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# The application of a system-based risk management framework and social network analysis to the Maritime Autonomous Surface Ship system: Who are the decision-makers in the wider system?

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## Abstract

Maritime Autonomous Surface Ships (MASS) currently have no formal regulations developed specifically for their operation, as their regulatory framework is still under development. Rasmussen's Risk Management Framework has been used to develop an actor map of the current MASS system in the UK, to show who the actors, decision-makers, and planners are within the wider sociotechnical system and the level at which they sit. From the actor map, two social networks were created, one to show the connections that currently exist between the actors within the MASS system and another to show what a future MASS system could look like if regulations and standards were put in place for MASS. Social Network Analysis was then used to investigate the wider MASS system's dynamics, to understand which actors currently have a high degree of influence within the UK MASS system, and where the shortfalls are in the current MASS system. The analysis showed that the industry and end user levels lacked support from the higher system levels, and the addition of formal regulations and standards in the future MASS system would increase the MASS system's resilience. System recommendations for each level in the Risk Management Framework were then made to suggest ways to increase the influence of the regulators and promote the safe operation of MASS.

KEYWORDS

Maritime Autonomous Surface Ships, risk management framework, social network analysis, sociotechnical system

## 1 | INTRODUCTION

There are various Maritime Autonomous Surface Ships (MASS) currently operational. For example, SEA-KIT International's Maxlimer and XOcean's vessel used for hydrographic surveys, which are both remotely operated MASS are manually operated by operators through a user interface, where they control inputs such as vessel speed and bearing. There is also an autonomous ship, the Mayflower, which is a joint project between MSubs, Plymouth University, ProMare, and IBM, where the automated systems onboard the MASS control and navigate the MASS (Maritime Coastguard Agency, 2020). However, there are currently no formal regulations that have been developed specifically for MASS, which brings concerns for the safety of their operation (Amro et al., 2020; Komianos, 2018; Nzengu et al., 2021). Although MASS are expected to bring safety benefits by removing human involvement in parts of the system, removing factors such as fatigue and boredom, also the automation has the potential to perform tasks more reliably, if they are not regulated appropriately they may bring in new hazards (Hoem et al., 2018; Kim & Schröder-Hinrichs, 2021). As MASS uses higher levels of automation due to the advancements in technology, there is a potential to introduce new errors and risks to the system (Hoem et al., 2018; Kim & Schröder-Hinrichs, 2021; Lützhöft & Dekker, 2002). Therefore, it will be important that MASS have an appropriate regulatory framework in place to support the safe development and operation of MASS.

The International Maritime Organisation (IMO) is a specialized agency of the United Nations (UN) responsible for developing international shipping regulations and standards for improving safety, sustainability and security in international shipping (International Maritime Organisation, 2023). The IMO consists of an Assembly, a Council, five main committees (Maritime Safety, Marine Environment Protection, Legal, Technical Cooperation and Facilitation) and several sub-committees, where international regulations and standards are created or amended (International Maritime Organisation, 2023). The IMO currently has 175 member states who participate in its meetings, including the UK, each member state can ratify the convention or standard into their own national law so it can be enforced by that member state (International Maritime Organisation, 2023).

The IMO has outlined four degrees of autonomy for MASS as shown in Table 1, the degree of autonomy of a MASS describes the location of the operator (on board the MASS or at a Remote Control Centre [RCC]), and it also describes the system's ability to make decisions on its own (International Maritime Organisation, 2021). This paper focuses on degree three of autonomy where the MASS is uncrewed, and the operator and other personnel are located at an RCC. However, the MASS may be operated at different levels of automation, from remotely operated where the operator has manual control of the MASS via a communications link, to monitored where the automated system is responsible for performing a task and the operator is overseeing the automation. In addition to exploring the potential problems with removing onboard human operators, this paper will also investigate the issues surrounding using higher levels of automation whilst operating MASS.

A regulatory scoping exercise for the use of MASS has been conducted by the IMO, as a first step to developing a regulatory framework (International Maritime Organisation, 2018; Jo et al., 2020). As part of the regulatory scoping exercise the IMO's Maritime Safety Committee (MSC) has reviewed the different IMO legal instruments to determine: whether they were applicable to MASS and whether they prevented MASS operations; whether they applied to MASS and did not prevent operations and required no actions; or they did apply and need to be amended or clarified and/or may contain gaps; or have no application to MASS operations (International Maritime Organisation, 2018; Jo et al., 2020). This involved reviewing various safety treaties such as the Safety of Life at Sea (SOLAS) convention, 1974; Standards of Training, Certification and Watchkeeping for Seafarers (STCW), 1978 and the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREG) as well as regulatory instruments (International Maritime Organisation, 2018; Jo et al., 2020).

The outcome of the regulatory scoping exercise was discussed and completed by the MASS Working Group, which met during MSC's 103rd session in May 2021 (International Maritime Organisation, 2021; Shiokari 2020). Common issues with the IMO instruments were the definitions relating to seafarers such as master, crew, and responsible person, as these would need to be defined for remotely operated and autonomously controlled ships (International Maritime

**TABLE 1** Degrees of autonomy for MASS as established by the International Maritime Organization (International Maritime Organisation, 2021).

| Degree of autonomy | Ship control | description |
|---|---|---|
| 1 | Ship with automated processes and decision support. | Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control. |
| 2 | Remotely controlled ship with seafarers on board. | The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions. |
| 3 | Remotely controlled ship without seafarers on board. | The ship is controlled and operated from another location. There are no seafarers on board. |
| 4 | Fully autonomous ship. | The operating system of the ship is able to make decisions and determine actions by itself. |

Organisation, 2021; Shiokari 2020). These definitions will be important to establish what the responsibilities of those involved in operating the MASS are, even though these roles are no longer on board the ship. The findings showed there was a lack of requirements for Remote Control Centres (RCCs) and the personnel that will be working at RCCs (Shiokari 2020). The development of requirements for the personnel working at RCCs will be needed to ensure that MASS is operated at levels at least as safe as manned vessels. Another identified gap was the requirements for onboard systems and equipment, especially for systems that require manual operations, such as firefighting and life-saving equipment (International Maritime Organisation, 2021; Shiokari 2020).

Although there is no formal legal framework for MASS specifically at present, organizations such as, Maritime UK have published a voluntary industrial code of practice for MASS up to 24 m in length, to provide practical guidance for the design, construction, and safe operation of MASS (Maritime UK, 2020). It is worth noting that even though there is no formal regulatory framework, MASS must still comply with existing regulations where they are relevant. The UK code of practice was prepared by the Maritime Autonomous Systems Regulatory Working Group (MASRWG), which included: national organizations (e.g., British Marine, National Oceanography Centre), classification societies (e.g., Lloyds Register EMEA and Bureau Veritas) and organizations from industry who design and develop MASS (Maritime UK, 2020). Currently, to be issued with a certificate for its particular operation a MASS must comply with all the requirements in the code of practice relevant to its MASS class (which depends on its overall length and maximum speed and the MASS' operating area) (Maritime UK, 2020). The code of practice has been reviewed by the Maritime Coastguard Agency (MCA), but the MCA has said it would require further investigation to publish the code of practice, and it would also be dependent on any regulations and standards produced by the IMO (Maritime UK, 2020). Whilst there is no primary legislation for MASS to operate in the UK and under the UK flag, the MCA relies on the exemption available in The Merchant Shipping (Load Line) Regulations 1998 to certify MASS (Department of Transport, 2021). In addition to the MASRWG UK code of practice, recognized classification societies have also produced technical codes for the design, build, and maintenance of MASS, such as Lloyd's Register Unmanned Marine Systems (UMS) code which was launched in 2017 to allow owners and operators to achieve certification that is acceptable to regulators and local authorities (Lloyd's Register, 2017). SEA-KIT International's MASS was the first MASS to be awarded certification under Lloyd Register's UMS code in July 2021 (SEA-KIT International, 2021). It is useful to investigate the UK MASS system as the UK is a highly influential member of the IMO, and other flag states do adopt or modify policies and regulations developed by the UK (Baumler et al., 2021).

The standards and regulations developed by the IMO and other international and national organizations will be important to the safe operation of MASS, as they will feed down to the legislation and regulations implemented by the UK government and regulators. Although the MSC of the IMO has indicated that new regulations could be developed for MASS, but this would not be before 2028 (Department of Transport, 2021). It has been highlighted that there is a need to consider the whole system when assessing the safety of maritime systems due to their increasing complexity (Relling et al., 2018). To ensure the safe operation of MASS, it will be important to consider the wider socio-technical system rather than just focusing on the MASS and its operator (Banks et al., 2018; Stanton & Harvey, 2017). It has been found in other domains, such as automated vehicles (Banks et al., 2019) that the introduction of new automated systems can have safety implications and bring regulatory issues. In the automated vehicle domain, it was found that vehicle manufacturers had been largely left to their own devices when it came to designing, testing, and marketing some of their automated systems (Banks et al., 2019). The analysis showed that lower levels of the system lacked appropriate support and guidance due to the lack of top-down influence in the system (Banks et al., 2019). Therefore, it will be important to consider what the influences are in the UK MASS system and whether each level has sufficient support and guidance.

MASS is still in an early stage of development, so there are still uncertainties surrounding their operation making, it difficult to predict the likelihood and types of failure that might occur (de Vos et al., 2021; Hoem et al., 2019) It is important to consider the potential of maritime incidents due to the introduction of MASS (de Vos et al., 2021; Hoem et al., 2019). It has been suggested that the use of uncrewed MASS will reduce the likelihood of collisions occurring, but the severity of these accidents may be higher due to the limited recovery capability if there is no longer any crew on board (Thieme et al., 2018; Wróbel et al., 2017). It will therefore be important to consider how systemic failures could lead to incidents during the operation of uncrewed MASS and what mitigation strategies could be put in place to reduce these risks. There are potentially new failures and uncertainties introduced when operating uncrewed MASS due to their remotely controlled nature (Goerlandt, 2020; Jalonen et al., 2017). An example of this is the possible loss of communications between the RCC and the MASS, if this were to occur, then the operator would have no way of communicating with the MASS or have any oversight of its automated systems (Ahvenjärvi, 2016; Burmeister et al., 2014; Kim & Schröder-Hinrichs, 2021; Ventikos et al., 2020; Wróbel et al., 2017; Wróbel et al., 2018). Also, it has been highlighted that the nature of the operators' work will have changed, so the skills and experience they require to safely navigate from an RCC rather than a bridge will also have changed (Goerlandt, 2020).

Wróbel et al. (2018) applied the System-Theoretic Process Analysis (STPA) to analyse the interactions between the different components in the operation of automated merchant vessels. It was shown that if some of the control actions were inadequate it could lead to failures propagating through the system rapidly due to the potential number of hazards introduced, which shows the need to consider the wider aspects of the MASS system (Wróbel et al., 2018). Relling et al. (2018) suggested that systemic safety models such as Accimap (Svedung & Rasmussen, 2002) and Event Analysis of Systemic Teamwork (EAST) broken-links approach (Stanton &

Harvey, 2017) would be appropriate to assess MASS safety, as these approaches include the wider system, not just sub-components of the system. The aim of this article is to analyse the current MASS system in the UK using the Risk Management Framework (Rasmussen, 1997) and then use Social Network Analysis (Baber et al., 2013; Driskell & Mullen, 2004) to investigate the wider MASS system's dynamics and to make recommendations for the UK MASS system. The approach was selected to analyse the MASS system as it has been suggested that it provides comprehensive coverage of an entire sociotechnical system, including those responsible for developing policies and implementing regulations, as well as international and national bodies involved in the system (Parnell et al., 2017; Salmon et al., 2012). It allows the different processes between the different system levels to be seen including the top-down processes from international, national bodies and regulators, middle-up processes from industry, and bottom-up processes from the lower system levels (Banks et al., 2019). It has also been found that the Risk Management Framework is applicable across multiple domains, including the maritime domain (Butler et al., 2022; Kee et al., 2017; Lee et al., 2017; Stanton & Salmon, 2019).

## 1.1 | Risk Management Framework (RMF)

One sociotechnical system approach is Rasmussen's (1997) RMF (see Figure 1), which can be used to show the interactions between different system levels. The original RMF hierarchy shown in Figure 1 consists of six levels: government, regulators/associations, company (industry), management (resource providers), staff (end users), and work (equipment and environment). It shows how different levels of a sociotechnical system are involved in managing the risks associated with operating that system. Top-down processes from the government writing the laws which are turned into regulations (Rasmussen, 1997). The regulations are then put into company policies for management to give to their staff, who can then use them to promote safe operations (Rasmussen, 1997). The RMF also shows the bottom-up processes in the sociotechnical system, how observations from members of staff get logged by management, which is then fed to the company level through reports (Rasmussen, 1997). These reports are then reviewed by the company, and incident reports are reviewed by the regulator and then feed back to the Government to inform the law (Rasmussen, 1997).

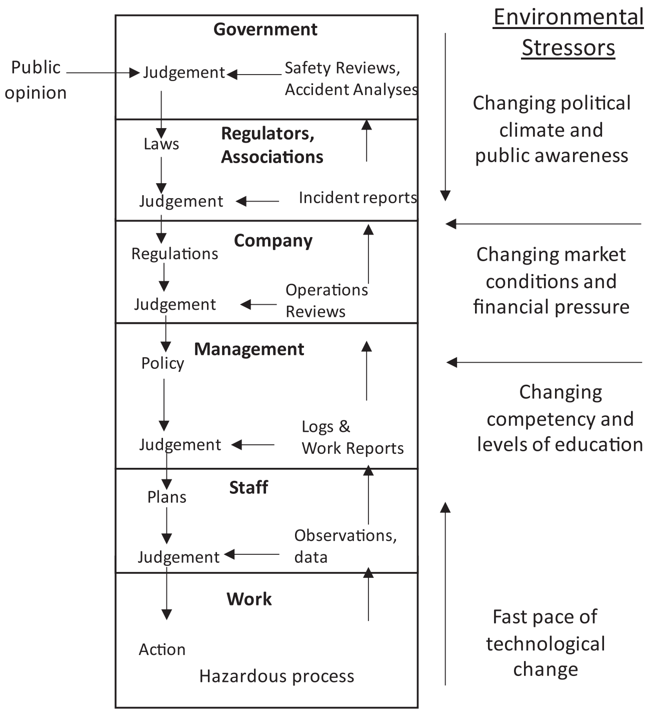

FIGURE 1 Rasmussen's risk management framework (Rasmussen, 1997).

Parnell et al. (2017) added two additional levels, international and national committees, to show how these committees influence government policies and legislation for in-vehicle technology use. For the application of the RMF to MASS in the UK, it will also be necessary to include these additional levels as international organizations such as the IMO, International Association of Classification Societies (IACS), and national committees such as Maritime UK influence how MASS are currently regulated and how they will be in future (Bratić et al., 2019; Department of Transport, 2021; International Maritime Organisation, 2021; Maritime UK, 2020).

Figure 2 shows the RMF adapted for the MASS system, it also shows different views of the system: at the micro level, there is the human–machine interaction between the end user (the operator) and MASS; at the meso level, it also includes the companies operating MASS and the resource providers involved in their operation; at the macro level, it extends the system view to include the regulating bodies (e.g., the MCA), government, national and international committees (e.g., the MASRWG and the IMO) (Klein & Kozlowski, 2000; Verbong & Geels, 2007). The RMF will be used to model the UK MASS system to show a macro system view and to show how each of the hierarchical system levels influences MASS operations, to look beyond just focusing on the micro view of just the operator and the MASS. It will show how the various international and national committees influence the MASS system by generating standards and policies, which are then fed down to governments informing their policies and developing legislation, this legislation informs the regulators (Banks et al., 2019; Parnell et al., 2017).

The regulations developed at these top levels (International Committees, National Committees, Government, and Regulators levels) will then influence the relevant industrial actors developing the systems and the resource providers (e.g., training centres, system architects, and human–machine interface designers) in the middle levels of the RMF hierarchy (Parnell et al., 2017). The middle levels of the RMF, the industry and resource providers levels, will then influence the two lowest levels of the hierarchy, the end-users (e.g., MASS operators) and their contextual environment (e.g., the MASS' automated system and the environmental conditions), through system design, policy and guidance to the operators. Within the RMF, there will also be bottom-up processes through reporting and

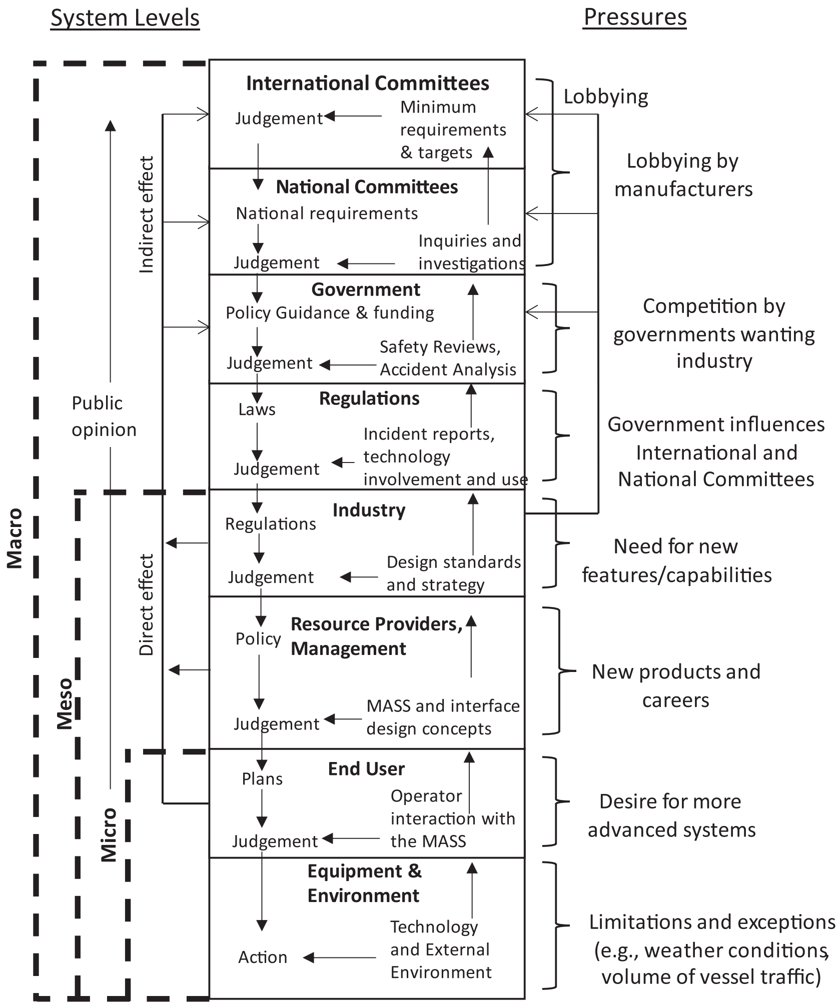

**FIGURE 2** Annotated RMF for MASS implementation (Adapted from Banks et al., 2019). MASS, Maritime Autonomous Surface Ships; RMF, risk management framework.

feedback from the equipment and environment levels and end-user levels to the resource providers and industry levels. There are also middle-up processes from the industry level (i.e., MASS manufacturers and technology companies) as the advancements in technology will drive the regulations being developed at the top levels of the hierarchy.

The RMF has previously been utilized in the maritime domain to analyse the Sewol ferry accident in South Korea using the Accimap framework (Svedung & Rasmussen, 2002), it showed how actors and decision-makers at each level of the sociotechnical system contributed to the accident (Kee et al., 2017; Lee et al., 2017). For example, it showed how the lack of an oversight body between the Korean Shipping Association and the Korean Register of Shipping meant that the weight limit of the ferry was not enforced, the Korean Shipping Association had the information on the weight limit, and the Korean Register of Shipping had the actual amount of weight the ferry carried, but there was no communication between the two to enforce the limit (Lee et al., 2017). The RMF has also been applied to maritime pilotage in New Zealand to understand how pilots make decisions and what factors influence their decision-making (Butler et al., 2022). The RMF was used to show the system level of each of the factors that affect decision-making, which showed that maritime pilots work in a highly complex and there are many system-wide factors that affect their decision-making process (Butler et al., 2022). Applying the RMF to the UK MASS system will show what connections there are within the system currently and what links may need to be made to strengthen the system, as the MASS system's regulatory framework is developed. This approach will be used to make suggestions on how to support each level of the MASS system and to show where any shortfalls are in the system.

## 2 | MODELING THE UK MASS SYSTEM USING THE RISK MANAGEMENT FRAMEWORK

The first step of modeling the UK MASS system was to identify the different actors, organizations, and decision-makers in the UK MASS system by creating an actor map. Rasmussen's (1997) RMF is often used to analyse accidents, by producing an Accimap to show how a particular event occurred by considering the whole system and to suggest system recommendations to mitigate these risks in the future (Debrincat et al., 2013; Kant & Khobragade, 2022; McIlroy et al., 2021; Parnell et al., 2017; Stanton et al., 2019; Underwood &

Waterson, 2014). Part of the Accimap approach is to create an actor map to show the different organizations, actors, and decision-makers involved in the events leading to the accident and the position of those actors on the RMF (Svedung & Rasmussen, 2002). Actor maps have previously been used in the maritime domain to investigate maritime pilot's decision-making (Butler et al., 2022), as well as in the road transportation domain to explore global road safety (McIlroy et al., 2019) and the UK's automated driving system (Banks et al., 2019; Parnell et al., 2017) and to explore the resilience of New Zealand's freight transport system in the event of natural disaster (Ivory & Trotter, 2017). The actor map of New Zealand's maritime pilotage system was used to explore the different factors that affect maritime pilots' decision-making and the system level of each of those factors (Butler et al., 2022). Applying the RMF to the UK road transport system showed system weaknesses at the different system levels (Banks et al., 2019). The actor map of New Zealand's freight transport system identified governance opportunities to support the resilience of the networks, such as creating a lessons-learned mechanism within the system and investigating actors with less visible roles, the local authorities to understand how they can be supported (Ivory & Trotter, 2017).

To develop the actor map for the UK MASS system shown in Figure 3, relevant actors were identified using previous actor maps that have been developed (Banks et al., 2019; Parnell et al., 2017), government documentation (e.g., Defence Maritime Regulator, 2020; Department of Transport, 2021), UK government (gov.uk) and UK parliament websites (parliament.uk), relevant organizations' websites (e.g., IMO, International Association of Classification Societies and Society of Maritime Industries) and Maritime UK's code of practice (Maritime UK, 2020). To create a social network, links were added between the actors in the actor map, depending on the relationship between the actors. A two-way link was added to and from the pair of actors if there was a two-way interaction between them, if the actors are working with each other or they have responsibilities to

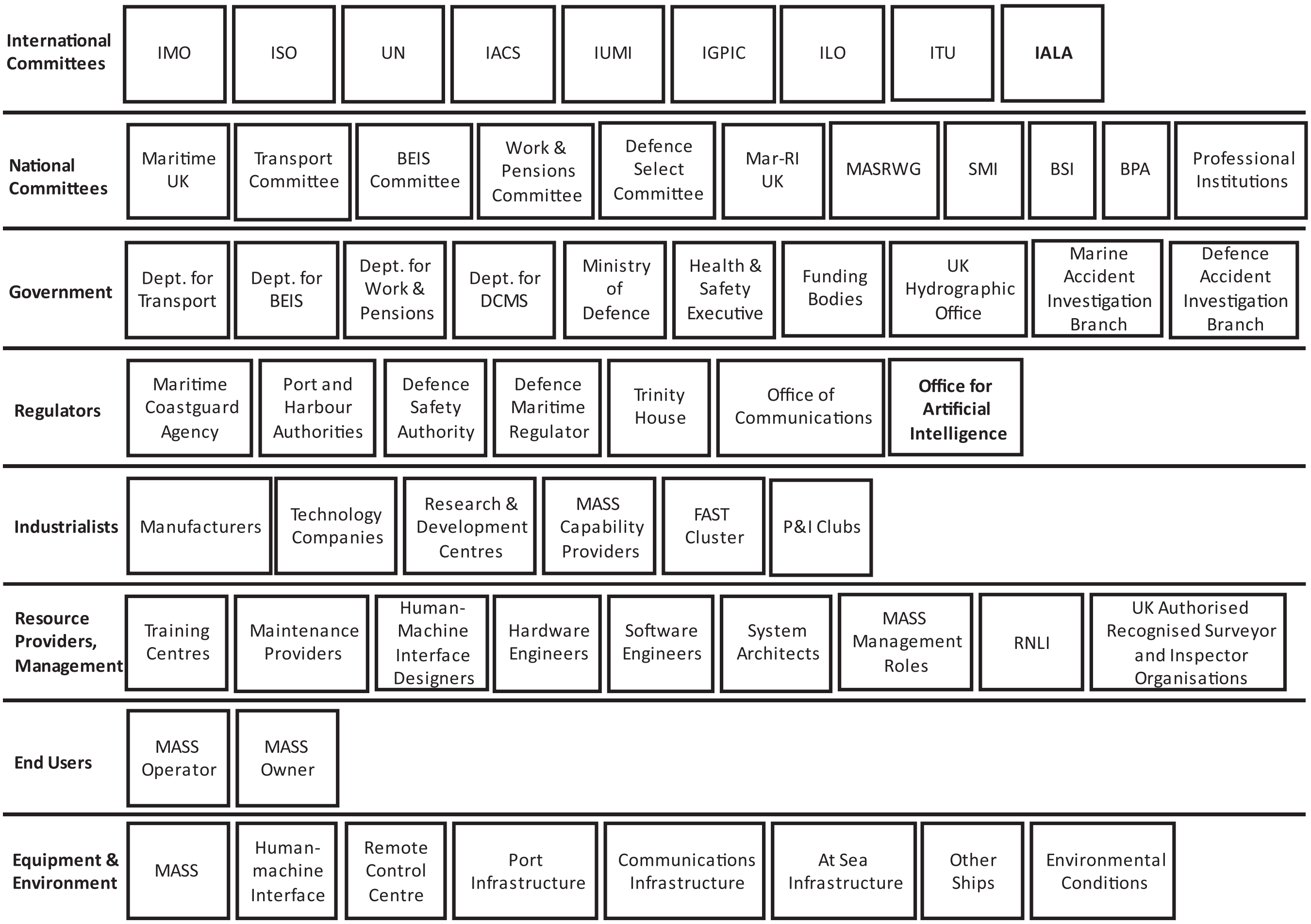

FIGURE 3 Actor map for the UK Maritime Autonomous Surface Ships (MASS) system. (*Note*: Actors included only in the future MASS system are highlighted in bold. International Maritime Organisation (IMO), International Standards Organisation (ISO), United Nations (UN), International Association of Classification Societies (IACS), International Union of Marine Insurance (IUMI), International Group of Protection and Indemnity Clubs (IGPIC), International Labour Organisation (ILO), International Telecommunication Union, International Association of marine aids to navigation and Lighthouse Authorities (IALA), Business, Energy and Industrial Strategy (BEIS), Maritime Research and Innovation UK (Mar-RI UK), Maritime Autonomous Systems Regulatory Working Group (MASRWG), Society of Maritime Industries (SMI), British Standards Institution (BSI), British Ports Association (BPA), Digital, Culture, Media and Sport (DCMS) and Royal National Lifeboat Institution (RNLI).

each other. For example, a two-way link was added between the International Association of Classification Societies (IACS) and International Standards Organisation (ISO) as they work cooperatively to develop international maritime standards. Another example of a two-way interaction was between the IMO and MCA, as the MCA enforces IMO regulations in the UK, but the MCA is also the UK's representative at the IMO. Other actors had one-way links added between them, where one actor had a direct influence over another, and there is no reciprocal relationship. Examples of one-way interactions within the social network were from Trinity House to Maritime UK, as Trinity House is a member of Maritime UK, and from Maritime Research and Innovation UK to technology companies, as the committee is responsible for giving out the projects to the technology companies.

Maritime UK's code of practice (Maritime UK, 2020) was one document that was used to develop the UK actor map and social network, as it contained a list of contributing organizations that are part of the MASRWG, who developed the UK code of practice. The list of contributing organizations was then reviewed and the relevant organizations' websites, e.g., National Oceanography Centre (noc.ac.uk), Lloyds Register EMEA (lr.org), and Ocean Infinity (oceaninfinity.com) were then used to understand what level of the RMF the actor would be positioned on and the type of category they might come under, for example, the National Oceanography was identified as a Research and Development Centre, Lloyds Register EMEA as a Classification Society and Ocean Infinity as a MASS Manufacturer. Similarly, international committees (e.g., International Group of P&I Clubs) and national committees (e.g., Maritime Research and Innovation UK) also included member lists on their websites which identified more actors and the organizations that they are affiliated with, which were added as one or two-way connections depending on the relationship between committees and the other actors. Then UK government and parliament websites were used to understand the responsibilities of the government departments (e.g., the Department of Transport and the Department of Business, Energy and Industrial Strategy) and agencies (e.g., the Maritime Coastguard Agency) to determine whether they were an actor within the UK MASS system and if there was any relationship with other public bodies. Government documentation, such as the Department of Transport's Future of transport regulatory review consultation on maritime autonomy and remote operations was used to understand the current regulations for MASS within the UK (Department of Transport, 2021). The Defence Maritime Regulations were also used to understand the current military regulations for MASS (Defence Maritime Regulator, 2020). Actors within the industry, end users, resource providers, management and equipment, and environment levels, were identified using other actor map examples (Banks et al., 2019; Parnell et al., 2017) and Maritime UK's Code of Practice (Maritime UK, 2020), one way and two-way connections were then identified between these actors based on the role of each actor.

It went through a three-stage review process to refine the actors and connections between the actors of the current and future MASS systems with three Subject Matter Experts (SMEs) involved in the development and regulation of MASS. A three-stage review process was used as the three SMEs had expertise in different aspects of the MASS system, so their combined experience and knowledge meant that all the RMF system levels were covered. The first SME consulted was an Associate Professor with 19 years of experience within the maritime domain and 6 years working with MASS, including operational experience in the development of MASS. Therefore, they had industry experience, operational experience as an end user, and knowledge of the resources providers and equipment and environment levels. This discussion was used to add to the initial social network of the current MASS system that had been created using documentation and organizations' websites. Links were then added to the network to show where the system is currently being developed and to show what links could exist in a future MASS system if there were regulations put in place for MASS.

The current and future MASS social networks were then taken to the second SME, a System Architect with 25 years of experience within the maritime domain experience primarily in the Defence sector. The SME had expertise on the industry and resource providers level and especially in the military domain, so could add and modify connections between the military actors (e.g., the Defence Maritime Regulator and Defence Safety Authority) within the MASS system. After this review, one actor and 27 connections were added to the current MASS network, and one link was removed in the network. The updated social networks were then taken to the third SME, an Autonomy Technical Specialist with 10 years of experience in the maritime domain and seven years working with MASS specifically. This SME had experience on the regulator, government levels as well as knowledge of the national and international committee levels in the maritime domain, so had a comprehensive knowledge of the higher system levels in addition to knowledge on the whole system. The current MASS network was then edited, adding 14 actors and 92 connections, and removing six connections. Figure 4 shows an extract of the current MASS network showing just the MASS node's connections within the current network. The full current MASS network is not shown here due to its complexity, but for the full current MASS network, see Appendix A.1. Two actors were then added to the MASS future network, and 12 connections were also added to the future network to give the final future network, the links added to create the future network are shown in Figure 6. For the full detailed version of the future network and the networks of each sublevel of the RMF see Appendix A.1.

## 3 | SOCIAL NETWORK ANALYSIS

Social Network Analysis was then used to assess the current and future networks' dynamics. Analyzing the UK MASS system as a social network shows which nodes have a high level of influence in the network (Banks et al., 2019). A node may have a high degree of influence due to the node's number of emissions and receptions to/from other nodes or due to its position in the network (Banks et al., 2019). Identifying the nodes that have a high degree of influence can show where greater redundancy is required in the system and show

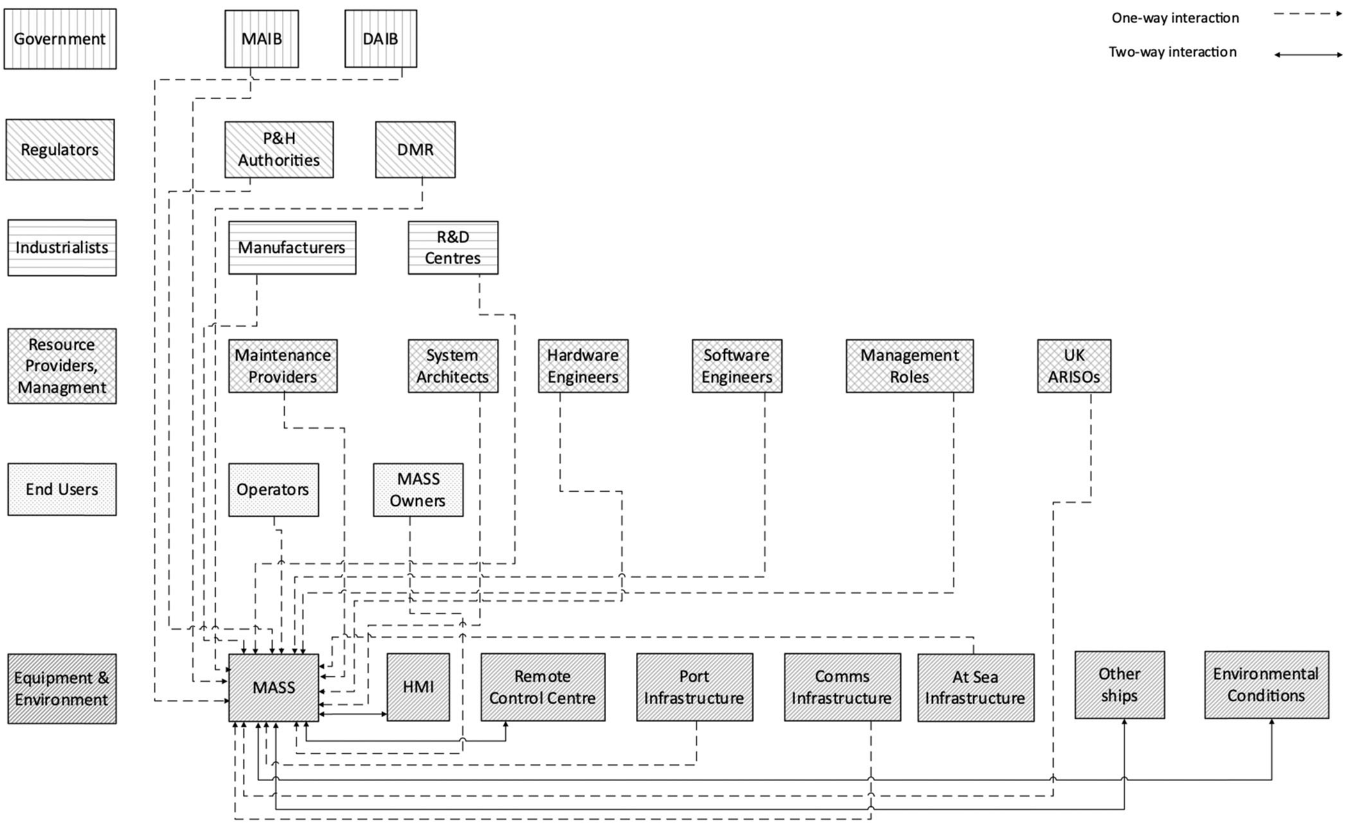

**FIGURE 4** Directed social network for the current UK Maritime Autonomous Surface Ships (MASS) system (*note*: larger dashed lines reflect one-way interaction whereas solid lines reflect two-way interaction between agents. Marine Accident Investigation Branch (MAIB), Defence Maritime Regulator (DMR), Defence Accident Investigation Branch (DAIB), Research and Development Centres (R&D Centres, UK Authorised Recognized Inspection and Surveyor Organizations (UK ARISOs), Human-Machine Interface (HMI).

the degree of influence of each of the RMF levels, showing where the system may need further support and allow system recommendations to be made for each RMF level (Banks et al., 2019; Plant & Stanton, 2016). The social network analysis results will also show how the different levels of the RMF for the MASS system interact with each other (Banks et al., 2019). By comparing the current and future social networks, it will show the effects of introducing regulations and standards specifically for MASS and how this would affect each RMF level and the system's dynamics. The global and nodal metrics used for the analysis can be seen in Table 2, along with their definitions. These network metrics were chosen as they have been used to analyse networks in several other applications to identify key nodes within networks and assess network dynamics such as distributed flight crews (Stanton et al., 2016), driving automation (Banks & Stanton, 2016; Banks et al., 2019), digital nuclear power plant controls crews (Zhang et al., 2022), and submarine command teams (Stanton et al., 2017). The global and nodal metrics were calculated using the Social Network Analysis tool AGNA (Benta, 2005), and the power centrality diagrams were produced using the Social Network Visualizer tool, SocNet V (Kalamaras, 2021). The results of the social network analysis for the current network and future network can be seen in Table 3 (global metrics) and Table 4 (nodal metrics).

## 3.1 | Current MASS network

Table 3 shows the results of the global metrics for the current network (see Appendix A.1 for the complete network) showing that there were 60 nodes found in the network and 298 edges (pairings of connected nodes). The network analysis for the future system is detailed in Section 3.2. The global metrics for the current network showed that the system is loosely coupled (i.e., the actors within the system act independently of each other) due to its low density (0.084) and cohesion values (0.053) (Plant & Stanton, 2016). The network density describes the comparison between the number of possible interconnections and the number of actual interconnections in the network (see Table 2), this network was found to have a low density as it is spread out with few links (Plant & Stanton, 2016). It was also found that the cohesion of the network was low, showing that there are a low number of reciprocal links in the MASS network. As 60 nodes were identified in the UK MASS network it showed the high number of actors and decision-makers within the system showing its complexity, as there are many decision-makers that can influence the safety of MASS operations.

Table 4 shows a summary of the nodal analysis results for the current network (see Appendix A.2 for the full results). The nodal metrics show that the government and industry levels have a much

**TABLE 2** Global and nodal metrics selected for analysis, along with their definition (Banks et al., 2019).

| | Metric | Definition | Maritime context |
|---|---|---|---|
| Global metrics | Nodes | The total number of "entities" or nodes within the network. | The total number of actors identified with the UK MASS system. |
| | Edges | Number of pairs of connected "entities" or nodes | The total number of connections between the actors within the UK MASS system. |
| | Density | Represents the level of interconnectivity between (Kakimoto et al., 2006). Essentially represents a fraction of the total number of possible relations (Neville A. Stanton et al., 2017). The following formula can be used:<br>Network density = $\frac{2e}{n\,(n-1)}$<br>where:<br>$e$ is the total number of links within the network<br>$n$ is the number of nodes within the network | The total number of connected actors/agents within the UK MASS system divided by the total possible number of connections (if all the actors were connected to each other). |
| | Diameter | The largest geodesic distance within the network (i.e., how many "hops" it takes to get from one side of the network to the other) (Stanton, 2014). It is calculated using the following formula (Bin et al., 2018):<br>Diameter = $\frac{\sum_{i} > j^{d_{ij}}}{n(n-1)/2}$<br>where:<br>$n$ is the number of node pairs<br>$d_{ij}$ is the shortest path between node i and j | The largest number of actors you would need to travel through to get from one side of the network to the other side, the network diameter is a measure of the distance between the actors within the MASS system. |
| | Cohesion | Presents the number of reciprocal links divided by all the possible connections (Stanton, 2014). | Refers to the number of two-way connections between the actors in the MASS network divided by the number of all possible connections. An example of a two-way connection is between the IMO and MCA, where the MCA is the UK representative to the IMO and the MCA enforces policies set out by the IMO. |
| Nodal Metrics | Emission | Total number of links emanating from a node within the network | For each actor, this is the number of links from that actor to another. |
| | Reception | Total number of links received by a node within the network | The number of connections being received from other actors with the MASS system. |
| | Sociometric Status | A measure of "how busy" a node is in comparison to all other nodes (Houghton et al., 2006). It is the number of emissions and receptions relative to the number of actors within the network and therefore provides an indication of node prominence within the network (Salmon et al., 2012). It is calculated using the following formula outlined by Houghton et al. (2006):<br>Sociometric Status = $\frac{1}{g-1}\sum_{j=1}^{g}(x_{ij}, x_{ji})$<br>where:<br>$g$ is the total number of nodes in the network<br>$i$ and $j$ are individual nodes<br>$x_{ij}$ are the number of communications between node i and node j<br>$x_{ji}$ are the number of communications between node j and node i | Sociometric status of the MASS system actors describes how connected that actor is to other actors within the system, i.e, how many connections there are from that actor to other actors and how many connections there to that actor from other actors. |
| | Centrality | Centrality is calculated to determine the most central or key nodes within the network (Stanton, 2014). There are a number of centrality metrics available in the literature, but we utilize the Bavelas–Leavitt (B-L) Centrality Index in this analysis. B-L centrality is the sum of all distances within the network divided by the sum of all distances to and from the node (Neville A. Stanton et al., 2017). It is calculated using the following formula outlined by Houghton et al. (2006):<br>B-L Centrality = $\frac{\sum_{i=1;j=1}^{g}\delta ij}{\sum_{j-1}^{g}(\delta ij + \delta ji)}$<br>where: | The centrality of the actors within the MASS system describes the position of the actor within the MASS system. The higher the actor's centrality the more central a position that actor has in the MASS system, which means that they have a greater influence on the other actors in the MASS system. |

(Continues)

**TABLE 2** (Continued)

| Metric | Definition | Maritime context |
|---|---|---|
| | $g$ is the total number of nodes in the network<br>$\delta ji$ is the geodesic distance between nodes | |
| Closeness Centrality | Indicates how close a node is to all other nodes within the network. Closeness is the inverse of farness. It is calculated using the following formula (Bavelas, 1950):<br>Closeness = $\frac{n-1}{\sum_j d(i,j)}$<br>where:<br>$n$ is the number of nodes within the network<br>$d(i,j)$ is the distance of the shortest path between nodes i and j | Closeness centrality describes how close an actor is to all the other actors within the MASS system. An actor in the MASS system with a high closeness centrality could have a high degree of influence within the network due to their close position with many other actors in the system. |
| Farness Centrality | Sum of the distances of the shortest paths from the node to every other node in the network (Stanton et al., 2017). | Farness centrality describes the distance from the actor to all the other actors within the MASS network. An actor with a high farness centrality would have a low degree of influence over the MASS system due to their distance from the other actors within the network. |
| Betweeness Centrality | The presence of an actor between two other actors (Stanton, 2014). It is calculated using the following formula, as outlined by (Freeman, 1977):<br>Betweeness = $\sum_{s \neq v \neq 1 \varepsilon V} \frac{\sigma_{st}(v)}{\sigma_{st}}$<br>where:<br>$V$ represents the node<br>$\varepsilon$ represents the edges or links between nodes<br>$\sigma_{st}$ is the total number of shortest paths from node s to t<br>$\sigma_{st}(v)$ is the number of those paths that pass through v | Betweenness Centrality describes how many times an actor is between other actors in the MASS network. An actor with a high betweenness value means they have a high degree of influence on the actors they are in between. |
| Power Centrality | Power Centrality is a generalized degree centrality that takes into account the number of connections of a node's neighbors and their weightings.<br>It is calculated using the following formula (Gil & Schmidt, 1996; Sinclair, 2009), for graph $G = (V, E)$, *let* $R(v, G)$ be the set of vertices reachable by $v$ in $V/v'$<br>Power Centrality = $\frac{\sum_{i \in R(v, G)} \frac{1}{d(v,i)}}{\lvert R(v, G) \rvert}$<br>where:<br>$d(v, i)$ is the geodesic distance from $v$ to $i$ in $G$<br>The index is taken to be 0 for isolates, the measure takes a value of one when $v$ is adjacent to all reachable nodes, and approaches 0 as the distance from $v$ to each node approaches infinity. For finite $N = \lvert V \rvert$, the minimum value is 0 if $v$ is an isolate, and otherwise $1/(N - 1)$. | An actor within the MASS system that has a high power centrality, has a high degree of influence within the MASS system due to its position relative to the other actors within the system. |

**TABLE 3** Results of the global network metrics for the current and future MASS networks.

| Global metric | Current network | Future network |
|---|---|---|
| Nodes | 60 | 62 |
| Edges | 298 | 352 |
| Density | 0.084 | 0.093 |
| Diameter | 8 | 8 |
| Cohesion | 0.053 | 0.054 |

higher number of emissions than the other system levels, with 61 and 60 emissions. The highest number of receptions were found in the equipment and environment level (54), as many of the nodes in this level are dependent on the higher levels. The second-highest number of receptions was seen in the industry level (53), the nodes within the industry level were found to be highly connected within the level and to the nodes within the resource provider's level.

To assess the importance of nodes within a social network Houghton et al. (2006) defined a key agent as a node with a sociometric status as greater than or equal to the mean status plus one standard

**TABLE 4** Summary of the nodal metrics results for the key nodes in the current and future MASS networks.

| | | Node metrics | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Emission | | Reception | | Sociometric status | | B-L centrality | | Closeness | | Farness | | Betweenness | |
| **Hierarchical level** | **Node** | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future |
| International Committee | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| National Committee | Society of Maritime Industries | 6 | 6 | 8 | 8 | 0.24 | 0.23 | 36.48* | 35.82 | 0.36 | 0.36 | 165 | 170 | 234.19 | 211.55 |
| | Maritime Autonomous Systems Regulatory Working Group | 4 | 4 | 15 | 15 | 0.32* | 0.31 | 38.19* | 39.90* | 0.35 | 0.39 | 168 | 157 | 251.39 | 228.98 |
| Government | Department of Transport | 10 | 10 | 9 | 9 | 0.32* | 0.31 | 38.06* | 39.09* | 0.43* | 0.46* | 138 | 133 | 441.90* | 334.54* |
| | Ministry of Defence | 9 | 9 | 6 | 7 | 0.25 | 0.26 | 36.02* | 36.96 | 0.41* | 0.44* | 143 | 139 | 456.14* | 418.19* |
| | Funding Bodies | 7 | 7 | 6 | 6 | 0.22 | 0.21 | 39.11* | 38.70 | 0.41* | 0.41* | 144 | 148 | 605.90* | 499.57* |
| | UK Hydrographic Office | 6 | 8 | 5 | 7 | 0.19 | 0.25 | 37.94* | 38.57* | 0.40* | 0.42* | 147 | 146 | 90.66 | 129.67 |
| Regulators | Maritime Coastguard Agency | 7 | 28 | 8 | 12 | 0.25 | 0.66* | 39.93* | 46.28* | 0.41* | 0.54* | 143 | 112 | 520.78* | 1007.83* |
| | Defence Maritime Regulator | 7 | 17 | 3 | 4 | 0.17 | 0.34* | 33.39 | 35.82 | 0.38* | 0.44* | 154 | 140 | 71.96 | 87.44 |
| Resource Providers, Management | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Industry | MASS Manufacturers | 18 | 18 | 15 | 16 | 0.56* | 0.56* | 39.51* | 40.31* | 0.42* | 0.42* | 142 | 145 | 337.33* | 253.15 |
| | Research and Development Centres | 18 | 18 | 12 | 14 | 0.51* | 0.52* | 43.09* | 45.20* | 0.47* | 0.48* | 125 | 126 | 868.24* | 814.04* |
| | Technology Companies | 13 | 13 | 12 | 14 | 0.42* | 0.44* | 38.32* | 39.22* | 0.40* | 0.40 | 149 | 154 | 316.05 | 268.38 |
| End User | MASS Operators | 8 | 8 | 11 | 13 | 0.32* | 0.34* | 37.20* | 37.93* | 0.35 | 0.35 | 168 | 172 | 544.61* | 476.02* |
| Equipment and Environment | MASS | 4 | 4 | 21 | 22 | 0.42* | 0.43* | 28.91 | 28.57 | 0.21 | 0.21 | 276* | 284* | 268.21 | 258.69 |
| | **Mean score** | **4.97** | **5.68** | **4.97** | **5.68** | **0.17** | **0.19** | **30.87** | **31.97** | **0.32** | **0.34** | **190.32** | **186.61** | **131.32** | **125.61** |
| | **Standard deviation** | **3.51** | **4.78** | **4.05** | **4.48** | **0.11** | **0.13** | **5.09** | **5.50** | **0.06** | **0.07** | **45.48** | **47.65** | **179.28** | **192.02** |

*Note*: Asterisks denote key nodes in the network.

Abbreviation: MASS, Maritime Autonomous Surface Ships.

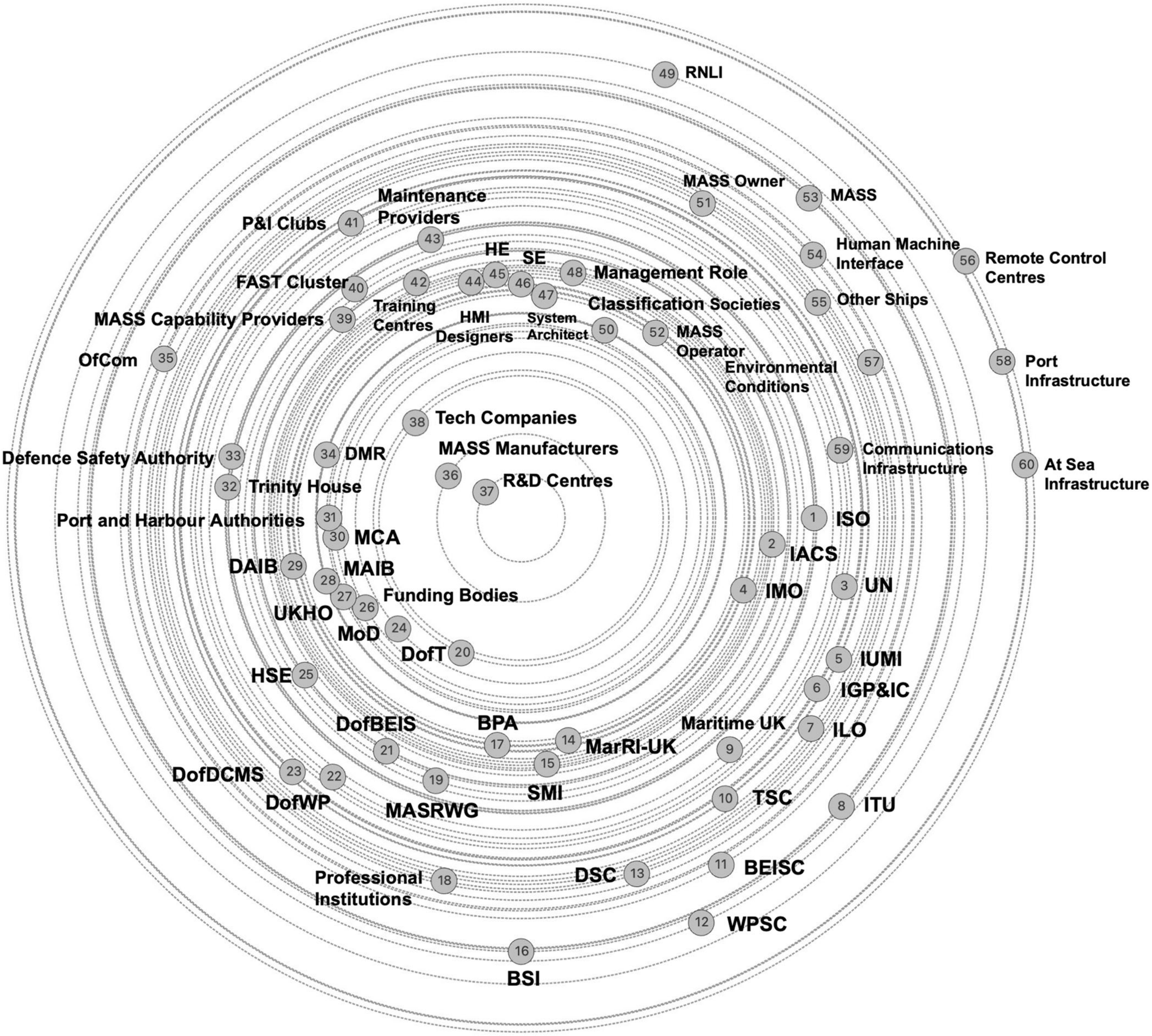

**FIGURE 5** Power Centrality plot for the current MASS network. (For abbreviations list see Table A.1 in Appendix A.1).

deviation (for this network, 0.17 + 0.11 = 0.28). This identified seven key agents for the current MASS network: manufacturers, research and development centres, technology companies, MASS, MASS operators, the MASRWG, and the Department of Transport. The nodes with the highest sociometric statuses were research and development centres, manufacturers and technology companies which are all nodes from the industry level. The industry nodes are highly connected to the resource providers (e.g., system architects, HMI designers, maintenance providers and training centres), end-users, and equipment and environment levels, to the other industry nodes, as well as being connected to various national committees. MASS had the next highest sociometric in the current network, as it is highly connected due to its direct dependency on the actors within the industry and resource provider's levels and its connections to other nodes within the equipment and environment level. The MASRWG was also identified as a key agent, it is a highly connected node as the group has developed the voluntary UK Code of Practice for MASS, and the group consists of: manufacturers, technology companies, classification societies, training centres, research and development centres, the Department of Transport, the MCA and the MoD. The MASS operators node was found to be a key node due to its connections with the equipment and environment level and its dependency on the higher levels such as the industry and resource providers levels. Lastly, the Department of Transport was found to be a key agent, which has connections to national committees (e.g., Transport Select Committee and British Ports Association), government bodies (e.g., the UK Hydrographic Office and Marine Accident Investigation Branch), and regulators such as the MCA and Trinity House.

The sociometric status of a node compares how busy a node is in comparison to the other nodes in the network, in contrast, centrality measures the position of a node and how central it is within the network rather than measuring how many connections it has (Houghton et al., 2006). Therefore, a node may have a high sociometric status but may not have a high level of centrality within the network. Houghton et al. (2006) also suggested that key agents in a social network could be identified using centrality, agents with a centrality higher than or equal to the mean plus a standard deviation (i.e., 30.87 + 5.09 = 35.96) can also be identified as key agents due to their central position within the network. Using centrality identifies eleven key agents in the current MASS network: research and development centres, the MCA, manufacturers, funding bodies, technology companies, the MASRWG, the Department of Transport, the UK Hydrographic Office, MASS operators, the Society of Maritime Industries and the MoD. Similarly to sociometric status, the centrality results show that the industry level has a high degree of influence within the system as research and development centres, manufacturers, and technology companies were all identified as key agents, and the research and development centre node had the highest centrality. The MCA was identified as having the next highest centrality after the industry nodes, although it was found to have a low sociometric status. Funding bodies, the UK Hydrographic Office, the MoD, and the Society of Maritime Industries were all identified as key agents using centrality even though the nodes had low sociometric statuses. Key agents were also found within the government and national committee tiers, with the Department of Transport and the MASRWG having high centrality. MASS operators were also found to have high centrality within the MASS network, as well as having a high sociometric status.

The other centrality metrics (closeness, farness, and betweenness) also showed similar findings with research and development centres, the Department of Transport, manufacturers, the MCA, the MoD, and funding bodies having the highest values of closeness and the lowest values of farness. The nodes with the highest values of betweeness were research and development centres, funding bodies, MASS operators, and the MCA, which were all identified as key agents using centrality. Similarly, the power centrality results shown in Figure 5, show that the industry nodes, research and development centres, manufacturers, and technology companies have a high degree of influence due to their positions within the network.

The results of the social network analysis of the current network showed that the industry level had the highest levels of influence within the system. The results also showed whilst there are key agents within the national committee tier (the MASRWG and the Society of Maritime Industries) the top-down influence did not reach the regulator tier with only the MCA being identified as a key agent using centrality. To strengthen the MASS system, it will be important the standards and regulations are developed specifically for MASS. To give both the civilian and military regulators a higher degree of influence within the system to ensure that MASS are appropriately regulated and that the lower tiers such as industry and resource providers have the necessary guidance. The results also suggest that greater redundancy is needed in the system, as the MASS operator node was identified as a key agent using both centrality and sociometric, suggesting that there needs to be more support for operators from the other system levels.

### 3.2 | Future MASS network

The MASS system will keep being updated as new technologies, regulations and standards are developed. This future MASS network has been developed as a starting point for discussion of what the future MASS system in the UK may look like. To create the future MASS network (see Appendix A.1 for the full future network), only two nodes were added to the current network the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and the Office for Artificial Intelligence. Also, 54 links were added (shown in Figure 6), mainly from the civilian and military regulators, the MCA, and the Defence Maritime Regulator, to the industry, resource providers, and equipment and environment levels. Further links were added from Professional Institutions (e.g., the Institute of Marine Engineering, Science and Technology) to training centers, and then from training centers to MASS management roles and MASS operators to show the effects of the development of training courses and standards specifically for MASS. Table 2 shows the results of the global metrics for the network showing that there are 62 nodes in the network and 352 edges, which is 54 more edges and two more nodes than the current MASS network giving the future MASS network a higher density (0.093) even though two more nodes were added to the network. The cohesion of the network also increased slightly to 0.054 due to the added reciprocal links within the future MASS network.

A summary of the nodal metric analysis results for the future network is shown in Table 3 (see Table A.2 for the full results). In contrast to the current MASS network, where the largest number of emissions were found in the government and industry tiers, and the regulator level in the future network had the highest number of emissions (69), followed by the government tier (66). In the future network, the tiers with the highest number of receptions were the industry level (63) and the equipment and environment tier (60), which was similar to the receptions found in the current network.

The mean sociometric status plus a standard deviation was used to identify key agents within the future MASS network (i.e., 0.19 + 0.13 = 0.32). This identified seven key agents within the future MASS network: the MCA, manufacturers, research and development centers, technology companies, MASS, the Defence Maritime Regulator, and MASS operators. The main changes to the key agents from the current network were the addition of the two regulators, the MCA and DMR, and both the MASRWG and the Department of Transport no longer being identified as a key agent using sociometric status. The additional links from the MCA in the future MASS network increased the sociometric status from 0.25 in the current network to 0.66 in the future network, making it the node with the highest sociometric status. The nodes with the next highest

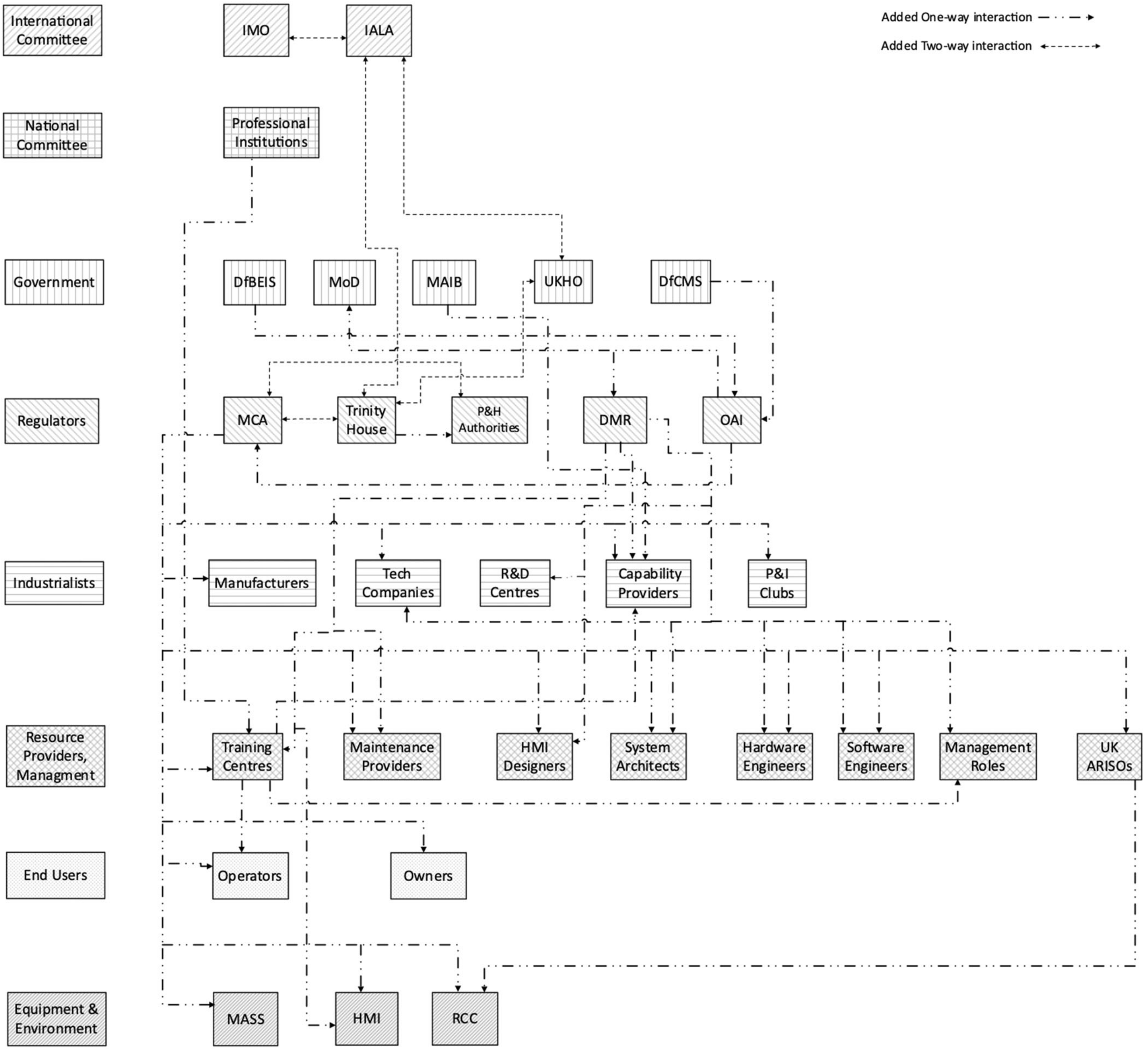

**FIGURE 6** Directed social network showing the links added to create the future Maritime Autonomous Surface Ships (MASS) network (*note*: dashed lines with dots reflect one-way interactions which have been added to create the future network, and smaller dashed lines reflect two-way interactions that have been added. International Maritime Organisation (IMO), International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), Department of Business, Energy and Industrial Strategy (DofBEIS), Ministry of Defence (MoD) UK Hydrographic Office (UKHO), Department for Culture, Media and Sport (DfCMS), Maritime Coastguard Agency (MCA), Marine Accident Investigation Branch (MAIB), Port and Harbour Authorities (P&H Authorities), Office for Artifical Intelligence (OAI), Research and Development Centres (R&D Centres), Protection and Indemnity Clubs (P&I Clubs), UK Authorised Recognised Inspection and Surveyor Organisations (UK ARISOs), Human-Machine Interface (HMI), Remote Control Centre (RCC).

sociometric statuses were manufacturers, research and development centers and technology companies, whose sociometric statuses had increased slightly as the number of receptions for these nodes increased due to the added links mainly from the regulator level. The MASS node was also found to have the highest sociometric status, which increased slightly in the future network. The DMR was also found to be a key node within the future network as like the MCA links were added from the DMR node to industry, resource providers, and the equipment and environment nodes, as if these current regulations for MASS had been introduced in the future network. Lastly, the MASS operator node was also still identified as a key agent.

The centrality results identified eight key agents within the network: the MCA, research and development centers, manufacturers, the MASRWG, technology companies, the Department of Transport, the UK Hydrographic Office, and MASS operators. Similar to those found in the current except for the Society of Maritime Industries, the MoD and funding bodies nodes are no longer identified as key agents. The MCA also had the highest centrality result as well as the highest sociometric status, showing that if there were regulations specifically for MASS, it would lead to the MCA having a much higher degree of influence within the MASS system. The closeness and farness metrics also showed similar findings with the MCA, research, and development centers, the Department of Transport having the highest values of closeness and the lowest values of farness.

Figure 7 shows the power centrality results in the future network, showing that the changes to the network have resulted in the MCA having the highest power centrality and, therefore, a greater influence within the network, and the DMR power centrality also increased. In the future network, the MCA, research and development centres, the IMO, funding bodies, and MASS operators were found to have high values of betweeness. This was similar to the current network, although the MCA node then had the highest betweeness value, which was much higher than the other nodes. Also, the IMO's betweeness centrality was found to be higher in the future network, although it was not identified as a key node in either the current or future network. The MASS operators' node had a decrease in betweeness in the future network but still had one of the highest values. The future MASS network results show that the addition of formal regulations to the MASS network gives the regulators a higher influence within the MASS system, however, the industry nodes and the MASS operator still also have high degrees of influence within the system.

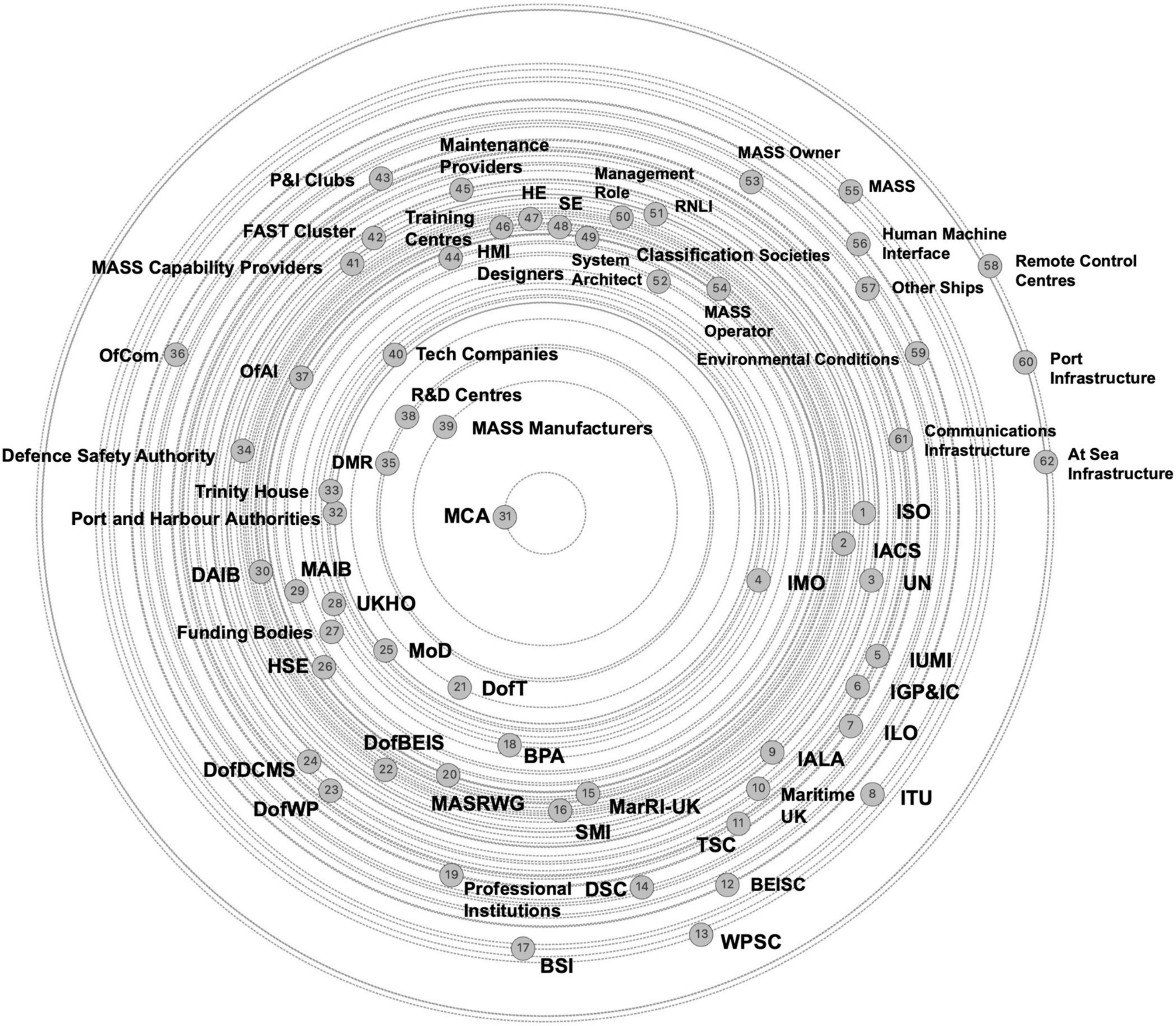

FIGURE 7 Power Centrality plot for the future Maritime Autonomous Surface Ships (MASS) network. (For abbreviations list see Table A.1 in Appendix A.1).

**TABLE 5** MASS system recommendations for each hierarchical level in the RMF.

| Hierarchical level | Findings | Recommendations |
|---|---|---|
| International Committees, National Committees, Government | • The comparison of the current and future MASS system analysis showed a lack of influence from the regulators due to the absence of regulations from higher levels.<br>• The analysis showed in both the current and future systems that the MASS operator had a high degree of influence within the system, due to its number of connections and position within the network. | **1.** Provide legislation for MASS specifically or alter current legislation to include definitions/ clarifications for MASS where applicable.<br>**2.** Clearly outline the roles and responsibilities of the master and the operator for the different levels of automation. |
| Regulators | • The results of the social network analysis showed that the industrialists have a high degree of influence with the current and future MASS system but did not have connections to the regulators in the current network.<br>• The social network also showed there was a lack of connections between the regulators and resource providers, including regulations for training centers for MASS operators. | **3.** Provide clear guidance to industrialists and resource providers on testing, maintenance, and certification for MASS.<br>**4.** Give guidance to resource providers and end-users on training qualifications that are required to operate a MASS at the different levels of automation. |
| Industrialists | • MASS was defined as a key actor within the MASS system so it will be important that it undergoes sufficient testing before being operated.<br>• The MASS operator was also found to have a high degree of influence, so it will be important that they are sufficiently supported by using human-centered design approaches and that they have appropriate guidance on the operational constraints of the MASS. | **5.** Ensure that the MASS has undergone sufficient testing and that potential risks during operation have been identified.<br>**6.** Provide clear guidelines to end-users on the operational constraints of the MASS.<br>**7.** Use human-centered design principles when designing the MASS' systems. |
| Resource Providers | • The comparison of current and future social network results showed that in the current MASS system that training centers do not have a high degree of influence but that it can be improved by the addition of training courses and qualifications specifically for MASS. | **8.** Provide appropriate training courses for operators of MASS and other roles involved in operating MASS. |
| End User | • The MASS operator was found to be both a highly connected and central actor within the network, so it will be important they understand their role and responsibilities during operation and the limitations and constraints of the MASS. | **9.** Operators will need to have a clear understanding of what their roles and responsibilities are during operation.<br>**10.** Operators will also need to understand what the operating constraints and limitations of the MASS are. |
| Equipment and Environment | • The social network results showed that the MASS node is highly connected within the network, so it will be necessary for MASS to be appropriately maintained, as failures could affect many other actors within the network. | **11.** Make sure that MASS are appropriately maintained in line with the guidance given by industrialists and regulators. |

Abbreviations: MASS, Maritime Autonomous Surface Ships; RMF, risk management framework.

## 4 | DISCUSSION

System recommendations have been made for each level of the UK MASS system based on the social network analysis findings and are shown in Table 5, to suggest ways that each level could improve the overall system's safety. The analysis of the UK MASS system has shown that there are many decision-makers within the UK MASS system, with 60 actors being identified in the Actor Map for the current MASS system. It has shown how the different RMF levels are involved in the overall safety of the system and, therefore, how different decision-makers within the system levels can influence safety. Similarly, the application of the RMF to maritime pilotage showed how different factors across the RMF system levels influence how maritime pilots make decisions, showing the applicability of the RMF in the maritime domain (Butler et al., 2022). It also showed the complexity of operations in the maritime domain due to the wide range of factors identified, and the actor map generated here also shows the complexity of the maritime domain, as 60 actors were identified across all the RMF levels for the current system and the number of actors will increase as the system develops further (Butler et al., 2022). Other applications of the RMF in the maritime domain also support these findings, Lee et al. (2017) and Kee et al. (2017)

analyses of the Sewol Ferry accident highlighted how shortfalls in the legislator and regulators levels can influence the rest of the system levels below leading to an accident. These applications of the RMF highlight the importance of looking beyond the more obvious decision-makers within a sociotechnical system, for example, the operators and those working within an RCC and consider how others in the higher level system levels (e.g., regulators and government bodies) decisions will also affect the safety of the system.

Although MASS are expected to bring safety benefits by removing onboard operators and, therefore, the risk to life of the crew, the differences in how they will be operated due to their remote operation will mean that the operators will have to be more reliant on their automated systems to operate the ship making the human-machine interaction more critical than it might be on a conventional vessel (Man et al., 2018). One important issue will be providing operators and other personnel within an RCC with the necessary information to safely operate and navigate the MASS even though they will no longer have all of the same sensory feedback as they would onboard (Mallam et al., 2020; Man et al., 2016). This lack of 'ship sense' will affect their ability to maintain their situational awareness and respond to situations appropriately (Man et al., 2016). The use of human-centered design approaches will be necessary to support operators when they are in a predominately monitoring role to keep operators engage in their tasks so that the MASS' automated systems are being supervised (Man et al., 2018). Industrialists, resource providers and end users will need further guidance on how to design and develop their MASS systems to minimize the risks of these human-machine interaction issues leading to incidents and accidents.

The application of the RMF and Social Network Analysis to the UK MASS system has shown the importance of actors within the international committees, national committees and regulators levels to system safety. Similar to Banks et al.'s (2019) findings for the automated driving system in the UK, in the current MASS system nodes in the industrialist's tier of the RMF were found to have high sociometric statuses and centrality within the network. There was also a lack of influence from the nodes within the regulator tier in both the automated driving system and the current MASS system (Banks et al., 2019). However, the MASRWG and Society of Maritime Industries were found to be key agents in the national committee's tier in the MASS system, whereas none was found in the automated driving system (Banks et al., 2019). This suggests there is a need for a greater top-down influence from the international and national committee levels to inform the new regulations and standards that are required to increase safety within the system. Although there is currently a lack of formal regulation from the regulators, national committees such as the MASRWG are working on developing the regulatory framework for the UK. Banks et al. (2019) recommended that a combined top-down and bottom-up sociotechnical approach should be taken, to ensure that innovation is not inhibited, and appropriate regulations and policies are in place to enable their safe operation, which suggests a similar approach may be applicable for the UK MASS system (Banks et al., 2019).

Kim and Schröder-Hinrichs (2021) highlighted the need for the MASS regulatory framework to be developed with proactive measures to reduce the gap between the regulatory framework and the technological developments, whilst ensuring that the framework does not inhibit innovation. The findings have shown that there is a high degree of influence from industry within the MASS system, which suggests that a proactive approach may need to be taken to reduce this gap (Kim & Schröder-Hinrichs, 2021). The development of regulations specifically for MASS will be necessary to ensure that they can interact safely with crewed ships (Hoem et al., 2021). This will be particularly important for preventing collisions between crewed ships and MASS as the International Regulations for Preventing Collisions at Sea (COLREG) 1972 rely on the judgment of the onboard seafarer (Jo et al., 2020). For example, COLREG Rule 5 states, "Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision," guidance will be needed on how should be achieved when the master is no longer onboard the vessel, and they are operating a MASS from an RCC. In addition to standards for interacting with conventional vessels, MASS will also need to be able to interact with other MASS safely, so further amendments may be required to include these new aspects (Hannaford & Hassel, 2021).

Due to the differences in how crewed and uncrewed ships are operated there are many gaps in the current standards and regulations which need clarification for remote operators, such as definitions for "master," "crew," and "responsible person" and regulations referencing being onboard the vessel (Shiokari 2020; Yoshida et al., 2020). The future MASS system developed showed that the MASS operator node was a key agent within the network as it had a high sociometric status and centrality. Therefore, it will be important that the roles and responsibilities of the operator and other roles involved in their operation are clearly outlined for the different levels of MASS automation (Kim & Schröder-Hinrichs, 2021; Man et al., 2015; Saha, 2021). It has been suggested that these roles and responsibilities could be defined using an operational envelope (Hoem et al., 2021). The operational envelope could be defined by the relevant operational constraints such as weather conditions, traffic, and geographic complexity (Hoem et al., 2021).

Whilst there is a lack of formal regulations, the MASRWG code of practice will be an important part of the MASS system as it develops and will need to be updated along with technological developments, especially as formal regulations from the IMO are not expected before 2028 (Department of Transport, 2021). However, there are gaps in the code of practice developed by MASRWG, as there is currently no guidance from the higher levels of the system some of the standards can only refer to crewed ships. For example, it is suggested that operators should have appropriate certification for a similar manned vessel. However, it has been highlighted by Deling et al. (2020) that there are many aspects of knowledge and skills that remote operators will need that are not currently included in seafarer training under the International Convention on Standards of Training, Certification and Watchkeeping 1978, such as gaps in automation knowledge, lack of training on diagnosing automated system faults and the aspects relating to the remote control. It has been suggested that operators will need an overall understanding of the vessel and the RCC and how these parts of the system work together (Saha, 2021). The development of appropriate training courses for MASS operators will be important, to ensure that operators develop the necessary skills to operate MASS safely, as their operation will differ from that of a conventional crewed ship.

It has also been identified that operators require training for intervening in emergencies, and it was suggested that simulators and virtual reality could be used to give operators experience in these scenarios (Saha, 2021; Yoshida et al., 2020). Kim and Mallam (2020) Delphi study of the International Convention on Standards of Training, Certification and Watchkeeping (STCW) 1978 leadership competencies, and it was suggested that new knowledge, understanding, and proficiency (KUP) for leadership will also be required for operators at RCCs. The feedback from the SMEs that a new KUP should be added to the STCW KUPs, the knowledge, and ability to acquire, handle and comprehend large amounts of system information as when the operators are working at an RCC they will potentially be receiving large volumes of sensor data, and there will be less personnel in the RCC versus on a manned bridge so the way in which they will need to comprehend and interpret different system information to inform their decision-making might change. This shows that not only will the technical regulations and standards developed for the ships be important, but the regulations and standards for RCC personnel will also be important as these will affect how the operators and other roles, such as the master and chief officers and chief engineers are trained. It has been highlighted that the experience and training of the remote MASS operators will be critical to the safe navigation of ships (Deling et al., 2020; Yoshida et al., 2020). Various professional institutions such as MASSPeople and CEbotiX are already investigating training requirements for operators of MASS and developing training standards for operators (Furgo, 2021; National Oceanography Centre Innovations Ltd, 2021). The development of these training courses for MASS operation will then lead to the added links from training centers in the future MASS system network, which helped to improve the system's resilience.

One limitation of this approach is the subjectivity of the development of the social networks of the UK MASS system, the SMEs selected may have influenced the actors identified and the links between them due to their own biases. However, these risks have been mitigated by consulting three SMEs when creating the UK MASS networks, whose combined experience in the maritime domain covered all the RMF system levels, and the networks went under multiple reviews. The UK MASS system networks could be developed further in the future by being reviewed by other SMEs with different types of experience, as this might impact the actors and connections included. However, whilst the MASS system is still under development, this provides an initial analysis of the UK MASS system will continue to change whilst it develops, and more MASS becomes operational. There will be more changes when new regulations and standards are put in place nationally and internationally, as the IMO has still yet to put into place any regulations and standards specifically for MASS, but this is likely to be further in the future. It could be that the IMO or MCA for the UK could keep a 'living document' that could be updated as the system evolves.

Although the IMO was not found to be a key node within either MASS network, it will still be an important node as any international regulations developed for MASS will then be enforced by the UK's flag state representative, the MCA. This suggests there are limitations in using this approach as the links within the networks are not weighted in terms of their importance. Therefore, the networks do not reflect the IMO's importance and the difference in importance between other nodes of the networks. However, as MASS is still in the early stage of development, this approach provides a starting point for further discussions on how the MASS system might be supported during this process, and it could also be applied to other new technology areas such as Uncrewed Aerial Vehicles (UAVs) and artificial intelligence. This suggests that in future applications, the method may need to be extended to include a weighting scale for the links within the social network created to model the sociotechnical system. As this was the first application of the method to the MASS system, it was beyond the scope of the current article, but in future applications of the method a weighting system could be developed for the links between the actors in the network. For example, higher weightings could be assigned to links that have come from legislation that may have been put in place by the MCA or the IMO. Also, in some cases, there may be a strong connection between a pair of actors, which could be given a higher weighting, and if there is a weaker connection, where information is exchanged but there's not necessarily a direct influence of one actor over another the link could be given a lower weighting.

There are other Human Factors methods that could be used to analyse future sociotechnical systems, like the UK the MASS system and could be applied to further the findings here, such as Cognitive Work Analysis (Vicente, 1999), which can be applied to future systems to provide a comprehensive system analysis. Although CWA could be used to identify recommendations for the MASS system, the analysis would not necessarily show the different stakeholders and decision-makers involved in the entire MASS system, which was an advantage of using the RMF to create an actor map and using Social Network Analysis to investigate the influence of each of those decision-makers. Methods such as System Theoretic Process Analysis (STPA) (Leveson, 2011) and Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) could be used to identify further recommendations for the MASS system, as they can also be used to proactively assess risk in new and developing systems, once there is greater knowledge of how uncrewed MASS will be operated from RCCs and the control structures that have been put in place for their operation. Another method that would provide a comprehensive system analysis would be the Event Analysis of the Systemic Teamwork Framework-Broken Links (EAST-BL) (Stanton & Harvey, 2017) method, which could be used to identify the risks when there are communications failures between actors and tasks in a sociotechnical system. This approach would also identify who the actors are within the MASS system, however, it may not be appropriate to apply it to the social networks developed due to the scale of networks, and further field data would be required to understand which links might be broken during an accident or incident. EAST-BL could be applied to a MASS case study or specific MASS use case to better understand the risks of communication failures, once there is more knowledge of the specifics of MASS operations. Applying EAST-BL to a MASS case study could overcome some of the weaknesses in the combined RMF and Social Network Analysis approach, as the field data could be used to apply weightings to the social, tasks and information networks.

### 4.1 | Further work

Further work will be required to investigate the UK MASS system as it develops whilst its regulatory framework is put into place and suggest what can be done to improve the system further. The developed UK MASS network shown has been created as a starting point for this discussion but will require updating as the system develops. The networks created could be validated using field data from operational MASS in the future when the technology is more established and to extend the method by creating a weighting system for the different links between the actors. Although the future UK MASS system will show improved resilience, there will still be a need to further investigate ways of supporting industrialists and the end-user to create greater redundancy within the system. Further work could investigate how standards might be developed for the new aspects of operating MASS, including the requirements for RCCs and their personnel, including the standards for their training. Also, the effects of failures within the MASS system could be investigated to understand what effects this would have on the system and what could be done to mitigate those risks. The networks were done for the UK MASS system. Generally, the networks could be extended to include the different regulations related to ship type, ship size (overall length and tonnage), and the area of operation (open ocean, pilotage, or inland waters) to show how each aspect might affect the system. The actor map and social network analysis method could also be applied in other flag states to explore the differences between them and the UK.

## 5 | CONCLUSIONS

A sociotechnical systems approach has been applied to the MASS system in the UK, and it has shown that there are many different actors within the system, and the system goes beyond just the MASS and the operator. Two social networks of the UK MASS system were developed, one to show the connections that exist in the current UK MASS system and a second to show a future MASS system showing the effects of the development of MASS-specific regulations and standards. Social Network Analysis was then used to analyse the dynamics of the current and future MASS networks. The results showed that there is a need for a greater top-down influence in the current system from the international, national, government, and regulator levels of the RMF to promote the safe development and operation of MASS. Also, the results showed that greater redundancy is needed within the MASS system, so there is less reliance on the end user. Recommendations have been given to improve the UK MASS system's safety by giving recommendations for each level of the sociotechnical system. The future MASS system shown contained additional links between the civilian and military regulators (the MCA and the Defence Maritime Regulator) and lower levels of the network, which showed that the development of a formal regulatory framework improved the system's resilience by creating a greater top-down influence. The MASS system is continuously changing as the regulations and standards are still being developed for MASS, including the development of training standards and qualifications for operators.

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## DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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# APPENDIX A: RISK MANAGEMENT FRAMEWORK FOR UK MASS SYSTEM—MASS CURRENT AND FUTURE ACCIMAPS IN FULL AND BROKEN INTO SECTIONS

Figures A.1–A.8,

**TABLE A.1** Abbreviations used in UK MASS social network diagrams.

| Hierarchical level | Node | Abbreviation |
|---|---|---|
| International Committees | International Standards Organisation | ISO |
| | International Maritime Organisation | IMO |
| | United Nations | UN |
| | International Association of Classification Societies | IACS |
| | International Union of Marine Insurance | IUMI |
| | International Group of P&I Clubs | IGPIC |
| | International Labour Organisation | ILO |
| | International Association of Marine Aids to Navigation and Lighthouse Authorities | IALA |
| | International Telecommunication Union | ITU |
| National Committees | Transport Select Committee | TSC |
| | Business, Energy and Industrial Strategy Committee | BEISC |
| | Work and Pensions Select Committee | WPSC |
| | Defence Select Committee | DSC |
| | Maritime Research and Innovation UK | MarRI-UK |
| | Society of Maritime Industries | SMI |
| | British Ports Association | BPA |
| | Maritime Autonomous Systems Regulatory Working Group | MASRWG |
| Government | Department of Transport | DfT |
| | Department of Business, Energy and Industrial Strategy | DfBEIS |
| | Department of Work and Pensions | DfWP |
| | Department of Culture, Media and Sport | DfCMS |
| | Ministry of Defence | MoD |
| | Health and Safety Executive | HSE |
| | UK Hydrographic Office | UKHO |
| | Marine Accident Investigation Branch | MAIB |
| | Defence Accident Investigation Branch | DAIB |
| Regulators | Maritime Coastguard Agency | MCA |
| | Port and Harbour Authorities | P&H Authorities |
| | Defence Safety Authority | DSA |
| | Defence Maritime Regulator | DMR |
| | Office of Communications | OfCom |
| | Office for Artificial Intelligence | OAI |
| Industry | Research and Development Centres | R&D Centres |
| | Technology Companies | Tech Companies |

(Continues)

TABLE A.1 (Continued)

| Hierarchical level | Node | Abbreviation |
|---|---|---|
| | Future Autonomous at Sea Technologies Cluster | FAST Cluster |
| | Protection and Indemnity Clubs | P&I Clubs |
| Resource Providers, Management | Human–Machine Interface Designers | HMI Designers |
| | Royal National Lifeboat Institution | RNLI |
| | Software Engineers | SE |
| | Hardware Engineers | HE |
| Equipment and Environment | Maritime Autonomous Surface Ship | MASS |
| | Human–Machine Interface | HMI |
| | Remote Control Centre | RCC |

**TABLE A.2** **Social network analysis results for the MASS csocial networks**—Nodal metric results for current and future MASS networks.

| | | Node metrics | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Emission | | Reception | | Sociometric status | | B-L Centrality | | Closeness | | Farness | | Betweenness | |
| Hierarchical Level | Node | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future |
| International Committee | International Standards Organisation | 5 | 5 | 4 | 4 | 0.15 | 0.15 | 27.32 | 28.22 | 0.33 | 0.35 | 179 | 174 | 194.87 | 194.46 |
| | International Association of Classification Societies | 6 | 6 | 5 | 5 | 0.19 | 0.18 | 29.97 | 30.21 | 0.36 | 0.36 | 164 | 168 | 160.42 | 116.71 |
| | United Nations | 4 | 4 | 1 | 1 | 0.08 | 0.08 | 23.12 | 24.41 | 0.30 | 0.34 | 197 | 178 | 14.67 | 12.02 |
| | International Maritime Organisation | 6 | 7 | 6 | 7 | 0.20 | 0.23 | 33.10 | 36.16 | 0.37 | 0.44 | 158 | 138 | 416.50 | 506.21 |
| | International Union of Marine Insurance | 3 | 3 | 3 | 3 | 0.10 | 0.10 | 26.19 | 26.97 | 0.30 | 0.32 | 195 | 191 | 4.52 | 3.28 |
| | International Group of P&I Clubs | 3 | 3 | 2 | 2 | 0.08 | 0.08 | 26.25 | 27.03 | 0.31 | 0.33 | 191 | 187 | 15.20 | 6.42 |
| | International Labour Organisation | 2 | 2 | 3 | 3 | 0.08 | 0.08 | 25.60 | 25.94 | 0.30 | 0.32 | 196 | 193 | 23.81 | 17.70 |
| | International Telecommunication Union | 2 | 2 | 5 | 5 | 0.12 | 0.11 | 27.65 | 28.43 | 0.24 | 0.26 | 242 | 237 | 67.75 | 81.04 |
| | International Association of Marine Aids to Navigation and Lighthouse Authorities | - | 3 | - | 3 | - | 0.10 | - | 31.10 | - | 0.35 | - | 174 | - | 21.11 |
| National Committee | Maritime UK | 4 | 4 | 8 | 8 | 0.20 | 0.20 | 32.63 | 32.32 | 0.32 | 0.33 | 182 | 187 | 97.34 | 74.8 |
| | Transport Select Committee | 2 | 2 | 1 | 1 | 0.05 | 0.05 | 27.72 | 28.01 | 0.31 | 0.32 | 192 | 190 | 0.75 | 0.67 |
| | Business, Energy and Industrial Strategy Committee | 2 | 2 | 1 | 1 | 0.05 | 0.05 | 25.04 | 24.72 | 0.27 | 0.27 | 221 | 225 | 0.65 | 0.59 |
| | Work and Pensions Select Committee | 1 | 1 | 1 | 1 | 0.03 | 0.03 | 22.79 | 22.60 | 0.25 | 0.25 | 239 | 243 | 0.00 | 0.00 |
| | Defence Select Committee | 1 | 1 | 1 | 1 | 0.03 | 0.03 | 26.37 | 26.72 | 0.29 | 0.31 | 201 | 199 | 0.00 | 0.00 |
| | Maritime Research and Innovation UK | 5 | 5 | 5 | 5 | 0.17 | 0.16 | 35.80 | 35.38 | 0.37 | 0.37 | 158 | 163 | 109.52 | 60.73 |
| | Society of Maritime Industries | 6 | 6 | 8 | 8 | 0.24 | 0.23 | 36.48* | 35.82 | 0.36 | 0.36 | 165 | 170 | 234.19 | 211.55 |
| | British Standards Institution | 1 | 1 | 1 | 1 | 0.03 | 0.03 | 21.38 | 21.83 | 0.25 | 0.26 | 237 | 234 | 0.00 | 0.00 |
| | British Ports Association | 6 | 6 | 4 | 4 | 0.17 | 0.16 | 31.99 | 33.63 | 0.38 | 0.43 | 157 | 141 | 74.68 | 70.42 |
| | Professional Institutions | 1 | 2 | 2 | 2 | 0.05 | 0.07 | 29.51 | 30.13 | 0.29 | 0.3 | 207 | 206 | 6.66 | 0.54 |
| | Maritime Autonomous Systems Regulatory Working Group | 4 | 4 | 15 | 15 | 0.32* | 0.31 | 38.19* | 39.90* | 0.35 | 0.39 | 168 | 157 | 251.39 | 228.98 |
| Government | Department of Transport | 10 | 10 | 9 | 9 | 0.32* | 0.31 | 38.06* | 39.09* | 0.43 | 0.46 | 138 | 133 | 441.9 | 334.54 |
| | Department of Business, Energy and Industrial Strategy | 5 | 6 | 4 | 4 | 0.15 | 0.16 | 33.19 | 32.87 | 0.35 | 0.36 | 167 | 169 | 126.44 | 167.77 |

(Continues)

**TABLE A.2** (Continued)

| | | Node metrics | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Emission | | Reception | | Sociometric status | | B-L Centrality | | Closeness | | Farness | | Betweenness | |
| Hierarchical Level | Node | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future |
| | Department of Work and Pensions | 3 | 3 | 2 | 2 | 0.08 | 0.08 | 29.66 | 29.52 | 0.33 | 0.33 | 181 | 183 | 141.44 | 141.53 |
| | Department of Digital, Culture, Media and Sport | 3 | 4 | 3 | 3 | 0.10 | 0.11 | 29.51 | 30.37 | 0.30 | 0.33 | 194 | 183 | 99.71 | 125.81 |
| | Ministry of Defence | 9 | 9 | 6 | 7 | 0.25 | 0.26 | 36.02* | 36.96 | 0.41 | 0.44 | 143 | 139 | 456.14 | 418.19 |
| | Health and Safety Executive | 4 | 4 | 3 | 3 | 0.12 | 0.11 | 29.58 | 30.85 | 0.36 | 0.41 | 163 | 150 | 109.18 | 130.16 |
| | Funding Bodies | 7 | 7 | 6 | 6 | 0.22 | 0.21 | 39.11* | 38.70 | 0.41 | 0.41 | 144 | 148 | 605.90 | 499.57 |
| | UK Hydrographic Office | 6 | 8 | 5 | 7 | 0.19 | 0.25 | 37.94* | 38.57* | 0.40 | 0.42 | 147 | 146 | 90.66 | 129.67 |
| | Marine Accident Investigation Branch | 7 | 8 | 1 | 1 | 0.14 | 0.15 | 30.37 | 30.05 | 0.38 | 0.38 | 156 | 162 | 22.47 | 7.36 |
| | Defence Accident Investigation Branch | 7 | 7 | 1 | 1 | 0.14 | 0.13 | 24.99 | 24.72 | 0.35 | 0.35 | 169 | 176 | 10.95 | 5.14 |
| Regulators | Maritime Coastguard Agency | 7 | 28 | 8 | 12 | 0.25 | 0.66* | 39.93* | 46.28* | 0.41 | 0.54 | 143 | 112 | 520.78 | 1007.83 |
| | Port and Harbour Authorities | 8 | 9 | 3 | 5 | 0.19 | 0.23 | 32.72 | 36.73 | 0.39 | 0.45 | 150 | 137 | 132.52 | 124.65 |
| | Trinity House | 5 | 9 | 2 | 5 | 0.12 | 0.23 | 29.74 | 36.16 | 0.33 | 0.43 | 181 | 141 | 40.25 | 84.27 |
| | Defence Safety Authority | 3 | 3 | 2 | 2 | 0.08 | 0.08 | 28.41 | 29.00 | 0.34 | 0.37 | 172 | 167 | 68.78 | 69.78 |
| | Defence Maritime Regulator | 7 | 17 | 3 | 4 | 0.17 | 0.34* | 33.39 | 35.82 | 0.38 | 0.44 | 154 | 140 | 71.96 | 87.44 |
| | Office of Communications | 3 | 3 | 2 | 2 | 0.08 | 0.08 | 25.89 | 26.18 | 0.26 | 0.27 | 226 | 222 | 19.35 | 11.17 |
| | Office of Artificial Intelligence | - | 3 | - | 2 | - | 0.08 | - | 30.13 | - | 0.40 | - | 151 | - | 100.30 |
| Industry | MASS Manufacturers | 18 | 18 | 15 | 16 | 0.56* | 0.56* | 39.51* | 40.31* | 0.42 | 0.42 | 142 | 145 | 337.33 | 253.15 |
| | Research and Development Centres | 18 | 18 | 12 | 14 | 0.51* | 0.52* | 43.09* | 45.20* | 0.47 | 0.48 | 125 | 126 | 868.24 | 814.04 |
| | Technology Companies | 13 | 13 | 12 | 14 | 0.42* | 0.44* | 38.32* | 39.22* | 0.40 | 0.40 | 149 | 154 | 316.05 | 268.38 |
| | MASS Capability Providers | 5 | 5 | 6 | 10 | 0.19 | 0.25 | 34.19 | 35.49 | 0.33 | 0.33 | 180 | 186 | 111.20 | 81.50 |
| | FAST Cluster | 3 | 3 | 6 | 6 | 0.15 | 0.15 | 34.29 | 34.13 | 0.34 | 0.34 | 174 | 177 | 12.98 | 7.40 |
| | P&I Clubs | 3 | 3 | 2 | 3 | 0.08 | 0.10 | 28.48 | 30.69 | 0.30 | 0.30 | 199 | 206 | 40.28 | 24.96 |
| Resource Providers, Management | Training Centres | 5 | 8 | 5 | 8 | 0.17 | 0.26 | 33.29 | 36.27 | 0.35 | 0.37 | 169 | 166 | 26.63 | 58.77 |
| | Maintenance Providers | 5 | 5 | 5 | 7 | 0.17 | 0.20 | 31.99 | 33.93 | 0.31 | 0.31 | 191 | 196 | 21.99 | 14.74 |
| | HMI Designers | 7 | 7 | 5 | 7 | 0.20 | 0.23 | 32.91 | 35.38 | 0.35 | 0.35 | 170 | 172 | 2.58 | 2.49 |
| | Hardware Engineer | 6 | 6 | 4 | 6 | 0.17 | 0.20 | 32.91 | 35.27 | 0.35 | 0.35 | 169 | 172 | 1.10 | 0.80 |

**TABLE A.2** (Continued)

| | | Node metrics | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Emission | | Reception | | Sociometric status | | B-L Centrality | | Closeness | | Farness | | Betweenness | |
| Hierarchical Level | Node | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future | Current | Future |
| | Software Engineer | 7 | 7 | 5 | 7 | 0.20 | 0.23 | 33.10 | 35.49 | 0.35 | 0.36 | 168 | 171 | 1.90 | 1.56 |
| | System Architects | 8 | 8 | 6 | 8 | 0.24 | 0.26 | 33.29 | 35.71 | 0.35 | 0.36 | 167 | 170 | 2.90 | 2.56 |
| | MASS Management Roles | 7 | 7 | 7 | 9 | 0.24 | 0.26 | 33.00 | 33.73 | 0.32 | 0.32 | 185 | 193 | 130.00 | 74.69 |
| | RNLI | 1 | 2 | 1 | 1 | 0.03 | 0.05 | 23.94 | 31.36 | 0.21 | 0.36 | 279 | 171 | 2.29 | 0.00 |
| | UK Authorised Recognised Surveyor and Inspector Organisation | 6 | 7 | 2 | 3 | 0.14 | 0.16 | 34.09 | 35.06 | 0.38 | 0.39 | 154 | 156 | 179.54 | 117.57 |
| End User | MASS Owner | 3 | 3 | 4 | 5 | 0.12 | 0.13 | 29.35 | 30.37 | 0.27 | 0.27 | 216 | 222 | 85.44 | 43.53 |
| | MASS Operators | 8 | 8 | 11 | 13 | 0.32* | 0.34* | 37.20* | 37.93* | 0.35 | 0.35 | 168 | 172 | 544.61 | 476.02 |
| Equipment and Environment | MASS | 4 | 4 | 21 | 22 | 0.42* | 0.43* | 28.91 | 28.57 | 0.21 | 0.21 | 276 | 284 | 268.21 | 258.69 |
| | Human–machine Interface | 2 | 2 | 5 | 7 | 0.12 | 0.15 | 29.97 | 31.27 | 0.26 | 0.27 | 224 | 230 | 74.97 | 76.72 |
| | Other Ships | 2 | 2 | 8 | 9 | 0.17 | 0.18 | 30.61 | 31.10 | 0.26 | 0.27 | 224 | 230 | 135.68 | 78.96 |
| | Remote Control Centre | 1 | 1 | 12 | 14 | 0.22 | 0.25 | 23.99 | 24.31 | 0.18 | 0.18 | 334 | 344 | 0.00 | 0.00 |
| | Environmental Conditions | 3 | 3 | 1 | 1 | 0.07 | 0.07 | 28.55 | 28.22 | 0.26 | 0.27 | 223 | 229 | 73.09 | 75.60 |
| | Port Infrastructure | 1 | 1 | 2 | 2 | 0.05 | 0.05 | 19.79 | 20.41 | 0.18 | 0.18 | 328 | 339 | 2.03 | 0.75 |
| | Communications Infrastructure | 3 | 3 | 2 | 2 | 0.08 | 0.08 | 29.35 | 29.14 | 0.30 | 0.30 | 198 | 205 | 6.58 | 1.94 |
| | At Sea Infrastructure | 1 | 1 | 3 | 3 | 0.07 | 0.07 | 22.26 | 22.04 | 0.18 | 0.18 | 330 | 340 | 2.03 | 0.75 |
| | **Mean score** | **4.97** | **5.68** | **4.97** | **5.68** | **0.17** | **0.19** | **30.87** | **31.97** | **0.32** | **0.34** | **190.32** | **186.61** | **131.32** | **125.61** |
| | **Standard deviation** | **3.51** | **4.78** | **4.05** | **4.48** | **0.11** | **0.13** | **5.09** | **5.50** | **0.06** | **0.07** | **45.48** | **47.65** | **179.28** | **192.02** |

*Note*: Asterisks denote key nodes in the network.

Abbreviations: FAST, Future Autonomous at Sea Technologies; MASS, Maritime Autonomous Surface Ships; RNLI, Royal National Lifeboat Institution.

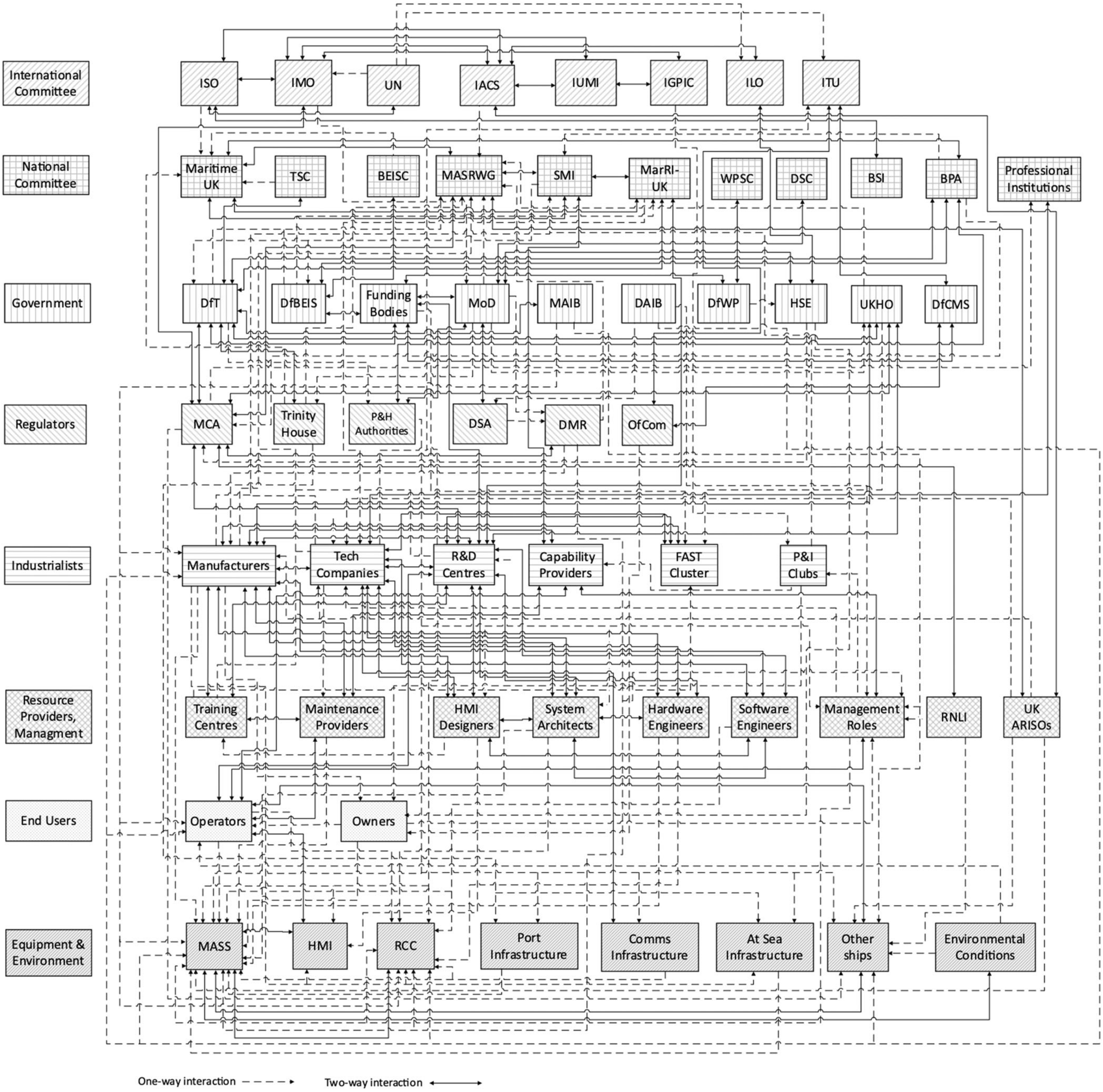

**FIGURE A.1** Directed social network for the current UK Maritime Autonomous Surface Ships (MASS) system (*note*: larger dashed lines reflect one-way interaction whereas solid lines reflect two-way interaction between agents and see Table A.1 for definitions of abbreviations.).

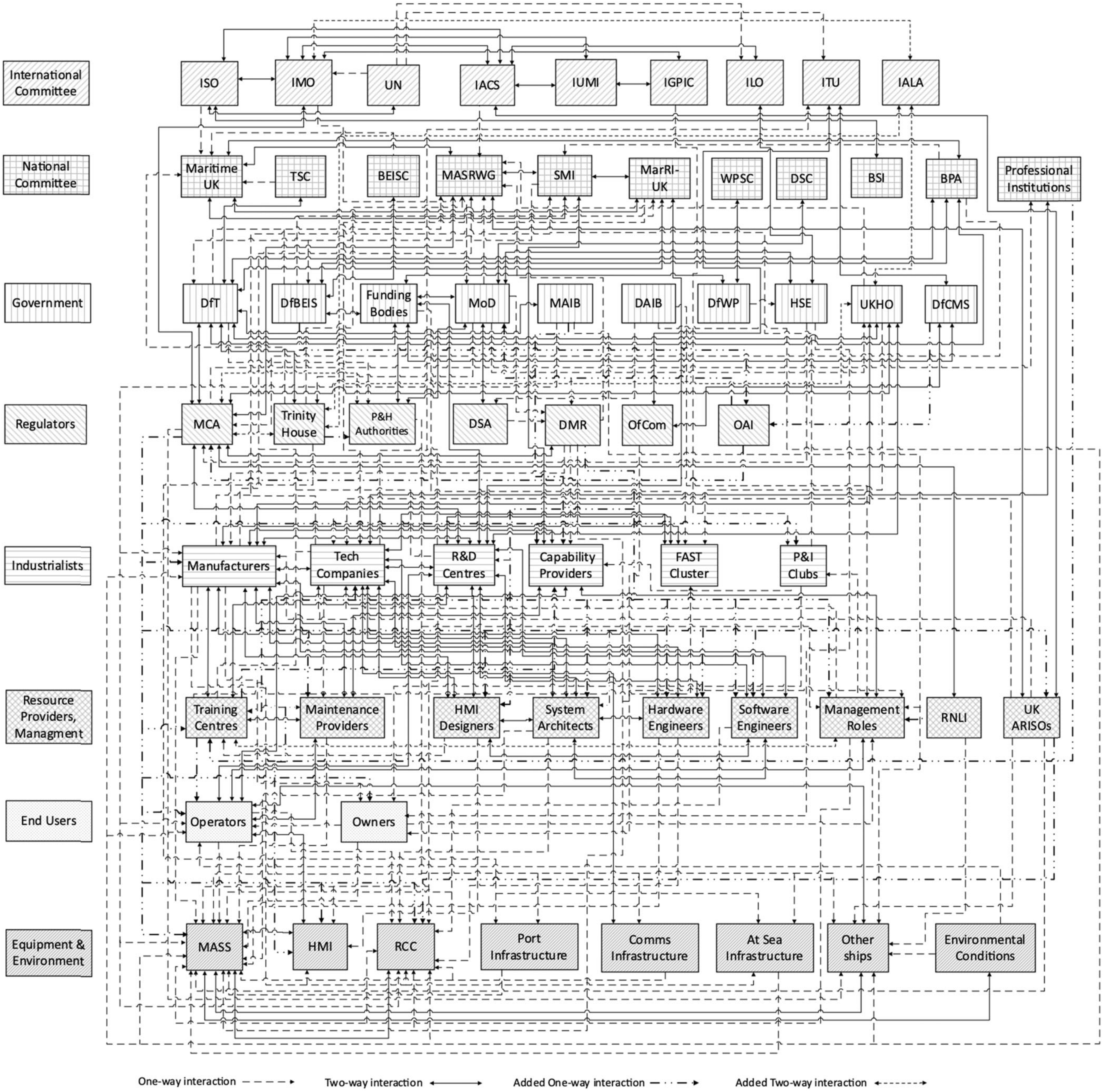

**FIGURE A.2** Directed social network of the future Maritime Autonomous Surface Ships (MASS) network (*note*: larger dashed lines reflect one-way interaction whereas solid lines reflect two-way interaction between agents. Dashed lines with dots reflect one-way interactions which have been added to create the future network, and smaller dashed lines reflect two-way interactions that have been added. See Table A.1 for definitions of abbreviations).

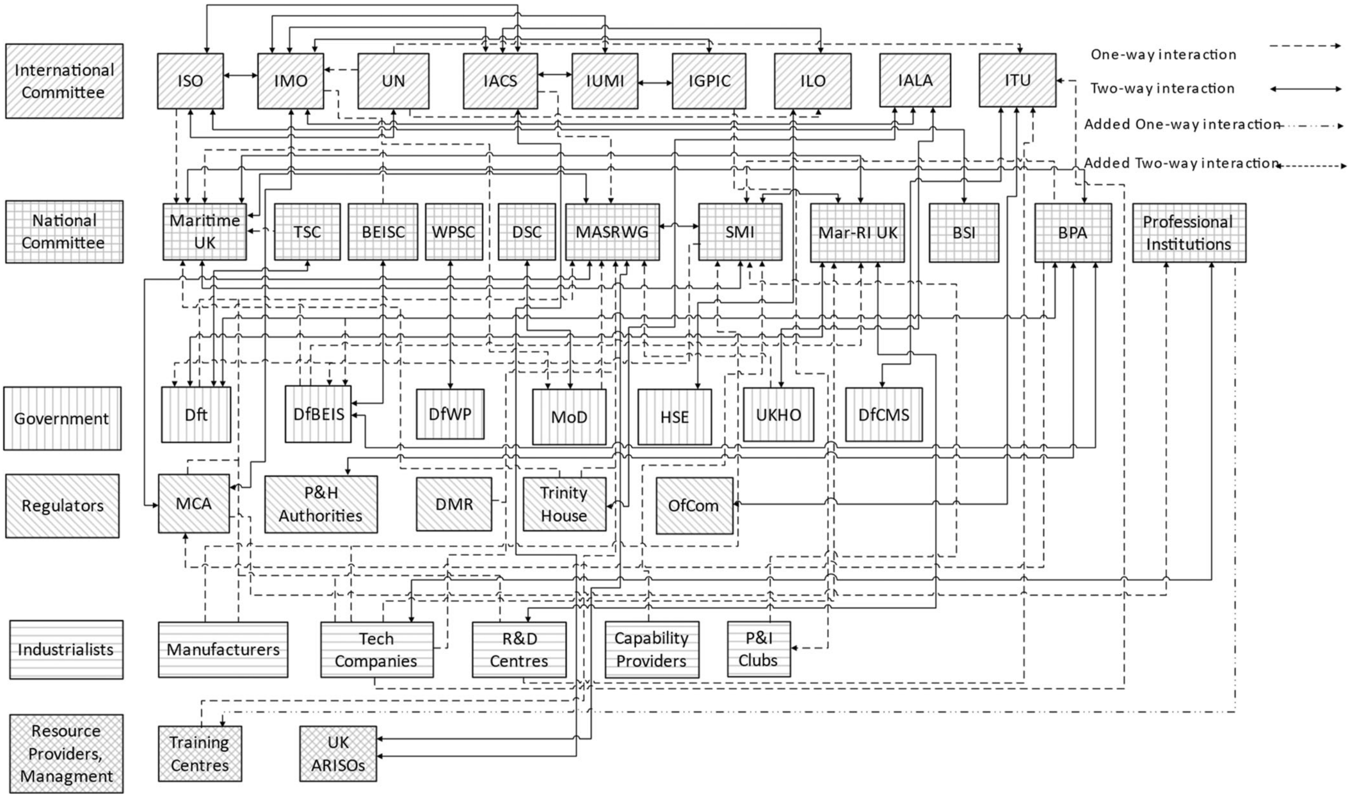

**FIGURE A.3** Social network showing the international and national committees nodes' connections within the current and future Maritime Autonomous Surface Ships (MASS) social networks developed.

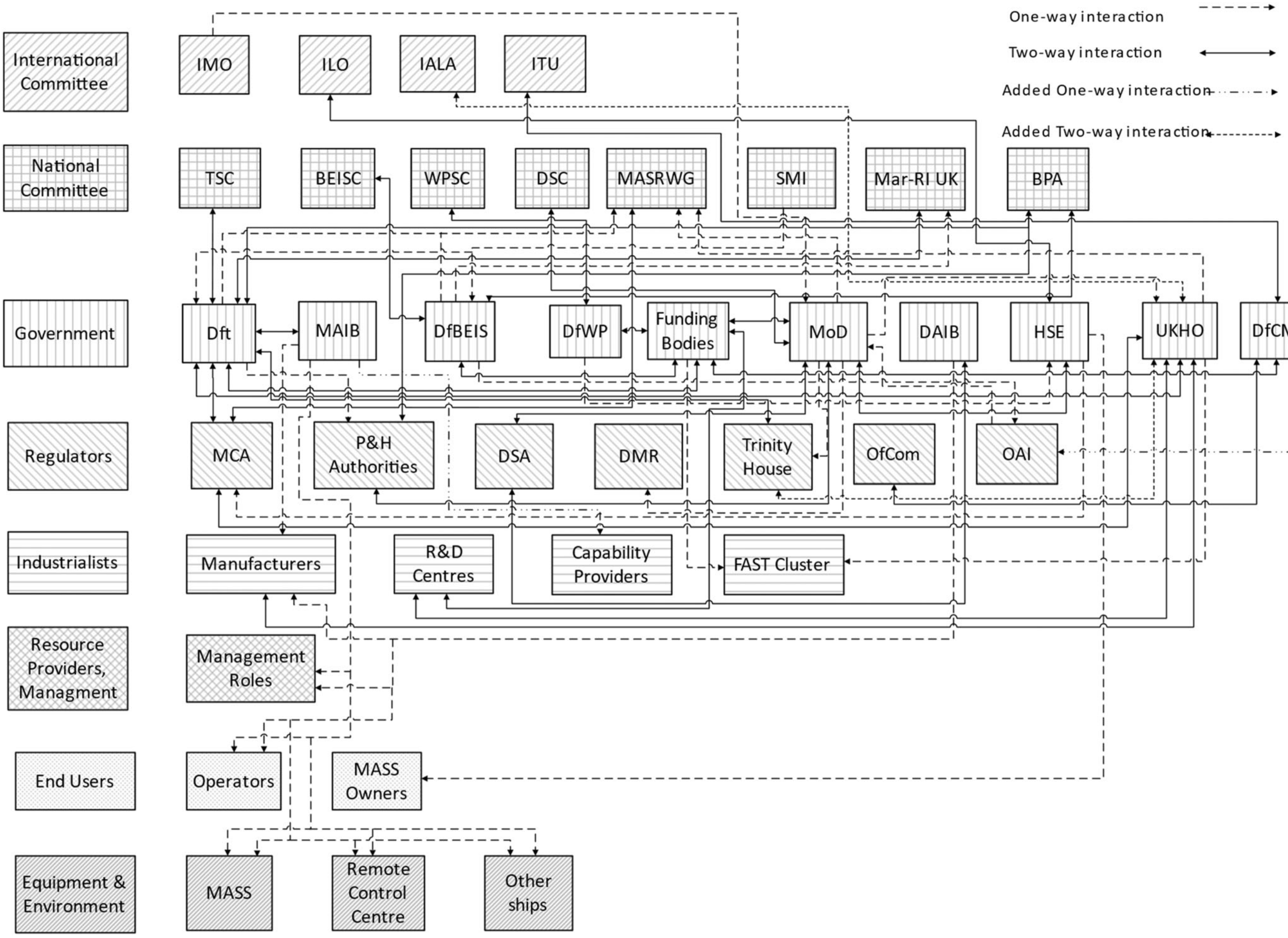

**FIGURE A.4** Social network showing the government nodes' connections within the current and future Maritime Autonomous Surface Ships (MASS) social networks developed.

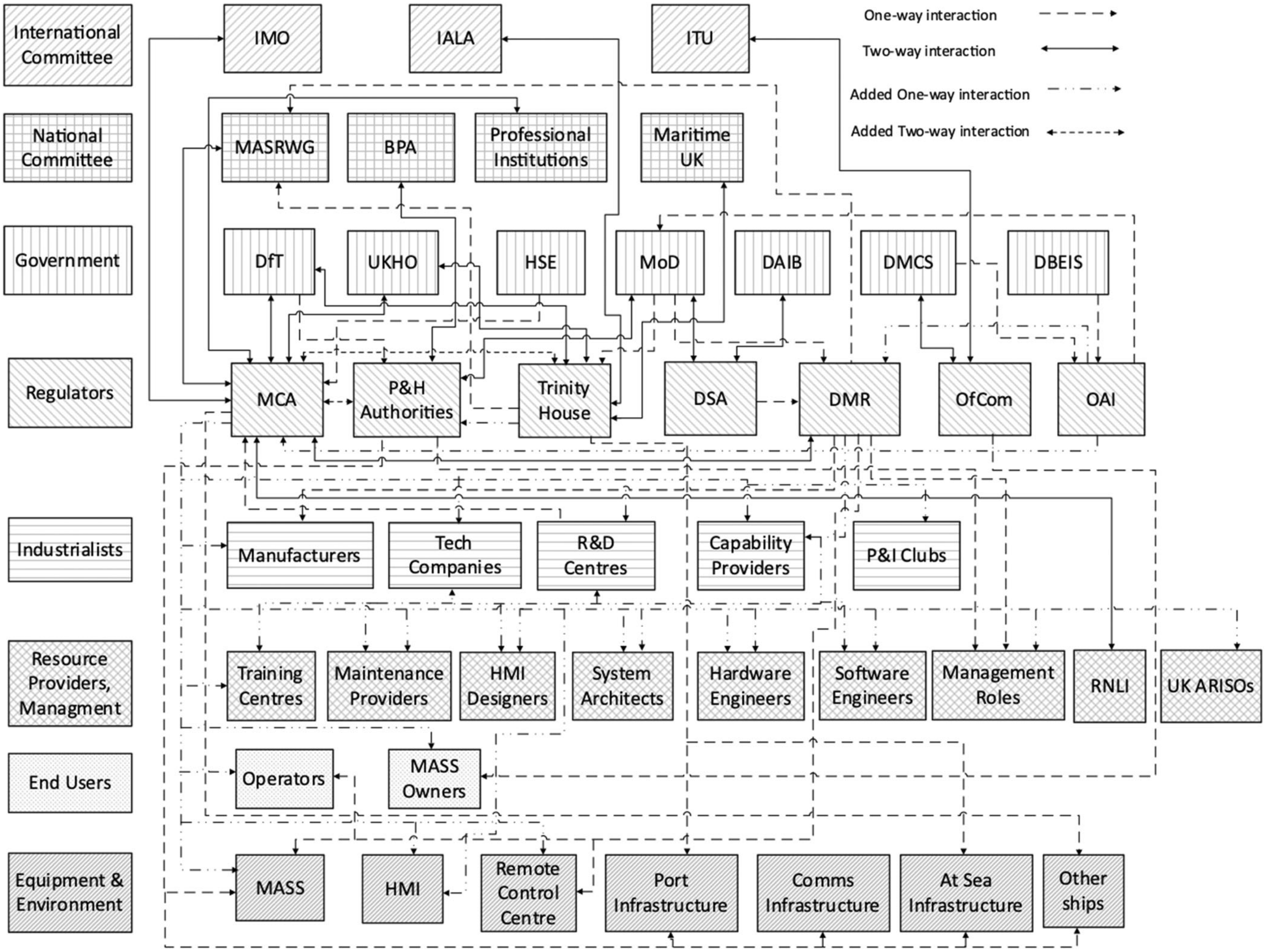

**FIGURE A.5** Social network showing the regulators nodes' connections within the current and future Maritime Autonomous Surface Ships (MASS) social networks developed.

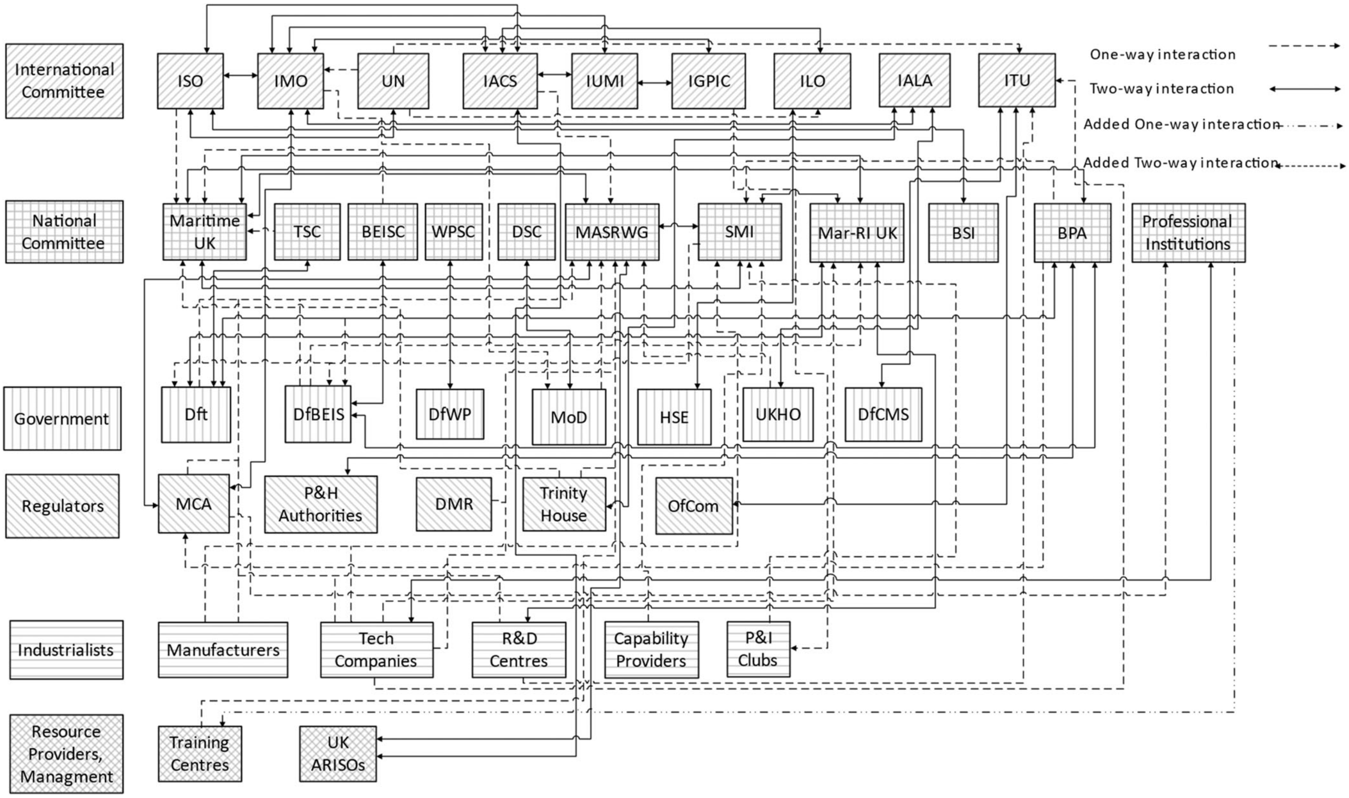

**FIGURE A.6** Social network showing the industry nodes' connections within the current and future Maritime Autonomous Surface Ships (MASS) social networks developed.

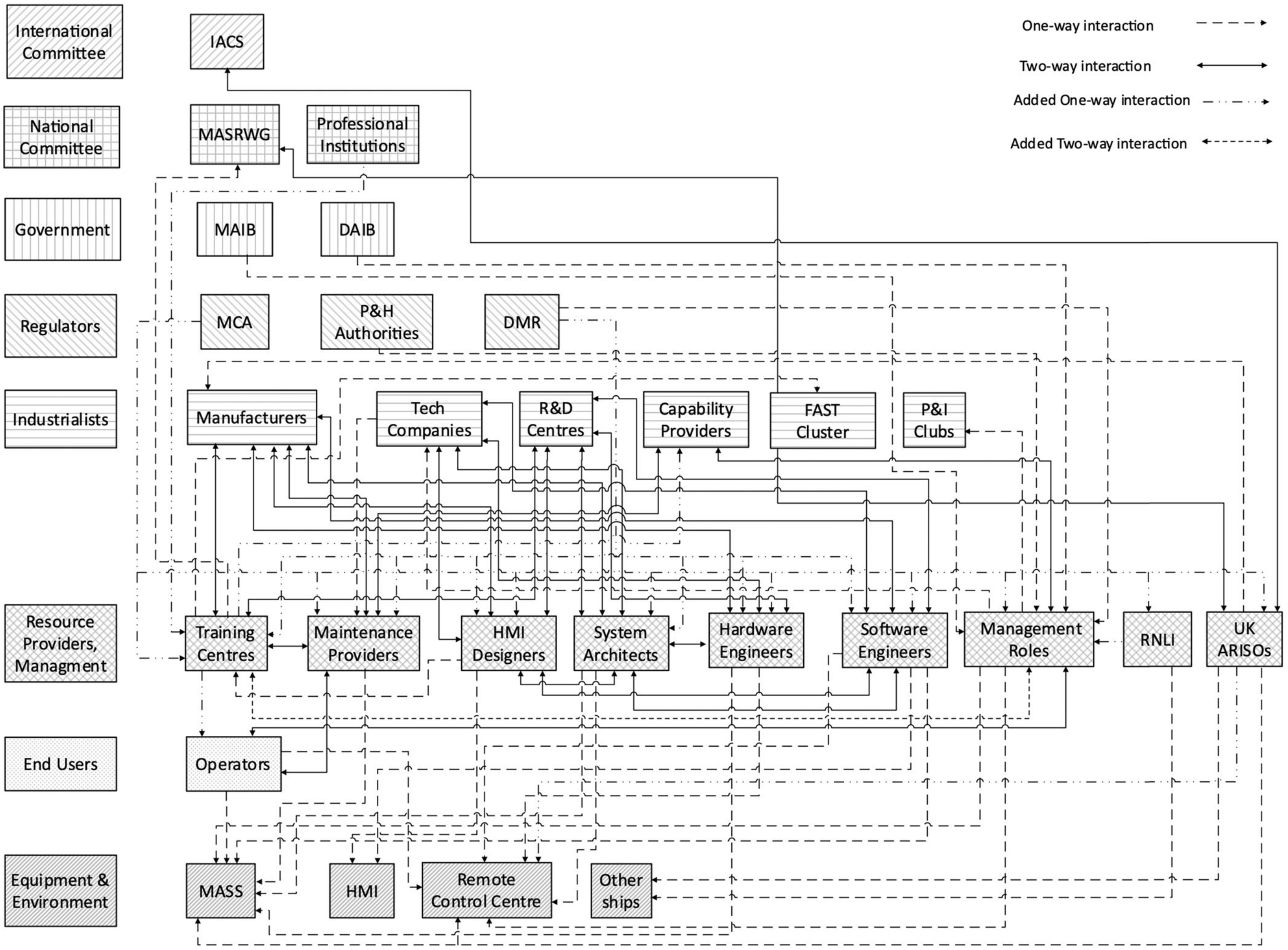

**FIGURE A.7** Social network showing the resource providers nodes' connections within the current and future Maritime Autonomous Surface Ships (MASS) social networks developed.

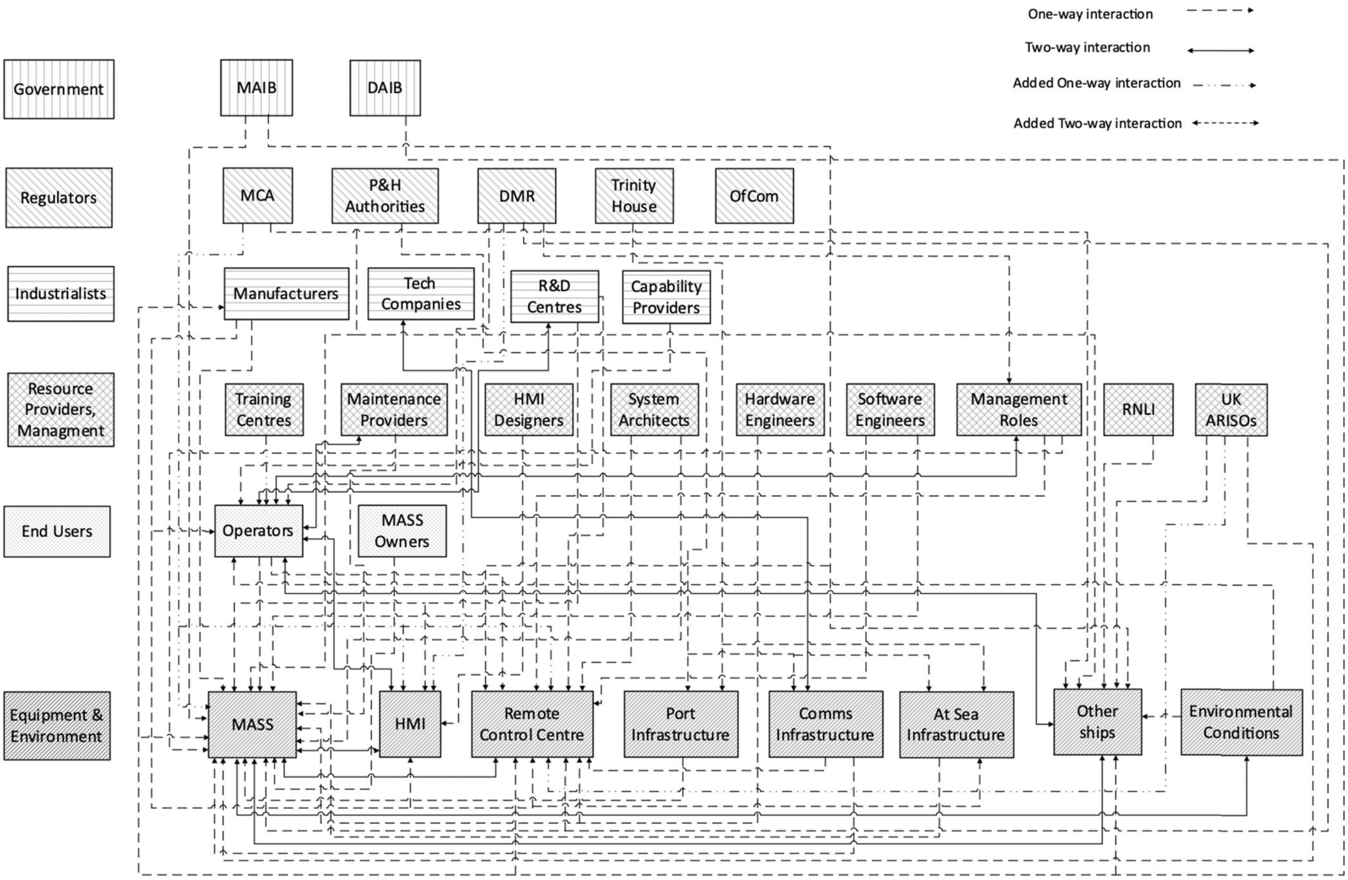

**FIGURE A.8** Social network showing the end-users and equipment and environment nodes' connections within the current and future Maritime Autonomous Surface Ships (MASS) social network developed.