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Evaluating stakeholders' interactions for future autonomous European inland waterway transport

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Abstract
The European Inland Waterway Transport (E-IWT) industry is transitioning towards a new reality governed by higher levels of autonomous systems. While the E-IWT system is preparing for future changes in technical, legal and business frameworks, it is important to examine the system from a socio-technical perspective. Using a Socio-Technical System (STS) framework, the IWT system was segmented into four subsystems: Technical, Personnel, Work Design, and the Environment. Twenty-nine (29) actors covering 19 nodes within the 4 subsystems were interviewed using a pre-questionnaire survey, which was analysed employing a thematic analysis. Two themes emerged as key findings detailing the subsystems in 3 different scenarios: 1. Work as Done- (a) current conventional operation; 2. Work as Imagined- (b) manned and (c) unmanned remote-control operations. For all 3 scenarios, the results identified task, organisation, data and information for 4 subsystems, and existing or foreseeable gaps to the emergence towards higher Levels of Automation (LOA) through those scenarios. Findings forecast a shift in roles and responsibilities from the vessel to the shoreside, likely including a 'shift in hub' from vessel-centric operations to Remote Operation Centres (ROCs), requiring real-time communications, extended redundancies, goal-based regulatory changes, and ROC design requirements. The result further highlights misalignment among different subsystems and the necessity of integrated socio-technical approaches, including stakeholder collaboration, regulatory alignment, and system standardisation, to support the transition towards higher LOA in E-IWT.

Keywords Socio-technical system, Inland waterway transport, Autonomous shipping, Work as done, Work as imagined, Stakeholder analysis

Introduction

The concept(s) of future remote operation centres (ROC) and unmanned vessel operations are envisioned to improve operational flexibility and energy efficiency. Moreover, the interest in economic and technological investments in the introduction of autonomous shipping has increased after the COVID-19 pandemic (Kurt and Aymelek 2022) and is evident from the increased presence of domain stakeholders (e.g. ship owners, operators, ports, classification societies, national regulatory authorities, and the International Maritime Organization (IMO) activities in this space. At the same time, there are innovative companies that are engaged in backward and forward linkages of the Inland Waterway Transport (IWT) business with increasing investments in this emerging shipping segment. However, compared to rapid technical advancements, there is less development in the regulatory domain. Even if technological developments may appear to be maturing to enable autonomous operations at sea, operational and regulatory gaps[1] will be present (Ahmed et al. 2023; Saha 2021).

With more emergent autonomous shipping influencing the IWT system, it is critical to consider the Socio-Technical System (STS) in IWT to ensure safe, effective and sustainable interactions among the stakeholders. Interaction refers to 'more than communication', rather a 'combination of communication, collaboration, relation, contact, exchange, and dealing' to perform actions and functions within a complex STS. STS is often described as a holistic overview of the whole system covering several interactive and interdependent interactions between and among system elements where 'the whole is greater than the sum of its parts' and 'the single processes are ordered for the maintenance of the whole' (Bertalanffy 1928, 1968; Hofkirchner and Schafranek 2011; Skyttner 2001). It is vital to investigate socio-technical studies on both micro and macro level perspectives (Trist 1981). There are several studies investigating the technical and legal aspects of autonomous shipping, but research focusing on the STS of the European IWT (E-IWT) is limited (Saha et al. 2023). An ethnographic approach investigating such a unique IWT system from a 'holistic view', i.e. seeing the dataset as a whole, is necessary (Nurani 2008).

This research is important in both novelty and relevance. Research focusing on the impacts of increasing automation in E-IWT is novel due to its emergent complexity within socio-technical interactions. Unlike more traditional and current research focus of the maritime transport sectors (e.g. bulk carriers, cruise industry, energy sectors), inland waterways involve dense, disjointed regulated networks with diverse stakeholders. Therefore, research must address technological advancements, regulatory adaptation, labour transitions, and environmental effects through the exploration of the impact of higher levels of automation upon economic, social, and ecological consequences to provide these critical insights for policy, innovation, and system-wide resilience. From a societal lens, higher levels of Automation (LOA) enhance supply chain resilience, improve worker safety, and address labour shortages, thus supporting economic growth in the E-IWT industry.

This study aims to evaluate the E-IWT, from an ethnographic perspective (Lutzhoft et al. 2019; Nurani 2008), examining existing interactions among E-IWT stakeholders through a work as done (WAD) lens and forecasting the future work- work as imagined (WAI) based on current stakeholders' interactions (Hollnagel 2012), considering potential changes in procedures, equipment, and training. WAD represents how the task is performed now, whereas WAI explains how the same task is assumed to be performed (Hollnagel 2012) or will be performed as changes in procedures (e.g. equipment, training) are introduced. To fill in the gaps between WAD and WAI, it is suggested to clarify

[1] ¨gaps¨ in the context of this paper, refer to the theoretical or operational disconnections within an STS that prohibits its ideal functioning/ interactions between and among the system components (i.e. human actors and the technologies that are part of the system.

the existing functions and then find ways to continue those functions within the new circumstances (Hollnagel 2017a). Current knowledge only from 'existing reality' (i.e. WAD) is not sufficient to forecast the future (i.e. WAI) (Hollnagel 2017a, 2017b). This approach will also deploy an 'actor network' to determine the common ground for future stakeholders' interactions. Actor Network Theory (ANT) identify the system elements (Latour 2007) and explains actor relationships within a complex STS (Iyamu and Sekgweleo 2013; Latour 1987).

The outcomes of this study should not be to report 'concrete suggestions' but rather 'predictions of future concepts of operations' based on both known and foreseeable variables and other current transportation sectors undergoing similar transitions. Both current and foreseeable stakeholders' interactions are evaluated to gather a 'holistic view' from the E-IWT stakeholders, to evaluate their preparedness to adapt within amended. Instead of identifying 'what to do', it has an approach of 'what and how it can be done'. Thus, this study not only identified gaps but also explored future challenges, possibilities, and preparations for future autonomous E-IWT operation. To understand the gaps within the concepts of operations influencing the emergence of WAI towards WAD in the E-IWT STS, the following research questions were considered:

I. What are the gaps, barriers, challenges and opportunities for the system to adapt to higher levels of automation?
II. Are the subsystem stakeholders prepared to address and adapt to automation-related challenges expected with an E-IWT system?

Background

The E-IWT

The E-IWT is comparatively distinct from other shipping sectors. The system is both localized having micro-level interactions at regional and national territories, and broader macro-level interactions at a European level. The E-IWT industry has a persistent shortage of crew (Lednický and Dávid 2010; Pauwelyn and Turf 2022), an old fleet with a large number of family-owned vessels comprising many small companies (CCNR 2024; Notteboom 2007), and growing climate uncertainties (e.g., low draft in dry seasons) (Bernardini et al. 2018; van Dorsser et al. 2020). However, the industry is experiencing continuous investment in automation and digitalisation via several new projects and commercial initiatives. There is a growing industry and public demand for greening in shipping and an extended focus from the European Commission to shift cargo from road to rail and waterways, as described in the 'green deal' (European Commission 2019).

Automation and socio-technical transition

Advanced deployment of digitalization and automation technologies is no longer in discussion within the shipping domain; rather, it is becoming an operational reality (Bolbot et al. 2020; Ghaderi 2020; Kurt and Aymelek 2022). Continuous research efforts and investments within the European Union (AutoBarge 2021; Bolbot et al. 2020; Gkoumas et al. 2021) and different innovation and technology developers (Kongsberg Maritime 2017; Rolls-Royce, 2018) are ushering in a new era in E-IWT segments. Recent literature also confirms that technological advances have matured in areas such as navigation, collision avoidance, and control systems, but adoption barriers persist in regulation, human factors, and integration with port and logistics networks (Li and Yuen 2024; Nakashima et al. 2023; Van Baelen et al. 2022; Wang et al. 2024). However, this increased attention has not broadly included a socio-technical lens critical for a systems approach to understand the implications of higher LOA related to technical and regulatory aspects in the IWT system (Saha et al. 2023).

Actor-network perspectives on maritime automation

ANT provides such a framework by tracing how human (e.g., skipper, operator, agent, insurers, etc.) and non-human actors (e.g., vessels, software, regulations, and even hydrological conditions) assemble into a unified network that enables or constrains automation. ANT emphasises processes of enrolment, translation, and stabilisation (Callon 1999; Latour 2007), drawing attention to how E-IWT STS will be redistributed when autopilots, sensor suites, or traffic management platforms are introduced (Saha 2025). Maritime and port studies employing ANT demonstrate its utility in unpacking assemblages of technology, infrastructure, and regulation (Bartłomiejski and Kowalewski 2022). In E-IWT, an ANT lens highlights how automation can redefine the future STS (e.g., the interaction between automated navigation systems, crew licensing regimes, and river authority traffic rules), reconfiguring operational practices and accountability.

E-IWT as a socio-technical system

This study combines the STS perspective with the ANT framework to cover both structural and relational dimensions of the E-IWT system. STS facilitates the conceptualization of system components, i.e. interdependent subsystems, where ANT focuses on actor networks within and across the subsystems. For this study, *IWT STS* refers to an all-inclusive framework covering all IWT stakeholders to design a work system from a systems theory and actor network aspects, where all actors collectively contribute to the accomplishment of the system goals.

This work organises the E-IWT STS into 4 different subsystems (Hendrick and Kleiner 2001). 1. Technical subsystems explain 'what' the system is comprises of; 2. Personnel subsystem operates the system; 3. Work design subsystem explains 'how' the system is designed, and 4. The environment represents the 'external environment' that influences the system elements. Within these subsystems, current researchers identified various nodes (Saha 2025) within each subsystem, describing the system boundaries as presented in Table 1. All these nodes interact with and among themselves to enable the proper functioning of the system. An interaction refers to 'more than communication', rather a 'combination of communication, collaboration, relation, contact, exchange, dealing' to perform actions and functions within a complex STS.

Methods

This research employed several methodological frameworks to investigate how emerging technologies related to digitalisation, artificial intelligence and increasing LOA might impact upon the E-IWT STS. The principal focus is to understand the relationships between the E-IWT subsystems and nodes. To date, a 'benchmarking' exercise by the current authors looked to document these interactions as work done in today's current ecosystem (Saha 2025). This paper focused on how future work is perceived based on the present. To operationalise and answer the research questions mentioned in Sect.

Table 1 Informants' details with description of the subsystems and nodes

Subsystem	Nodes	sample	Location of affiliation	Main (current) role in the IWT system	Remarks on the role	Experiences in- (Years)		
						current role	IWT segments	Industry
Technical subsystem	T1. Inland barge: the vessel	2	Germany (DE)	Inland shipping service operator		10	10	24
			DE	Inland shipping vessel owner	Inland shipping service operator	4	41	36
	T2. Port infrastructure (technical mechanism)	1	DE	Logistics service provider		6	13	14
	T3. Supporting Operation/ control stations	1	The Netherlands (NL)	VTS operation	also provides: P3, W2, E1, E2	7	12	20
	T4. Navigational and cargo operational components	2	Finland (FI)	Maritime technology developer		26	1	26
			DE	Inland shipping service operator		24	24	24
	T5. Machinery and bunker operational components	0	0			0	0	0
Personnel sub system	P1. owner: legal owner of the barge	3	DE	Inland shipping vessel owner	ship owner + 1st captain	10	20	20
			NL	Inland shipping vessel owner	P2 + T1 also, sailing onboard (family business)	26	37	37
			DE	Inland shipping company	inland OIL tanker company	3	20	21
	P2. onboard operators	2	DE	Barge Master	1st captain	12	20	20
			Sweden (SE)	Inland shipping service operator	Also, T1 is applicable	8	8	40
	P3. Shore side (port and company) assistants	2	DE	subsidiary of terminal operator		10	7	20
			DE	customs	not directly fit in this STS, we do perform as assigned	25	0	42
	P4. regular service: supply and logistics service providers	1	DE	Logistics service provider		10	0	27
	P5. irregular /non periodic service	3	DE	Insurance service provider	in house claim handler	2	7	15
			France (FR)	Classification Society		5	3	25
			DE (not recorded)	other financial Institution/EU taxonomy expert	financial broker, expertise, focusing environmental regulation	5	1	30

Table 1 (continued)

Subsystem	Nodes	sample	Location of affiliation	Main (current) role in the IWT system	Remarks on the role	Experiences in- (Years)		
						current role	IWT segments	Industry
Work design sub system	W1. international and national regulations, safety guidelines	2	Belgium (BE)	Maritime economist		17	42	17
			UK	PSC		16	0	44
	W2. advanced technical supports	2	BE	R & D PM	also, T3	1	1	9
			BE	Maritime technology developer	ex-operator & owner; we play all roles.	9	9	40
	W3. intermodal and hinterland connections	1	BE	Logistics service provider		2	0	10
The environment	E1. inland waterways	1	FR	Waterway management authority	also provide regulations and guidelines (W1) & services e.g. lock management (T3)	1	1	25
	E2. port arena (surrounding the port)	1	NL (Survey)	maritime consultant		13	0	35
	E3. Society (people living around, political leadership)	1	DE	Maritime association		5	5	35
	E4. Funder / financer	1	BE	other financial Institution/ship financing bank		23	15	32
	E5. regulators (IMO, EMSA, national authority)	2	NL	regional govt. authority		2	25	30
			DE (survey)	Port authority	T3, P3, W1, and E5	6	12	23
	E6. associations (interest groups) and activist	3	DE	Innovation cluster	initiating innovation transfer and projects, including IWT projects	6	11	17
			DE	Maritime association	Registered Association	13	9	17
			DE	Insurance service provider	insurance association	30	20	45
	Total:	31	28 recorded + 1 unrecorded interview, 2 survey inputs		Average:	10,9	12,1	26,5

Introduction, this study gathered the perceptions and opinions of the current E-IWT stakeholders. Using system theory and STS theory approaches, E-IWT STS was systematically categorised into 19 different nodes under 4 subsystems within the E-IWT system, as detailed in Table 1. All the elements, i.e., stakeholders, actors and tools enabling current operations within the E-IWT system belong to any of these 19 nodes. Primary data were gathered from E-IWT stakeholders representing all 4 subsystems, thus collectively representing the whole IWT system. Participants elaborated on their role(s) within the current E-IWT system (WAD) and then shared their perceived views of the future of a more autonomous E-IWT (WAI). This approach provides a holistic overview of the future E-IWT and facilitates generating a thematic map showing future E-IWT stakeholders 'interaction method' for autonomous E-IWT (see Fig. 3 Sect. Data and information).

Sampling

An open 'call for collaboration' towards IWT stakeholders occurred using an online form in both English and German. This initial call to participate was circulated via different communication channels, such as social media, three professional associations working in the European IWT domain, and personal networks. This online form solicited a short company profile and their consent to be interviewed. A total of 28 completed responses were received, where 17 were primarily interested in being interviewed in English. Only 10 of these respondents were finally interviewed; the remainder had later indicated a lack of availability or did not fit the stakeholder profile pertinent to this study.

To reach further potential informants, categorized email invitations were sent to potential industrial stakeholders with the support of project collaborators and promotion during the author's attendance at workshops and conferences. Following 'purposive sampling' (Tongco, 2007) techniques, another round of email invitations was sent, with a greater focus on informants fitting nodes not yet populated.

Finally, a total of 31 responses indicating availability were received via the initial online survey form (call for collaboration) or email reply. Two were unable to attend the one-hour long interview and provided inputs (covering E2 and one E5) following the same questionnaire structure used to seed the interviews, which were coded alongside the interview transcripts. And one of the interviewees opted out of being recorded, but still was interviewed. Simple informant demographics are detailed in Table 1. The informant has an average of 12 years of involvement in the IWT domain, with an average of 26.5 years of overall professional services. In this round of solicitation, one IWT operator volunteered to host a 3-day research visit onboard in an inland barge for interviews and observations. This provided the researcher with valuable information and context about how work is done in today's IWT system.

Data collection

Potential participants first answered an online questionnaire, which identified the themes grounding the future interviews and site visits. A total of 31 questionnaires were filled out, of which 29 also participated in interviews. A 3-day inland vessel trip was conducted to observe and analyse the current E-IWT system. All informants confirmed their voluntary participation both when completing the online questionnaire and at the beginning of the recorded interview sessions. All data collection and processing followed the requirements of the General Data Protection Regulation (GDPR). Interview data were anonymized and de-identified to ensure that no individual participants could be identified in the analysis or reporting.

The semi-structured interactions (Pathak and Intratat, 2016; Wood, 1997) focused on the vessel and its crew's behavioural attributes, current phenomena, reliability and acceptance towards current and futuristic automation. Three scenarios: (i) current conventional inland vessel, (ii) remote control manned inland vessel, and (iii) remote control unmanned inland vessel were considered in the interview while discussing current and foreseeable changes in LOA in the E-IWT system. These scenarios represent IMO's LOA 1, 2 and 3, respectively (IMO, 2018, 2023).

The interviewed participants covered a minimum of 5 (average of 7) participants from each subsystem, as detailed in Table 1. Inputs from two online surveys were considered for E2. Eventually, there are at least 1 to a maximum of 3 respondents from all nodes except T5, which is considered represented by T4, as they have overlapping stakeholders and functions. Maritime technology developers and inland operators interviewed under T4 also engage with propulsion, bunker, and machinery-related systems. However, the absence of a dedicated T5 informant is still a limitation. The inclusion of participants from all four subsystems and key E-IWT stakeholders across the major participating countries strengthens both the saturation and representativeness of the dataset. 29 interviews were recorded (1 was recorded by written notes taken during the conversation rather than a digital recording). Interviews lasted approximately an hour and were transcribed using AI tools called '*Avidnote*' and reviewed manually before transferring the transcription to a qualitative data analysis tool called *Nvivo*.

Data analysis

The data were collected through: (a) questionnaires and (b) semi- structured interviews. The questionnaire data were used to create themes for the semi-structured interviews, allowing the participants to further elaborate and explain their thoughts. The interviews were recorded and transcribed verbatim. This data and the questionnaire answers were then analysed to identify themes following Braun and Clarke (2012) using Nvivo software (https://nvivo.de/en/). This method employed a six-phase (familiarization with the data, initial codes, searching for theme, reviewing theme, defining theme, and producing report) thematic analysis where initial codes were deductively derived from the interview guide and iteratively refined using the dataset. Coding was done by one author and later reviewed by another author. Data saturation was monitored throughout the coding process. Saturation was considered reached when successive transcripts produced no new codes within each subsystem; from approximately the 25th interview onwards, no novel codes emerged across the four subsystems. The coding of the data resulted in two themes (WAD and WAI) and several sub-themes as presented in Fig. 1 and described in Table 2.

These themes were divided into two sections covering the three scenarios (see Sect. Data collection) used for the questionnaires and interviews. This assessed WAD within the current conventional operations (Sect. E-IWT STS- WAD (Scenario a)), and WAI that would consider futuristic manned remote control and unmanned remote control operations (Sect. E-IWT STS- Work as Imagined). A reflective summary from each of these sections is presented as an overview in Figs. 2 and 3.

Theme and subthemes	Files quoted	Total quotations
WAD	24	102
(clear) gaps	18	44
area for collaboration	24	80
communication	5	9
Data & information	27	117
WAI	20	48
area for collaboration	14	29
communication	3	16
Manned RC'	13	35
(foreseeable) Gaps	14	23
data & information	10	22
Unmanned RC	17	34
(foreseeable) gaps	19	47
data & information	12	28

Fig. 1 Nodes under two different themes (NVivo), indicating reference coded under each theme

Table 2 Overview of data analysis approaches

Data source	Data set	Method	Analysis	Result
a. primary inputs on questionaries, b. interview transcription	excel sheet created digitally (thick) Interview data, transcribed	Semi-structured interview	Thematic analysis using Nvivo software	4.1: WAD- summary/overview as Fig. 2 4.2: WAI – summary/overview as Fig. 3

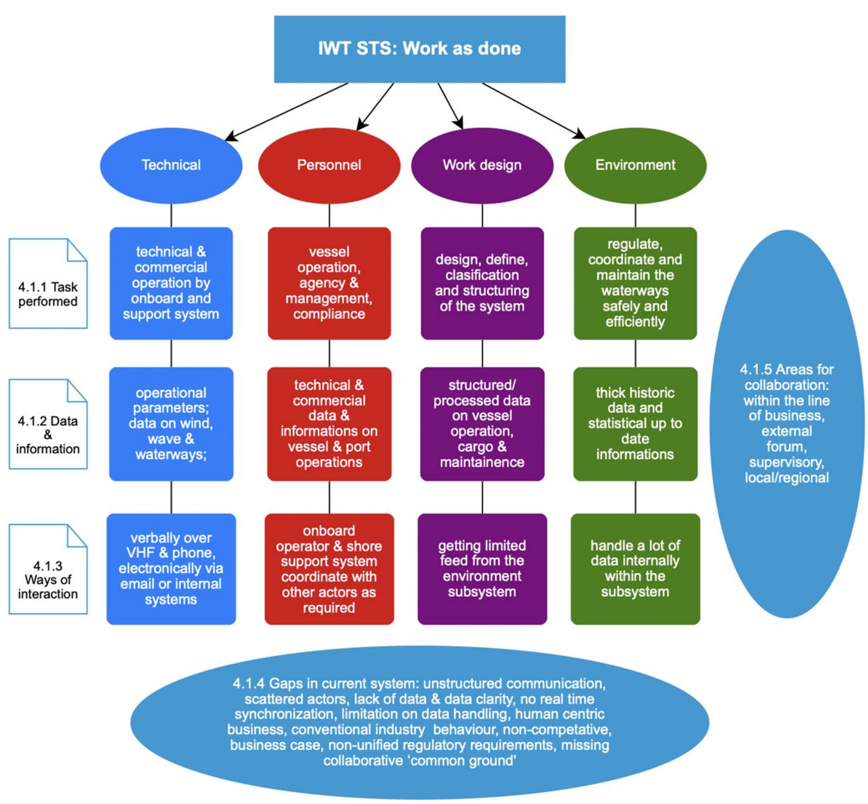

Fig. 2 E-IWT STS – work as done. Mapping of current stakeholders' tasks, interactions, data flows, and identified gaps across the four subsystems

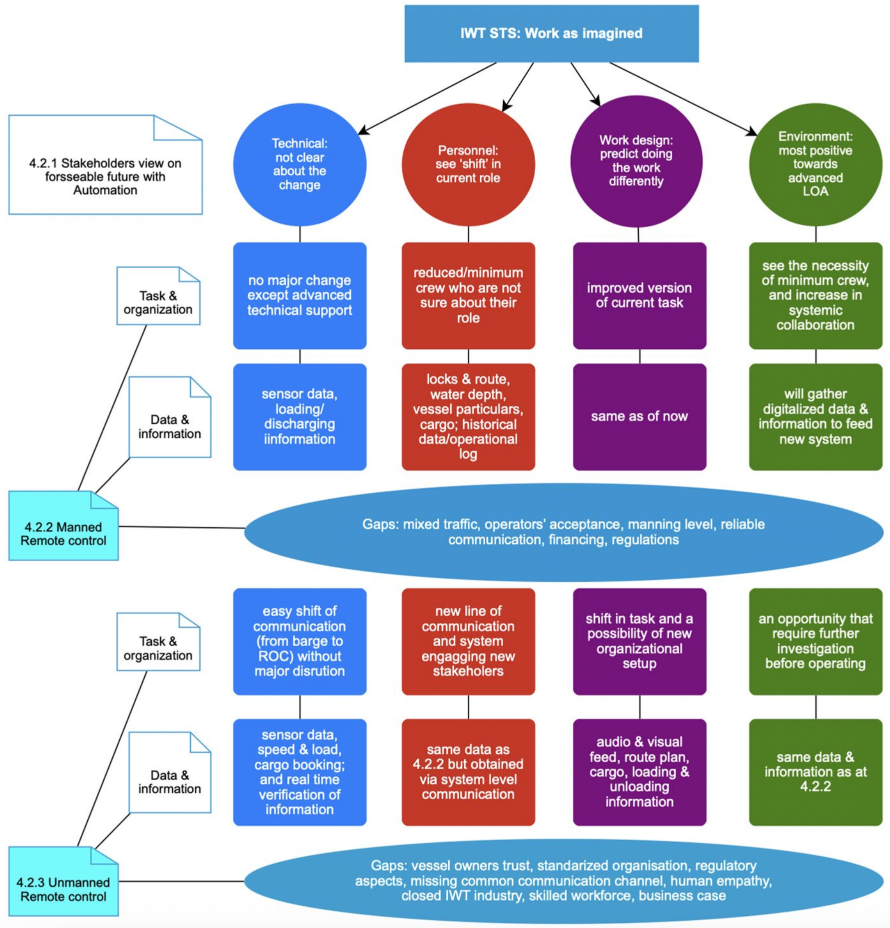

Fig. 3 E-IWT STS – work as imagined. Anticipated reconfiguration of stakeholder tasks, data flows, and interactions under manned and unmanned remote-control scenarios."

Results

This section details the findings from the questionnaire and interview data. Figure 1 lists the themes and subthemes/nodes, the number of interviewees who provided responses about each theme/node, and the number of opportunities where data/text were quoted for each node. Following a thematic analysis of questionnaire and interview data, two major themes: WAD (Fig. 2) and WAI (Fig. 3) emerged, each generating subthemes (AKA Nodes) and are detailed in Sect. E-IWT STS- WAD (Scenario a) and E-IWT STS-Work as Imagined.

E-IWT STS- WAD (Scenario a)

Figure 2 provides an overview of the findings under the first theme, WAD. This section details how actors perform ¨tasks¨ within their current positions and roles with the operations. It continues with the data and information handled by each subsystem. Lastly, it explains three subthemes: interactions, gaps, and areas for collaboration. Here, *'gap'* refers to (theoretical) disconnection within an STS that prohibits ideal functioning/ interactions between and among the system components, i.e. human actors and the technologies that are part of the system.

Tasks performed

The technical operations, i.e. navigation, manoeuvring, etc. or the cargo operation, i.e. loading, unloading, etc., are typically done by vessels with small (2–4) crew members. They have people working on shore to inform ships about the situations, manage the traffic and act on hazardous situations. The operational components also perform several value-added services, such as packing/unpacking of goods.

Personnel onboard operate the vessel, and they live there as well. And, in many cases, the owner is the captain of the vessel, covering a wider range of tasks. Apart from navigation and cargo, there is also maintenance, painting, cleaning of the ship, maintenance of the main engine, and everything to keep the vessel running. There are agents and brokers, or a shore-side management team for bigger companies, to optimize commercial (cargo and customer) management activities. Shore-side assistances are dedicated to coordination and facilitating services such as: additional assistance like technical assistance, documentation, survey, certification, insurance service, claim handling, and interacting with various actors.

The work design subsystem assures, improves, and verifies the operational efficiency and compliance by following international and national regulations and safety instructions, operational and structural inspection, and finally supporting with hinterland (from/to port to/from last mile) services such as: warehouse, transportation, and last mile delivery. The work design subsystem actors also follow up on the current affairs of regulatory platforms with the aid of data gathering, analysis, research, collaborating and lobbying to some extent, participating in different innovation projects.

The external environments often have innovation clusters, forums, and working groups that primarily facilitate networking, stakeholder convergence, and collaborative troubleshooting while actual work is being carried out by the navigation stakeholders. Financers undertake financing by evaluating the business plan, annual report and portfolio of the company or the investor and mostly get it directly from the barge owner/CEO. Waterway authorities maintain and regulate the fairways and entire water resources, regulate the vessels running on the channel and encourage businesses to collaborate.

Data and information

Components within the technical subsystem deal with elements such as water level, weather forecasts, bunker levels, winds, waves, and current information. This system is often merged with the Automatic Information System (AIS), which is a short-range coastal tracking system used on ships. Actors also need booking information from customers; everything related to cargo from stakeholders involved in the transport chain. To undertake technical operations, they need to know restrictions on the waterways and the operation of communicating with the respective authorities. Control stations for inland ships use maps provided by data from the AIS radar, combined and collect tracks from the ships for analysis. There is often overlap or contradictory information. Operational components combine them and send them to the corresponding targets/stakeholders. Often, this information is largely unfiltered or improperly monitored by the barge operator.

The personnel subsystem deals with both technical and commercial data. These are: depth and height from the bridge, tidal height, engine hours, filters and oil, size of the barge, the loading capacity, cargo plan- information about the quality, quantity, port of origin, load port, discharge port; slots for loading and discharging. Support services also require both technical (such as information from condition-based maintenance systems, ship-shore communication, data infrastructure onboard, data exchange protocols) and commercial information (such as notice of claim and other commercial documents, i.e., commercial invoice detailing cargo value, packing list, and customs clearance, bill of lading or the airway bill).

Work design subsystem deals with structured data, i.e. data on calculated vessel emissions, certification, data about the vessel- equipment available onboard, trajectory of the operation, operational hours, barge load, draft, arrival and departure, and port information. But this is not real-time and arrives separately. For example, they get information from the police, customs and such only if there's an area where they have a concern. Once the customer provides orders to receive/deliver the cargoes into the warehouse, storage constraints are needed, such as the dates of delivery or the truck equipment capacity, to plan the shipments.

The component within the environment poses a lot of thick data, such as lock operating time, water level data, and water flow data. the shape and size of the various rivers and basins, status of the various locks and dams, maintenance schedules, traffic conditions, bridge specifications and opening hours, and road traffic over those bridges. It's either collected from own sensors or external resources. There are both national information systems and European Information Systems (EURIS).

Forms of stakeholder interaction

For onboard operation, '*all current communication is done by VHF, but it's simpler for inland shipping*' (T3). On the other hand, '*direct communication with the customer always goes via e-mail or telephone*' (T2). Large amounts of data challenge the capacity of shore-side assistance. There are individual and/or isolated communication systems for different ports, locks, bridges, and operators. Onboard personnel communicate with VTS centres, canal locks, and port operation centres.

People onboard and shore side assistance gather the actual information, interacting with the port and other associated authorities independently and only when required. Work design subsystem lacks a feed of information from other subsystems, especially from the regulator. '*Information flow from regulators is for a selected group*' (W1). The environment subsystem is subject to considerable data streams. It receives and projects data from other subsystems (see E1 through E6, Table 1) in an unstructured way. This information does feedback to other subsystems, but not necessarily in a closed-loop manner. In general, there is a lack of real-time data, and data reliability is limited.

Gaps in current interactions

E-IWT business is human-centric. The human is at the centre of the system. The system requires considerable interactions by actors/stakeholders who are often known to each other. '*If you are new, you have to know a lot of new information*' (E5). '*That's all person-to-person communication*' (E6).

Many informants indicated that communication is either verbal or unstructured over voice and text within the E-IWT system. There is always a limitation in communicating in real time, and often information is fed-forward into the system, manually, by a human. *In the high-density moments, you have a lot of data to process*' (T3). '*If it is more work* *to process the data, then it's not helping'* (E3). Statistical information is insufficient, and sources are unreliable within the IWT system. This may be a result that, operationally, E-IWT actors are very much decentralized and not well connected, especially when the service is outsourced. '*We have no connection to Terminal or to the barge operator normally. The only external People we work with are the surveyor, lawyer... we will connect with external companies only If we do regress against them'* (P5).

Regulations, other than international requirements such as the IMO, are flagged/national. The administrative procedures involve a lot of entities that work mostly independently. '*It's quite confusing, but we have a lot of people who are responsible for locks, bridges, waterways in our region*' (E5). '*You get the information from the customer, you get the information from the pilot, you get the information from all entities separately*' (T2).

Existing collaboration

Current stakeholders' collaborations have four dimensions:

(i) while performing their designed roles, stakeholders collaborate in various ways to ensure safe and efficient business functions. Stakeholders collaborate in various forums, working groups, clusters, and associations, particularly on the external environment subsystem. They give feedback and share ideas to accumulate pertinent information and data, consolidated information which serves industry needs and requirements.
(ii) interconnected actors, within a subsystem, collaborate at local and regional levels to achieve a better output (e.g. improved safety, operational efficiency, time effectiveness, competitiveness) from their activities; '*it's a collaboration between us because we manage a number of dams and locks on the river and other people who manage dams and locks kind of upstream from us'* (E1).
(iii) supervisory actors collaborate between and among themselves on planning, operation, coordination, control and administration. These collaborations are identified in Table 1 (see T2, T3, P3, W1 and E1 as examples).
(iv) local/regional actors collaborate with their neighbouring actors. '*We work closely with our Department of Environment, Customs and Border Control, Coast Guard and such agencies. So, if they have a suspicion that something is wrong, they'll call us and vice versa*' (W1). Such examples are barges that are geographically co-located, such as nearby barges, port, canal, and with prescribed oversight from various actors from local and national authorities.

Benchmarking WAD

The data reported in Table 1; Fig. 2 provide a benchmark of the existing E-IWT system. Most of the practices described have been a feature of these socio-technical systems for decades (not in centuries). However, to understand how future changes in automation are to emerge in this industry, this calibration exercise if critical, if not obvious to those most familiar with daily operations. The rest of this paper examines how the nature of work (WAI) is perceived to change by current stakeholders as autonomy becomes more prevalent in daily or routine concepts of operations.

From an STS standpoint, the WAD configuration shows limited joint optimisation. Technical efficiency is maintained at the expense of personnel coordination, while the work design and environment subsystems operate largely in parallel rather than in mutual adaptation. From an ANT standpoint, the network is only partially stabilised, where several actors (e.g., customs, insurers, financiers) operate outside the principal interaction loop and are not fully enrolled into the operational network.

E-IWT STS- Work as Imagined

Figure 3 summarises the empirical findings describing the future E-IWT STS. The informants were asked to reflect and respond to two different remote vessel operation scenarios: (a) manned remote-control operations, and (b) unmanned remote control operations (see Fig. 3). These scenarios explore the perceived view of the E-IWT stakeholders towards future levels and forms of automation.

Stakeholders' perceptions of higher levels of automation in the foreseeable future

Actors within the technical subsystems seem not to have a clear opinion and have less confidence about the impacts of the introduction of higher levels of automation into the system. '*I think it (remote operation) would be tricky. The best is something without locks, without bridges. Because there's always a risk (otherwise)*' (T4). This type of statement will be reviewed later in Sect. Discussion; however, this informant seems to be confusing disruption in the industry with current or existing technical barriers.

Actors within the personnel subsystem acknowledge a 'shift' in their current roles and the inevitability of emerging roles and operational functions in future. They also see it as more critical if the barges are manned and still have remote operations support rather than having no people and having a remote operation. A work design subsystem predicts different ways of doing work than it is now, where tasks can be performed both physically and remotely without having the necessity of being onboard.

Stakeholders within the external environment system are the most positive towards perceived advances due to expected changes in LOA. They see it as a 'process' and expect additional system requirements, thus additional attention on gathering, analysing and sharing information. '*I think it will be a process. It will not happen from today to tomorrow. It will be a process. I think automatic barges will happen step by step or on a smaller scale, probably with people, later without people*' (E3). They have different views on foreseeable changes within their organization and ways of working. Some don't expect to experience many changes as an 'external' actor/stakeholder, where other expecting to face new challenges and requirements.

Manned remote control: WAI (scenario b)

This section reports stakeholders' views on future conditions in which a vessel is remotely controlled while one or more people remain onboard, as summarized in Fig. 3.

Task and organization Technical subsystem informants do not foresee a major change if a vessel remains manned; however, advanced technical supervision and support may be required to meet regulatory demands. *'That will not change any drastic situation to act as we are doing now, expecting that the remote operator has access to all technologies to help emergency intervention or clear the barge manually if needed. So, I don't think they will change anything for us if it's remotely controlled' (T4).*

Concerns regarding the complement and role(s) of personnel on board (POB) were raised. In these regards, a third-party service can still oversee prescribed operational tasks, but a protocol for communication and information-sharing must be devised and implemented to bridge common ground between POB and onshore personnel. The concerns regarding future concepts of operation envision POB as reduced/minimum crew operations and express a concern about future roles onboard if the vessel is remotely controlled. '*You don't need to do the watchkeeping duty, but you are on standby at the ship anyway. So, what is the extra value of a system like that?' (P1 + P2).*

Informants about the work design subsystem also viewed this scenario (4.2.2) as an improvised version of their current regular task(s). They also have strong views on this scenario with digital connectivity and tasks distributed between humans and machines.

The actor(s) within the environment subsystem explain why a person is required to be onboard, even if it is remotely controlled. 'There's no rule for a ship when there's no person on board' (E5). This is currently a regulatory requirement and satisfies existing safety and operational practices and procedures. Here, an increasing level of systemic collaboration will be necessary in many operations, such as traffic management.

Data and information Both the onboard and remote operator(s) will need secured and pertinent data and information from the lock operator(s), inland port, and cargo owner (as examples). The remote operator will need the data about the locks and the routing, data from the water depth under the ship, the ship's navigation and machinery particulars, and cargo operation. Further, it will necessitate collecting historical data, operational log, running hours, real time data from the machinery or systems from the vessel. These issues were identified by both the onboard/remote operators. 'You do navigation, then you need data from maybe the lock operator, the inland port, the cargo owner (P1 + P2) the remote operator will also need the data about the locks and the routing, data from the water depth under the ship, the ship's navigation and machinery particulars, and cargo operation. 'But navigation is 90% autonomous, which will necessitate collecting historical data, logs of operation, real-time data from any device, any machinery, or any system from the vessel, and running hours. Uh, the change of fuel and those things´ (P5).

The work design subsystem will have the same data and information as of now. The work design subsystem actors do not see the generation of new data and information. However, they will share the processed data and information with their client (owners) besides the onboard operator.

The environment system views the possibility of gathering and using plenty of unused data as they will be continuously receiving big data streams, some needed for real-time operations and other data for voyage and operational planning. As one informant suggested, 'o*ur information we get today is coming through the owner or the external stakeholders. And in the case of remote control, it will remain the same for us. We're not on board the ship*' (E4).

Foreseeable gaps Whilst there is still much debate about both the positive and negative impacts of automation upon the industry, there is still a need to anticipate the barriers and challenges. There are foreseeable gaps that must be planned by the industry to overcome.

A mixed traffic having both conventionally manned and remotely operated (partially or completely) manned vessels will create further operational complexity. Having a mix of humans and technologies within the same communication loop needs to be better understood. Onboard operators' acceptance towards hierarchy of command and how decision-making roles are shared or allocated will be challenging. Their acceptance on remotely control system is also vital. The coordination with ROCs will largely depends on the composition and compliment and how this sustains the concepts of operations. *It will be more complex when we have both autobots and the conventional one, rather than having all autoboats*' (E3). '*VHF is in is an open chat. There are lot of things that go unsaid. Which a computer may or may not pick up, if you if you have a mix of humans and non-humans on the same chats, because So, that has to be completely, completely reviewed. And, I suppose am safety and rescue procedures have to be reviewed too, to some extent*' (E1). This understanding will need to consider competencies, and skill sets necessarily to adapt and perform with the new system.

To scale up business, reliable communications are necessary with wider coverage. '*The wide band of VHF is too small for big data communication*' (T3). Costs of introducing new technology might be a barrier as financiers require strong business plans, supported by end-user examples, to assess the extent of return on investment for developing and providing these types of services.

Technical advancements, specific to operational and environmental safety, will continue to face regulatory barriers. '*Regulation is a very important aspect in this field, and at the moment, there is no rule that you can start to sail your barge manned but remotely. So, you need permission for each vessel on each route*' (W2).

Unmanned remote control: WAI (scenario c)

Stakeholders within the four subsystem stakeholders provided their views on unmanned remote-control operation of an inland vessel and its impact on the E-IWT system.

Task and organization Actors from the technical subsystem are aiming to accept this scenario without major disruption to their task and organization. They also believe that communication can be shifted easily since they usually don't talk to the barge operator, but only to the barge company or the agent of the barge.

Personnel foresee the creation of new means of communication and the necessity of newer systems engaging new stakeholders. A ROC is expected to be the future point of contact or the *de facto* hub of the system.

Work design will see a shift in their task. Even a new organizational setup may emerge with a possibility of owning and operating the vessel by this subsystem, which currently does not exist. This might necessitate new standards in the roles of actors within the work design system and b. developing autonomous vessel systems and standards to support these new roles.

The external environment foresees unmanned remote-control operation as an opportunity that requires further investigation before operationalization. Challenges need to be addressed, ensuring proper safety before eliminating the regulatory barriers. '*Because they're remote control, we have to have an answer. How it works. How safe it is…*' (E6).

Data, information and communication The technical subsystem will require strong and well-functioning data sensors, a method of communications with cameras, steady and reliable power aboard the ship, speed and load data streams, as well as cargo booking data. Data verification should be done before handing those over to the ROC. Operational approval for ROC operation will continue to come from the vessel system, necessitating reliable, redundant, and real-time vessel-ROC communication.

For personnel, the data set is the same as now, but with a more standardized structure and presentation, on the ROC displays and workstations. The communication to obtain data will be completely different. '*The ship-shore communication system will include the data providers, the cloud network, the cloud server and all such data infrastructure*' (P5).

For the work design subsystem, sensors will generate a lot of data, and the cameras will likely be the most important detection sensor for most operational activities. Besides, route planning and monitoring, cargo data, and loading/unloading operational data will be required. Finally, autonomous IWT barge design(s) that consider cargo capacity, access for maintenance, responsible propulsion systems that optimize for energy efficiency and environmental protection regulations will be necessary.

The environment will deal with similar information and data sets, but it requires being more sophisticated. '*I don't think there is a limitation on getting information, whether there is stuff or no stuff on board the vessel*' (E4). *I mean, then (our) services to navigators might include telling them exactly. How they should navigate* (E1).

Foreseeable gaps Inland vessel owners who are also often the operators are not yet confident in such an advanced LOA. It will slow down the innovation development and block further financing as well. Until a viable business case is identified, the operational costs will likely not decrease and may even become higher. The E-IWT industry is a very ¨closed¨ industry, and stakeholders are not willing to share data. '*If different parties share more data, then the business flow will be more efficient, but it just needs to conquer the challenge of if you will lose the business by doing so*' (W3).

It will be challenging to create a 'common ground' for providing a unique platform of interactions for all stakeholders who require receiving and transmitting data and information in real-time to become reliable. Unautomated manual inputs will be a threat. The current Global System for Mobile communication (GSM) data infrastructure for real-time communication and data exchange is very limited, unreliable and not promising to address the necessity of remote operation. *'That's the belief for the whole European waterways, we will not have the high density of 5G everywhere within the next 20 years'* (T3). It is also not capable of addressing all kinds of cyber-attacks or jamming attacks.

The problem when introducing automation or removing personnel or some personnel functions is that activities may not get properly ¨closed¨. This may be due to inattention to standards of operations or because the AI that drives autonomous tasks does not think or behave like humans. Automation just completes the task as the algorithm dictates. It is yet to be determined how 'human empathy' will be replaced by machines – the ¨seamanship qualities¨. '*It really is a people's business with personal networks as well. And at the moment, I don't know any efficient tool that is capable of doing that'* (E6). For advanced automation, the E-IWT industry must recruit people who possess non-technical competencies that were never really considered important or necessary in traditional concepts of operations.

Technology developers view regulatory changes and operator compliance as the main barriers to implementing their latest autonomous solution. On the other hand, the regulators say, '*We don't change our regulation before we've tried if it works'* (E5).

Table 3 Comparison of WAD & WAI across E-IWT STS

Subsystem	WAD (current operation)	WAI		Key gaps (envisioning WAI)
		Manned remote control	Unmanned remote control	
Technical	Barge centric system, manual coordination supported by inconsistent interactions	Shore based technical support with new line of communication and interaction	Advanced technical support with standard & redundant means of communication	Proven & approved means of real time data handling in collaborative ways
Personnel	Skipper centric experienced based operation, direct interaction with scattered actors	Minimum crew, confusion on command responsibility	New line of interactions engaging new stakeholders (actors)	Vessel owners trust, human empathy
Work design	Structured and defined functions, limited data availability	Improved version of WAD	Shift in organization supported by data analytics	Missing 'common ground' and standardized organization
Environment	Non-unified regulatory requirements	Support it widely	A potential opportunity for further investigation	Closed & conventional E-IWT industry, regulatory uncertainty

Comparative analysis of WAD vs. WAI

Synthesising the descriptive findings from the interview data, this section compares interaction patterns between WAD and WAI across subsystems. Table 3 provides a summary of Sect. E-IWT STS- WAD (Scenario a) and E-IWT STS- Work as Imagined detailing key features under each subsystem for all 3 scenarios. Table 3 also highlights alignment gaps for each subsystem, envisioning the implementation of WAI.

Across both WAI scenarios, the redistribution of tasks from vessel to ROC illustrates an ANT translation process in which human and non-human actors are reassembled into new configurations. The persistent reservations expressed by technical and personnel subsystem actors indicate, however, that their enrolment into the emerging network remains incomplete, threatening the stabilisation of the future STS.

Discussion

While we do not know how future, emergent automation elements will disrupt the E-IWT STS, it is critical that the industry prepares itself for change. This will take a socio-technical systems approach to solve what are the most wicked problems faced by the transportation industry. The process will be a reiterative one, describing the transitions between our understanding of WAI, envisioned by industry stakeholders, to an operational understanding of WAD.

Are we ready?

The comparative synthesis (Sect. Comparative analysis of WAD vs. WAI) of empirical data highlights that the transition towards WAI will not be uniform, as subsystems have varied behaviour. A broad interpretation of the results reveals two patterns acting to inform industry stakeholders' opinions regarding system modifications or a transition into a very different-looking system. While there is often a focus on system readiness (see Sect. Stakeholders' perceptions of higher levels of automation in the foreseeable future), actors who are more focused on day-to-day operations within the technical and personnel subsystems are less confident with the foreseeable shift, but actors accept that changes are coming. This lack of confidence may be a result of the limited inclusion of the subsystem actors in describing how and what these changes may manifest themselves – a lack of end-user feed-in. This reflects lower readiness and acceptance at these two subsystem layers. On the other hand, the work design and the environment subsystems seem more confident and feel less challenged within E-IWT system. Actors are more willing to accept these changes while shifting their 'ways of doing the activities/actions and interactions'. Actors within these sub-systems, such as regulators, are greatly responsible for directing (and managing) these changes (Saha et al. 2023), thus have more concrete expectations of 'what are the changes and why' and are more confident about meeting the challenges of an industry with increasing levels of automation. These differences reflect that the foreseeable shifts towards WAI are primarily led by technological and regulatory expectations, whereas operational realities continue to depend on human-centric practices. Such divergence between current and envisioned systems illustrates a systemic misalignment, as subsystems are not developing at the same pace and may constrain the transition towards advanced LOA.

Addressing the gaps in future STS

As most of our informants from all subsystems explain, none of the E-IWT STS subsystems is entirely ready for the emerging autonomous era. Unique characteristics of the E-IWT system (such as a family-owned/single-barge company structure, older fleet, etc.) make it even more challenging to adjust to the changes driven by higher levels of automation. As we identified the gaps (see Sect. Gaps in current interactions), the results described the personnel subsystem as being very much localized, human-centric, and conventional, thus 'not willing to change' and adapt to a newer system. This subsystem's inability or resistance to change will effectively slow down the process of reshaping the IWT system towards advanced LOA. From an STS perspective, this gap highlights the necessity of joint optimization across subsystems to enable systems functioning 'as a whole'. From the ANT perspective, the transition can be read through three mechanisms (translation, enrolment, and stabilisation) described in Sect. Actor-network perspectives on maritime automation. Translation is visible in the way a ROC reconfigures the skipper's situated decision-making into distributed monitoring tasks shared between remote operators and algorithms. Enrolment remains incomplete since technical and personnel subsystem actors (skippers, owners, onboard crew) have not yet been brought into the emerging network on terms they accept, while regulators and technology developers continue to operate in mutually conditional standoffs (Sect. Unmanned remote control: WAI (scenario c)). Consequently, stabilisation is hindered, and potential future actors (such as an ROC or an automated system) are not effectively aligned with existing actors, preventing the formation of stable socio-technical networks. Improved coordination and integration of both human and non-human actors in the evolving system is vital to address this gap. A collaborative systems approach, including all subsystem stakeholders, will be necessary to change these perceptions and attitudes. Besides addressing the identified gaps, it could facilitate creating trust towards newer system(s) and other emerging actors and technologies, which is eventually important to bring forward the personnel subsystem actors.

Opportunities and challenges

Higher LOA is an opportunity for the E-IWT system. It could replace the necessity of 24/7 human supervision (Kurt and Aymelek 2022), creating more operational and manning flexibility. This flexibility could contribute to attracting future generations to work in the E-IWT industry. A mix of manned and remotely controlled unmanned vessels enables vessel trains or platooning (Meersman et al. 2020). While this will likely require a third-party service provided for small barge enterprises, it could result in a lower personnel cost.

Regardless of the LOA deployed onboard, ROC overview and operational ¨advice¨ will still be necessary. As one of the informants states- *´The good thing about those vessels is that one traffic controller can control several vessels together, so there is one captain for the first barge, the barge in front and then the two other vessels behind can follow that barge, and the traffic controller monitors that and makes sure it is going smoothly*' (W2).

A collaborative stakeholder approach could also be the framework of a new business model. Several stakeholders could join forces to share operational data and create common ground amongst subsystem elements (see Sect. Existing collaboration). An example of this common ground could be that 2–3 carriers collaborate and have one 24 – 7 operations team situated at a ROC. A ROC operator, a conventional operator, an autonomous mooring and/or crane service providers could team up to offer an attractive business case. Collaboration can create opportunities, breaking the barrier of a 'scattered E-IWT industry', increasing common understanding and trust, and providing new solutions, new employment opportunities and business cases.

The gaps identified in the three ¨scenarios¨ i.e. current operation, future manned and unmanned remote-control operation, suggest data-driven information streams such as predicting traffic flow, forecasting for terminal logistics, and speed recommendation for the carrier, will become more critical. There will be a need to improve the technical standardization of information storage, verification and exchange. If the workforce is well-trained and knows how to take advantage of systems designed for transparency, then a safer and more reliable E-IWT will evolve.

While introducing higher LOA, real-time communication will be critical, as it is in current operations. We need to make sure that there is a reliable real-time connectivity between the ROC and the barge itself, whether manned or unmanned, to ensure safe and efficient operation. '*'If this is information given by a human calling us or entering something into a system, or if it's provided automatically, it doesn't make a difference. So, until unless you have the information more or less real-time or up to date, you are fine to go. It doesn't matter if it's manned or unmanned.'*(P4) Therefore, a remote operations solution must ensure proper communication protocols, strong data connectivity and security (i.e. barriers against cyberattacks) before being included in the concept of operations.

These findings are consistent with previous studies on maritime and inland waterway automation, highlighting both the operational potential and socio-technical challenges of higher levels of autonomy (Bolbot et al. 2020; Ghaderi 2020; Kurt and Aymelek 2024). Issues related to human–system interaction (Amodeo 2020; Li and Yuen 2024), regulatory adaptation (Ahmed et al. 2023; Saha 2021), and trust in automated systems (Aalberg et al. 2024; Poornikoo et al. 2025) are recurrent across the literature.

Whereas previous studies such as Li and Yuen (2024) report human–system trust as a sector-wide concern, our findings localise this concern primarily within the technical and personnel subsystems. These contrasts highlight the unique characteristics of the E-IWT system, such as fragmented ownership and strong reliance on human-centred practices, which may further complicate the transition towards higher LOA.

Future ways of system interactions

At present, most of the operational interactions are barge-centric, thus the captain onboard remains the hub of those interactions/nodes. However, ROCs will become the new operational hub of the system as the LOA increases. This shift indicates a wider reconfiguration of the STS, where co-ordinational focus will shift from the onboard skipper to distributed technical actors. Effective information flow, ensuring structured interactions, will be critical to achieve the envisioned system's performance.

Redundant, real-time and standardized communications

Introducing redundancies and maintaining existing established systems, procedures, and technologies could be a smart choice while defining future ways of interactions between the vessel and the ROC, creating a sense of shared situation awareness. For example, providing the VHF for the remote operator so they can communicate, as it seems like the captain on board is communicating. The display screens at ROC can be identical to the displays onboard.

As far as the communication goes via objects/devices onboard and between/within a ROC, radio communications will remain the protocol, except that messages will become digitalized. Consequently, the amount of verbal communication using radio communication should be reduced largely. However, the E-IWT stakeholders, particularly the operational actors from technical and personnel subsystems, may still feel less confident. As one of the informants mentioned- '*Maybe the communication will be simpler, but it's more critical because there's no backup on the vessel. If no people are on board and you come to port, we must have a communication to the port from the land side station*' (P2). Therefore, creating redundancy is required to build that missing trust of the technical and personnel subsystem actors to maintain safe and efficient operations.

Shift in regulatory practice

There is a conflict between technological development and rules and regulations to move to a more complex socio-technical system with increasing changes in automation (see Sect. Unmanned remote control: WAI (scenario c)). Technology developers may see regulations as an innovation showstopper. Whereas Regulators prefer to change regulations once the technology has met certain performance-based milestones. This will create a technology-regulatory conflict, a paradox that has proven difficult to resolve in the past regulatory changes or new introductions.

Limitations and future research directions

This qualitative study provides key E-IWT stakeholders' insights into future operations, making the findings context-dependent and exploratory. And the analysis focuses on anticipated rather than implemented systems; actual developments may differ in practice. Future research should therefore examine real-world implementations of remote and autonomous operations, particularly focusing on ROC design from ergonomics, ROC operators' training and skill requirements, and their trust in automation.

Comparative studies across regions and other maritime transport sectors, such as short sea shipping, would further support understanding how STS evolve over time and how identified gaps can be addressed in practice.

Conclusions

Expected by many, the emergence of increasing levels of Automation, Artificial Intelligence, and Machine Learning will create major disruptions in the shipping industry and is expected to transform the E-IWT sector in fundamental ways. This study confirms that there will be profound changes in the way work is both imagined and done in this sector, not only from technical but also from socio-geographical- economic perspectives across the ecosystem. This is why this research chose to use a systems approach, and more specifically, a socio-technical framework to study these issues. By adopting an STS perspective, this research demonstrated how technological artefacts, regulatory frameworks, human actors, and environmental constraints are deeply interdependent in shaping transition pathways for E-IWT.

Theoretically, the study extends socio-technical transition and actor-network perspectives to inland shipping, demonstrating that automation is a socio-technical reconfiguration rather than a purely technical shift. The description of what elements are part of the E-IWT ecosystem was undertaken. Though this analysis is likely far from complete (at the time of this research) because of the reality of the ¨wickedness¨ of these problems, rapid changes to human-centred elements, such as education, continuing education, regulation and business models, remain largely unexplored.

The findings from this study also have policy implications that can support the EU's vision of modernizing E-IWT (European Commission 2019). The missing bridge between WAD and WAI indicates that the current policy is more focused on technological advancement and short of addressing the socio-technical integration. Policy should not only support technological innovation but also facilitate structural alignments between subsystem actors. Besides, developing harmonised standards for data exchange, communication protocols, and remote operations to enable interoperability, policy initiatives should encourage stakeholder collaboration and the inclusion of operational actors in the design and implementation of future systems, ensuring that end-user perspectives are integrated. Addressing these aspects could support a more balanced and resilient transition towards higher LOA in E-IWT. For the industry, the findings reflect the need to develop collaborative operational models among different actors, invest in training and reskilling of personnel, and ensure robust communication and data-sharing infrastructures to support remote and autonomous operations.

In sum, this research shows that the transition towards higher LOA in E-IWT is not simply a matter of technical deployment but a socio-technical challenge. Recognising and addressing this complexity is essential if automation is to deliver on its promises of safety, efficiency, and sustainability for the sector. A key empirical insight is the shift of the operational hub from vessel to shore-based ROC, accompanied by a redistribution of roles, responsibilities, and interaction patterns. However, misalignments among subsystems should be addressed to ensure an effective shift in the operational hub.

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Data availability
The datasets generated and/or analysed during the current study are not publicly available to ensure non disclosure of informants identity but are available from the corresponding author on reasonable request.

Declarations

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Not applicable.

Consent for publication
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Competing interests
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