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A systematic literature review of factors influencing the regulation of autonomous inland shipping in Europe

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Abstract

The onset of autonomous inland shipping comes with regulatory challenges. First, regulations currently in place do not permit the operation of autonomous ships, mainly due to crewing requirements. Second, autonomous transport modes are deemed to be disruptive technologies that present a particular challenge to public regulators with regard to their potential for unforeseen risks and uncertainties inherent to their implementation. From a public regulator's perspective, it is, therefore, of the utmost importance to identify and regulate the factors currently hindering the introduction of autonomous inland shipping, on the one hand, and the newly emerging issues, on the other hand, to minimise potential risk and uncertainty as much as possible. This paper presents a systematic literature review which was conducted to answer the research question: *What factors influence the regulation of autonomous inland shipping?* Following the outcome of the literature review, various factors could be identified, and four main categories of factors were established: technological, infrastructure, institutional and socio-economic readiness. The identified factors were subsequently discussed with regard to their significance for the regulatory agenda in light of factors found in the literature on autonomous maritime ships. The findings are of relevance for public regulators and policymakers working in the field of autonomous inland shipping. Moreover, the results presented in this paper might be also of interest for those seeking regulatory innovation regarding autonomous processes in other modes of transport.

Keywords Autonomous ships, Inland waterway, Regulation, Policy, Systematic literature review, Factors, Technology readiness, Infrastructure readiness, Institutional readiness, Socio-economic readiness

1 Introduction

The onset of autonomous inland shipping comes with regulatory challenges. First, existing regulations in Europe do not permit the operation of autonomous inland ships, mainly due to crewing requirements. Rules requiring human intervention need to be adapted to accommodate technology accordingly. Second, autonomous transport modes are deemed to be disruptive technologies that present a particular challenge to public regulators regarding their potential for unforeseen risks and uncertainties inherent to their implementation. Consequently, new rules governing these emerging risks need to be adopted. The institutional setting of public regulators in European inland shipping poses a particular difficulty for a holistic and harmonised regulation of autonomous inland shipping; several public regulators at the international, transnational and national level are involved in the adoption of inland navigation rules. However, for an efficient European inland shipping network,

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a harmonised approach to the regulation of autonomous inland shipping is indispensable [50].

Existing research on regulating autonomous or unmanned inland ships is restricted in scope and highly fragmented in terms of findings for the regulatory agenda. More precisely, in previous studies different regulations were analysed with regard to human interaction and individual provisions governing aspects of navigation, safety, environmental protection duties have been identified as regulatory barriers to the operation of autonomous or unmanned inland ships [3, 28, 50]. Yet, there is more to the regulatory agenda than adapting existing rules; autonomous inland ships will fundamentally change the way we think about shipping – and how it is currently being regulated. More specifically, regulatory gaps must be identified and addressed by adopting new rules.

From a public regulator's perspective, however, the challenge in regulating disruptive technologies lies in determining what exactly needs to be regulated and how this can be achieved because "*…it is difficult to assess the regulatory problems linked to a new development when the details of that development are not known*" [35, p. 22]. To overcome this regulatory uncertainty from a research perspective, the research presented in this paper consists of a systematic literature review of relevant studies in the field of autonomous inland shipping. The underlying rationale of this research approach was to understand in a holistic manner all relevant factors that are most likely influencing the future regulation of autonomous inland ships. By this, not only regulatory barriers could be identified but also regulatory gaps, i.e. newly emerging issues that need to be regulated.

The scope of the present research focuses on autonomous inland shipping in Europe. Literature with respect to autonomous maritime ships is beyond the scope of the systematic literature review because the objective of the review was guided by the need to systematically appraise previous research on autonomous inland shipping only. Findings relating to the regulation of autonomous maritime ships will nevertheless be significant for validation purposes and gaps identification, as will be explained below. With regard to the subject matter of the research objective, to avoid a semantic discussion the term 'autonomous' is used, corresponding to level 5 of the CCNR's Definition of levels of automation in inland navigation [10]. Notably, in literature the term 'unmanned' often refers to either remotely controlled or (fully) autonomous shipping operations. Although the term 'crewless' is gender-neutral, the term 'unmanned' is (still) much more present in current legislation and has not yet been uptaken by the literature. Therefore, the latter term was preferred in the systematic literature review. Furthermore, the research conducted here focuses solely on public law aspects thereby excluding rules regarding liability issues, insurance matters and aspects of criminal law.

The aim of the systematic literature review was to answer the following research question (RQ):

What factors influence the regulation of autonomous inland shipping?

Based on the findings of the literature review, answers to the following three sub-research questions were sought:

Sub-RQ1: *Which of the identified influential factors are also factors that need to be addressed by regulation?*

Sub-RQ2: *Which potential gaps can be identified based on findings from factors found in literature on autonomous maritime shipping?*

Sub-RQ3: *What conclusion(s) can be drawn from the findings to the questions above in terms of input for the regulatory agenda of autonomous inland shipping?*

It is expected that the findings of this paper are of direct relevance for public regulators and policymakers investigating regulatory solutions in the field of autonomous (inland) shipping. The research presented in this paper serves as an important basis for future research on regulation and autonomous inland shipping. The findings might also be of interest to anyone working or researching on regulatory aspects of autonomous processes in other modes of transport, such as rail, road and air. Moreover, research findings and possible solutions for a regulatory framework for autonomous inland ships in Europe can be of inspiration to other regions in the world that also seek regulatory innovation in the field of autonomous shipping.

As for the remainder of this paper, Sect. 2 describes the systematic review, how it was achieved and presents the findings. Section 3 discusses the findings with regard to their relevance to the regulatory agenda by referring to regulatory factors found in relation to autonomous maritime ships, as identified in the literature and formulates some recommendations for public regulators and policymakers. Section 4 concludes on the findings and recommendations.

2 Systematic literature review

The present research aims to answer the research question by undertaking a systematic review of the existing literature on factors that are influential to the regulation of autonomous inland shipping. In general, a systematic literature review serves to provide a comprehensive overview of the state-of-the-research in a specific area, to present the research found in a clearly structured manner and to add value to the existing research landscape [47]. Section 2.1 of the present paper explains the search process in a comprehensive manner. It follows Sect. 2.2 in which a detailed presentation of the findings as per category is given.

2.1 Methodology

The methodology adopted consisted of a scoping review and a systematic review, following the example of Veitch and Alsos [49]. The scoping review included an electronic search on the topic based on exclusion and inclusion criteria relating to keywords matches found in title, abstract, keywords or text, language, peer-reviewed and year of publication. In total, six different databases and academic journal search platforms were used; these consisted of Web of Science, Scopus, EBSCO Discovery Service (including Science Direct), Google Scholar, Social Science Research Network and Academia.edu. The keywords used were "autonomous" or "unmanned" combined with "inland" and "ship*", "vessel*" or "waterway". To narrow down the scope to articles featuring legal, regulatory or policy-related aspects, the additional phrase of "regulat*" or "law" or "polic*" was used. Another keywords combination used was "inland shipping" and "innovation" and "regulation". Boolean operators ('AND' and 'OR') as well as strings were used accordingly to ensure a broad indexing of potential studies; it also resulted in many duplicates. Besides the keywords used, the following additional criteria were applied to sort the articles and include them in the review: the articles included were no more than 10 years old; peer-reviewed and in English, French or German language. A preliminary search indicated that the academic literature on this topic is predominantly written in English. Furthermore, academic literature written in other languages on autonomous ships was found to focus exclusively on the maritime sector. Thus, the choice was made to conduct the keyword search in English. Rarely were articles written in other languages identified in the searched databases due to their bilingual abstracts, which also included one in English; however, these were eventually excluded owing to their lack of relevance to the subject matter.

It followed a systematic review in which a full text analysis in light of the research question was conducted. Studies were analysed regarding information that contributed to the research question. For this, articles were reviewed for information regarding regulatory, economic, operational, risk and safety-related or policy-related aspects of autonomous inland shipping operations, as determined by the presence of one or more of the identified keywords in the article's title, abstract, keywords or full text. Articles found but with a focus on unmanned or remotely controlled shipping operations were not excluded since factors influencing the adoption of unmanned or remotely controlled operations will most likely also be relevant to the implementation of autonomous shipping operations.

Some articles were not explicit as to inland or autonomous maritime shipping operations but took a more general approach; these articles were also included in the review. A total of 30 studies were included in the review. Reference lists of the reviewed studies were not examined; the objective of the review was to present a representative study of available evidence rather than presenting all existing papers written on the topic. Based on the articles reviewed, numerous factors were identified including those identified by authors cited in the reviewed studies. It followed a categorisation exercise with the support of an industry group with representatives from the inland shipping sector in which similar sub-factors were grouped into main factors. Based on their subject matter relevance, the main factors were subsequently allocated to four main categories. These categories were: technology, infrastructure, institutional and socio-economic readiness.

To validate the factors identified in the systematic literature review with regard to their relevance to the regulatory agenda, and to identify potential gaps, an additional review of factors that need to be regulated as identified in literature on legal and regulatory aspects of unmanned and autonomous maritime shipping was carried out. Figure 1 shows the research approach.

2.2 Findings

Table 1 gives an overview of the relevant four categories technology, infrastructure, institutional and socio-economic readiness. The literature review allowed to identify numerous factors that influence the regulation of autonomous inland shipping per category. Below, each category is described in detail.

2.2.1 Category 1: Technology readiness

Technology readiness is one of the most vital conditions before any new technology should be introduced to the market. Moreover, the readiness of a certain technology can be described in two ways: first, readiness can be regarded as the fact of the technology being able to operate in a prespecified way and, second, it describes its capability to be adaptive for future modifications; both are determinant for failure or success of the new technology. Three main factors were found in literature to drive technology readiness: the overall autonomous ship technology, safety aspects inherent to the operation of autonomous applications, and research and innovation development.

2.2.1.1 Ship technology To ensure technology readiness, the overall autonomous ship technology cannot

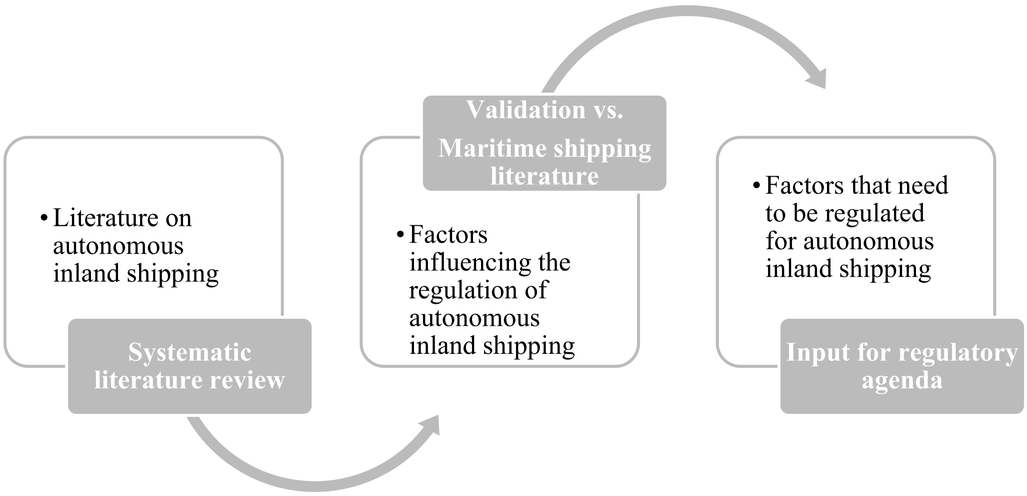

Fig. 1 Research approach

Table 1 Categories and factors

Category	Factors
Technology readiness	Ship technology, Safety, Research and innovation
Infrastructure readiness	Development of intelligent infrastructure, Remote control/supervision, Compatibility for mixed traffic and within overall supply chain
Institutional readiness	Rules and regulations, Policies, Security and risk management, Authorisation and inspection, Public service management
Socio-economic readiness	Social acceptance, Business readiness, Skilled labour

be ignored. Autonomous ships require highly advanced technologies to be successfully operative. First and foremost, an autonomous ship due to its uncrewed nature needs to be aware of its immediate environment whilst operating. This means that for the ship to be able to operate in a sufficiently safe manner, it is necessary for the ship to be able to acquire and process information to detect and circumvent obstacles standing in its pathway. As to the nature of these, obstacles can be classified into static (known or unknown) obstacles relating to the waterway infrastructure such as bridges, locks, quays or waterway cross-sections, and dynamic (known or unknown) obstacles such as other ships, persons or jetsam [30]. Since ships in general move much slower than other transport modes, and particularly with regard to dynamic obstacles, manoeuvrability and new positioning of the ship following the detection of such obstacles may be delayed. Therefore, to ensure safe navigation, the understanding of the intentions and future positions of crewed and uncrewed ships is crucial. Consequently, technology must be capable to determine a ship's exact position as well as predicting and communicating its intentions and future manoeuvres to leave sufficient time for other ships to react [24]. Delays or loss of information exchange due to differences in computation speed can harm the communication network between ships, potentially leading to collisions [44].

In contrast to sea shipping, inland ships are often faced with geographical and infrastructural specificities such as narrow (natural or artificial) waterways, river- or canal-crossing bridges, a usually much higher traffic density than at sea and the presence of strong currents in some inland waterways [53]. Especially in case of dense traffic situations, ships are expected to behave in a certain way by following collision avoidance rules [45]; therefore, algorithms must be developed in such a way to comply with current collision avoidance regulations [44, 53], but also be capable of adopting local path planning for various encounter scenarios [17].

In general, smart ships, including autonomous ships, present an essential part of the overall smart shipping system [52]. According to Xiao et al. [52], the concept of 'smart ship' encompasses more than intelligent navigation; it also includes intelligent hull, cabin and mooring system as well as intelligent energy efficiency and cargo management. This means that a smart ship needs to be able to monitor the operation status of the main propulsion-related equipment and systems in the engine room, to analyse and evaluate the operating status and health status of equipment and systems based on status monitoring data; route and speed design and optimisation were found to be also very important.

The technology assuring smart shipping operations needs to be stable, robust and effective. In terms of quality check and technology readiness assurance, technical compliance certificates will be necessary to assure the technology is ready to operate in a safe manner [50]. For this purpose, certification procedures proving technology readiness will need to be established by competent authorities or organisations.

2.2.1.2 Safety In contrast to conventional modes of transport, an increased need for safety and security analyses was found in relation to the implementation of intelligent transport systems and autonomous processes [16]. In respect of distinguishing safety and security aspects, a general distinction can be made between threats caused by deliberate (intended) actions with the aim to have a certain impact can be defined as security concern while hazards constitute unintended mistakes or errors that may trigger safety issues [16, citing Lautikeri et al. (2022) and Gromule et al. (2017)]. Any safety risk constitutes an important factor of technology readiness: the technology must operate in such a safe way to avoid any unintended mistakes or errors.

When comparing autonomous vehicles of different transportation modes and the challenges with regard to the different environments in which they operate, inland ships were classified to operate in an environment in between that of trucks with relatively well-defined lanes and (sea-going) ships, with little problems of unexpected occurrences [45]. Besides the functional availability of the technology, situation awareness constitutes a predominant concern with regard to safety assurance of the technology [7, 40]. A lack of situation awareness occurs when the surrounding is not properly (wrongly or not at all) determined; this can happen when, for example, objects are not detected and recognised, or the weather is not properly conceived [7]. To keep the occurrence of hazards as low as possible, preventive and mitigate measures applicable to the specific safety concern must be established [7]. Amongst the measures found to prevent loss of situation awareness are more advanced sensors as information acquisition systems and training whereas installed abnormalities' detection systems and a control transfer to the remote control centre could serve as mitigative measures in case situation awareness is lost [7].

In case of thruster and steering system failures, technology must be construed in such a way to allow redundancy in components used for propulsion and self-reconfiguration for propulsion plant as preventive measures; if the propulsion system becomes completely unavailable, there could be an automatic drop of anchor and visual and audible notifications to other ships to mitigate the safety risk [7]. Mixed traffic poses particular challenges for the safety assurance when operating autonomous vehicles [45, citing Baheti et al. (2011)].

As to the safety standard applicable, Veitch and Alsos [49] argue that the 'at least as safe as' standard is flawed in light of introducing autonomous systems to reduce occurrences of human error and advocate a higher safety standard for autonomous transport modes. In the same sense, other authors [45, citing Bagloee et al. (2015)], advocate that as a general rule the current and future risk must be below the threshold currently accepted in society. They also admit that a main problem with identifying the applicable safety standard is to identify the potential hazards and the associated risks, particularly with respect to new hazards that may evolve from the development of increased autonomy.

2.2.1.3 Research and innovation Further research in innovation development seems to be indispensable also from a safety perspective to tackle, on the one hand, new hazards of existing technology, and, on the other hand, hazards of future innovation. To continuously improve technology, development and subsequent implementation of other innovation elements were found to include those that replace ultimately all essential processes onboard, i.e. with the purpose to navigate, (un)moor, (un)load, maintain the engine room, supervise loading while constantly adjusting on all irregular weather conditions, different waves and tides [50].

2.2.2 Category 2: Infrastructure readiness

Next to ship technology, autonomous inland ships will only be able to operate if infrastructure is adapted to support the new technology sufficiently and adequately. For this, important changes will need to be made with regard to digital and physical infrastructure because the way ships operate and communicate with the environment will significantly alter.

2.2.2.1 Development of intelligent infrastructure For autonomous shipping operations, barriers hindering the adoption of digital infrastructure were found to score the highest amongst current infrastructural barriers in the development of intelligent supply chains [26, citing Zhang and Lam (2019)]. The first and foremost change that occurs with the implementation of autonomous inland ships will be that the way of communication will fundamentally change; data will be the new language to communicate. In terms of communication, to make sure that the infrastructure currently in place and uncrewed operations speak the same language, they need to use overall compatible systems [27]. Communication infrastructure is required to allow safe, secure and reliable communication [31, 50]. The more autonomous ships will be operated, the more data will need to be handled by the infrastructure. The technology implemented to operate autonomous ships needs a multitude of various data resources such as wind, current, traffic monitoring and predicted positioning; safe navigation presupposes safe decisions based on these data and for this reason, data needs to be robust [24]. Internet and above all electricity supply must be available to ensure the availability of robust data at all times [52]. For this, smart waterways, including physical infrastructure components, will need to be construed to process data and allow big data exchange, including continuous data synchronisation in real-time [50].

Furthermore, digital infrastructure must ensure the collection, storage and updating of surveying as well as mapping data and updating navigation support data [52]. Moreover, the data retrieved needs to be adequately cleaned and, if necessary, corrected to be further processed [34]. Besides adopting smart waterways, smart ports will need to be construed to provide for better traffic management [34, 52]. Adapted port infrastructure will also need to include automated mooring processes and a sufficient level of e-government, that is the use of technology to provide governmental public services to allow, for example, online document transaction [50].

2.2.2.2 Remote control/supervision In general terms, the implementation of advanced shipping technology is expected to bring significant changes to the way humans interact with machines. In this regard, Saha et al. [38] studied the various stakeholders and technology roles in the socio-technical system of inland shipping, and identified the potential changes that may occur in the system. Although the human operator is not foreseen in autonomous inland shipping, it is expected that humans will still be present to ensure monitoring tasks, intervene when necessary, and make decisions that go beyond the decision-making capacity of the programmed algorithm [50]. In principle, remote monitoring and supervision can occur from anywhere provided the technological conditions such as internet connectivity are fulfilled. However, the prevailing view is the construction of onshore centres for this purpose [25, 31, 49, 50]; it has also been suggested that support can be ensured by way of aerial devices to reduce the risk of collision [34].

Peeters et al. [31] describe the design requirements that need to be fulfilled by an onshore control centre: the centre needs to acquire a multitude of different information with regard to sailing, observation, safety and emergency, security and technical aspects; the information acquired needs to be subsequently transferred to the human operator to provide a sufficient degree of situation awareness and sense-making capabilities. According to Veitch and Alsos [49], human monitoring plays an essential part even for the most advanced processes including autonomous shipping operations, speaking of a collaborative human-artificial intelligence (AI) system. The benefit of such systems could result in greater system performance than that could be achieved by either human or AI performing alone, thereby going beyond the purpose of introducing AI to reduce the event of human error. However, a clear distribution of responsibilities between humans and AI as part of the 'operational design envelop' needs to be established [49], citing [7].

Especially in the case of remotely controlled shipping operations, if the remote control fails, it has been noted that there should be reliable emergency procedures to dock automatically and in a safe way [50]. This procedure could also be relevant to autonomous operations being monitored by the control centre when the connection is lost, when, for instance, crossing national borders or switching the network provider.

2.2.2.3 Compatibility for mixed traffic and within the overall supply chain As the implementation of autonomous ships will follow a gradual process, conventional vessels will still be operating alongside autonomous vessels for some time. For this reason, the current infrastructure needs to be adapted to accommodate both conventional as well as highly automated and autonomous vessels [49].

Shipping plays an essential part of intermodal freight transport. This has also consequences for the implementation of autonomous inland vessels. In the context of connected transport chains, it has been noted that the sole implementation of autonomous ships will not automatically result in better functioning transport chains due to the fact that different legs within a transport chain are strongly interconnected [40]. Accordingly, if automation applications are applied in different transportation modes and are combined, the overall reliability of the entire transport chain is expected to improve. This is not the case if only a single link within the overall transport chain is made autonomous: coordination issues amongst the different transport links may arise, making the overall reliability of autonomous applications in inland shipping more disadvantageous than beneficial within the entire supply chain.

2.2.3 Category 3: Institutional readiness

The third category features factors that are relevant from the institutional readiness perspective. Here, institutional readiness describes the organisation's (both public and private) preparedness to respond and adapt to autonomous inland shipping technology.

2.2.3.1 Rules and regulations Rules and regulations play an important factor in the future adoption of autonomous inland shipping operations in Europe. The adaptation of the current regulatory framework is necessary before autonomous inland ships can be implemented at a large scale. Rules currently in place in inland shipping oppose the operation of the new technology mainly because autonomous inland ships are uncrewed and important safety functions need to be ensured by the human operator [3, 13, 26, 28, 50].

At the same time, regulatory gaps relating to new roles and responsibilities as well as new emerging risks need to be identified and regulated. Unified legal definitions and description of roles and responsibilities, including open questions of liability, of new actors, such as the remote control centre personnel, are needed [50]. Collision prevention rules might need to be adapted in terms of situation awareness and remote control monitoring; requirements for the algorithm taking over the role of the human operator needs to be stipulated [24]. Furthermore, rules need to explicitly address risk mitigation [8].

2.2.3.2 Policies Policies can have a predominant role in shaping the future implementation of technologies by way of supporting technology development and feasibility. Based on policies, important guidance on operating autonomous inland ships can be provided in an informal, fast way before laws will be adopted to regulate the new technology in a formal way. Regulatory issues associated with autonomous inland shipping operations can be defined by way of policy measures; these should be uniform to respond best to the structural challenge of autonomous inland shipping [26, 27].

Additionally, policy decisionmakers play a crucial role in granting derogations and adjusting current rules to further the development and implementation of autonomous inland shipping innovation [50]. The European Union (EU) plays a central role in shaping the future of autonomous inland shipping in the EU through its important policymaker powers; by way of promoting new technologies and innovation in inland shipping, the EU supports the development of the sector towards being more sustainable, efficient, accessible and multi-modal [19].

2.2.3.3 Security and risk management Uncrewed operations offer opportunities for new risks and security measures will need to be adapted accordingly. The deterrent effect of humans being present onboard will no longer be available. Autonomous ships require another level of security against theft or vandalism of expensive robotic systems and cargo due to their uncrewed nature [50]. Besides security concerns against theft and vandalism, cyber risks pose significant threats to autonomous shipping operations and infrastructure, including ports and remote control centres [5, 6, 15, 16, 25, 27, 34, 44, 50, 52].

The most critical scenarios have been identified to relate to access to the ship control centre, GPS signal related attacks or malware installation on the collision avoidance system or the situation awareness system [5–7]. With the increase of autonomous ships, the increase in cyber-attacks is expected; new hacker groups will emerge ranging from generic, amateur, ethical, criminal hackers to former malicious employees or external providers to activists, competitors, terrorists and even states [5]. Amro and Gkioulos [1] advocate a new cyber risk management approach by establishing different preventive and mitigative defence layers. The development and integration of automated processes for the evaluation of cyber security controls within different cyber assets involved in the operation of autonomous ships is needed. Additionally, liability questions in the event of damage or loss due to cyber-attacks will need to be tackled [50].

2.2.3.4 Authorisation and inspection New authorisation and inspection procedures will need to be established for autonomous inland ships. Existing requirements for conventional ships will be outdated by technology advancement and no longer applicable to the approval process of autonomous ships. Bolbot et al. [8] recommend that because the introduction of autonomous inland ships depends on a number of factors and cannot be based only on a risk matrix of potential safety and other risks, the approval should be based on a case-by-case basis. This presupposes a sufficient level of evaluation capacity in terms of personnel and regulatory standardisation bodies [50].

Following approval, as with conventional ships, regular inspection will need to be necessary. To maintain public safety, inspectors need specialised knowledge applicable to the technology of autonomous ships [50].

2.2.3.5 Public service management According to a study on accidents in European inland waterways conducted by Bačkalov et al. [4], it was found that most accidents could not be attributed to human error. The study suggests that ship safety can be improved through advanced automation only if both the waterway and the ships are in good condition and properly maintained.

For this, public service management, navigation administration and support ability for autonomous ships need to be established [52]. According to Zhang et al. [54], reliability and maintenance management are essential for uncrewed ships: on the one hand, technology needs to be designed to allow for remote maintenance when the ship is on route; on the other hand, when it is necessary for ships to be maintained in ports this puts higher demands on the maintenance arrangements during port stays.

2.2.4 Category 4: Socio-economic readiness

Socio-economic readiness as the fourth and last category of factors presented here might be a game changer in whether autonomous inland ships will be ultimately implemented at large in Europe: business readiness and social acceptance of autonomous inland shipping technology will largely depend on trust in the technology and an effective risk mitigation by way of regulation. For this, regulation is indirectly vital to the commercial feasibility of autonomous inland ships. Factors accounting to socio-economic readiness were social acceptance, business readiness and the availability of skilled labour.

2.2.4.1 Social acceptance Besides hard institutional conditions such as rules and regulations, soft institutional conditions will also influence the implementation of autonomous inland ships. Amongst these are politics and cultural values but also social acceptance. In terms of social acceptance, autonomous ships must prove to be trustworthy, safe and reliable [50].

As noted by Bolbot et al. [8], societal risk acceptance criteria may result in more stringent matrix ratings compared to the individual risk criteria. Vagia and Rødseth [45] investigated societal acceptance of different types of autonomous vehicles. Autonomous ships were classified as medium to high hazards, having high damage potential but overall few in numbers and moving in general in uncluttered environments. More particular, benefits and concerns are being perceived differently according to different autonomy degrees [18].

2.2.4.2 Business readiness As noted by Colling et al. [13] in the context of vessel platooning, where a fleet is mainly composed of many individual small family businesses, as it is the case in the Rhine region, it is more likely that those individual businesses will join the services of a third party organiser when considering the operation of vessel trains. In contrast, where a fleet is composed of mainly big (state-owned) shipping companies, investment in new technologies will be less burdensome and companies may set up their own vessel train concept or operate as part of small alliances.

According to Rødseth [37], from a socio-economic perspective it is more likely that, at least with regard to the first implementation period of autonomous ships, operators will preferably aim at implementing only constrained autonomy of uncrewed vessels, thereby opting for the use of remote control centres for supervision purposes, as opposed to full autonomy. The reason for this is that, based on a cost–benefit assessment, the costs incurred to guarantee supervision of autonomous operations by way of a remote control centre is relatively small compared to costs incurred resulting from accidents. It seems that shipowners are reluctant to leaving their high value ships unsupervised. As technology is constantly being developed there will be in future more reliance on autonomous operations, however, for the time being the handling of rare and difficult situations may not be covered by the technology itself, leaving those situations to be handled by the remote control centre as the more cost-effective choice.

2.2.4.3 Skilled labour Unregulated training—specific aspects including skills but also qualifications, roles and responsibilities—whether concerning safety control mechanisms or competency requirements constitute important constraints to the safe operation of autonomous vessels [49]. In principle, offshore labour previously working onboard will ultimately be replaced entirely by autonomous applications. Personnel skilled in having previously worked onboard, i.e. boatmaster and crew, will not be automatically shifted to working as personnel of the remote control centre. The reason for this is that the tasks of personnel working in the context of autonomous shipping operations will change considerably, onshore employment will be divided into workforce skilled in technology-creating and workforce trained in monitoring and controlling autonomous shipping operations [40].

Remote control centre personnel will need to acquire a set of different skills and competences. It is expected that personnel will need to be able to monitor various processes at the same time; loss of situation awareness, data misinterpretation, capacity overload and lack of emotional attachment risk too much reliance on machines which may result in less monitoring and caretaking and to new additional human weaknesses described as 'cognitive lackadaisicalness' [50]. Special consideration will need to be given to any kind of cyber threats for which training and awareness regarding cybersecurity policies will need to be established [1]. Personnel must be adequately and sufficiently trained and aware of these new cognitive lackadaisicalness and threats to ensure the safe functioning and efficiency of the remote control centre and the autonomous shipping operation.

3 Discussion

In the following section, the findings presented above will be discussed. Some (obvious) interesting conclusions could be drawn. A subsequent discussion sheds light on the question whether the influential factors also constitute factors that are relevant to the regulatory agenda.

3.1 Factors that influence the regulation of autonomous inland shipping in Europe

The review of the 30 articles revealed numerous factors. To avoid redundant classification of factors essentially meaning the same, they were grouped according to similar meanings based on the functional equivalence of the concepts used. Depending on the subject matter, factors were subsequently distributed to one of the four categories (technology, infrastructure, institutional, and socio-economic readiness) (see Table 2).

Despite the search was performed to find articles that were published within a 10-year publication time range dating back to early 2014, the first relevant articles that could be included in the review were published only in 2019 with a steady increase in publications (with the exception of the year 2021) reaching a peak number of relevant publications in 2022 (see Table 3).

In terms of the factors most cited, the one that has been discussed the most frequently in the relevant studies refers to 'security and risk management' with a total of 12 references found, followed by the factors 'development of intelligent infrastructure' (7 references); 'rules and regulations' (7 references); and 'ship technology' (7 references) (see Table 2). Following a quantitative analysis based on the number of occurrences in the identified studies, these three factors appear as the most important in influencing the regulation of autonomous inland shipping.

In terms of potential limitations of the study presented here, only a database search was conducted in the systematic review. An additional snowball search system could have allowed for the identification of other possible sources and potential sub-factors. The supplementary review of maritime literature could potentially mitigate this shortcoming.

3.2 Factors and their relevance to the regulatory agenda

From a regulatory perspective, factors identified in the literature that influence the regulation of autonomous inland shipping might not be identical to those that would actually need to be regulated. The difficulty here lies in determining—without engaging in speculation—whether an influencing factor also constitutes a *hard regulatory factor*, i.e. a factor that needs to be regulated because it directly hinders the structural implementation of autonomous ships. Regulation-influencing factors may nevertheless give important hints as to the factors that—most likely—will be subject to regulatory intervention. To validate the factors retrieved from the systematic literature review with regard to their relevance to the regulatory agenda, and by this, to answer sub-RQ1: *Which of the identified influential factors are also factors that need to be addressed by regulation?*, following the structure of the previous section, the factors were analysed in light of factors relevant to autonomous maritime shipping regulation, as determined in the literature. Furthermore, the additional review of factors as identified in literature on legal and regulatory aspects of unmanned and autonomous maritime shipping disclosed several gaps with regard to the results retrieved from the systematic review of inland shipping literature and thereby tackled sub-RQ2: *Which potential gaps can be identified based on findings from factors found in literature on autonomous maritime shipping?*, as will be discussed in more detail below.

3.2.1 Category 1: Technology readiness and regulation

3.2.1.1 Ship technology Autonomous ship technology as much as conventional ship technology will be subject to regulation. The relationship between autonomous ship technology and regulation is twofold: On the one hand, autonomous ships will need to be construed to meet current standards. This is, for example, the case with regard to current collision avoidance rules. In maritime shipping, the prevailing opinion is that autonomous maritime ships must comply with existing collision avoidance rules [14, 21–23, 32, 41, 43, 48].

On the other hand, it is expected that autonomous maritime shipping technology will fundamentally change ship design due to new technological aspects essential for the operation of autonomous shipping operations. For this reason, new construction requirements will need to be established to reflect the required state of technology necessary for autonomous ships [14]. Adapting regulations in light of technology advancements, for example, to replace human activity by automated systems has long been practice; therefore, introducing fully automated systems will present no precedence in the history of regulation [35].

Whether the appearance of autonomous inland ships will significantly differ from the one of conventional inland ships needs to be seen. However, the issuance of new construction requirements and technical conditions for autonomous inland ships will be certain.

Table 2 Regulation-influencing factors as found in the literature review

Category	Influencing factor	References
Technology readiness	Ship technology	Vagia and Rødseth [45] Verberght and van Hassel [50] Hüffmeier et al. [24] Peeters et al. [30] Yuan and Gao [53] Gao et al. [17] Tran et al. [44]
	Safety	Vagia and Rødseth [45] Streng and Kuipers [40] Bolbot et al. [7] Fan and Yang [16] Veitch and Alsos [49]
	Research and innovation	Verberght and van Hassel [50]
Infrastructure readiness	Development of intelligent infrastructure	Verberght and van Hassel [50] Hüffmeier et al. [24] Peeters et al. [31] Kashav et al. [26] Krause et al. [27] Restrepo-Arias et al. [34] Xiao et al. [52]
	Remote control/supervision	Verberght and van Hassel [50] Peeters et al. [31] Karetnikov et al. [25] Restrepo-Arias [34] Veitch and Alsos [49] Saha et al. [38]
	Compatibility for mixed traffic and within overall supply chain	Streng and Kuipers [40] Veitch and Alsos [49]
Institutional readiness	Rules and regulations	Verberght and van Hassel [50] Bačkalov [3] Hüffmeier et al. [24] Nzengu et al. [28] Bolbot et al. [8] Colling et al. [13] Kashav et al. [26]
	Policies	Grzelakowski [19] Verberght and van Hassel [50] Kashav et al. [26] Krause et al. [27]
	Security and risk management	Verberght and van Hassel [50] Bolbot et al. [5] Bolbot et al. [6] Bolbot et al. [7] Amro and Gkioulos [1] Dobiáš [15] Fan and Yang [16] Karetnikov et al. [25] Krause et al. [27] Restrepo-Arias et al. [34] Xiao et al. [52] Tran et al. [44]
	Authorisation and inspection	Verberght and van Hassel [50] Bolbot et al. [8]
	Public service management	Zhang et al. [54] Xiao et al. [52] Bačkalov et al. [4]

Table 2 (continued)

Category	Influencing factor	References
Socio-economic readiness	Social acceptance	Vagia and Rødseth [45] Verberght and van Hassel [50] Bolbot et al. [8] Goerlandt and Pulsifer [18]
	Business readiness	Colling et al. [13] Rødseth et al. [37]
	Skilled labour	Verberght and van Hassel [50] Streng and Kuipers [40] Amro and Gkioulos [1] Veitch and Alsos [49]

3.2.1.2 Safety As much as in inland shipping, technical requirements to ensure situation awareness and communication to react, for example, in dynamic environments has been found to be a crucial aspect in safe autonomous maritime shipping operations [14, 32, 36, 43]. This could also entail the ability of autonomous ship technology to make decisions that go beyond compliance of collision avoidance rules when necessary, as found in the literature on autonomous maritime ships [35]. Therefore, learning capacity and spontaneous – not preprogrammed – reactions of AI will become essential in safety assurance of autonomous shipping operations. With regard to inland shipping, this could be also an important aspect in case of narrow or congested rivers or canals that requires regulatory consideration.

Besides, assisting persons or ships in distress constitutes a well-established principle of international maritime law and good seaman ship. Therefore, new requirements will need to be established so that unmanned ships will be able to provide at least a satisfactory level of assistance despite having no personnel onboard to assist [14]. This duty is less obvious in the case of inland waterways but nevertheless important. Therefore, it can be argued that autonomous inland ships should satisfy alternative assistance requirements to comply with the obligation.

Table 3 Year of publication in correlation with number of relevant studies

Year of publication	Number of references found
2014–2018	0
2019	4
2020	6
2021	2
2022	14
2023	4

As much as in inland shipping, there has been a dynamic discussion about the ultimate safety standard applicable to autonomous shipping operations. Pritchett [32], for example, advocates that autonomous maritime ships should fulfil higher safety standards than conventional ones due to eliminating human error. According to Ringbom [35], the standard applicable to autonomous ships must at least be equal to current safety standards. Further research in this respect is needed. Another aspect that has been raised with regard to autonomous maritime shipping is that of adapted reporting requirements with respect to incidents involving dangerous goods [48]. Arguably, the same could apply to autonomous inland shipping operations in light of historical environmental disasters involving major chemical spills as happened on the Rhine river multiple times.

3.2.1.3 Research and innovation Legal deviation from current and future regulations to ensure innovation development of autonomous ship technology has also been found an important aspect in maritime shipping [39]. Therefore, regulation should be flexible to support technology advancement in either sector.

3.2.2 Category 2: Infrastructure readiness and regulation

3.2.2.1 Development of intelligent infrastructure Adapted infrastructure constitutes a necessary condition for a successful large-scale implementation of autonomous inland ships in Europe. For this reason, technology readiness of infrastructure will need to be regulated as much as autonomous shipping technology itself. Based on the findings retrieved from the inland shipping literature, regulation should foster a harmonised development of intelligent infrastructure to ensure that at least the most important prerequisites in terms of infrastructure are established to support the operation of autonomous ships that goes beyond the one within (national) experimental testing zones.

In maritime shipping, particular infrastructure issues that need to be regulated were found to concern compliance of autonomous ships with reporting obligations in digital format, especially when entering territorial waters [14] and communication requirements between the ship and the shore control centre [36]. Both are also important in inland shipping, albeit reporting obligations are of less political nature than in maritime shipping since rivers and canals are often shared by several riparian states in Europe.

3.2.2.2 Remote control/supervision As shown above, remote monitoring or supervision will still be present in autonomous inland shipping operations; this has also been endorsed with regard to maritime shipping. Evidently, temporary, or exceptional, remote control of the autonomous maritime ship becomes necessary when the ship encounters a problem that it cannot independently resolve for which control temporarily handed over to humans might become compulsory [11, 51]. Whether humans should automatically take over control in congested waters as suggested by Pritchett [32] will ultimately depend on technology advancement and learning capability of the system.

Obviously, the environments in which inland waterway and sea-going ships operate are of very different nature. Consequently, albeit operating in different environments and responsibilities of remote control station personnel will differ in respect of monitoring shipping operations in inland waterways or on the high seas, it can be assumed that humans gaining control of the ship either due to sudden technology failure or prescribed in specific areas like ports will be equally applicable to autonomous maritime and autonomous inland waterway operations.

3.2.2.3 Compatibility for mixed traffic and within the overall supply chain For the successful implementation of an innovation, integration of the innovation within the overall (maritime) supply chain is determinant [9]. In general, according to Sys and Vanelslander [42], a regulatory framework with harmonised rules can support the move forward towards an innovative maritime supply chain network. Consequently, the implementation of autonomous inland ships is dependent on the sector's readiness to integrate automated systems in general. Regulation can play a decisive role in ensuring a trend in this direction.

3.2.3 Category 3: Institutional readiness and regulation

3.2.3.1 Rules and regulations As for institutional readiness, the overall regulatory framework will need to be adapted to no longer pose a direct hindrance to autonomous shipping operations; gaps in regulations that would otherwise regulate new emerging aspects relating to autonomous shipping need to be tackled. In maritime shipping, regulatory barriers were found in respect of rules relating to collision avoidance, obligations with regard to the rescue of distressed vessels and persons at sea [12, 20, 32, 48] and environmental protection duties [21] as well as general definitions and responsibilities of master and crew [12, 14, 32]. As much as for autonomous inland ships, a predominant regulatory barrier present current manning requirements and any safety assurance that is premised on human presence on board to ensure navigational safety which potentially render any autonomous maritime ship unseaworthy, depending on the interpretation of being 'reasonable fit for the intended person' [11, 12, 21, 29, 32, 35, 48].

Apart from these regulatory barriers, several regulatory gaps were identified, amongst them new definitions and responsibilities with respect to remote control station personnel as a predominant gap in current regulation [11, 12, 14, 32, 35, 46, 48, 51]. With respect to remote control station personnel duties, it was noted that allocation of responsibilities needs to be specifically addressed by regulation when navigational obligations could change according to specific circumstances; in this case, remote control station personnel could be obliged to mandatorily take over [14].

For either shipping sector, it is important that in such cases allocation of responsibilities is clearly regulated as otherwise unpredictable liability issues could arise. In addition, as noted in the context of autonomous maritime shipping, responsibilities of pre-programmers and guidelines for ethical dilemmas relating to how much and which decision competence should be left to the system and pre-programmed choices [14, 51]. A clear regulation of software decision-making in ethical dilemma situations involving, for instance, a potential collision with humans needs to be established for both maritime and inland waterway shipping.

In some maritime ports, mandatory pilotage is necessary. For this reason, the definition and responsibilities of pilots in the context of autonomous shipping need to be reconsidered [21, 29, 48, 51]. Pilotage is dependent on the area in which a ship is operating, and can be equally applicable to inland waterway ships, albeit pilotage is less common in inland waterway ports due to the general smaller size of inland waterway ships. In the context of innovation development, in general, regulation should explicitly permit derogations from the legal framework to further innovation development and to create a legal basis for the continuous improvement of autonomous shipping technology [14]. This confirms the finding stated above with regard to autonomous inland shipping.

3.2.3.2 Policy In maritime supply chain innovations, policy can play a pivotal role in reducing the level of uncertainty and encouraging innovation [42]. To support a structural transformation towards autonomous maritime shipping operation, a uniform approach is needed [35]. This confirms the finding above in that a uniform approach in the regulation of autonomous inland ships is needed.

3.2.3.3 Security and risk management As shown above, regulation should further provide adequate security measures against new emerging risks, in particular against cyber risks including protection of sensitive data and secure data transfer. Measures against cyber risks have also been found a predominant concern for autonomous maritime ships [14, 29, 35, 36]. Besides cyber security threats, the need for anti-terror safeguards [14] and security measures in case of piracy attacks have been raised for autonomous maritime ships [29, 32]. Both can occur in inland waterways as well but are less frequent in European inland waterways. In the context of pollution accidents, technology needs to ensure preventive and mitigative measures formerly ensured by crew on board [14]. This also counts for inland shipping.

3.2.3.4 Authorisation and inspection As shown above, to ensure that autonomous ships stay safe and fulfil the required operational standards, regular inspection and enforcement procedures should be subject to regulation. Similar to the findings with regard to autonomous inland ships, certificates that were formerly kept physically on board the maritime vessel need to be digitalised [14]. According to Pritchett [32], certification ability that an autonomous maritime ship meets legal safety requirements could be ensured by a classification society or port state authority. The same approach could be adopted in inland shipping.

3.2.3.5 Public service management New rules for training and certification of Vessel Traffic Services (VTS) personnel have been identified as significant in relation to autonomous maritime operations [46]. In the context of inland shipping, this means that for public service management to be efficient, it needs to be able to communicate and handle autonomous inland shipping as much as conventional shipping.

3.2.4 Category 4: Socio-economic readiness and regulation

3.2.4.1 Social acceptance With regard to autonomous maritime shipping, it has been noted that results from tests with autonomous ships serve as a knowledge base for regulatory innovation and can create societal support by demonstrating the benefits to society in terms of higher safety levels, less environmental impact and more inexpensive and efficient ship transport [14]. The same holds true for inland shipping, as shown above.

3.2.4.2 Business readiness In the context of innovation in the maritime supply chain, regulation can help to create stability in unstable times of business restructuring due to increasing technology implementation [42]. Policy and regulation can therefore have a significant impact in business development, be it in inland waterway or maritime shipping.

3.2.4.3 Skilled labour As with remote control station personnel for autonomous inland shipping operation, educational, training and qualification requirements for remote control station personnel need to be adopted for autonomous maritime ships [14, 35].

3.3 Towards an adaptive regulatory framework for autonomous inland shipping

Following the discussion above which shed light on the factors that will be, or most likely will be, subject to regulatory intervention before autonomous inland shipping can be adopted in Europe, and to answer sub-RQ3: *What conclusion(s) can be drawn from the findings to the questions above in terms of input for the regulatory agenda of autonomous inland shipping?*, the next issue lies in determining the most effective way of regulation. In general, regulation can be divided into soft and hard regulatory instruments: whereas hard regulation indicates mandatory instruments like law, soft regulation refers to voluntary instruments such as codes of conduct, best practices, standards or recommendations [33]. Despite its non-mandatory nature, soft regulation can be an important regulatory means, especially in relation to innovations implementation when risks and uncertainties are not entirely known at the time of implementation and rapid technological developments happen.

Based on the 'adaptive law theory', law can be maladaptive in responding to (rapidly) changing societal and economic circumstances; to better respond to such changes, law needs to become adaptive and flexible, thereby also allowing for (legal) uncertainty and more discretionary decision making [2]. Consequently, rapid regulatory adaptation becomes a key factor in regulating emerging technologies. Here, soft regulation can respond in a much faster and flexible manner since the issuance of soft regulatory instruments, in general, is much less time consuming than adopting new laws and regulation which is based on more formal procedures; this becomes an important advantage of regulating via soft law measures in the case of fast developing and newly emerging technologies such as autonomous processes. However, for an effective long-term regulation, hard regulation provides more trust and legitimacy to the public.

For this reason, public regulators and policymakers need to establish the most effective regulatory measure for regulating autonomous inland shipping in the short, medium and long term. Figure 2 presents a regulatory agenda-setting for autonomous inland shipping and shows the objectives within the different regulatory timeframes, starting with the initial regulation, which will then develop into an adapted regulation and ultimately ending with an adaptive (and ongoing) regulation.

The research in this paper aims to cover the analysis of issues that need to be regulated in the short term and will therefore be subject to the initial regulation of autonomous inland shipping. However, the determination of whether an issue (factor) would need to be addressed by way of soft or hard regulation would go beyond the scope of this paper. To be able to answer the question of *how* to regulate autonomous inland shipping in Europe, further research is needed, involving empirical research to better understand potential impacts of the initial regulation on industry and society.

4 Conclusion

The research presented in this paper is based on a systematic literature review and subsequent gap analysis in the field of autonomous or unmanned inland shipping. The objective of the review was to identify the factors that are influential on the regulation of autonomous inland shipping, as guided by the research question *What factors influence the regulation of autonomous inland shipping in Europe?*, and driven by the need for a comprehensive overview of the state-of-the-research in the area.

The findings from the review and subsequent analysis of findings are summarised as follows:

First, from the systematic literature review numerous factors were identified that influence, or most likely will influence, the future regulation of autonomous inland shipping in Europe. Given this, factors were aligned, when necessary, and allocated to one of the four main categories: technology readiness (ship technology, safety, research and innovation), infrastructure readiness (development of intelligent infrastructure, remote control/supervision, compatibility for mixed traffic and within the overall supply chain), institutional readiness (rules and regulations, policies, security and risk management, authorisation and inspection, public service management) and socio-economic readiness (social acceptance, business readiness, skilled labour).

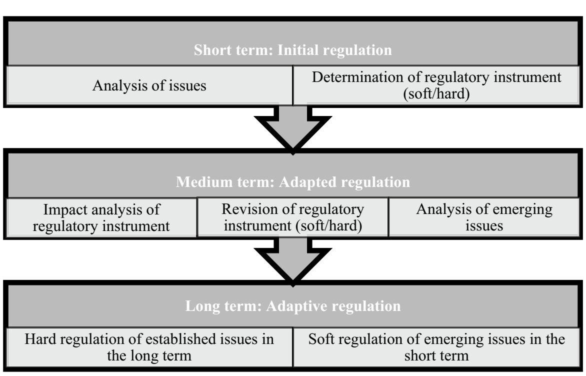

Fig. 2 Regulatory agenda-setting for autonomous inland shipping

Second, although all of the factors found in the literature must be considered when implementing autonomous inland ships, influential factors might not constitute automatically factors which also require addressing by regulation. For this reason, the factors were subsequently discussed in light of factors and sub-factors found to be relevant to regulatory intervention in the field of autonomous maritime shipping. The underlying rationale of the validation step was twofold: First, the identified influential factors in inland shipping could be validated with regard to their significance for the regulatory agenda in inland shipping. Second, potential gaps in inland shipping literature could be detected by finding additional sub-factors of established factors that were found to be also relevant to autonomous inland shipping regulation.

The overall objective of the research presented in this paper was to establish in a systematic and comprehensive way the currently identified regulatory barriers and potential gaps that need to be addressed by regulation for a future implementation of autonomous inland ships in Europe. Additional sub-factors retrieved from the state-of-the-research knowledge in autonomous maritime shipping regulation completed the findings of the systematic literature review, and thereby allowed to establish a more complete set of regulatory barriers and potential gaps that need to be addressed by public regulators and policy makers.

All in all, the identification of factors that need to be regulated serves as an important basis for future research on regulation of autonomous inland ships. Having determined what needs to be regulated with regard to the implementation of a disruptive technology paves the way for the next step that consists of determining how to regulate, i.e. addressing by soft or hard regulation. As shown above, soft and hard regulation can have different impacts on the implementation of disruptive technologies. Therefore, public regulators and policymakers are advised to make use of soft and hard regulation when adopting regulation of autonomous inland shipping. This also involves a continuous impact analysis of the initially chosen regulatory instrument, and, if applicable, a subsequent revision of these. The ultimate goal of the regulatory agenda-setting should be an adaptive regulation of autonomous inland shipping in which established issues are addressed by hard regulation in the long term, and emerging issues are regulated by way of soft regulatory means in the short term.

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Author contributions
Sophie C. Orzechowski: Data curation; Formal analysis; Investigation; Methodology (lead); Validation; Visualisation; Writing—original draft (lead); Writing—review and editing (equal). Wouter Verheyen: Funding acquisition; Conceptualisation (lead); Methodology (supporting); Supervision (equal); Writing – original draft (supporting); Writing—review and editing (equal). Christa Sys: Conceptualisation (supporting); Supervision (equal); Writing—original draft (supporting); Writing—review and editing (equal).

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Declarations

Competing interests
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