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ARTICLE

A systemic review of shipboard SCR installations in practice

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Abstract Growing customer demands and more stringent regulations to reduce harmful air emissions from ships have resulted in an increased interest for the installation of shipboard abatement technologies. Specifically, the selective catalytic reduction (SCR) technology to reduce emissions of nitrogen oxides (NO_x) was early adopted by several Swedish shipping companies. The potential NO_x reduction efficiency of the SCR is well established, but the practical experiences of shipboard installations have been less documented. This paper reviews from a systems perspective the practical experiences of marine SCR installations in Swedish shipping. The aim is to identify important not only technical but also human and organizational conditions necessary for safe, efficient, and sustainable SCR operations at sea. Further, to investigate to what extent the capabilities and limitations of human operators and maintainers are taken into account in the design and installation phase of the systems. Two focus group interviews ($n=10$) and five individual interviews were held with relevant stakeholders in the industry, following a semi-structured schedule on the themes installation, operation, maintenance, and training. The results show that deficiencies in the overall system design—with a combination of technical issues, maintenance access problems, and untrained operators with inadequate understanding of the SCR process—have led to inefficient, costly, and unsafe operations. It is concluded that installations and operations of marine SCR systems, and possibly other forthcoming abatement technologies, would benefit from the use of traditional ergonomic principles and methods. This would in turn contribute towards increased sustainability and a reduced environmental impact from shipping.

Keywords Human–machine system · Human element · Selective catalytic reduction · Revised MARPOL Annex VI · NO_x

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Abbreviations

ECA	Emission control area
IMO	International Maritime Organization
MARPOL	The International Convention for the Prevention of Pollution from Ships
NO_x	Nitrogen oxides
SCR	Selective catalytic reduction

1 Introduction

Growing awareness of environmental implications by global shipping activities has given rise to an increased focus on strategies for safe, efficient, and sustainable sea transports (IMO 2011b; OCIMF 2012; INTERCARGO 2012). Great emphasis is accorded to safety at sea, in terms of prevention of human injury or loss of life and damage to the marine environment or property (IMO 2002), and efficiency, in balancing utilized resources (e.g. financial, time, human, or material) against accomplished goals (Stopford 2009; Kreitner 2009). Sustainability encompasses all this and more, requiring the reconciliation of environmental, social equity, and economic demands (WCED 1987). Using the framework proposed in Cabezas-Basurko et al. (2008), sustainable sea transports can be seen as "a cost-effective commercial activity, in which the environmental load is not bigger than that which the environment can currently and in the future bear, and that the social community (directly and indirectly) in contact with it is not being negatively affected".

Measures to reduce the marine pollution to air include the development and implementation of various regional and supranational incentives towards the abatement of emissions of nitrogen oxides (NO_x). NO_x is known to have an impact on the natural environment, such as eutrophication and acidification at land and sea (Pleijel 2009), and on the public health, primarily through ground-level ozone and secondary particulate matters (HELCOM 2012; AEA 2009).

The differentiated fairway dues in Sweden and the NO_x fund in Norway are two examples of regional incentives. The environmentally differentiated fairway dues based on vessel size and emitted NO_x were introduced by the Swedish Maritime Administration in 1998 (SJÖFS 1998:13). The reduced fairway due is given upon the condition that an emission measurement report, conducted by an accredited measurement institute, is provided to the Administration every third year. The Norwegian NO_x fund was set up in 2007 as a non-profit cooperative effort (NMD 2007). The participant enterprises are exempted from the NO_x tax, while instead obligated to pay a NO_x fee to a fund, from which they can apply for economical support for installation and operation of NO_x abatement technology (NHO 2011).

Although not legally mandatory, these incentives have encouraged installations of NO_x abatement technology on numerous merchant vessels, independent of age; primarily in the short sea shipping sector with frequent port calls in Swedish and Norwegian waters. But more stringent legislation is ahead on a supranational level that is likely to have a great impact on the global shipping community. Most notably, tier III in the revised convention of marine pollution (MARPOL) Annex VI imply an approximately 80 % reduction of NO_x compared with today's engines (IMO 2009). On January 1, 2016, tier III enters into force in designated emission control areas

(ECA) for all new buildings and vessels undergoing a major conversion. This will give rise to an increased demand on NO_x abatement technology suitable for marine installations with its harsh environment and strict demands on limited space for the installation. However, in 2011 at IMO MEPC 62, it was decided to establish a correspondence group to review the status of the technological developments to implement the tier III NO_x emissions standards (IMO 2011a). The review is to be completed not later than 2013.

There are several different NO_x abatement technologies available on the market, including internal engine modifications, exhaust gas recirculation, direct water injection, humid air motor, and selective catalytic reduction (Entec 2005). However, not all technologies are able to reach tier III by themselves; some must be used in combination with other technologies. Currently, selective catalytic reduction (SCR) is considered one of the most effective technologies on the market that single-handedly can meet tier III (Entec 2005; Lövblad and Fridell 2006; IMO 2012). During the last 15–20 years, SCR has been extensively investigated for reduction of NO_x from land-based heavy-duty vehicles (see, for instance, Heck and Farrauto 1995; Pârvulescu et al. 1998; Koebel et al. 2000; Gabrielsson 2004). Research and application of marine SCR installations have, however, remained sparse throughout the years, possibly due to the lack of legal requirements or other incentives. Further, preceding research and development activities have primarily focused on technical aspects and engineering principles. The human and organizational elements within the system have largely been disregarded.

The advent of mechanization, automation, and communication technology made many manual tasks redundant, turning the human operator into a supervisor, rather than a controller of technical systems. Thus, the operators have moved "out of the loop", intervening within the control loop primarily for abnormal situations (Sheridan 2006; Norman 1990). Out-of-the-loop performance problems are related to the loss of manual skills and an impaired awareness of the systems' state and processes (Endsley and Kiris 1995). As technical systems increase in complexity, the gap between the human operator and the machine tends to increase as well. It is difficult for the operators to understand what the technical systems actually do and how to correctly detect and assess problems. This gap between human and machine has caused errors, incidents, and accidents affecting safety and efficiency of operations in several domains, including the maritime (Lee 2006; Reason 1990).

Contemporary SCR units are highly automated, but in order to ensure effective catalytic NO_x reduction, there are still several important technical parameters to monitor and control during operation, such as exhaust gas temperature and flow, urea injection and back pressure. Certainly, safe and efficient operation and maintenance pose demands on the level of knowledge, skills and competence of the crew as operators and supervisors of the SCR. But, responsibilities can also be found on management level. In the installation phase, when ordering and designing an SCR unit, the management is responsible for ensuring that relevant operational requirements are identified and met. During operations and maintenance, the allocation of adequate resources such as personnel, time, and materials may be considered.

1.1 Aim and purpose

The present paper draws from the practical experiences of the pioneering SCR installations in Swedish short sea shipping. The purpose is to explore the human–machine aspects of SCR installations from a systems perspective. The aim is to identify important not only technical, but also human and organizational conditions necessary for safe, efficient, and sustainable SCR operations. Further, to investigate to what extent the capabilities and limitations of human operators and maintainers are taken into account in the design and installation phase of the systems.

2 Research design

Due to the scarcity of previous research in the problem domain, an explorative, qualitative research design was adopted. For the purpose of data completeness and, to a lesser extent, confirmation of data, a combination of focus group interviews and individual interviews was used (Lambert and Loiselle 2008). This combination of data collection methods allowed us to elicit rich, detailed information on practical experiences of marine SCR installations. In order to enable as broad an understanding of the topic as possible, data collection was made from a range of stakeholder participants representing different interests and views. All interviews were held in Swedish and the translation of quotes in this paper is made by the authors.

2.1 Focus group interviews

Focus group interviews are usually characterized by five elements: they involve (1) a group of people, composed of (2) participants with certain features important to the researcher, that (3) solicits qualitative data in a (4) carefully planned focused discussion, in order to (5) gain understanding of the chosen topic through the eyes of the target audience (Krueger and Casey 2009). The group dynamics and interaction that occur in focus group interviews are a vital part of the method, using the communication between research participants to generate data. Instead of a researcher asking individuals to respond to a series of questions in turn, the participants are encouraged to, in their own vocabulary, ask each other questions, narrate anecdotes, and comment on each other's experiences and points of view (Krueger and Casey 2009). Focus group interviews are particularly useful for exploring participants' knowledge and experiences, probing not only *what* people think but *how* they think and *why* they think that way (Kitzinger 1995).

Two focus group interviews were held ($n=10$) with top or middle managers recruited on the basis of their anticipated first-hand knowledge and experiences of SCR catalysts. The participants represented two different SCR manufacturers, one in each focus group, and six Swedish shipping companies that have installed SCR catalysts during the past 15 years, holding a valid NO_x certificate issued by the Swedish Maritime Administration (SJÖFS 1998:13). Together, the shipping companies represented the segments of liquid bulk, roll on/roll off, passenger, and offshore supply vessels.

The two focus groups were moderated by the same, professional moderator with extensive knowledge on the features and routines of the shipping industry, but purposely less versed in the technical details surrounding SCR units. Thus, the moderator had the advantage of being able to instill a sense of mutual respect within the groups and communicate in a shared vocabulary but still be emotionally detached from the topic of the study (Krueger and Casey 2009). The authors of this paper acted as listeners, observers, and analysts.

Both focus groups followed the same semi-structured interview guide with predominantly open-ended questions about SCR installations on the three themes of the following:

(1) installation; newbuilding and retrofit, decision making, stakeholder communication;
(2) operation, service and maintenance; usability, accessibility, manuals, support, outage, costs; and
(3) knowledge and training; before and after installation, knowledge transfer.

The guide was developed through considerable reflection by the researchers, in collaboration with the moderator. Each focus group interview lasted for approximately 90 min and were video- and audio-recorded for transcript and analysis. The focus groups concluded with the participants anonymously answering a structured questionnaire to assess if the group discussions had succeeded in capturing the most important practical experiences on the three themes, respectively, whether the participants felt that they had the opportunity to express their opinion, and the potential usefulness of the discussions to the participants.

2.2 Semi-structured qualitative interviews

Individual interview is a frequently used data collection method in qualitative research and is typically chosen to gather comprehensive accounts of attitudes, views, and knowledge regarding a given topic. Kvale (1997) describes the qualitative research interview as a conversation with a structure and a purpose, aiming for insights and new understandings. The knowledge process in an interview is an interactive process between interviewer and interviewee. Hence, it is important to check continuously that the interpretation of the said is accepted by the informant. By using semi-structured interviews, it is feasible to compare the answers from several interviews and, to some extent, make some generalizations.

Five individual, semi-structured interviews were held, using the same thematic interview guide as the focus group interviews, but allowing for flexibility to probe for details or further discuss issues. Additional questions were asked and answers probed on an individual basis during the interviews. The informants were not randomly selected, but chosen among specific stakeholders with experiences considered relevant by the researchers. The informants were recruited from the Environment and Sustainability unit at the Swedish Shipowners' Association; the Transport Policy and International Cooperation unit at the Swedish Maritime Administration; a senior technical manager at a leading marine mutual insurer; an expert consultant with a large buyer of dry cargo transport; and a vetting coordinator at an oil company. The interviews lasted for approximately 1 h and were audio-recorded for transcript and analysis.

2.3 Data analysis

In qualitative research, the dividing line between data collection and data analysis can be vague, and there are few well-established and generally accepted rules for analysis (Bryman and Bell 2007). Rather than being a distinct activity following the data collection, qualitative data analysis occur continuously in a dynamic interplay, shaping the next phase of data collection by developing new routes of inquiry and refining questions (Krueger and Casey 2009). The analyzing and interpreting of data can be described as a process to bring structure, order, and meaning to the data, in short—making sense of the data. The central elements of analysis in this work is guided by the strategies described by Mays and Pope (1995) and include transcription of audio and video recordings and an iterative systematization, categorization, and recombining of data to look for meanings and causes.

3 Adopting a systems perspective on marine SCR installations

The following section introduces the theoretical framework behind the systems perspective adopted for analysis in this study followed by some necessary introductory knowledge on the basic functions of a typical marine SCR installation.

3.1 Systems thinking and sociotechnical systems

Systems thinking constitute an established analytical view of organizations as complex systems made up of interrelated parts coordinated to achieve certain goals and most usefully studied as a whole. Blanchard and Fabrycky (2006) describe the elements of a system as follows:

1. Components are the operating parts of a system and consist of input, process, and output.
2. Attributes are the properties of the components that characterize the system.
3. Relationships are the links between components and attributes.

In the words of the influential philosopher of the systems movement, West Churchman (1968):

> How can we design improvement in large systems without understanding the whole system, and if the answer is that we cannot, how is it possible to understand the whole system?

Churchman claimed that, rather than knowing all there is to know about a studied system, it is important to understand the possible implications of our lack of comprehensive knowledge. It is because we never know enough that understanding and critical judgment become essential, from an intellectual as well as a moral point of view.

Apart from the technical artifacts, human actors and the social infrastructure are essential for the functionality of the system as a whole, aptly described in the concept of sociotechnical systems (Emery and Trist 1960). Humans are present in all work systems, as inventors, designers, users, operators, maintainers, and so forth. Even a highly automated system requires people—if there is nothing else to start, stop, and monitor the system. Often, users and operators also perform service and maintenance on machinery and equipment in the system. Unlike the other components in the system, the human actors are free to act and often complete the feedback loop between system performance and system goal; they correct system failures (Hughes 1987). A sociotechnical system refers to the interdependency of social and technical aspects in a system. The starting point is a perceived lack of mutual understanding of the technical society in which engineers allegedly ignore the social concerns of their work, and social scientists ignore technology. In this respect, a systems model can be a tool to bring both sides together and portray both social and technical phenomena; the "technization" of society and the socialization of technology (Ropohl 1999). The benefits of a sociotechnical system that is designed to take the operators abilities and limitations into account include reduced learning time for new equipment, fewer incidents, and accidents related to misuse or misunderstandings, and reduced risk for musculoskeletal disorders among users.

3.2 Selective catalytic reduction

The SCR technology is based on the selective reaction between ammonia and NO_x in the exhaust gas over a base metal catalyst, where NO_x is reduced into elemental nitrogen (Heck and Farrauto 1995):

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$

$$4NH_3 + 2NO_2 + O_2 \rightarrow 3N_2 + 6H_2O.$$

The main functions of SCR for marine applications involve the injection of a urea solution in the hot exhaust gasses upstream the catalytic converter (catalyst), which thermally decomposes to ammonia and reacts with NO_x to form nitrogen and water over a base metal catalyst containing vanadium oxide.

However, under normal pressure and temperatures, ammonia is a highly volatile gas; hence, the use of urea, as a reducing agent, is favored. When heated, urea decomposes into ammonia and isocyanic acid where the acid in the presence of water is further decomposed over the catalyst into ammonia and carbon dioxide (Lundström 2010). The ideal thermal decomposition process of 1 mol of urea gives 2 mol of ammonia and 1 mol of carbon dioxide (Koebel et al. 2000):

$$NH_2 - CO - NH_{2\,(solid)} \rightarrow NH_{3\,(gas)} + HNCO_{(gas)}$$

$$HNCO_{(gas)} + H_2O_{(gas)} \rightarrow NH_{3\,(gas)} + CO_{2\,(gas)}.$$

Further, the choice of base metal in the catalyst is dependent on the operating temperature, where a vanadium-based catalyst works well in the temperature range of 260–450 °C (Heck and Farrauto 1995). It is therefore commonly used in catalysts for automotive diesel engines (Koebel et al. 2000) but also for marine applications

(Lövblad and Fridell 2006) with a reported catalytic NO_x reduction efficiency of 90 % (Entec 2005).

However, almost all catalytic materials decay in activity with time where three major factors are sintering (loss of surface area), attrition (powdering of catalyst, blocking reactor, reducing gas flow), and poisoning (loss of catalytic activity per unit area), respectively (Bowker 1998). An important deactivation mechanism for an SCR catalyst operating downstream a diesel engine, in the presence of ammonium, sulfur, and water, is the formation of ammonium sulfates which may result in pore blocking and related catalytic deactivation (Huang et al. 2002, 2003; Zhu et al. 2001; Kijlstra et al. 1996).

Furthermore, the catalytic NO_x reduction efficiency is also dependent upon the space velocity, which is calculated by dividing the exhaust gas flow (in cubic meters per hour) with the catalyst volume (in cubic meters) (Heck and Farrauto 1995). It has been showed that an increased space velocity over a vanadium-based catalyst may lead to increased deactivation, and Huang et al. (2002) suggest that the deactivation could be reduced by a decreased space velocity.

Evidently, the SCR installation includes several technical components which have to be carefully designed in order to work as a well-integrated NO_x reducing system. An example of a typical SCR installation according to DEC Marine AB (2011) is illustrated in Fig. 1.

4 Results

The two focus groups and the five individual interviews elicited rich and varied accounts of practical experiences of SCR installations on a management level. Below is a distilled version of the findings from the focus groups and the interviews, respectively, structured on the themes of the interview guide: installation, operation, service and maintenance, and knowledge and training. The following are the results of the focus group questionnaires.

4.1 Installation of marine SCR catalysts

On the theme of installation of SCR catalysts, the data were sub-divided in the segments of motives for installation, choosing a supplier, and decision-making structures.

4.1.1 Motives for installation

Two clear motives for an SCR installation, either a retrofit on an existing vessel or a newbuilding, emerge: corporate environmental image and commercial benefits. A main driving force has been meeting customer or cargo owner's demands for NO_x abatement technology. In some cases, the cargo owner has even funded the initial SCR installation, while others, depending on charterparty, compensate for the urea.

In an individual interview, a representative for an oil company believes that the cargo owners are a significant driving force:

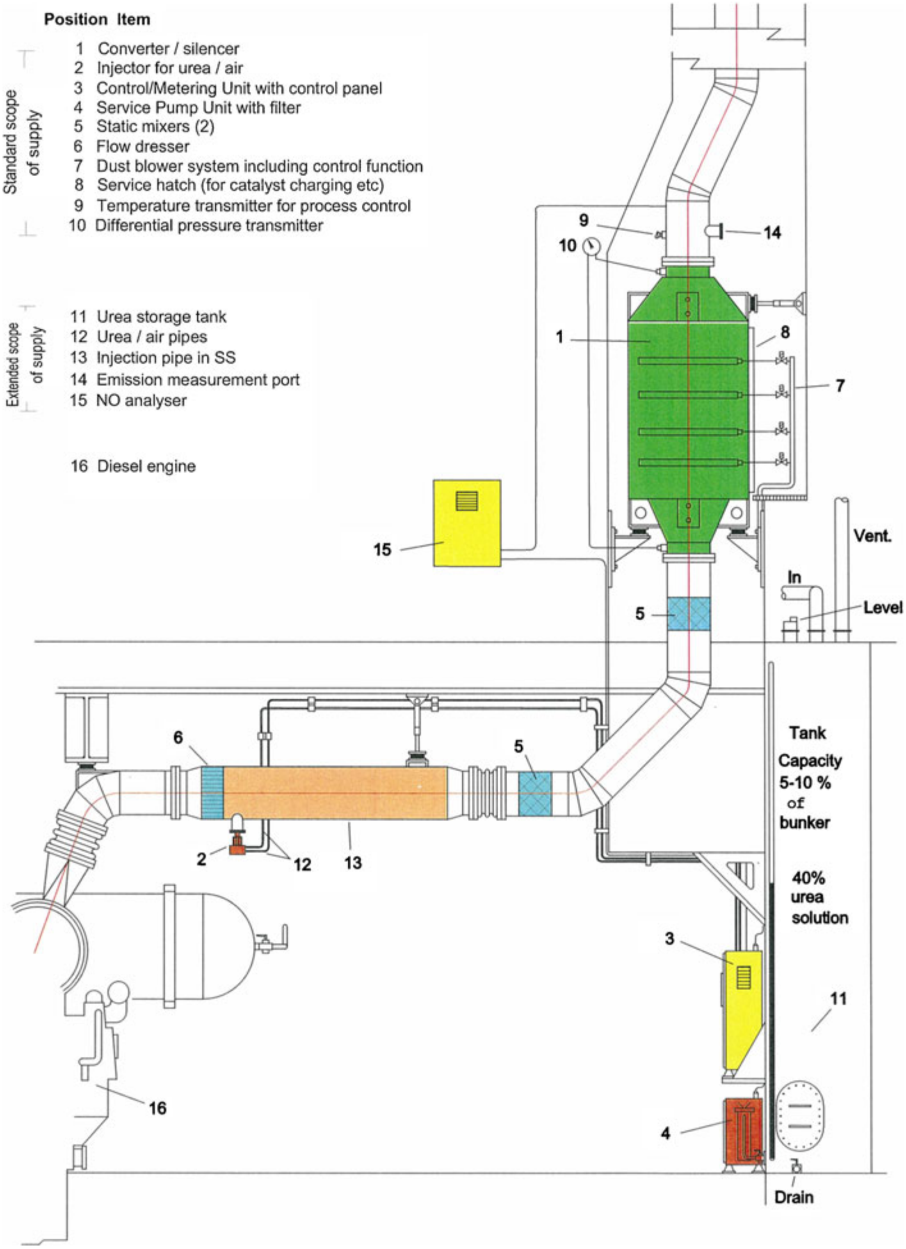

Fig. 1 An example of a typical marine SCR installation according to DEC Marine AB. Used with permission from DEC Marine AB 2011

> Frankly, I do not think any of the shipowners [that they have contracted] would have installed any kind of exhaust gas cleaning unless we had put it forward as a direct demand.

The commercial benefits such as environmentally differentiated fairway dues and port fees have been effective principally within the RoPax sector (vessels built for both wheeled cargo and passenger transport), with multiple port calls every day and vessels that spend a lot of time in the fairway. According to a project manager on a RoPax company, the investment in SCR catalysts on two RoPax vessels had a pay-back time in just over 2 years. In one focus group, the informants representing two different tanker companies, however, claimed that the differentiated fairway dues made little or no difference for them:

> Well, you can never get the money back [for the installation]. It is only a cost. Yes, I agree. Unless you get paid on TC [time charter] or traffic, for example, the Norwegian coast all the time, there are no incentives what so ever to install this type of equipment if you do not have a company policy for the environment and are ready to take this cost, because you will never get the investment cost back during the prevailing market, as it is now.

The tanker owners both continue to describe how they try to market the added value to brokers and oil companies, but although there is a candid interest in environment issues, it is difficult to get the customers to, in fact, pay extra for the NO_x abatement. Conversely, in the individual interview the oil company representative states that they require all ships on time charter for them to be equipped with NO_x abatement technology. They as charterers pay for the urea consumption and the costs for installation of SCR are supposedly compensated for in the contract. Likewise, an informant with offshore supply vessels in their fleet added that having SCR on board had been crucial when receiving a contract for work in Alaska.

This limited interest in differentiated fairway dues has also been noted by the Swedish Maritime Administration that recently has seen a declining number of applications for renewing NO_x certificates.

4.1.2 Choosing an SCR supplier

Generally, for both a retrofit and newbuilding installation, the price is the prime consideration and the second is how flexible and adaptable the system is to the vessel.

For a retrofit installation on an existing vessel, the informants have mainly used references from other shipping companies on which SCR supplier to choose, some-times also in communication with the engine maker. Though, limited space is always an issue, and the installation can be even further complicated if the vessel was not built prepared for SCR at an initial design phase.

Conversely, a newbuilding installation is considered to be rather easy and the SCR supplier is generally chosen from the "makers list" presented by the shipyard, as of other equipment and machinery. This was especially the view of the two participating SCR suppliers, who said that they mostly engage with the shipyards as customers rather than the shipowners directly as is the case for a retrofit. But, several informants argued that quality and functionality of the installation depends on the shipyard and the relation between the yard and the shipowner. One informant described a case where they as shipowners had a longstanding relationship with a yard they considered to have good technical competence:

> … basically, we just told them [the yard] which SCR we wanted and then we did not have anything to do with it until we started it up to check that it worked. […] If we had made this installation somewhere else we would have done it in cooperation with the maker in an entirely different way, but here there was no reason. They took care of it brilliantly.

Another informant described a similar scenario:

> … the problem is, I mean, you have your makers list, but if you do not go down and specify what you want, it is a bit of a lottery. The primary is not that the system works, but … as long as the pieces are there, some yards reckon you will just slide out of the claims period and then the owner has to take the costs to make the systems actually work.

4.1.3 Decision making

The decision making regarding SCR installations is predominantly made on top management level in the shore organization. As described earlier, the decision can be more or less prompted by the customer or cargo owner who, in some cases. also has been deeply involved in the process, both financially and technically. The end-users—the crew on board—are however rarely involved.

> …the crew have not worked with catalysts before at all, they have no knowledge of it, so we at the office take care of the tenders… in the end we hand over the papers to the purchasing manager to negotiate the last per cent.

In one case, however, the crew have played a significant part in the process. On a vessel with one of the first marine SCR installations in Sweden, done in the mid-1990s, the recent process for replacing the old SCR with a new system was managed largely by the crew. One of the focus groups had participants from both supplier and company, one of them working as chief engineer on the vessel. Here, years of trouble-shooting and efforts to operate the old, regularly malfunctioning SCR system had led to a somewhat personal relationship between the supplier and crew.

4.2 Operation, service, and maintenance

On the theme of operation, service, and maintenance of SCR catalysts, the data were sub-divided in the segments of urea supply and quality (an area evidently of great interest for most informants), technical design issues, operation and operational disturbances, and service and maintenance.

4.2.1 Urea supply and quality

The supply and quality of urea prompted many discussions in both focus groups, and the subject was also given ample attention in the individual interviews. Good urea quality was considered essential for a well-functioning SCR system, generally, the more expensive, the better the quality. The informants with RoPax vessels operating in the Baltic Sea reported no problems with either quality or supply, probably due to the nature of the traffic enabling them to have standing orders of urea and keep own depots.

But, informants with vessels with other port calls and vessels trading on the spot market reported numerous problems with both supply and quality, especially in ports outside northern Europe. Since urea deliveries commonly are made by truck from Sweden, the order must be placed in time. For vessels on the spot market this can turn into a proper logistics challenge with orders being placed based on an educated guess, trucks having to be rerouted to other ports, or canceled. Moreover, this has also led to a discussion on how these transports affect the environment and if, in the end, it can be justified from a life-cycle perspective. One informant said that under circumstances such as these, they opt not to operate the SCR.

On several occasions, vessels have received urea that was believed to be destined for agricultural use, resulting in severe operation disturbances. In an individual interview, an expert consultant with a dry cargo owner describes how they have encountered numerous problems due to poor urea quality. In one example, the vessel was in service for only 60 h before the catalytic blocks were completely clogged and had to be renewed.

4.2.2 Technical design issues

In any marine SCR installation, the space requirements are kept to an absolute minimum to ensure maximum cargo carrying capacity. As noted earlier, the restricted space is especially apparent in retrofitting, and several cases of conscious sub-optimizations of the SCR installation were described. For example, an insufficient exhaust pipe diameter, causing high gas velocities, in connection to an insufficient distance between the urea injectors and the catalyst, would not allow for a homogeneous mixture of urea and exhaust gas, hence resulting in a reduced overall SCR efficiency and the accompanied difficulties to achieve the NO_x emission targets. In another installation, it was perceived that the supplier had positioned the urea injector rather haphazardly without giving much thought to the above.

> We have seen that it is important where you put the catalyst. It can cause problem with the exhaust gas temperature, among other things, with too big a distance between. It amounts to pretty large costs when you have installed the system if you then have to rebuild it again and then the economists start talking—should we really go with this, is it worth it?

The operational temperature of the SCR is not reached as quickly as the exhaust gas temperature. Especially for ships passing through areas with speed limititions, such as the archipelago, it may take a long time to reach the working temperature adequate for NO_x reduction. Furthermore, the low engine load may lead to accumulation of soot and particles from the exhaust gas on the catalytic blocks, which then become deactivated. In cases like these, pre-warming of the SCR is necessary, but that in turn leads to increased emissions of carbon dioxide.

Early SCR systems were claimed to be poorly adapted to the harsh marine environment, considering vibrations and exhaust gas composition and soot due to the type of fuel and lubrication oil commonly used. An example of which were the early onboard NO_x measurement devices:

> These NO_x analysers, they are also something taken from ashore. Having such a system up in the funnel with hoses and filters and air… it is far from optimum.

More recent SCR installations are however perceived as being better adapted in that respect. In one case, it is described how the installation of SCR systems on main and auxiliary engines even contributed to lower noise levels, a circumstance appreciated by both engine crew and the ports.

4.2.3 Operation and operational disturbances

It was noted during the focus groups and individual interviews that many informants initially said to have no problems with the SCR and that it supposedly is a very easy system to operate.

> It works very well, in principle you push a button and then you don't do anything but fill urea.

However, as time passed during the discussions and interviews, plenty of complications began to surface with technical components such as urea injectors, air blowers, and urea dosing. Yet, the same informant was still very satisfied with the operation, revealing tremendous patience:

> … it has been 2.5 years now and it has worked without, well I believe this injector nozzle fell off and broke once and then nothing worked, and some air blowing jets have broken, but those are small things. The functionality has been, I mean it runs 100 per cent, except when it shuts down by itself.

Further, it became clear that the chemical process of the SCR is not well known. Several of the informants gave evidence to the complexity of the SCR system, picking up the term "hocus-pocus" from an earlier similar statement from another informant in the same focus group:

> … as long as it works, there are no questions asked, but when you are in deep water—asking what is happening, why is it not working? I have experienced from both supplier and from our own crew and technical management ashore that it is a bit of 'hocus-pocus', one is guessing, are not really sure—should we test another type of stones [the metal catalysts]?, and so on. In principle, the definitive answer does not exist.

The functionality of the SCR is verified officially through the mandatory NO_x certification measurement every third year (SJÖFS 1998:13) for those vessels that have been granted reduced fairway dues. Some shipping companies have opted to measure more often while others have no extra monitoring in between these measurements, thus having no control of the functionality of the SCR and the related NO_x reduction over the intermediate time period of 3 years. On the whole, the measurement of NO_x and ammonium slip was regarded as costly and cumbersome, especially concerning the time it takes to get the results. As much as 3–4 weeks have been known to lapse between measurement and report, and if the result is not good, the measurement has to be redone.

4.2.4 Service and maintenance

The lack of space for the installation obviously affects accessibility for maintenance and service tasks. The system includes a number of parts that need to be changed and filters to be cleaned regularly, and this was not always well accommodated for in the design and installation phase. When the catalyst stones need to be changed, this is done by opening special hatches. Several layers of cassettes of old stones weighing 25–30 kg are removed and new ones put in place, sometimes through a barely 50-cm-wide opening. This hazardous task involves heavy lifting, turning of the body with a heavy load, and the assuming of awkward body postures with apparent risk for acute and/or long-term musculoskeletal disorders. Two of the informants had experienced occupational health and safety incidents during maintenance work. In one case, four people were hospitalized due to respiratory problems after changing contaminated stones without protective equipment. In the other incident, a large steel plate came loose inside the SCR and nearly hit a welder, missing his head by a few centimeters.

Service instructions and intervals are recorded in typical service manuals. These are, however, not always written in such a clear and precise manner as the crew would have wanted. While, on the other hand, the suppliers argue that the manuals are indeed written for readers assumed to have a certain pre-understanding of technical and electrical matters. On a RoPax ferry, the crew arranged for the service manual to be updated after 2 years of operation since they thought the instructions were "poorly described".

Although the interviews contained a number of stories ranging from minor operational failures to severe breakdowns, none of the informants had ever made a claim to the insurance company. Nor had the informant working as senior manager at a marine insurer heard of any such claims. The reasons for this can be found in the large deductible (ranging from US$ 75,000 to 200,000) and the need for the incident leading up to the potential claim to be a sudden and unexpected event. Hitherto, all costs associated with these failures and breakdowns, primarily for equipment and working hours, have therefore been carried by the owner, sometimes together with a cargo owner. The extra costs for overuse of urea due to mismanagement and/or poor tuning of the SCR are carried by the owner or cargo owner depending on charterparty.

Examples were also given on long delivery times for spare parts. In one extreme case, the SCR was inoperable for 9 months, while the vessel had to wait for delivery of new stones.

4.3 Knowledge and training

Just as the operational problems developed from none to several during the interviews, a similar pattern was noted regarding the need for knowledge and training. Initially, it was unanimously stated that the SCR is not a system that requires any extra training or knowledge. A vessel contains hundreds of systems with the SCR being just one of them, and the crew is expected to be able to operate the SCR on the basis of their previous engineering experiences. In addition, since the SCR is not a safety critical system it is not prioritized for special training.

> … the vessel moves just as well from A to B without it. So, I believe it takes some sort of interest and engagement from the people on board, like the chief engineer; otherwise it is easier to shut it down, then you don't even have small problem. It is not like a main engine. A malfunctioning main engine—that is a huge problem you have to solve. If the SCR is not working, well it is just as well.

Further, since a shipping company has at least two, sometimes three, persons employed for each position on board, it is regarded too costly to educate every operator, including costs such as salary and subsistence allowance. After the initial installation, the supplier usually instructs the operators that are on board at the time. The crew are therefore supposed to educate and transfer the knowledge to each other.

Nevertheless, during the interviews, a number of examples on arrangements of extra training were reported. One company had even engaged a researcher specializing in combustion technology to give lectures to all engine officers on board:

> … we had all engine officers on board there, to give them an understanding for what happens. No one can explain the catalytic process, it is just there, we have to accept that, but what happens when you inject urea and what it takes to make it work and all that, temperatures and such. That, I think is well appreciated. Then perhaps you get another understanding for how the process works. […] One needs to have an understanding of what you are doing, because this is nothing you study at the merchant marine academy.

The same informant continued to describe how they afterwards "kicked out" the SCR supplier since they now felt that they had more knowledge than the supplier who could not contribute to the solution of the operational disturbances they experienced.

Both suppliers, on the other hand, expressed a clear interest in operator training. It was stated by one of the suppliers that they do not consider the SCR installation to be a complete delivery until they have ensured that a knowledge structure among the crew is in place. At least one person on board should have specific knowledge on how to operate the SCR.

> I know that I can avoid a dreadful amount of telephone calls to me as supplier if I know that at least one person knows enough.

Among the cargo owners, there was no distinct request for training; rather, it was taken for granted that the crew had adequate knowledge and training to ensure safe operation of all systems on board, including the SCR. The external expert with the dry cargo owner had once, however, participated in a project with a shipowner in creating generic guidelines for SCR operation that had been communicated to various stakeholders, among others the Swedish Maritime Administration.

4.4 Results of the structured questionnaire

The six questions in the structured questionnaire aimed to assess if the group discussions had succeeded in capturing the most important practical experiences on the three themes, respectively, and the potential usefulness of the discussions. On the questionnaire, it was also possible to leave individual statements. This was done by seven out of ten participants.

Overall, the participants in both focus group interviews considered it rewarding to participate (Fig. 2). Individual statements indicate the significance of having these meetings physically, face-to-face. One participant wanted more time for discussion, another more stakeholders, and a third wanted to exclude the SCR suppliers, thus potentially opening up the discussions further.

According to the questionnaire responses (Fig. 2), the participants felt that the focus group discussions succeeded well in capturing the most important practical SCR experiences regarding installation; operation, service, and maintenance; and knowledge and training. All participants also said that they had learned something from the discussions.

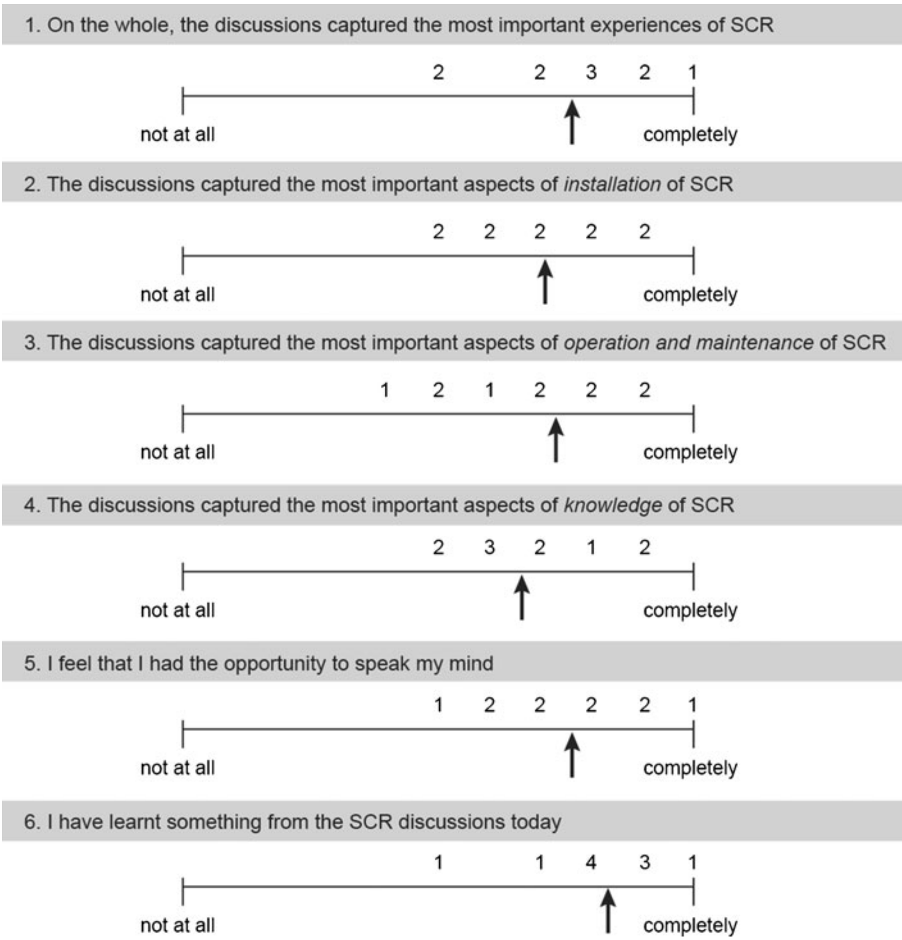

Fig. 2 Results from the questionnaires answered after the two focus groups. Rating values and median values (indicated with an *arrow*) from ten participants

5 Discussion

5.1 Methodological considerations

The purpose of this paper was to explore the human–machine aspects of SCR installations from a systems perspective. In order to obtain a comprehensive understanding, the research design included triangulation of methods (Bryman and Bell 2007) by combining focus groups and semi-structured individual interviews. Since the data collection is based on a limited number of group and individual interviews, the informant participation is important in that the informants are honest, consistent, they keep to the subject, and give comprehensive answers (Kvale 1997). There is a possibility during interviews that the informants might offer answers and reflections that put themselves and/or the companies they represent in a good light. This possibility has been considered, and the study has strived for a critical approach in the analysis of the empirical data. The selection of informants was purposeful rather than random, and the fact that the authors during the project were approached by people who volunteered to participate in the focus groups indicates an interest in the study. Far from all possible stakeholders were included in the study. There were, for example, no respondents representing classification societies or the inspectorate at the maritime division of the Transport Agency.

The study is limited by its clear Scandinavian focus with the boundaries set by prevailing national and regional regulations and conditions. But with the onset of the Revised MARPOL tier III, the results of this study will be relevant also outside Scandinavia and underlines the need of considering not only the strict technical aspects of SCR but also the human-oriented aspects when evaluating the overall efficiency of SCR.

The results of the two focus group evaluations indicate that the study succeeded in capturing what was set out to capture; thus, the authors believe the internal validity (Bryman and Bell 2007) to be good. The results also show that, to a large extent, the informants felt that they could speak their mind and that they learnt from the experience pointing towards the usefulness of face-to-face group meetings for creating common awareness and knowledge transfer.

5.2 Stakeholder relations

One of the most prominent findings to emerge was the importance of rapport (mutual understanding or trust) between the different actors in the system—supplier, shipyard, shipowner, cargo owner/customer, and operator. When the dialog is working, it seems, so is the SCR. This is consistent with, for example, Guinan (1986) who proposes that communication between designers and users is positively related to the outcome of the design. In the context of this study, however, it seems that also the relationship between shipyard and shipowner is of great importance for the outcome. The informants who have built their ships at yards with which they have long-term relations have expressed confidence and trust in the yard's technical competence. These informants trust the yard to have an honest ambition of making the SCR system work and not only put the pieces together. But, the mutual trust must work both ways.

In one example, the yard was said to have stated early on that it was not possible to build according to specifications. The owner, however, insisted, a number of operational problems followed, and ultimately, at great expense, a major alteration was needed.

During the design and installation phase, the knowledge resources of the crew are not utilized since the crew often lacks previous experience on operating an SCR. This line of thought, however, does not acknowledge the knowledge on the context in which the system is about to operate in. A previous research shows several benefits of involving operators in workplace design. Some benefits are related to the results of the design, others to the expected gains in the operators' qualification and motivation, and some with the functionality of the entire work organization (Launis 2001). In complex work processes, it is ever more likely that the operator can contribute on the topic of task execution, work activities, and work environment during normal and abnormal operations. In addition, the participative design process implies an expansive learning of all stakeholders involved; the operators convey experience and feedback regarding usage to the designers, and the designers provide understanding of the system's function and operation. The mutual understanding supports the designer in designing more operable systems and the operators to operate them more efficiently and reliably (Launis 2001). It is therefore suggested that a collaborative installation process involving both operators on board and technical management in the shore organization would contribute towards a deeper understanding of how the SCR works, thus enabling a more efficient NO_x reduction. It is believed that this would be possible for both installations on new buildings and for retrofit installations. For a newbuilding where the crew have yet to be appointed, it is possible to instead utilize the knowledge and experiences of other engine officers or cadets that can represent the "typical users", as described, for example, in a study involving nautical cadets in a bridge design process (Österman et al. 2011).

5.3 Maturity of infrastructure and technology

The distribution and quality of urea prompted many discussions during both focus groups and individual interviews. Informants operating vessels with various port calls as opposed to a regular schedule had experienced difficulties in ordering and receiving urea, especially when being rerouted to another port with short notice. Concerns were also expressed among the informants regarding the net environmental load of using urea that has been transported by lorry from Sweden to continental Europe. However, a previous research on environmental trade-offs in NO_x removal from ships suggests that a marine SCR installation gives a considerable decrease in environmental impact including the transport of urea (Andersson and Winnes 2011). On the topic of urea quality, a quality standard similar to the standard for land-based applications is supposedly under way also for marine use and would likely be beneficial for the quality of SCR operations.

During the focus groups and individual interviews, the success stories were far outnumbered by the stories of things falling apart, clogged stones, and ineffective NO_x reduction. Even the cases where the SCR reportedly ran without problem turned out to have room for improvements, suggesting a high threshold for problems among the informants. One is so used to face technical complications that it takes a lot to acknowledge that there is a problem. This phenomenon, a normalization of the conditions can have social or psychological reasons. One form of normalization is the so called system evolution (Backström 1996) where the human continuously adapts to small, solitary changes in a system that slowly becomes more and more unstable without anyone really noticing. When an accident or breakdown suddenly occurs, it is often described as a bolt out of the blue.

The findings suggest that many of the difficulties of operating SCR systems can be found in the design and installation phase. The SCR is seemingly viewed more or less as a "black box", with no one to tell what actually happens inside. The system builders appear to lack sufficient knowledge on the importance of the urea injection design and exhaust gas velocity over the catalysts for a well-functioning SCR; this can, in turn, lead to costly, sub-optimized installations with poor NO_x reduction. Drawing from the interview results, it seems that this built-in sub-optimization occasionally may have been conscious.

The restricted space on board not only affects the technical functionality, in terms of correct exhaust gas velocity and placing of urea injectors for an efficient thermal decomposition and subsequent catalytic reduction, but it was also found to affect the accessibility for routine and repair work increasing the risk for human errors and occupational accidents. To accommodate for the limited space, it is therefore suggested that traditional human factors engineering tools, such as methods for analyses of tasks, functions, and interfaces analyses (Stanton et al. 2005), are used routinely.

5.4 Knowledge and training

On the theme of knowledge and training, a lack of structure for knowledge transfer was identified. Since the SCR is regarded neither as safety critical nor as a particularly complex system—despite the several expressions of how incomprehensible the catalytic process is—no special training is required, and no special training courses are offered by the SCR suppliers beyond the introduction at the initial start-up. This requires that for good functionality and efficiency, the SCR installation, in general, and its user interfaces, in particular, must be designed for good guessability (it is easy to correctly guess how something works and what happens is, for example, a certain button is pushed) and learnability (it is easy for the operator to learn how it works and remember correct actions) (Jordan 1998).

Moreover, it was found that the crew was expected to transfer the knowledge to colleagues and successors, something that demands that the instructor possess pedagogical as well as technical skills. To adequately transfer knowledge, one must have a thorough understanding of how the SCR works, and also dedicated time, since the SCR is but one of many systems to master for an engine officer.

It is further believed that more knowledge is needed on a number of technical aspects that appear to affect the functionality of the SCR. Future experiments are needed to assess the impact of various types of urea qualities and also the effect on exhaust gas composition of different types of marine fuel and lubrication oils commonly used. Today, the vessels take active part in the development of SCR systems for marine applications, both technically and economically. The costs for malfunctioning SCR installations are carried chiefly by the shipping company, sometimes in collaboration with the cargo owner. The costs are primarily associated with necessary re-designs, material, working hours, energy, and waste, such as overuse of urea or catalyst stones not operating its full estimated service life. For inefficient or non-existent NO_x reduction, when the problems have escalated to a decision to simply shut the SCR off, the costs can also be measured on a societal level in terms of unhealthy emissions to air and increased eutrophication and acidification at land and sea.

It is fair to believe that many human, technical, and organizational aspects identified in this study can be transferred to other existing and forthcoming marine systems on board. On the topic of environmental technology, the near future sees a number of pending installations such as marine scrubber systems to remove sulfur dioxide from exhaust gas and water treatment systems to remove organisms from ballast tanks.

6 Conclusions

The present study contributes to the body of knowledge on marine SCR installations by adding a systems perspective of the installation, comprising technical, human, and organizational conditions for safe, efficient, and sustainable operations of SCR catalysts on ships.

Although the actual NO_x reduction with marine SCR catalysts is high in successful installations, there are still technical and operational issues that need to be resolved for forthcoming SCR installations. Principally regarding the supply and quality of urea, the design, and placing of urea injection, and exhaust gas composition due to various marine fuels and lubrication oils.

The results indicate that there are currently no structures or procedures in place to ensure that physical and cognitive capabilities and limitations of the human operators and maintainers are taken into account in the design process. Also lacking is a structure for training and the development and transfer of knowledge on how the SCR works and how to properly operate and maintain the SCR. This absence of structures and procedures are a contributing source to the common operational disturbances with an increased risk for occupational accidents and unnecessary harmful air emissions to the environment. The costs for this are carried by shipowners, cargo owners, and the society.

In conclusion, using traditional ergonomic principles and methods in the design and installation process of marine SCR systems, and possibly other forthcoming abatement technologies, would contribute towards an improved overall system performance. It would also contribute towards reaching future environmental targets regarding NO_x emissions from short sea shipping.

In general, it seems that clear and concise incentives are needed for installation and operation of marine SCR: either regulations, customer demands, or other commercial benefits. Unless incentives are in place, the development will stall. The regulations must be enforced on an international level to ensure competition on equal grounds.

Further, it is believed that the face-to-face focus group meetings had a positive impact on the common awareness among the shipowners and the SCR manufacturers, creating improved dialog and knowledge transfer between the stakeholders.

7 Further work

Further work is needed on the issue of marine SCR installations. Proposed areas of continued research includes flow reactor experiments using different types of urea as a NO_x-reducing agent and flow reactor experiments, where the exhaust gas composition is varied by the use of different marine fuel standards.

Continued research is also needed on the topic of incorporating ergonomic methods and principles in the toolboxes of naval architects, ship designers, and suppliers of marine equipment, as well as on the topic of end-user participation in ship design.

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