Marine Accident Problem-TSM:Traffic Scheme Management-MTM:Marine Traffic Management-UP:Urban Policies-WFE:Water Flow Effect-EI:Ecological Interpretation-RF:Risk Factors-P:Pollution-GM:Grandwater Modeling-SD:Salinity Distribution-ED:Environmental Damages-HM:Hydrodynamic Modeling-E:Evaluation-IS:Istanbul Strait-CS:Canakkale Strait-MS:Marmara Sea-CI:Canal Istanbul-OW:Other Waterways-SM:Simulation Model-HM/MHM:Heuristic and Meta-Heuristic Methods-OM:OtherMethod.

Table 2 Number of transits, non-transit, and total ship passages

Transit Routes	Non-Transit Passage	Transit Passage	Total Passage
Transit route 1	7518	0	7518
Transit route 2	3509	4882	8391
Transit route 3	2537	11055	13592
Transit route 4	662	11058	11720
Transit route 5	9940	0	9940
Transit route 6	1929	6462	8391

3.2 Parameters of the simulation model

The traffic flow and queue model simulation is conducted using Simio 11 software. Before model construction, maritime traffic system parameters are defined and categorized into four main groups, each comprising several sub-parameters to establish a coherent modelling framework. This categorization improves representational accuracy and ensures consistency throughout the simulation process.

(i) Traffic

•**Ship Data:** Historical real-world records serve as inputs for the simulation model, ensuring accuracy in traffic representation.

•**Ship Specifications:** Noisy data are refined by categorizing ships according to relevant characteristics. To ensure dataset consistency, local vessel traffic is excluded from the analysis.

•**Traffic Flow Direction:** The traffic system accommodates bidirectional movement (northbound and southbound) within the TSS and Canal Istanbul. The total length of the navigational routes is 31 km in the Istanbul Strait, 70 km in the Canakkale Strait, and 45 km in Canal Istanbul.

(ii) Straits

•**Specific Waterway Physical Characteristics:** Special operational rules apply due to the narrowing of straits and shallow coastal regions.

•**Environmental Conditions:** Given the dynamic weather and current conditions in the straits, temporary or permanent closures may occur. Accordingly, real-world waiting times associated with such closures are incorporated into the model.

•**Ship Speed:** Maintaining a constant speed within the straits is not feasible. Accordingly, a triangular distribution (9, 10, 12 Nm/h) is implemented to represent stochastic navigation times. Speed limits are strictly enforced, preventing ships from exceeding designated values or overtaking one another. The selected speed range is consistent with operational limits defined by the Directorate General of Coastal Safety and the Canal Istanbul EIA Report.

•**Waterway Entry and Exit Points:** The model defines key transition points where ships initiate, terminate, or transfer their passage in both the northern and southern directions of the straits.

(iii) Queue

•**Service discipline:** The queuing system requires a predefined service discipline (FCFS, LIFO, SIRO, SPT, PR, PSPO, and NPSS) to regulate ship entries into the strait or canal. Since the AIS dataset inherently reflects real vessel arrival and departure sequences determined by operational conditions in the Turkish Straits, the FCFS discipline is retained to maintain empirical consistency between observed and simulated traffic behaviour.

•**Priority rules:** A priority-based scheduling mechanism is implemented for ship entries and encoded within the simulation logic. Each ship is assigned a numerical priority value starting at 1 to ensure consistency.

•**Scheduling:** Ships are prioritized according to predefined navigation rules. Passenger vessels receive the highest priority, while ships carrying hazardous cargo are assigned a lower rank. To align the scheduling system with the simulation logic, time and date information are incorporated, and ships are sorted into separate scheduling files by direction before being integrated into the model.

•**Waiting times:** Waiting times for ships entering the service canal are not constant and vary across vessels. These variations are incorporated into the model using real ship data.

•**Number of queues:** A queuing mechanism based on priority ranking forms at the entry points of each service canal. This queue develops sequentially in front of the designated service canals for each direction.

•**Arrival rate:** Ship arrivals from different sources follow a uniform distribution across the system.

(iv) Rules and Regulations

•**General transit rules:** These are standard regulations that apply to all ships navigating through the entire TSS, including both straits and the canal.

•**Local strait rules:** This category includes specific navigation regulations that apply to different sections of the Turkish Straits System, each governed by its own set of operational constraints.

Key model parameters include straight passage time, entry and exit times, and arrival times, all derived from real-world data rather than random assignments. The model enhances realism by incorporating actual ship departure times and waiting intervals, thereby minimizing randomness in the scheduling logic. Data from six transfer routes are integrated into the model through the *Data* section, where each route is represented by a dedicated table functioning as a static input parameter (Figure 3(a)). Data selection is performed through priority-based variable coding embedded in the model logic. Figure 3(b) illustrates how these values are transferred into the simulation software modules. While passage times vary among ships, they remain consistent with predefined priority rules. The simulation model's logic diagram connects various processes and parameters, outlining system inputs, queue structures, and decision points. Figure 4(a) depicts north-to-

south ship traffic, while Figure 4(b) illustrates south-to-north traffic, demonstrating data integration and statistical result generation.
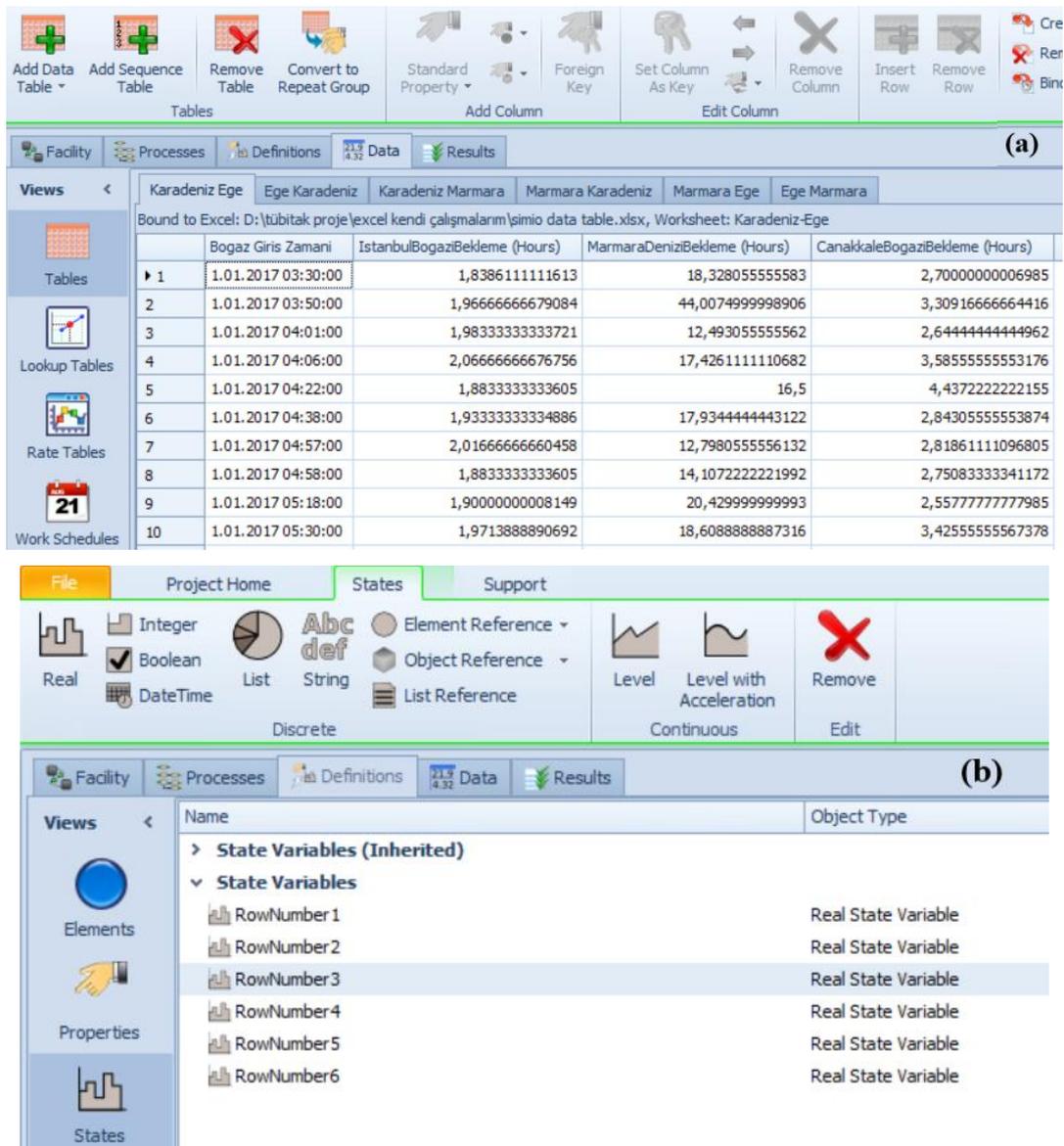

Fig. 3 (a) Simio representation of the data table. (b) Simio representation of state variable definition

3.3   Modelling the maritime traffic

Simulation is a key tool for modelling complex real-world problems that are difficult to evaluate analytically [73-76]. In the maritime industry, it plays a crucial role in traffic management, port operations, ship scheduling, accident analysis, shipbuilding, and flow optimization [38,59,53,77-80]. The simulation model employed in this study operates as a dynamic system and follows a discrete-event simulation approach, reflecting temporal variations in model variables. It schedules ship flows while ensuring compliance with navigational rules and continuously monitors nodal points, bottlenecks, and delays. The primary objective is to examine how interactions between ship traffic in the Istanbul Strait and Canal Istanbul influence overall system performance. To evaluate the impact of Canal Istanbul, this study develops two maritime traffic simulation models: one examining its effects on the Istanbul Strait and the other assessing the overall TSS structure.

•**Model 1:** Canal Istanbul operates under a two-way ship traffic configuration, allowing the passage of both transit and non-transit ships.

•**Model 2:** Canal Istanbul operates under a one-way ship traffic configuration, permitting only transit ships to pass.
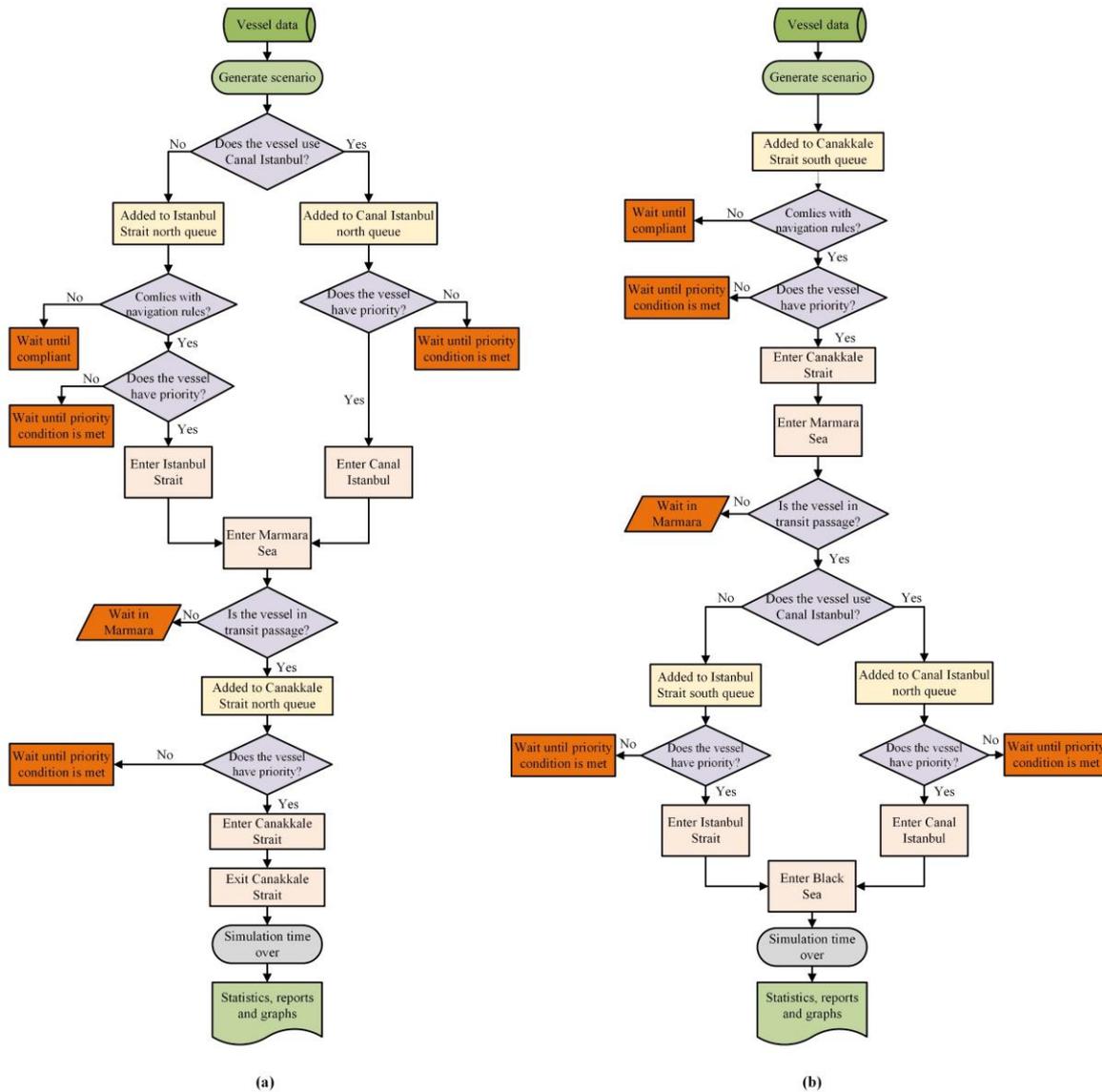

Fig. 4 (a) North-to-south ship traffic flowchart. (b) South-to-north ship traffic flowchart

3.3.1   Simio simulation software

SIMIO is a multidirectional modelling tool that integrates objects and processes, enabling flexible system modelling [81]. It includes key components such as entities, sources, sinks, paths, models, projects, properties, states, events, resources, and transporters. The modelling process follows a structured logical sequence consisting of Assign, Delay, Seize, Transporter, Release, and Decide operations. Fundamental modules and triggering processes are integrated via adapter codes, ensuring consistency with the system's logic. This approach enables the automatic generation of both the main system model and the corresponding logical execution model.

SIMIO employs an object-oriented modelling framework in which processes and events are coded based on queuing theory principles. The simulation relies on two primary criteria: queue structures forming in front of the system and those forming at the service canals. The system operates as a holistic structure that explicitly incorporates the queuing mechanism (Figure A1). Under steady-state conditions, when one queuing theory parameter is known, other performance measures can be computed using mathematical relationships [82].

The simulation technique introduced by Giffin [83] provides a methodological foundation for cases in which system complexity prevents the direct application of classical queuing theory models [84]. In this study, SIMIO evaluates queuing performance using the parameters TimeInSystem, NumberInSystem, TimeInStation, and NumberInStation.

3.3.2   Queuing model of the straits and Canal Istanbul

The model operates under two directional flows: southbound and northbound. Ships arrive at the entrance of the strait or canal and join the queue according to the designated traffic direction. Each ship is assigned a priority level based on navigational rules and proceeds accordingly. As new ships enter the system, the priority sequence is updated, dynamically restructuring the queue. Once traffic restrictions are lifted, a ship enters the waterway, allowing the subsequent vessel to proceed. The passage process strictly adheres to established navigation rules, and ships exit the simulation system upon completing their transit.

The priority order for ships entering the service canal after queuing is determined by the guidelines specified in the Maritime Traffic Regulations [28, 29]. As previously noted, passenger ships are assigned the highest priority, whereas ships carrying hazardous cargo receive the lowest priority. Risk-free general cargo ships are prioritized after passenger ships, provided that they comply with hull length limitations. Ships are grouped by arrival time and enter the waterway under a first-come, first-served (FCFS) discipline, ensuring equal priority among vessels within the same category [18].

The Istanbul Strait and Canal Istanbul operate under a one-way vessel traffic system (Figure 5(a)), whereas the Canakkale Strait allows two-way vessel traffic (Figure 5(b)). In the one-way system, southbound traffic flows continuously, while northbound traffic is temporarily halted within designated time windows, leading to queue formation. In the two-way system, ships navigate simultaneously in opposite directions without such restrictions.

A single service mechanism is insufficient to represent the system entirely. The TSS service mechanism (Figure A2(a)) follows a single-channel, single-phase queuing structure, in which ships line up before a single service point. In this framework, servers serve as entry and exit points, while inputs act as resources that facilitate ship transfers. In contrast, the Canal Istanbul–integrated model (Figure A2(b)) adopts a multi-channel, multi-phase queuing structure, incorporating multiple service points and sequential processing stages to provide greater operational flexibility.
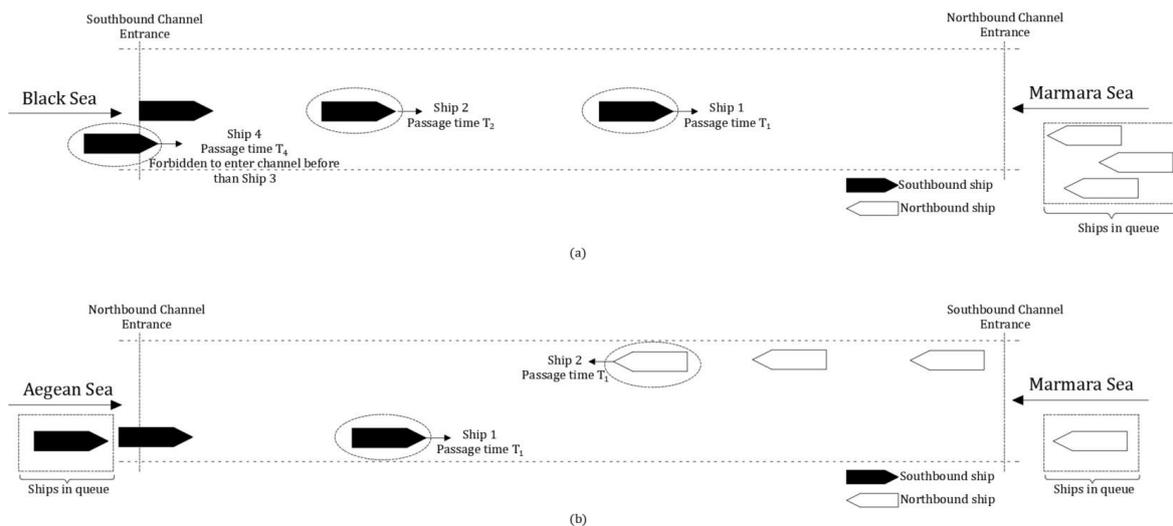

Fig. 5 (a) Queue structure in the Istanbul Strait. (b) Queue structure in the Canakkale Strait

3.3.3   Model 1: Two-way ship traffic

The current TSS logic model is aligned with the R&R framework, ensuring compliance with existing regulations. A two-way flow structure integrates Canal Istanbul while maintaining access for both southbound

and northbound vessels. The first model incorporates four transit routes, enabling both transit vessels (Routes 3 and 4) and non-transit vessels (Routes 1 and 6) to use the canal. The simulation model is developed in Simio, where key modules such as *Source, Sink*, and *Server* are interconnected through *Path* and *TimePath* links. Ships are modelled as Entity objects, with six Source modules that introduce route-specific data and corresponding Sink modules that collect simulation outputs. Server modules positioned at entry and exit points monitor queue structures and waiting times. Vessels in the *InputBufferContents* section proceed to subsequent Server modules according to the predefined flow diagram. Ships navigating the Istanbul Strait follow the same priority order before diverging into two waterways, one through the Istanbul Strait and the other via Canal Istanbul, and subsequently converging at a single exit point, thereby ensuring consistency in entry and exit locations. Navigation paths are defined using nodes. *BasicNodes* (gray) represent intersections, whereas *TransferNodes* (blue) control transport logic and destination selection. *TimePaths* assign specific transit durations and regulate vessel movement according to the first-come, first-served rule. Passage conditions, waiting times, and predefined logic rules are encoded within designated entity property sections, including Arrival Logic, Table Row Referencing, and State Assignments. The model incorporates physical and mathematical parameters derived from real-world data. A vessel departing from the northern entrance of the Istanbul Strait follows a route of 17 nautical miles through the Istanbul Strait, 110 nautical miles across the Sea of Marmara, and 38 nautical miles through the Canakkale Strait. Travel times from departure ports to strait entry points are also incorporated. Each scenario is simulated over one year, and the resulting outputs are generated for further analysis (Figure 6).
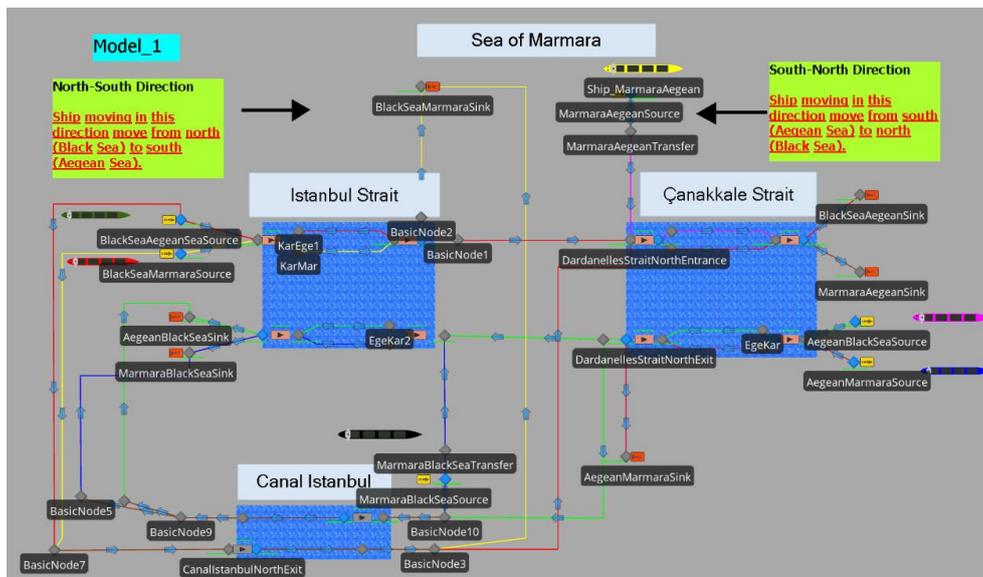

Fig. 6 Interface representation of Model 1

3.3.4   Model 2: One-way ship traffic

In Model 2, Canal Istanbul operates as a one-way vessel traffic system, reflecting the current maritime traffic structure. Both models are derived from the TSS simulation framework. Canal entrance and exit points function as intersection nodes, where northbound and southbound vessels queue according to predefined navigation directions. Similar to the Istanbul Strait, the canal remains open for 12 hours in each direction and operates under the same navigational restrictions. Only Transit Routes 3 and 4 are permitted, while non-transit vessels are excluded from canal passage. A single node represents both canal entrance and exit points, and bidirectional path connections are used to track vessel movements. This configuration reduces model complexity while preserving operational accuracy. The interface visualization of Model 2 is presented in Figure 7. As in Model 1, the simulation is conducted over one year for all scenarios, producing statistical outputs for comparative analysis.
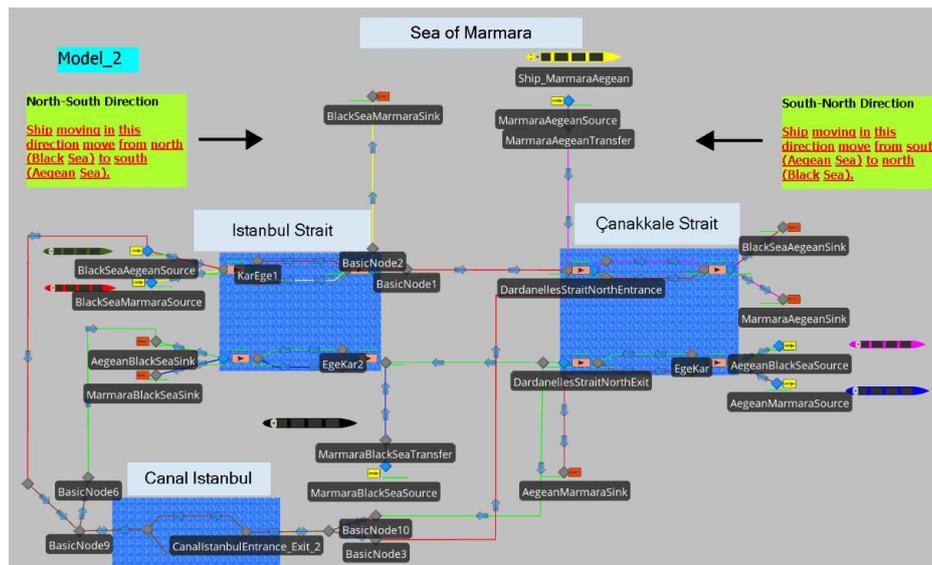
Fig. 7 Interface representation of Model 2

3.4 The outputs of the simulation model and scenario evaluation

The simulation model is executed over one year to assess the effects of system parameters through scenario-based analysis. A total of ten scenarios, including the baseline condition, are evaluated, with each scenario run for ten iterations. Table 3 presents the selection weights used to distribute ship traffic between the Istanbul Strait and Canal Istanbul across scenarios. These weights represent the proportion of maritime traffic assigned to each route. The first scenario corresponds to the existing TSS configuration, in which all vessels transit the Istanbul Strait. For example, in Scenario 4, 70 % of vessels navigate through the Istanbul Strait, while 30 % are routed via Canal Istanbul (Figure A4).

In line with the Environmental Impact Assessment (EIA) Report of Canal Istanbul, a comparison of vessel type and dimensional constraints defined for Canal Istanbul with the characteristics of ships currently transiting the Istanbul Strait indicates that no limiting conditions would prevent Bosphorus-transiting vessels from using the canal. Accordingly, the scenarios assume that vessels presently operating in the Bosphorus are potentially eligible to transit Canal Istanbul. Traffic allocation between the two waterways is implemented using predefined percentage intervals ranging from 10 % to 90 %, with routing determined randomly within each scenario. This approach enables an unbiased, system-level assessment of congestion and operational performance under varying utilization levels, without incorporating behavioural or economic decision factors.

The effects of Canal Istanbul on the Turkish Straits System are evaluated through scenario analyses based on both maximum and average values derived from the simulation outputs. The simulation software records system-level performance indicators, including *NumberInSystem* and *TimeInSystem*, within the Results section (Figure A3(a)). Queue-related metrics, such as the number of waiting vessels and their corresponding waiting times, are documented using the *NumberInStation* and *TimeInStation* parameters (Figure A3(b)).

4. Simulation Results

The simulation framework includes ten scenarios, each executed ten times, resulting in a total of 100 simulation runs. Scenario outputs are compiled using the reporting tools available in Simio, from which statistical performance indicators are derived.

4.1 Results of Model 1

The simulation results are examined at two analytical levels: system-level and route-based. System-level results describe the overall operational behaviour of the Turkish Straits System. In contrast, route-based results focus on the individual components of the system: the Istanbul Strait, the Canakkale Strait, and the Sea

of Marmara. Table 4 presents route-based performance indicators, including queue lengths and waiting times, reported as both average and maximum values. Waiting times are expressed in hours.

Table 3 Scenario-Based Distribution of ships Between the Istanbul Strait and Canal Istanbul

Scenario	Selection Weight	
	Istanbul Strait Traffic (%)	*Canal Istanbul Traffic (%)*
Scenario 1	100	0
Scenario 2	90	10
Scenario 3	80	20
Scenario 4	70	30
Scenario 5	60	40
Scenario 6	50	50
Scenario 7	40	60
Scenario 8	30	70
Scenario 9	20	80
Scenario 10	10	90

The baseline scenario corresponds to historical traffic conditions, while the remaining scenarios reflect predefined traffic distribution weights. Based on InputBufferContents data from the Server modules at the northern and southern entrances to the Istanbul Strait, the number of waiting vessels declines consistently across scenarios. The average queue length decreases by 92.3 %, while the maximum number of vessels observed in a single replication decreases by 71.8 %. The average waiting time is reduced by 13 %, and the maximum waiting time recorded under the most congested conditions decreases by 56 %, although the reduction in average waiting time is comparatively modest.

Table 4 Simulation Results of Model 1: Vessel Traffic and Waiting Times Under Different Scenarios

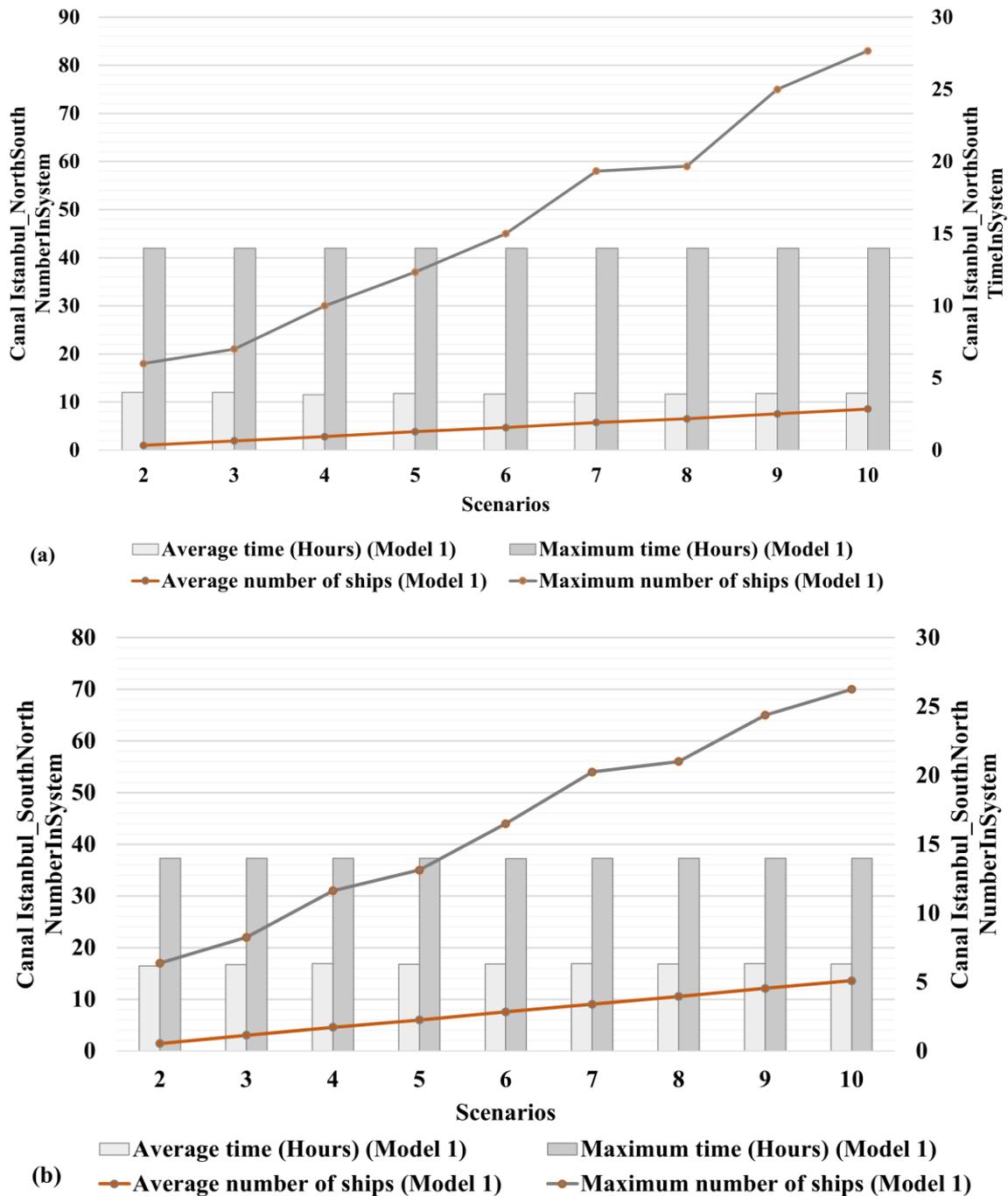| Istanbul Strait										
Scenario ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of vessels										
Average vessels passed	13	10	8	7	6	5	4	3	2	1
Maximum vessels passed	71	62	58	53	48	44	39	34	30	20
Waiting time in the queue										
Average waiting time (hrs)	10	8.81	8.8	8.8	8.7	8.7	8.9	8.8	8.7	8.7
Maximum waiting time (hrs)	524	471	386	379	352	275	461	372	233	226
Canakkale Strait										
Scenario ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of vessels										
Average vessels passed	26	19	19	19	19	19	18	18	18	17
Maximum vessels passed	105	77	78	74	75	73	74	75	74	75
Waiting time in queue										
Average waiting time (hrs)	20.45	15.41	15.29	15.17	15.06	14.93	14.81	14.69	14.57	14.45
Maximum waiting time (hrs)	77	43	43	43	43	43	43	42	41	40
Sea of Marmara										
Scenario ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of vessels										
Average vessels passed	112	103	97	92	87	81	75	70	64	59
Maximum vessels passed	326	328	316	303	295	292	254	246	232	218
Waiting time in queue										
Average waiting time (hrs)	87	112.27	112.36	112.4	112.53	112.12	112.49	112.38	112.14	112.07
Maximum waiting time (hrs)	1127	1163	1145	757	1145	757	746	757	695	688

Fig. 8 (a) Number of vessels and waiting times in Canal Istanbul for Model 1 in the north-south direction. (b) Number of vessels and waiting times in Canal Istanbul for Model 1 in the south-north direction.

In the Canakkale Strait, which operates under a two-way traffic regime, more vessels queue than in the Istanbul Strait, although waiting times remain relatively short. The average queue length decreases by 34.6 %, and the maximum queue size observed across all replications decreases by 28.5 %. The average waiting time declines by 29.3 %, while the maximum waiting time recorded under peak congestion conditions decreases by 48 %.

In the Sea of Marmara, the total number of vessels decreases by 47.3 % when evaluated using average values and by 33.1 % when considering maximum values. In contrast, the average waiting time increases by 28.8 %, and the maximum waiting time rises by 24.5 %.

In Model 1, Canal Istanbul operates under a two-way traffic configuration. As illustrated in Figure 8, ship density and waiting times differ between the northern and southern entrances of the canal. Scenario-based

analyses indicate that congestion levels are higher at the Marmara Sea entrance than at the Black Sea entrance, primarily due to increased traffic demand and prevailing flow dynamics. At the southern entrance of the Istanbul Strait (Figure 9a), the average queue length decreases by 90.3 %, while the maximum queue size observed in any replication decreases by 83.3 %. However, the average waiting time increases slightly by 3.5 %. At the northern entrance of the Istanbul Strait (Figure 9c), the average number of vessels in queue decreases by 89.0 %, and the maximum queue size decreases by 84.0 %. In comparison, the average waiting time increases by 6.0 %.

At the northern entrance of the Canakkale Strait (Figure 9b), the average queue length increases by 63.8 %, and the maximum number of vessels recorded in a single replication rises by 38.2 %. The average waiting time increases by 63.7 %, attributed to traffic convergence from both Canal Istanbul and the Istanbul Strait, resulting in temporary congestion in the Canakkale Strait.

4.2 Results of Model 2

The route-based results for the one-way traffic configuration of Canal Istanbul are presented in Table 5. Across all components of the system, vessel densities exhibit a gradual decline in both average and maximum values.

In the Istanbul Strait, the average number of vessels in queue decreases by 61.5 %, while the maximum number observed in any single replication decreases by 40.8 %. The average waiting time decreases by 13 %, and the maximum waiting time recorded under peak congestion conditions decreases by 59.3 %.

In the Canakkale Strait, which is not directly influenced by Canal Istanbul operations, the average number of vessels in queue decreases by 34.6 %, and the maximum value decreases by 28.5 %. The average waiting time declines by 29.2 %, while the maximum waiting time decreases by 46.7 %.

In the Sea of Marmara, the number of vessels in the queue decreases in both average and maximum terms. However, the average waiting time remains nearly unchanged across scenarios. Along the southbound route of Canal Istanbul, the average waiting time is approximately four hours, whereas along the northbound route it increases to between eight and nine hours (Figure 10). This outcome indicates that congestion is more pronounced at the Marmara Sea entrance of Canal Istanbul, where northbound vessels experience longer waiting periods.

At the southern entrance of the Istanbul Strait (Figure 11a), the average number of vessels in queue decreases by 89.7 %, while the maximum queue size decreases by 76.1 %. The average waiting time decreases by 1 %. At the northern entrance of the Istanbul Strait (Figure 11c), the average number of vessels in queue decreases by 89.0 %, and the maximum queue length decreases by 84.3 %. The average waiting time increases slightly by 1.39 %.

In contrast, at the northern entrance of the Canakkale Strait (Figure 11b), the average number of vessels in queue increases by 65.5 %, and the maximum number recorded in a single replication increases by 42.6 %. The average waiting time increases by 65.6 %, indicating heightened congestion in this section of the system.
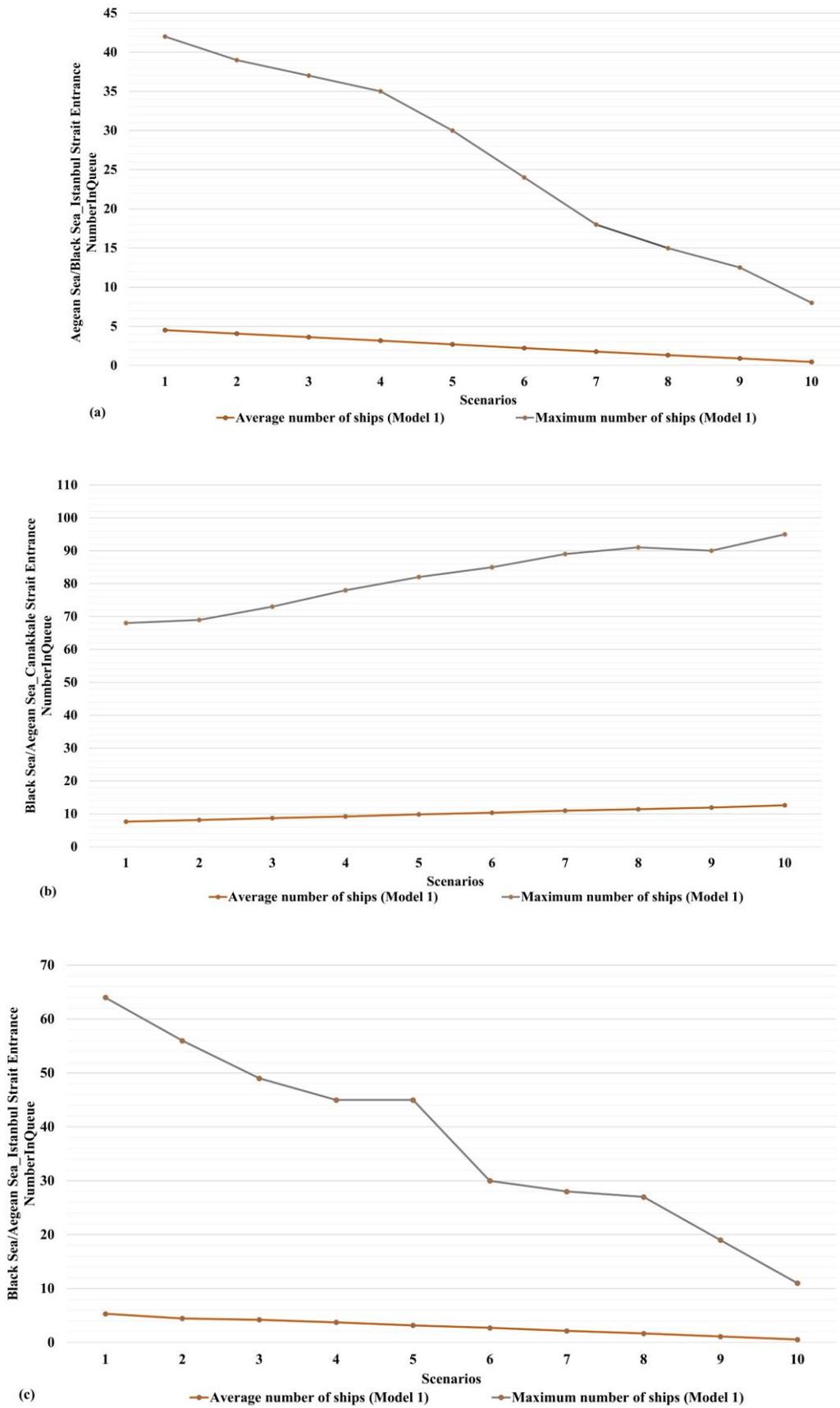
Fig. 9 (a) Queue length at the southern entrance of the Istanbul Strait for Transfer Route 4 (Aegean Sea–Black Sea) in Model 1. (b) Queue length at the northern entrance of the Canakkale Strait for Transfer Route 3 (Black Sea–Aegean Sea) in Model 1. (c) Queue length at the northern entrance of the Istanbul Strait for Transfer Route 3 (Black Sea–Aegean Sea) in Model 1.

Table 5 Simulation Results of Model 2: Vessel Traffic and Waiting Times Under Different Scenarios

| Istanbul Strait										
Scenario ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of vessels										
Average vessels passed	13	10	9	8	8	7	7	6	5	5
Maximum vessels passed	71	64	62	61	59	54	54	49	45	42
Waiting time in queue										
Average waiting time (hrs)	10	8.84	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.7
Maximum waiting time (hrs)	524	472	464	472	464	276	374	359	237	213
Canakkale Strait										
Scenario ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of vessels										
Average vessels passed	26	19	19	18	19	19	18	18	18	17
Maximum vessels passed	105	78	76	75	73	75	73	74	75	75
Waiting time in queue										
Average waiting time (hrs)	20.45	15.41	15.3	15.19	15.07	14.93	14.81	14.69	14.58	14.46
Maximum waiting time (hrs)	77	43	43	43	43	43	43	42	42	41
Sea of Marmara										
Scenario ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of vessels										
Average vessels passed	112	102	97	92	86	80	74	69	64	58
Maximum vessels passed	326	322	309	300	289	259	260	234	215	202
Waiting time in queue										
Average waiting time (hrs)	87	103.72	103.79	103.78	103.84	103.16	103.29	103.07	104.41	103.08
Maximum waiting time (hrs)	1127	1146	756	1146	756	756	1126	1126	555	466
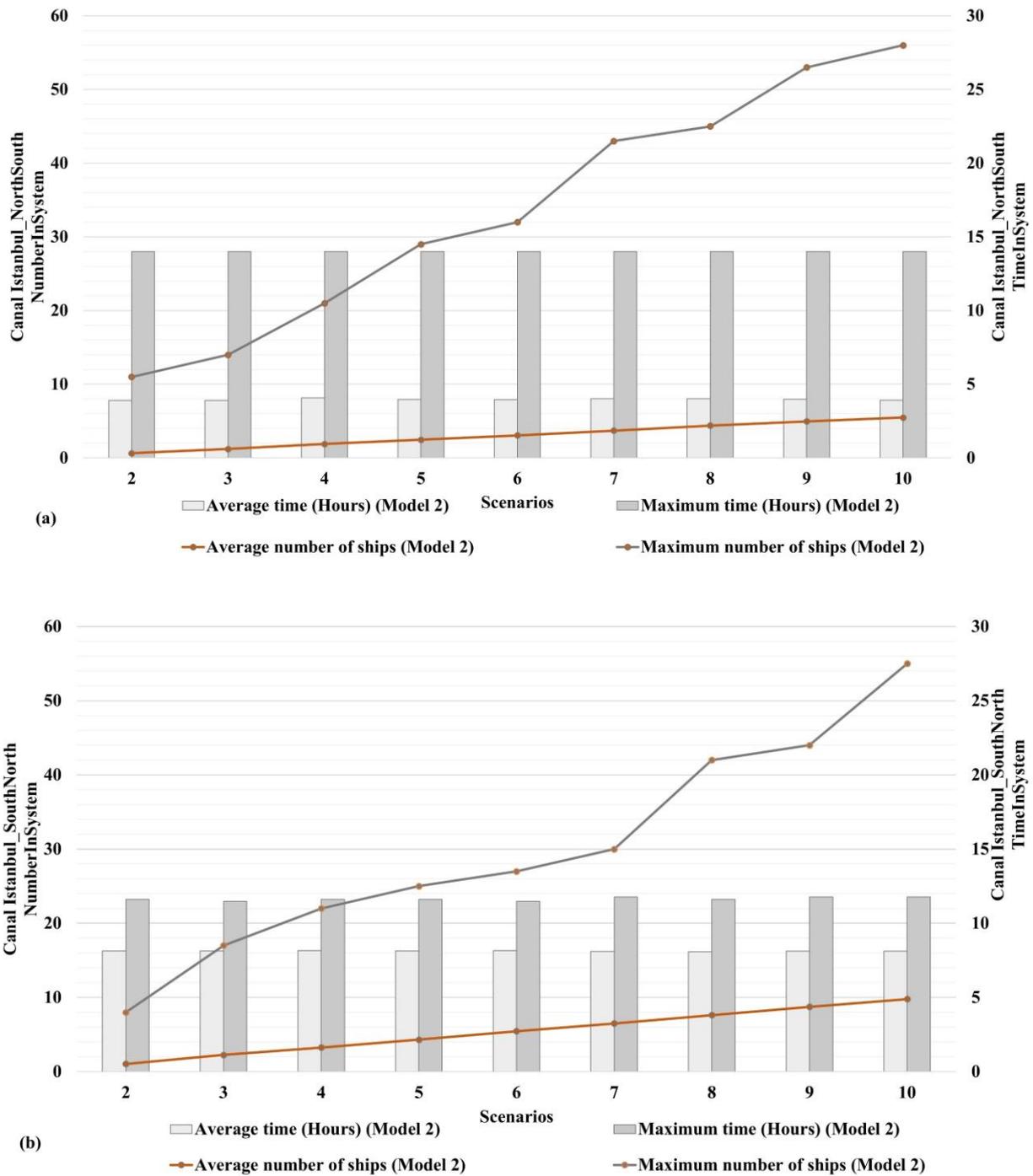
Fig. 10 (a) Number of vessels and waiting times in Canal Istanbul for Model 2 in the north-south direction. (b) Number of vessels and waiting times in Canal Istanbul for Model 2 in the south-north direction.
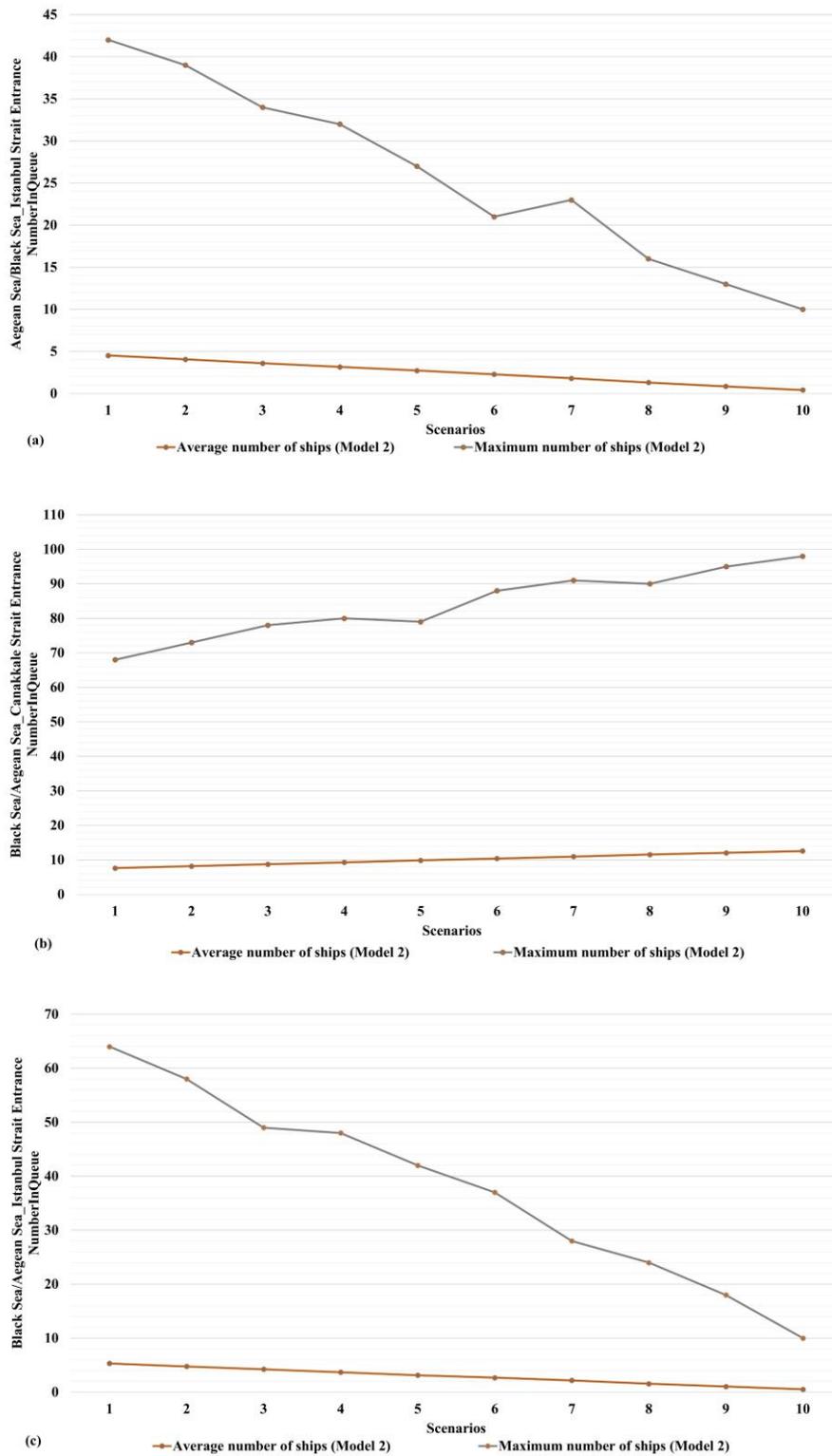
Fig. 11 (a) Queue length at the southern entrance of the Istanbul Strait for Transfer Route 4 (Aegean Sea–Black Sea) in Model 2. (b) Queue length at the northern entrance of the Canakkale Strait for Transfer Route 3 (Black Sea–Aegean Sea) in Model 2. (c) Queue length at the northern entrance of the Istanbul Strait for Transfer Route 3 (Black Sea–Aegean Sea) in Model 2.

4.3 Comparison of the Model 1 and Model 2

The previous sections provide a detailed evaluation of queue dynamics and system performance for both models. This section compares the overall performance of Model 1 and Model 2 by analysing total values

across different routes. The comparison focuses on Transfer Routes 1, 3, 4, and 6, which include both transit and non-transit vessels, with particular attention to queue behaviour.

Figure 12 presents the comparative results for both models and indicates no substantial differences in overall system performance. Figure 13 illustrates waiting times across the analysed routes, showing a decrease on Transfer Routes 3 and 4, where transit vessels operate. In contrast, waiting times increase on Transfer Routes 1 and 6, which are primarily used by non-transit vessels. This outcome suggests that the reduction in transit vessel density leads to increased waiting times for non-transit ships, indicating a redistribution effect within the system.

Table 6 compares key system performance indicators for Model 1 and Model 2 across all routes, focusing on the *NumberInSystem* and *TimeInSystem* parameters. Both models exhibit a consistent decline in average and maximum vessel presence, with optimal performance achieved under Scenario 10. Under this scenario, Model 2 has, on average, 4.4 % fewer vessels in the system than Model 1. Furthermore, at peak congestion levels, the one-way traffic configuration of Model 2 accommodates 5.4 % fewer vessels than the two-way traffic configuration of Model 1.

In Model 2, the average system presence time decreases from 74 to 71 hours, a 4 % reduction. The maximum system presence time decreases from 687 hours to 482 hours, representing a 30 % reduction relative to the two-way traffic model. These results demonstrate the superior efficiency of the one-way ship traffic configuration in reducing congestion and improving overall system performance.

The findings further indicate that two-way ship traffic in the Canal Istanbul may result in capacity saturation, longer waiting times, and an increased risk of collisions and navigational conflicts. Such conditions may force vessels to reduce speed, thereby increasing the complexity of traffic management. In contrast, a one-way traffic configuration optimizes canal capacity and reduces operational challenges. However, if canal traffic is dominated by high-risk vessels, ship density and waiting times may increase, potentially reducing system efficiency.

Overall, the results indicate that a one-way ship traffic model simplifies operational processes, minimizes waiting times, and enhances canal efficiency, thereby contributing positively to maritime traffic performance within the Turkish Straits System.

The simulation interface allows real time monitoring of model operations. The Speed Factor module in Simio adjusts the simulation execution speed, while the Step module enables sequential observation of entity movements throughout the system.

Table 6 Comparative Analysis of System Performance Metrics for Model 1 and Model 2 Scenarios

| Scenario ID	1	2	3	4	5	6	7	8	9	10
Number In System										
Average (Model 1)	140	131	126	121	117	111	106	101	96	91
Average (Model 2)	140	131	126	121	115	109	104	99	94	87
Maximum (Model 1)	369	353	344	323	320	306	285	283	273	261
Maximum (Model 2)	369	359	339	326	317	294	296	270	263	247
Time In System										
Average Hours (Model 1)	143	102	99	95	92	88	85	81	78	74
Average Hours (Model 2)	143	102	98	95	91	86	83	79	76	71
Maximum Hours (Model 1)	1357	1352	1267	880	1140	752	935	879	691	687
Maximum Hours (Model 2)	1357	1353	964	1353	964	770	1140	1140	540	482
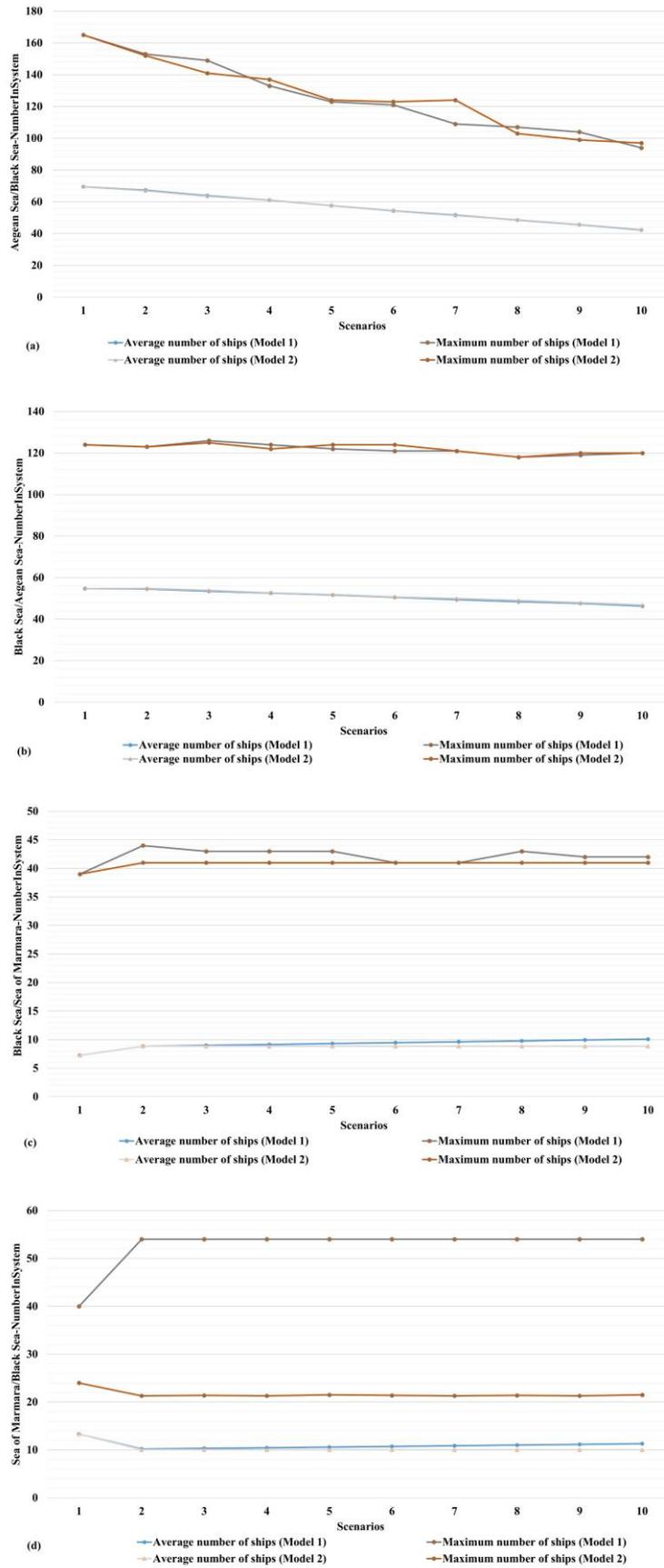
Fig. 12 (a) Comparison of the number of ships in the system on Transfer route 4. (b) Comparison of the number of ships in the system on transfer route 3. (c) Comparison of the number of ships in the system on transfer route 1. (d) Comparison of the number of ships in the system on transfer route 6.
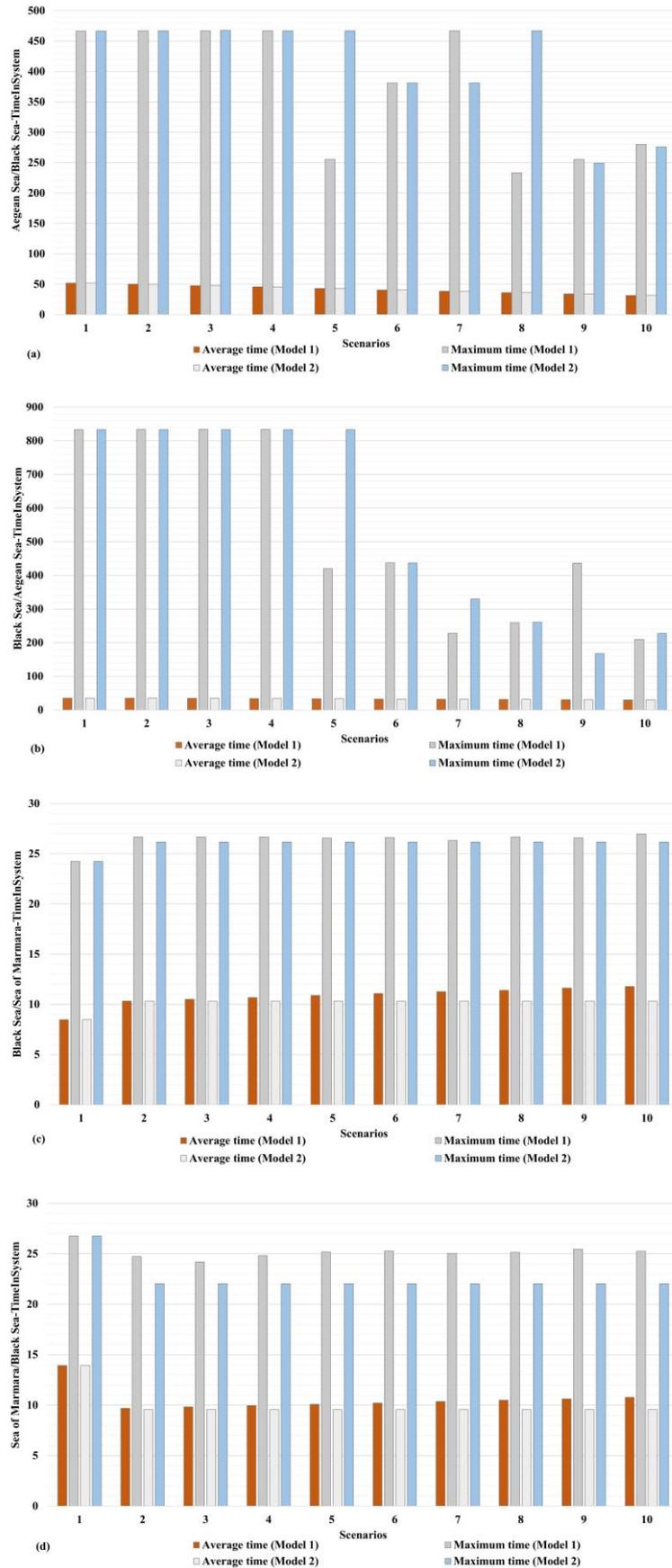
Fig. 13 Impact of One-Way and Two-Way Traffic on Ship Waiting Times Across Transfer Routes. (a) System time comparison on Transfer Route 4. (b) System time comparison on Transfer Route 3. (c) System time comparison on Transfer Route 1. (d) System time comparison on Transfer Route 6.

4.4 Validation

Simulation studies aim to ensure that model outputs are consistent with real world system behaviour. Although achieving identical results is not feasible, a close alignment between simulated and observed performance indicators is generally considered sufficient for validation. Accordingly, the validation process involves comparing predicted system performance metrics with empirical data using established statistical techniques. Events generated within the simulation model are systematically compared with real world occurrences to ensure behavioural and operational consistency.

The simulation model developed in this study consists of multiple sub models operating simultaneously within the main ship traffic framework. This parallel execution increases the complexity of system monitoring and validation. Therefore, the primary validation approach is to compare simulated ship traffic outputs with historical real-world data, as recommended in previous studies [20, 35-38, 59, 85,86]. The Simio monitoring module enables real time observation of entity behaviour and facilitates the detection of potential logic or sequencing errors within the model [75].

Throughout the validation process, ship arrivals, assigned attributes, queue movements, and system entry and exit events are closely monitored within each sub model. Any inconsistencies arising from modelling logic or parameterization are identified through this monitoring process and corrected accordingly. In addition to qualitative checks, quantitative validation metrics, including relative error, absolute error, and root mean square error (RMSE), are used to assess the predictive accuracy of the simulation results against observed values.

Table 7 presents the validation outcomes, comparing historical ship traffic data with simulated results. The entities *Ship_AegeanBlackSea* and *Ship_BlackSeaAegean* exhibit a relative error of 0, indicating a perfect match between simulated outputs and real-world observations. Similarly, the entities *Ship_AegeanMarmara* (SN), *Ship_BlackSeaMarmara* (NS), *Ship_MarmaraAegean* (NS), and *Ship_MarmaraBlackSea* (SN) display minimal deviations, with relative error values of 0.07, 0.18, and 0.012, respectively. The average absolute error across all entities is 0.0437 %, while the average RMSE value is 0.0525, indicating that the simulation results closely approximate real world traffic patterns with a significance level of approximately 0.05 %. Error values falling within a 95 % confidence interval further confirm the robustness and accuracy of the model [5, 20, 23, 37, 87].

Validation of queuing behaviour and congestion dynamics is further supported by descriptive statistical analysis of AIS-based waiting-time data. The results indicate that the average waiting time in the Istanbul Strait is 1.6 hours, with a standard deviation of 0.9 hours. In the Canakkale Strait, the average waiting time is 1.1 hours, with a standard deviation of 0.7 hours. In contrast, the Sea of Marmara exhibits substantially higher variability, with an average waiting time of 3.8 hours and a standard deviation of 5.4 hours.

The coefficient of variation values indicate that congestion in the Sea of Marmara is considerably more irregular, with a coefficient of variation of approximately 1.42, compared to approximately 0.56 for the Istanbul Strait and 0.63 for the Canakkale Strait. Positive skewness values observed across all regions, ranging from 1.2 to 3.8, indicate the presence of infrequent but severe congestion peaks, typically associated with traffic concentration during specific periods of the day.

These statistical characteristics, derived directly from real AIS data, are consistent with the simulation outcomes presented in Section 4.3, particularly the increased waiting times observed at the Marmara entrance of Canal Istanbul. The strong correspondence between real-world congestion indicators and simulated results reinforces the model's predictive capacity and supports the reliability of its queuing structure. Overall, the high level of agreement between observed and simulated data confirms the validity of the model and demonstrates its suitability for maritime traffic analysis and scenario-based evaluation.

Table 7 Error Analysis of Simulation Results

Ship Type	Number of Vessels			Average Absolute Error (%)	Average RMSE (%)
	Simulation Results	Real Data	Relative Error (%)		
Ship_AegeanBlackSea(SN)	11720	11720	0	0,0437	0,0525
Ship_AegeanMarmara(SN)	9934	9940	0,07		
Ship_BlackSeaAegean(NS)	13592	13592	0		
Ship_BlackSeaMarmara(NS)	7505	7518	0,18		
Ship_MarmaraAegean(NS)	8390	8391	0,012		
Ship_MarmaraBlackSea(SN)	9200	9206	0,07		

5. Discussion

This study develops and applies a simulation-based framework to evaluate the impact of the Canal Istanbul on ship traffic within the Turkish Straits System. Two alternative operational configurations are examined: a one-way ship traffic model (Model 2) and a two-way ship traffic model (Model 1). The simulation is constructed using one year of AIS data obtained from the Istanbul and Canakkale Straits and integrates state variables and key navigational parameters. The primary objective is to compare the performance of ship traffic flow under these two models across multiple transfer routes.

Initial results indicate that both models produce comparable results for overall ship numbers and waiting times. However, a more detailed examination reveals that Model 2 exhibits higher operational efficiency, primarily due to its ability to reduce transit ship density. This reduction indirectly influences non transit ship movements by easing congestion at critical points. The one-way transit configuration minimizes ship interactions and congestion, which is essential for maintaining continuity and predictability in maritime traffic operations. These findings provide important insights for the design of future ship traffic management strategies in constrained waterways.

The distribution of vessel types between the Istanbul Strait and Canal Istanbul emerges as a key determinant of ship density and waiting times. Model 2 demonstrates clear advantages, particularly when Canal Istanbul is dedicated to one way transit traffic. Scenario 10, in which 90 % of transit ships are redirected to Canal Istanbul and 10 % continue to use the Istanbul Strait, yields the most pronounced efficiency improvements compared to the current system configuration.

Answer to RQ-1: The results confirm that Model 2 outperforms Model 1 in reducing ship congestion and improving waiting time efficiency. In Scenario 10, where the majority of transit ships are rerouted through Canal Istanbul, overall ship density decreases by 36 % and waiting times are reduced by 50 %. These findings highlight the importance of optimized traffic redistribution and demonstrate that a one-way transit configuration enhances ship mobility, prevents excessive queuing, and mitigates navigational conflicts in high traffic corridors.

Answer to RQ-2: One way and two-way traffic configurations produce markedly different outcomes in terms of traffic flow, queue formation, and transit durations. One way ship traffic provides a more streamlined navigation process by limiting ship interactions and reducing conflict points. In contrast, two-way traffic introduces greater navigational complexity, often resulting in bottlenecks at entry and exit points. The results suggest that one way passage systems are more suitable for constrained waterways such as the TSS, where high ship density creates substantial operational challenges.

Answer to RQ-3: Scenario based analyses indicate that traffic distribution plays a critical role in overall system efficiency. Among all evaluated scenarios, Scenario 10 achieves the most balanced traffic flow by effectively utilizing Canal Istanbul as an alternative transit route. Conversely, scenarios in which most transit ships continue to use the Istanbul Strait led to increased congestion and longer waiting times. These findings demonstrate that strategically allocating ship traffic across multiple routes significantly improves system stability and operational efficiency.

Answer to RQ-4: The simulation results confirm that transit ships are the primary contributors to congestion within the TSS, particularly at critical chokepoints such as the Istanbul Strait. Redirecting transit ships through Canal Istanbul substantially reduces the operational burden on the Istanbul Strait, resulting in smoother traffic flow. However, non-transit ships, which predominantly operate between the Sea of Marmara and the Aegean or Black Sea, benefit less from canal integration. This suggests that while transit ship redistribution improves overall system performance, additional measures are necessary to achieve balanced traffic conditions across all vessel categories.

Answer to RQ-5: Canal Istanbul significantly reduces queuing congestion at both the northern and southern entry points of the Istanbul Strait. In Scenario 10, the number of ships waiting in queues at the Istanbul Strait decreases by more than 50 %, and the maximum waiting time is reduced by 56 %. These results confirm that Canal Istanbul effectively redistributes ship traffic and alleviates congestion at major transit bottlenecks. At the same time, the analysis reveals localized increases in waiting times in the Sea of Marmara and the Canakkale Strait, particularly near southern junctions where traffic streams from Canal Istanbul and the Istanbul Strait converge. This outcome reflects a spatial redistribution of congestion rather than a deterioration in overall system efficiency. The Sea of Marmara functions as a transitional zone connecting two high traffic straits, and temporary vessel accumulation is a natural consequence of this convergence. From a navigational perspective, this trade off highlights the importance of adaptive traffic management and speed control regulations to sustain balanced operations throughout the TSS. Although the model does not explicitly account for collision probabilities or hydrodynamic risk factors, the findings provide valuable system level insights into navigational safety and long-term operational sustainability.

Despite the insights obtained, further research is required to expand the scope of analysis and refine the simulation framework. Incorporating larger datasets and a wider range of parameters would enhance statistical robustness. Future studies should also consider seasonal variations, changing meteorological conditions, and emergency traffic management strategies. This study represents an initial step toward evaluating alternative approaches to ship traffic management within the TSS. Examining individual system components deepens understanding of their interactions and cumulative effects on traffic flow. While Canal Istanbul significantly improves efficiency in the Istanbul Strait, its impacts vary across different regions, indicating the need for continued research to optimize ship traffic operations and maintain balanced maritime traffic distribution throughout the entire system.

6. Conclusions

This study develops a dynamic simulation model to evaluate the impact of the Canal Istanbul Project (CIP) on ship traffic flow within the Turkish Straits System (TSS). As one of the world's busiest and most strategically significant maritime corridors, the TSS faces increasing congestion due to growing ship sizes and cargo capacities, strict transit regulations, unpredictable closures, and extended waiting times. Canal Istanbul has been proposed as an alternative maritime route to alleviate congestion, enhance navigational safety, and improve overall maritime efficiency.

To assess its feasibility and operational effectiveness, two alternative simulation models were developed: Model 1, which allows two-way ship traffic through the Canal Istanbul, and Model 2, which implements a one-way ship traffic system. The simulation framework integrates historical Automatic Identification System (AIS) data, maritime traffic regulations, and principles of queuing theory to accurately represent real-world navigational conditions. A scenario-based analysis is conducted to compare ship density and waiting times under different traffic redistribution strategies.

The findings indicate that although both models yield similar overall traffic distributions, Model 2 performs better in terms of congestion reduction and operational efficiency. The most pronounced improvement is observed in Scenario 10, in which 90 % of transit ships are redirected to Canal Istanbul, resulting in a 36 % reduction in overall ship density and a 50 % decrease in waiting times. These results clearly demonstrate the effectiveness of diverting transit ship traffic away from the Istanbul Strait. A detailed examination of individual TSS components provides several important insights:

•**Istanbul Strait:** Ship congestion and waiting times decrease by more than 50 %, leading to a substantial improvement in navigational efficiency. Increased use of the Canal Istanbul significantly alleviates pressure on the strait, enabling smoother, more predictable traffic flow.

•**Sea of Marmara:** Although congestion in the Istanbul Strait is reduced, ship density and waiting times increase in the Sea of Marmara, indicating a spatial redistribution rather than a complete elimination of congestion. This finding highlights the need for additional traffic regulation and coordination strategies in this transitional maritime zone.

•**Canakkale Strait:** Ship density and waiting times decline by approximately 30 % overall; however, the queue length at the Marmara Sea entrance of the Canakkale Strait increases by nearly 40 %, suggesting that traffic redistribution may generate new localized bottlenecks that require further operational optimization.

Overall, the results confirm that Canal Istanbul has the potential to improve navigational efficiency within the TSS, particularly by significantly reducing congestion in the Istanbul Strait. At the same time, the findings reveal new challenges in traffic distribution, especially in the Sea of Marmara and at the Canakkale Strait junctions. These outcomes suggest that while Canal Istanbul represents a viable alternative transit route, its long-term effectiveness depends on the implementation of a holistic, system-wide ship traffic management strategy.

This study represents the first comprehensive simulation-based analysis of Canal Istanbul's impact on TSS ship traffic, employing a data driven queuing and traffic flow modelling approach. Unlike previous studies that primarily focus on risk assessment, regulatory frameworks, or localized traffic behaviour, this research quantitatively evaluates the effects of a newly proposed maritime corridor on congestion levels, transit efficiency, and waiting times across the entire system. The results demonstrate that Canal Istanbul can substantially enhance maritime traffic performance, particularly in the Istanbul Strait, while also introducing new operational challenges that require further research and policy refinement.

Future studies should adopt a multidisciplinary perspective, integrating traffic simulation, economic impact analysis, environmental sustainability considerations, and legal and institutional frameworks to develop a comprehensive strategy for optimizing ship traffic in constrained maritime corridors. Expanding the simulation framework and incorporating real time maritime data will contribute to a more resilient, efficient, and sustainable ship traffic management system within the TSS.

ACKNOWLEDGEMENTS

DATA AVAILABILITY

The data set used in this study is available on Mendeley Data and can be accessed at the following link: https://data.mendeley.com/preview/y9d7rwb7tc?a=7c63556b-9e82-4023-86bd-4f451fff2049. The data is publicly accessible, and researchers can download and analyse the dataset freely.
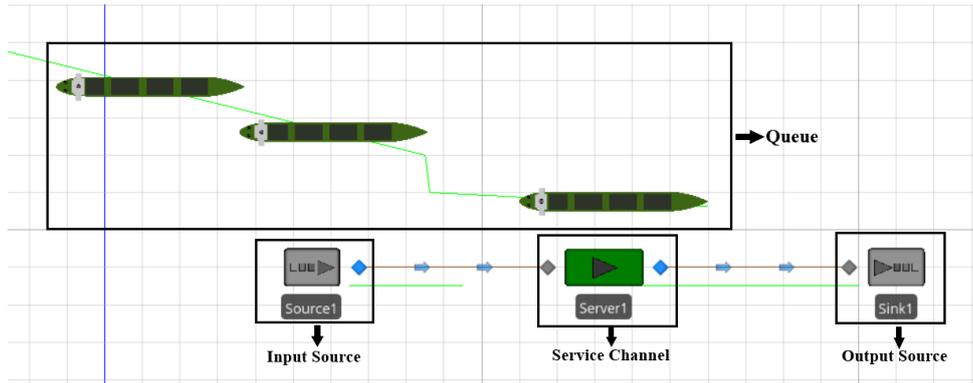
APPENDIX

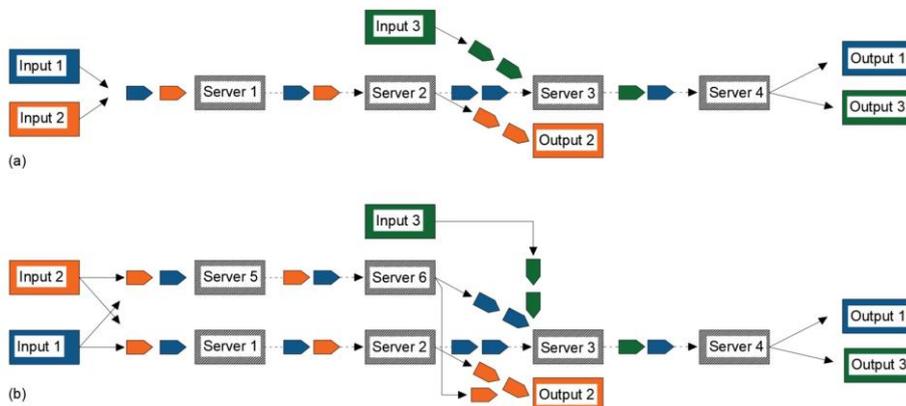Fig. A1 Simio-based queue system representation

Fig. A2 (a) Existing service mechanism of the TSS. (b) Service mechanism of Canal Istanbul.

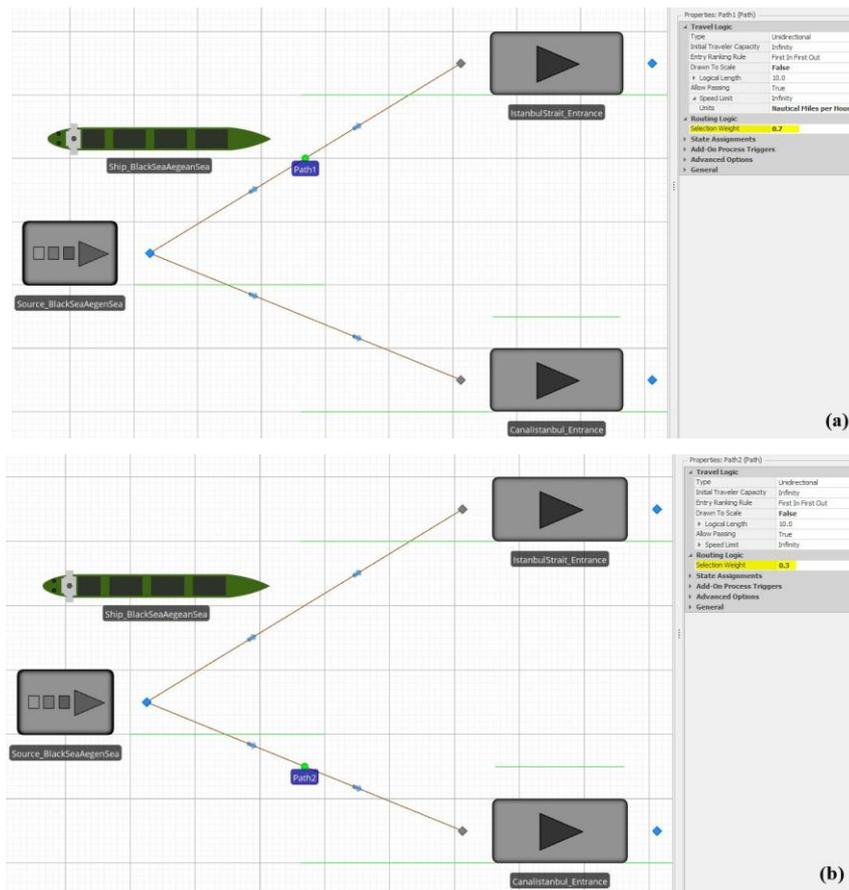Fig. A3 (a) System result screen. (b) Queue result screen.

Fig. A4 (a) Scenario-based weight distribution for the Istanbul Strait. (b) Scenario-based weight distribution for Canal Istanbul.

REFERENCES

[1]   Afcan, 2018.Le service d'information de trafic maritime dans les détroits Turcs (TSVTS), *Rue de Bassam* - 29200 Brest.

[2]   Kutluk, E., 2018. İstanbul Boğazı'ndan geçen gemilerin oluşturduğu trafik yükünün çevresel etkileri: Ro-Ro gemileri özelinde bir inceleme. *Marmara Üniversitesi Siyasal Bilimler Dergisi*, 6(1),285-310. https://doi.org/10.14782/MARUSBD.412651

[3]   Ulusçu, Ö.S., Özbaş, B., Altıok, T., Or, İ., 2009. Risk analysis of the vessel traffic in the strait of Istanbul. *Risk Analysis: An International Journal,* 29(10),1454-1472. https://doi.org/10.1111/j.1539-6924.2009.01287.x

[4]   Aydogdu, Y.V., Yurtoren, C., Park, J.S., Park, Y.S., 2012. A study on local traffic management to improve marine traffic safety in the Istanbul Strait. *The Journal of Navigation*, 65(1), 99-112. https://doi.org/10.1017/S0373463311000555

[5]   Or, İ., Ozbas, B. Yilmaz, T., 2007. Simulation of Maritime Transit Traffic in the İstanbul Strait–II: Incorporating the Traffic Regime, Arrival Processes, Meteorological Conditions. *In Proceedings of the 21st European Conference on Modelling and Simulation*, 548-553. https://doi.org/10.7148/2007-0548

[6]   Yildiz, S., Uğurlu, Ö., Loughney, S., Wang, J., Tonoğlu, F., 2022. Spatial and statistical analysis of operational conditions influencing accident formation in narrow waterways: A Case Study of Istanbul Strait and Dover Strait. *Ocean Engineering*, 265, 112647. https://doi.org/10.1016/J.OCEANENG.2022.112647.

[7]   Özlem, Ş., Or, İ., Altan, Y.C., 2021. Scheduling and simulation of maritime traffic in congested waterways: An application to the Strait of Istanbul. *The Journal of Navigation*, 74(3), 656-672. https://doi.org/10.1017/S0373463320000715

[8]   Ma, Q., Pan, J., Zhou, Y., Zhou, S., Zhang, M., 2025. Optimization of maritime emergency base placement for inland waterway accident response: a case study of the Yangtze River. *Brodogradnja*, 76(1), 1-24. https://doi.org/10.21278/brod76107

[9]   Eski, Ö., Tavacioglu, L., 2024. A combined method for the evaluation of contributing factors to maritime dangerous goods transport accidents. *Brodogradnja*, 75(4), 75408. https://doi.org/10.21278/brod75408

[10]   Malekipirbazari, M., Aksakalli, V. Aydogdu, V., 2015, March. A temporal analysis of vessel type traffic in Istanbul Strait anchorages. *In 2015 International Conference on Industrial Engineering and Operations Management* (IEOM),1-7. IEEE. https://doi.org/10.1109/IEOM.2015.7093878

[11]   Arslan, O., Turan, O., 2009. Analytical investigation of marine casualties at the Strait of Istanbul with SWOT–AHP method. *Maritime Policy & Management*, 36(2), 131-145. https://doi.org/10.1080/03088830902868081.

[12]   Aydogdu, Y.V., 2014. A comparison of maritime risk perception and accident statistics in the Istanbul Straight. *The Journal of Navigation*, 67(1),129-144. https://doi.org/10.1017/S0373463313000593

[13]   Ece, N.J., 2019. Analysis of Marine Accidents in the Strait of Istanbul Using Qualitative&Quantative Methods. *Mersin University Journal of Maritime Faculty*, 1(1), 1-9. https://dergipark.org.tr/en/pub/meujmaf/649064

[14]   Erol, S., Demir, M., Çetişli, B., Eyüboğlu, E., 2018. Analysis of ship accidents in the Istanbul Strait using neuro-fuzzy and genetically optimised fuzzy classifiers. *The Journal of Navigation*, 71(2), 419-436. https://doi.org/10.1017/S0373463317000601

[15]   Görçün, Ö.F., Burak, S.Z., 2015. Formal safety assessment for ship traffic in the Istanbul Straits. *Procedia-Social and Behavioral Sciences*, 207, 252-261. https://doi.org/10.1016/J.SBSPRO.2015.10.094.

[16]   Ilgar, R., 2015. Çanakkale Boğazındaki gemi hareketliliği ve kaza risk haritasının belirlenmesi. *Türk Coğrafya Dergisi*, (65), 1-10. https://doi.org/10.17211/TCD.73754

[17]   Kılıç, A., Sanal, H.T., 2015. Çanakkale Boğazı'nda karaya oturmayla sonuçlanan gemi kazaları. *Balıkesir Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, 17(2), 38-50. http://fbed.balikesir.edu.tr/index.php/dergi/article/view/321.

[18]   Liu, K., Xin, X., Ma, J., Zhang, J., Yu, Q., 2019. Sensitivity analysis of ship traffic in restricted two-way waterways considering the impact of LNG carriers. *Ocean Engineering*, 192, 106556. https://doi.org/10.1016/J.OCEANENG.2019.106556.

[19]   Merrick, J.R., Van Dorp, J.R., Blackford, J.P., Shaw, G.L., Harrald, J., Mazzuchi, T.A., 2003. A traffic density analysis of proposed ferry service expansion in San Francisco Bay using a maritime simulation model. *Reliability Engineering & System Safety*, 81(2), 119-132. https://doi.org/10.1016/S0951-8320(03)00054-1

[20]   Özbaş, B., Or, I., 2007. Analysis and control of maritime transit traffic through the Istanbul Channel: a simulation approach. *Central European Journal of Operations Research*, 15(3), 235-252. https://doi.org/10.1007/S10100-007-0028-9.

[21]   Rahimikelarijani, B., Abedi, A., Hamidi, M., Cho, J., 2018. Simulation modeling of Houston Ship Channel vessel traffic for optimal closure scheduling. *Simulation Modelling Practice and Theory*, 80, 89-103. https://doi.org/10.1016/J.SIMPAT.2017.10.004

[22]   Yazici, M.A., Otay, E.N., 2009. A navigation safety support model for the Strait of Istanbul. *The Journal of Navigation*, 62(4), 609-630. https://doi.org/10.1017/S0373463309990130

[23]   Hang, F., Di, Z., Shanshan, F., Qing, W., Chengpeng, W., 2015, June. Modeling the ship traffic in the Three Gorges area. *In 2015 International Conference on Transportation Information and Safety* (ICTIS) 699-705. IEEE. https://doi.org/10.1109/ICTIS.2015.7232155

[24]   Mavrakis, D., Kontinakis, N., 2008. A queueing model of maritime traffic in Bosporus Straits. *Simulation Modelling Practice and Theory*, 16(3), 315-328. https://doi.org/10.1016/J.SIMPAT.2007.11.013.

[25]   Directorate General of Coastal Safety, 2022. Turkish Straits Ship Passage Statistic. https://denizcilikistatistikleri.uab.gov.tr/turk-bogazlari-gemi-gecis-istatistikleri (accessed 10 March 2023)

[26]   Directorate General of Coastal Safety, 2021. Sectoral Report for 2021. https://www.kiyiemniyeti.gov.tr/Data/1/Files/Document/Documents/XW/Cu/bY/hy/2021%20YILI%20SEKT%C3%96R%20RAPORU.pdf (accessed 10 March 2023)

[27]   Directorate General of Coastal Safety, 2020. Sectoral Report for 2020. https://www.kiyiemniyeti.gov.tr/Data/1/Files/Document/Documents/J8/ov/0T/Eh/2020%20YILI%20SEKT%C3%96R%20RAPORU%20.pdf (accessed 10 March 2023)

[28]   Directorate General of Coastal Safety, 2019b. Turkish Straits Maritime Traffic Order Regulation.

[29]   Directorate General of Coastal Safety, 2019. Sectoral Report for 2019. https://www.kiyiemniyeti.gov.tr/Data/1/Files/Document/Documents/Cj/1q/Wi/Y5/Sekt%C3%B6r%20Raporu%202019.pdf (accessed 10 March 2023)

[30]   Öztürk, B., Poyraz, Ö. Özgür, E., 2006. The Turkish Straits: Some Considerations, Threats and Future. Turkish Straits-Maritime Safety, Legal and Environmental Aspects. *Turkish Marine Research Foundation*, İstanbul. Publication, 25, 116-132.

[31]   Tonoğlu, F., Atalar, F., Başkan, İ.B., Yildiz, S., Uğurlu, Ö., Wang, J., 2022. A new hybrid approach for determining sector-specific risk factors in Turkish Straits: Fuzzy AHP-PRAT technique. *Ocean Engineering*, 253, 111280. https://doi.org/10.1016/J.OCEANENG.2022.111280

[32]   Uğurlu, Ö., Erol, S., Başar, E., 2016. The analysis of life safety and economic loss in marine accidents occurring in the Turkish Straits. *Maritime Policy & Management*, 43(3), 356-370. https://doi.org/10.1080/03088839.2014.1000992.

[33]   I.M. The Republic of Turkey Ministry of Transport, Maritime Affairs and Communications, 2019. Kanal İstanbul Projesi Çevresel Etki Değerlendirme Başvuru Dosyası [Application File of Environmental Impact Evaluation of Canal Istanbul], Ankara.

[34]   Köse, E., Başar, E., Demirci, E., Güneroğlu, A., Erkebay, Ş., 2003. Simulation of marine traffic in Istanbul Strait. *Simulation Modelling Practice and Theory*, 11(7-8), 597-608. https://doi.org/10.1016/J.SIMPAT.2003.10.001

[35]   Franzese, L.A.G., Abdenur, L.O., Botter, R.C., Starks, D., Cano, A.R., 2004. Simulating the Panama Canal: present and future. *In Proceedings of the 2004 Winter Simulation Conference*, 2, 1835-1838. IEEE. https://doi.org/10.1109/WSC.2004.1371537

[36]   Almaz, A.O., Or, I., Ozbas, B., 2006. Investigation of transit maritime traffic in the strait of Istanbul through simulation modeling and scenario analysis. *International Journal of Simulation*, 7(7), 1-9.

[37]   Almaz, O.A., Altiok, T., 2012. Simulation modeling of the vessel traffic in Delaware River: Impact of deepening on port performance. *Simulation modelling practice and Theory*, 22, 146-165. https://doi.org/10.1016/J.SIMPAT.2011.12.004.

[38]   Qu, X., Meng, Q., 2012. Development and applications of a simulation model for vessels in the Singapore Straits. *Expert Systems with Applications*, 39(9), 8430-8438. https://doi.org/10.1016/J.ESWA.2012.01.176.

[39]   Mandalaki, G., Manesis, S., 2013, April. 3D Simulation analysis of Patras new port operations in SIMIO platform environment. *In 2013 UKSim 15th International Conference on Computer Modelling and Simulation*, 554-558. IEEE. https://doi.org/10.1109/UKSIM.2013.56

[40]   Dong, F., Van Oyen, M.P., Singer, D.J., 2014. Dynamic control of the N queueing network with application to shipbuilding. *International Journal of Production Research*, 52(4), 967-984. https://doi.org/10.1080/00207543.2013.827803.

[41]   Sluiman, F.J., 2017. Transit vessel scheduling. *Naval Research Logistics* (NRL), 64(3), 225-248. https://doi.org/10.1002/NAV.21742.

[42]   Lalla-Ruiz, E., Shi, X., Voß, S., 2018. The waterway ship scheduling problem. *Transportation Research Part D: Transport and Environment*, 60, 191-209. https://doi.org/10.1016/J.TRD.2016.09.013.

[43]   Meisel, F., Fagerholt, K., 2019. Scheduling two-way ship traffic for the Kiel Canal: Model, extensions and a matheuristic. *Computers & Operations Research*, 106, 119-132. https://doi.org/10.1016/J.COR.2019.02.015.

[44]   Andersen, T., Hove, J.H., Fagerholt, K., Meisel, F., 2021. Scheduling ships with uncertain arrival times through the Kiel Canal. *Maritime Transport Research*, 2, 100008. https://doi.org/10.1016/J.MARTRA.2020.100008.

[45]   Li, J., Zhang, X., Yang, B., Wang, N., 2021. Vessel traffic scheduling optimization for restricted channel in ports. *Computers & Industrial Engineering*, 152, 107014. https://doi.org/10.1016/J.CIE.2020.107014.

[46]   Bolat, P., Kayisoglu, G., 2021. Arma model-based prediction of the number of vessels navigating the istanbul strait unassisted by maritime pilots. *Transactions on Maritime Science*, 10(01), 6-19. https://doi.org/10.7225/TOMS.V10.N01.001.

[47]   Zhang, M., Zhang, D., Fu, S., Kujala, P., Hirdaris, S., 2022. A predictive analytics method for maritime traffic flow complexity estimation in inland waterways. *Reliability Engineering & System Safety*, 220, 108317. https://doi.org/10.1016/J.RESS.2021.108317.

[48]   Wen, Y., Tao, W., Sui, Z., Piera, M.A., Song, R., 2022. Dynamic model-based method for the analysis of ship behavior in marine traffic situation. *Ocean Engineering*, 257, 111578. https://doi.org/10.1016/J.OCEANENG.2022.111578.

[49]   Chen, L., Qi, J., Shi, J., 2023. A cellular automata ship traffic flow model considering navigation rules in narrowing channel. *Alexandria Engineering Journal*, 69, 715-726. https://doi.org/10.1016/J.AEJ.2023.01.062.

[50]   Zhang, Y., Zheng, Q.Q., He, L.J., Tian, H.W., 2023. Ship traffic optimization method for solving the approach channel and lock co-scheduling problem of the Three Gorges Dam on the Yangzi River. *Ocean Engineering*, 276, 114196. https://doi.org/10.1016/j.oceaneng.2023.114196

[51]   Kundak, S., Baypınar, M.B., 2011. The crazy project–canal Istanbul. TeMA-Journal of Land Use, *Mobility and Environment*, 4(3).

[52]   Eldemir, F., Camci, F., Uysal, O., 2013, January. Analysis and simulation of Istanbul Strait marine traffic management strategies. *In Transportation Research Board 92nd Annual Meeting*, 13-1024.

[53]   Zhang, J., Santos, T.A., Guedes Soares, C., Yan, X., 2017. Sequential ship traffic scheduling model for restricted two-way waterway transportation. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 231(1), 86-97. https://doi.org/10.1177/1475090215621580.

[54]   Liu, Z., Liu, J., Li, Z., Liu, R.W., Xiong, N., 2017. Characteristics analysis of vessel traffic flow and its mathematical model. *Journal of Marine Science and Technology*, 25(2), 25. https://doi.org/10.6119/JMST-017-0109-1

[55]   Tütüncü, A.N., 2017. Montreux Convention and Canal Istanbul. *Milletlerarası Hukuk ve Milletlerarası Özel Hukuk Bülteni*, 37(1), 113-123.

[56]   Sözer, A., Ozsoy, E., 2017. Water exchange through canal İstanbul and Bosphorus Strait. https://doi.org/10.12681/mms.1877.

[57]   Nigussie, T.A., Altunkaynak, A., 2017. Modeling the effects of Project Canal Istanbul on the urban extent and hydrological response of Ayamama watershed, Istanbul. *In World Environmental and Water Resources Congress* 2017 1-11.

[58] Nigussie, T.A., Altunkaynak, A., 2017. Modeling urbanization of Istanbul under different scenarios using SLEUTH urban growth model. *Journal of Urban Planning and Development*, 143(2), 04016037. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000369

[59] Xin, X., Liu, K., Yang, X., Yuan, Z., Zhang, J., 2019. A simulation model for ship navigation in the "Xiazhimen" waterway based on statistical analysis of AIS data. *Ocean Engineering*, 180, 279-289. https://doi.org/10.1016/J.OCEANENG.2019.03.052

[60] Zhang, H., Ke, J., Dong, S., Yuan, Z., 2019. Simulation modeling of state-dependent queuing network: Impact of deepening on the vessel traffic in Yangtze River Estuary. *Advances in Mechanical Engineering*, 11(5), 1687814019845247. https://doi.org/10.1177/1687814019845247

[61] Nigussie, T.A., Altunkaynak, A., 2019. Modeling the effect of urbanization on flood risk in Ayamama Watershed, Istanbul, Turkey, using the MIKE 21 FM model. *Natural Hazards*, 99(2), 1031-1047. https://doi.org/10.1007/s11069-019-03794-y.

[62] Baba, E.C., 2020. The risks of mega urban projects creating a dystopia: Canal Istanbul. *City and Environment Interactions*, 6, 100039. https://doi.org/10.1016/J.CACINT.2020.100039

[63] Balcıoğlu, E.B., 2020. Determination and comparison of anionic surfactant and phosphate concentrations at the entrance and the exit of the Turkish Straits System (TSS). *Marine Pollution Bulletin*, 159, 111525. https://doi.org/10.1016/j.marpolbul.2020.111525.

[64] Ahmed, K.A., Altunkaynak, A., 2020. Modeling groundwater flow and seawater intrusion in the Terkos Lake aquifer due to Canal Istanbul excavation. *Arabian Journal of Geosciences*, 13(1), 10. https://doi.org/10.1007/s12517-019-4983-y.

[65] Saçu, Ş., Erdik, T., Stanev, E.V., Şen, O., Erdik, J.D., Öztürk, İ., 2020. Hydrodynamics of Canal Istanbul and its impact in the northern Sea of Marmara under extreme conditions. *Ocean Dynamics*, 70(6), 745-758. https://doi.org/10.1007/s10236-020-01358-4

[66] Saçu, Ş., Erdik, T., Şen, O., 2020. Salinity distribution at Canal Istanbul and its possible impacts on the Northern Marmara Sea. *China Ocean Engineering*, 34(6), 881-888. https://doi.org/10.1007/s13344-020-0080-y

[67] Menteşe, E.Y., Tezer, A., 2021. Impacts of infrastructure developments on ecosystem services potential in Istanbul. *Frontiers in Environmental Science*, 9, 614752. https://doi.org/10.3389/fenvs.2021.614752

[68] Şen, O., Saçu, Ş., Erdik, T., Öztürk, İ., Stanev, E.V., 2022. Assessing the potential impacts of the Canal Istanbul on the physical oceanography of the Turkish Straits System. *Continental Shelf Research*, 240, 104723. https://doi.org/10.1016/j.csr.2022.104723

[69] Enlil, Z., Dinçer, İ., 2022. Political dilemmas in the making of a sustainable city-region: The case of Istanbul. *Sustainability*, 14(6), 3299. https://doi.org/10.3390/su14063299

[70] Uluengin, D.M., Uluengin, M.B., Ceylanlı, Z., 2022. Branding 'New Istanbul's' Residential Real Estate: A Thematic Analysis of Residential Real Estate Ads for 'Canal Istanbul'and Environs. *Architektúra & Urbanizmus*, 56(1-2), 95-105.

[71] Mersin, K., Bayırhan, İ., Yıldırım, M., 2024. Possible Effects of the Canal Istanbul Waterway Project on Ship Emissions: Challenges and Prospects. *Journal of Coastal Research*, 40(1), 210-222. https://doi.org/10.2112/JCOASTRES-D-22-00094.1

[72] Xu, L., Huang, L., Zhao, X., Liu, J., Chen, J., Zhang, K., He, Y., 2025. Navigational decision-making method for wide inland waterways with traffic separation scheme navigation system. *Brodogradnja*, 76(2), 76201. https://doi.org/10.21278/brod76201

[73] Bonney, M.C., 1971. Simulation and Analysis of Industrial Systems. *Journal of the Operational Research Society*, 22(1), 92-93. https://doi.org/10.1057/JORS.1971.26.

[74] Chen, L.J., Yan, X.P., Huang, L.W., Yang, Z.L., Wang, J., 2018. A systematic simulation methodology for LNG ship operations in port waters: a case study in Meizhou Bay. *Journal of Marine Engineering & Technology*, 17(1), 12-32. https://doi.org/10.1080/20464177.2016.1276823

[75] Law, A.M., Kelton, W.D., Kelton, W.D., 2007. Simulation modeling and analysis (Vol. 3). New York: Mcgraw-hill.

[76] Lee, J.S., Yu, Y.U., 2023. Calculation of categorical route width according to maritime traffic flow data in the Republic of Korea. *Journal of Marine Engineering & Technology*, 22(5), 222-232. https://doi.org/10.1080/20464177.2023.2223396.

[77] Dragović, B., Tzannatos, E., Park, N.K., 2017. Simulation modelling in ports and container terminals: literature overview and analysis by research field, application area and tool. *Flexible Services and Manufacturing Journal*, 29(1), 4-34. https://doi.org/10.1007/S10696-016-9239-5

[78] Kang, L., Meng, Q., Liu, Q., 2018. Fundamental diagram of ship traffic in the Singapore Strait. *Ocean Engineering*, 147, 340-354. https://doi.org/10.1016/J.OCEANENG.2017.10.051

[79] Uğurlu, O., Yükseyıldız, E., Köse, E., 2014. Simulation model on determining of port capacity and queue size: a case study for BOTAS Ceyhan Marine Terminal. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, 8(1). https://doi.org/10.12716/1001.08.01.16.

[80] Wen, Y., Huang, Y., Zhou, C., Yang, J., Xiao, C., Wu, X., 2015. Modelling of marine traffic flow complexity. *Ocean Engineering*, 104, 500-510. https://doi.org/10.1016/J.OCEANENG.2015.04.051

[81]   Simio, 2022. https://www.simio.com/about-simio/what-is-simio-simulation-software.php (accessed June 1, 2022).

[82]   Kelton, W.D., Smith, J.S., Sturrock, D.T., Verbraeck, A., 2010. Simio & simulation: Modeling, analysis, applications. *McGraw-Hill Learning Solutions*.

[83]   Giffin, W.C., 1978. Queueing: basic theory and applications, Grid.

[84]   Sarıaslan, H., 1986. Sıra bekleme sistemlerinde simulasyon tekniği, *Ankara Üniversitesi Siyasal Bilgiler Fakültesi*. https://dspace.ankara.edu.tr/handle/20.500.12575/91736

[85]   Demirci, E., 2003. Simulation modelling and analysis of a port investment. *Simulation*, 79(2), 94-105. https://doi.org/10.1177/0037549703254523

[86]   Guolei, T., Yue, Q., 2018. Simulation Modeling for Ship Traffic Flow in Entrance Channel. *In Simulation Modelling Practice and Theory*. IntechOpen.

[87]   Goerlandt, F., Kujala, P., 2011. Traffic simulation based ship collision probability modeling. *Reliability Engineering & System Safety*, 96(1), 91-107. https://doi.org/10.1016/j.ress.2010.09.003