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# Human digital twins to inform ship design

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## *ABSTRACT*

*A key building block of digital twin solutions is a virtual counterpart for an asset that can be coupled to the asset throughout its lifecycle – predicting an asset's potential performance at design and providing insight into operation during service. This paper presents the development of human digital twins that integrate human factors into conventional ship design procedures, particularly focussing on seakeeping performance assessments. A novel method for incorporating human-centric performance criteria in seakeeping analyses is proposed and initial validation thereof is detailed. Human digital twins are seen to provide a platform for informing the ship design process using data captured during vessel operation.*

## KEY WORDS

Digital Twins; Ship Design; Human-Centred Design; Seakeeping; Motion Sickness

## INTRODUCTION

A visible rise in research interest is evident in reviews of digital twins in the maritime domain. Digital twin solutions comprise of virtual counterparts linked to assets and communication between the coupled digital and physical entities. This is not to be confused with geometric models that mimic the structural components of assets, particularly in the case of ships. Ship digital twins are recommended to be created at the inception of the physical ship lifecycle, at the beginning of design, to be coupled with the physical asset through production and operation to retirement. (Mauro and Kana, 2023; Madusanka *et al.*, 2023)

The most recent International Marine Design Conference state-of-the-art report on ship design methodology identified exploiting operation data from digital twins as an emerging development that will become an intrinsic part of future design processes (Erikstad and Lagemann, 2022). It is likely that a digital twin of an asset will contribute design data to the design stage of its coupled asset, shown by arrow (a) in Figure 1 for Ship 1. However, it is unlikely that a digital twin of an asset will contribute operation data to the design stage of the asset, as the design precedes the operation of the asset. It is more likely that digital twin of an asset already in operation may inform the design of next-generation or new, similar assets, as shown in Figure 1 for two ships, particularly by arrow (b).

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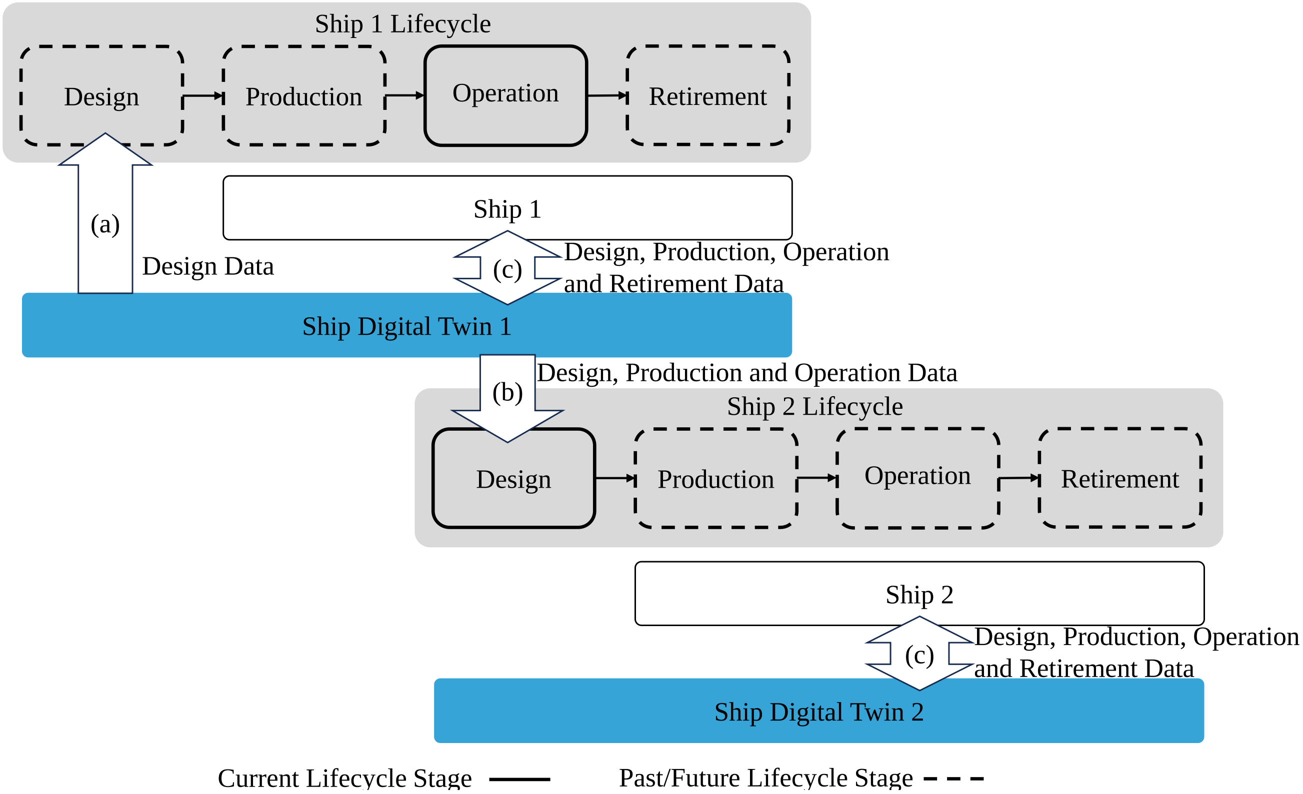


**Figure 1: A Digital Twin in Operation Informing the Design Stage of Another Asset.**

It is evident that data should be exchanged between the digital and physical entities within a digital twin solution throughout the physical ship lifecycle, represented by arrows labelled (c) in Figure 1 (Madusanka *et al.*, 2023). However, a gap in information flow from digital twin solutions that capture data during ship operation and send data to a new ship's design stage is highlighted in literature, represented by arrow (b) in Figure 1 (Fonseca *et al.*, 2023). The objective of the work presented is to propose information feedback from digital twins used during vessel operation to aid the ship design stage.

In maritime literature, as presented until now, digital twin developments are typically referred to for ships. However, human digital twins are the focus of attention in the work presented. Where a ship digital twin is coupled to a vessel, a human digital twin virtually mimics the identity, condition and behaviour of a person.

A human digital twin for a seafarer, called Mariner 4.0, was developed and trialled on board the SA Agulhas II (Taylor *et al.*, 2023a). Mariner 4.0 facilitated the study of motion sickness in real time during ship operation on a research expedition. Subjective feedback was captured from vessel occupants through a mobile application and sensor readings from a full-scale motion measurement system. The human digital twin developed personalised motion sickness criteria that can aid the diagnoses of motion sickness incidence (MSI), an estimate of the percentage of individuals in a group that may vomit on board (O'Hanlon and McCauley, 1974), using the motion sickness dose value (MSDV), a human-weighted metric of a level of ship motion that is known to induce motion sickness (ISO 2631-1, 1997). An MSDV can be calculated with Equation 1,

$$\mathrm{MSDV} = \int_0^T a_{\mathrm{w}}(t)\,\mathrm{d}t, \qquad [1]$$

where $a_{\mathrm{w}}$ is the frequency-weighted acceleration measured by z-oriented accelerometers and $T$ is the duration of exposure in seconds (ISO 2631-1, 1997). The z orientation is vertically aligned with the heave motion of a ship, but comprises additionally of roll and pitch components.

The work presented starts with a description of a baseline method to assess seakeeping performance that contextualises the proposed means for constructing an information loop from ship operation to design through human digital twins. A Mariner 4.0 deployment and results are detailed as an illustrative use case of the method for informing ship design using human digital twins. Thereafter, potential benefits and drawbacks of integrating human digital twins in ship design procedures are discussed.

It is envisioned that human digital twins will venture out to sea with their seafarer counterparts, returning to land with human-centric insight gained from ship operation that is of value for seakeeping assessments typically conducted in ship design.

## SEAKEEPING PERFORMANCE ASSESSMENT METHODS

It is common practice to define the specifications that a ship should achieve or criteria that a ship should not exceed during missions it is designed for, irrespective of the methodology selected for ship design (Erikstad and Lagemann, 2022). Performance criteria are selected to assess ship seakeeping, typically through forming operability envelopes (Tezdogan *et al.*, 2014). Figure 2 presents a foundational procedure for applying conventional seakeeping performance methods. The work presented does not intend to amend the extensively used procedure shown in Figure 2. Instead, the focus is on Step 9, which incorporates the development and selection of human-centric performance criteria.

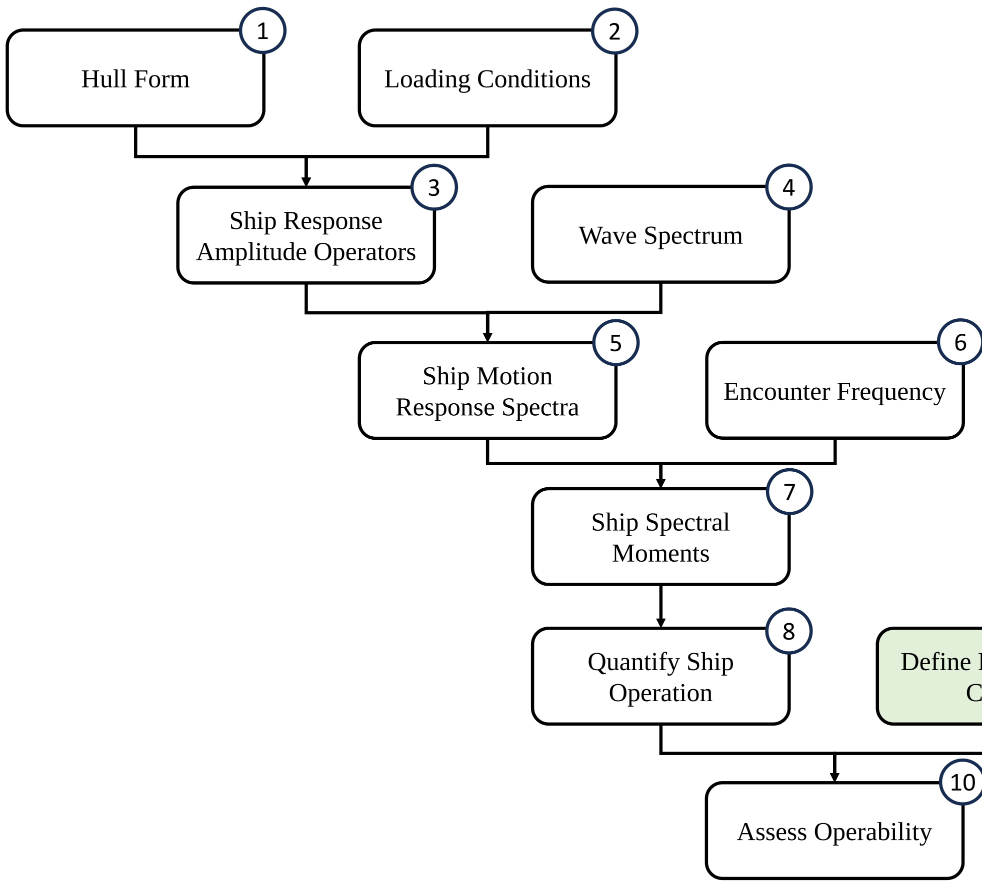


**Figure 2: Basis of Conventional Seakeeping Performance Methods (adapted from Tezdogan *et al.*, 2014; Scamardella and Piscopo, 2014; 2015).**

## DEVELOPMENT OF HUMAN-CENTRIC PERFORMANCE CRITERIA USING HUMAN DIGITAL TWINS

Taylor *et al.* (2023b) proposed that seafarers each be coupled with a unique virtual representation of their state and behaviour, which describes their condition of well-being while performing tasks on board. The virtual representations are human digital twins devoted to acquiring and managing data related to the seafarers they are coupled with during ship operation. The core functions of human digital twins are to acquire data, process data and provide information to support decision making. Data acquired could be related to a seafarer in particular, such as their heart rate measured by a wearable sensor, or their environment, such as rigid body motion of a ship that a seafarer is exposed to, measured by sensors installed on the ship structure. Information that human digital twins should inform seafarers of should be related to seafarers' virtual representations. For example, a seafarer could be notified if their vibration exposure associated with a task that they have scheduled will go above a safety threshold for whole-body vibration when completing a dangerous task. Thresholds in the work presented are values for metrics that quantify ship performance above which ship operation would be deemed unacceptable (NATO, 2000). If the task does exceed the safety threshold, then rescheduling to when the vibration of the ship is more acceptable would be advised.

Individualised data analyses can be conducted by each human digital twin in such a way that thresholds are determined to aid prediction of human response incidences, such as motion sickness (Taylor *et al.*, 2023a). It is common practice that a threshold is qualitatively selected or, more rarely, estimated from experiments (NATO, 2000). The work presented proposes the development of human-centric performance criteria during ship operation to capture invaluable real-world experiences that are not present during structured experiments traditionally performed at sea trials (NATO, 2000). This incorporates phenomena encountered during the full duration of a voyage into criteria development, such as adaptation to motion. Furthermore, criteria can be tailored to specific voyage scenarios and missions, including various durations of assessment.

Human-centric performance criteria are best developed for seafarers at an individual level that is associated with attributes unique to each seafarer, such as their age or previous seafaring experience. Thresholds are not strictly to be linked to the ship(s) a seafarer lives and works on, but rather metrics of ship operation. Hereby, seafarer-specific collections of human-centric performance criteria developed through human digital twins can be generated so that stakeholders can extract thresholds relevant to their ship or voyage missions. For example, a cruise ship designer may prefer to select characteristics of individuals that best describes an unadapted cohort. Comparatively, naval ship designers would be more inclined to work with thresholds of seafarers that are more tolerant to vessel motion.

## OBTAINING AND IMPLEMENTING SEAKEEPING PERFORMANCE ASSESSMENT METHODS THROUGH DIGITAL TWINS

Service-oriented architectures based on digital twins have been developed for maritime solutions (Erikstad and Bekker, 2021). The development and servitisation of the diagnostic motion sickness criteria through human digital twins is recommended, additionally motivated by service-oriented approaches being widely accepted (IEC, 2017). The architecture that displays the interactions between digital and physical counterparts to generate and use diagnostic motion sickness criteria is presented in Figure 3.

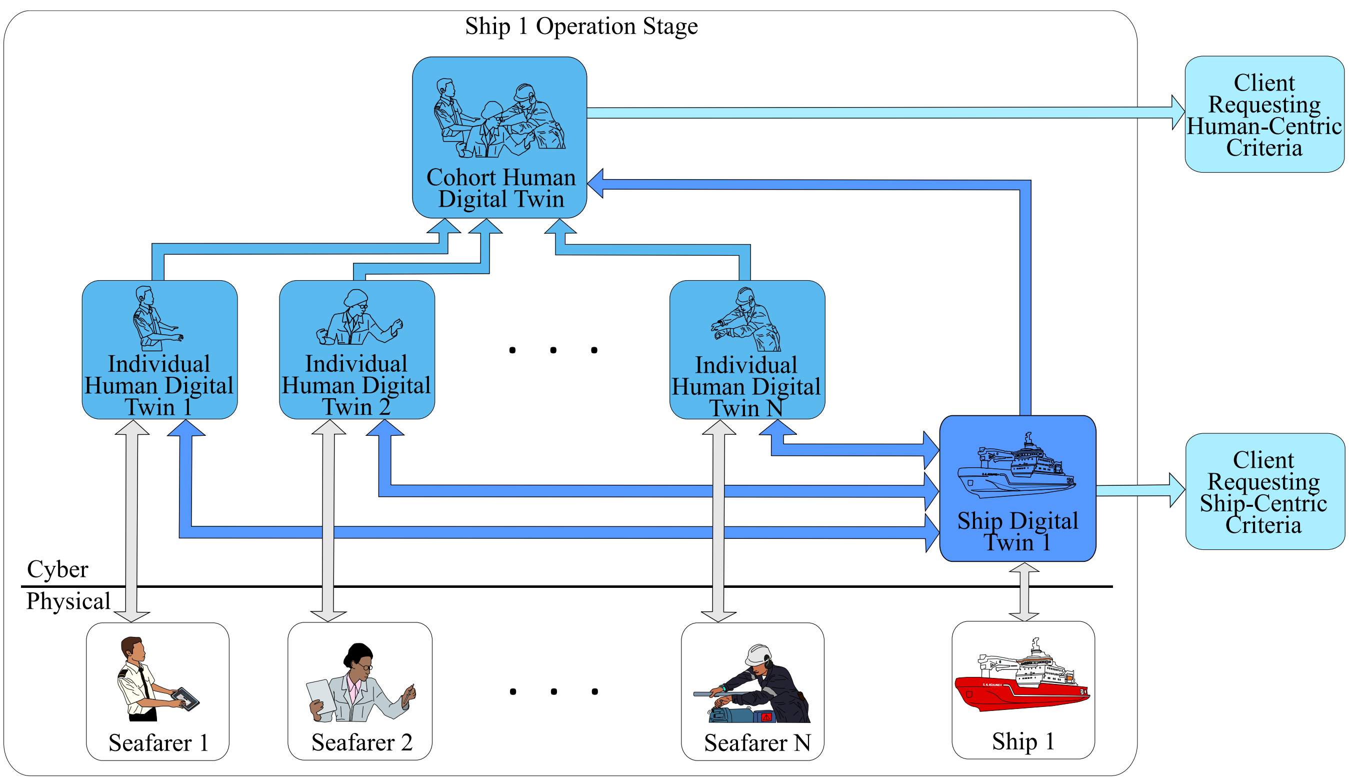


**Figure 3: Architecture Displaying the Interactions Required for the Development and Use of Diagnostic Human-Centric Performance Criteria Through Human Digital Twins.**

In Figure 3, the individual human digital twins are each coupled to unique seafarers, which generate personalised thresholds. Hierarchically, the thresholds from individual human digital twins are aggregated at a cohort level. The Cohort Human Digital Twin acts as a service provider that offers clients relevant human-centric thresholds.

Clients in the work presented could be any entity that is interested in retrieving a human-centric threshold based on seakeeping methods conducted for the purposes of performance assessments, which is recommended to be included in the functionality of Ship Digital Twin 2 shown in Figure 1. Moreover, full-scale ship measurements are managed by Ship Digital Twin 1, which provides information regarding the state and behaviour of the vessel, such as rigid body motion while travelling through open water during a voyage, or ship-centric criteria.

The work presented does not focus on automated control of the seafarer, but rather on informing stakeholders of relevant information at the appropriate time for making decisions. For example, the Cohort Human Digital Twin could provide the average motion sickness level of passengers to the navigating officers in a ship's Bridge via a user interface, which may be used to inform their next actions, such as adjust the ship speed and course.

# ILLUSTRATIVE USE CASE

Motion sickness is focussed on in this illustrative use case as it is a prevalent natural human response to ship motion. Symptoms can include nausea, vomiting, tiredness and bouts of depression in severe cases, none of which are conducive to comfort or productivity aboard (Stevens and Parsons, 2002; Mansfield, 2005). The effects of motion sickness on passengers and crew are sought to be minimised through seakeeping in ship design, which is detailed as a conventional means of motion sickness assessment. A proposed method of enhancing human-centric performance criteria development is then described, followed by a real-world deployment to showcase human digital twins in operation, working towards exploiting operation data to inform ship design.

## Conventional Motion Sickness Assessment

The MSI is widely adopted in seakeeping performance assessments (Tezdogan *et al.*, 2014; Scamardella and Piscopo, 2014; 2015). Criteria for the MSI that are reported in literature include:

- 5 % at 0.5 hours of exposure for naval crew (Baitis *et al*., 1994);
- 10 % of general passengers (ABS, 2021);
- 20 % of naval crew at 4 hours of exposure (NATO, 2000);
- 35 % over 2 hours (Tezdogan *et al.*, 2014).

The MSI can be computed from the second and fourth ship spectral moments. The MSI is related to absolute acceleration shipboard as described by Equation 2,

$$\mathrm{MSI} = 100 \cdot \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} \mathrm{e}^{\left[-\frac{1}{2}x^2\right]}, \qquad [2]$$

which expresses a cumulative distribution function using the standard normal distribution, where $z$ is given by Equation 3,

$$z = \frac{\log_{10}\bar{a} - \mu}{\sigma}, \qquad [3]$$

and $\sigma$ and $\mu$ can be determined empirically, and $\bar{a}$ is the absolute acceleration (O'Hanlon and McCauley, 1974; McCauley *et al.*, 1976). McCauley *et al.* (1976) found that $\mu$ is suitably estimated by Equation 4,

$$\mu = k_1 + k_2 \cdot \log_{10}\left(\frac{1}{2\pi}\sqrt{\frac{m_4}{m_2}}\right) + k_3 \cdot \left[\log_{10}\left(\frac{1}{2\pi}\sqrt{\frac{m_4}{m_2}}\right)\right]^2, \qquad [4]$$

where $k_x$ are constants to be resolved empirically, $m_2$ and $m_4$ are the second and fourth ship spectral moments described by Equations 5 and 6, respectively,

$$m_2 = \int_0^\infty \omega_e^2 \, S_z(\omega_e) d\omega_e, \quad [5]$$

$$m_4 = \int_0^\infty \omega_e^4 \, S_z(\omega_e) d\omega_e, \quad [6]$$

and are functions of the encounter frequency, $\omega_e$ (Lloyd, 1998; Scamardella and Piscopo, 2014; 2015). The absolute acceleration, $\bar{a}$, in Equation 3 can further be defined in terms of the fourth ship spectral moment (Lloyd, 1998). Only vertical ship motion is considered in recommended motion sickness assessments, hence the z subscript in the ship motion response spectra symbol, $S_z$ (ISO 2631-1, 1997).

Contrastingly to seakeeping performance assessments conducted in ship design, the MSI computed with the MSDV is adopted in international standards for the evaluation of motion sickness performed during vessel operation, such as full-scale sea trials, using Equation 7 (ISO 2631-1, 1997; Lawther and Griffin, 1987),

$$\mathrm{MSI} = K_m \cdot \mathrm{MSDV}. \quad [7]$$

$K_m$ is a constant that can empirically be determined for a specific seafaring group or be used as 1/3 for a mixed population of male and female adults that are unadapted to motion (ISO 2631-1, 1997). The MSDV can be computed with sensor measurements, using Equation 1, or seakeeping methods, using Equation 8,

$$\mathrm{MSDV} = \sqrt{m_{4w} T}, \quad [8]$$

where $T$ is again the duration of motion exposure and $m_{4w}$ is the weighted fourth ship spectral moment. $m_{4w}$ is denoted by Equation 9,

$$m_{4w} = \int_0^\infty \omega_e^4 \, S_z(\omega_e) G^2(\omega_e) d\omega_e, \quad [9]$$

where $G$ is the frequency weighting function (Scamardella and Piscopo, 2014).

## Proposed Motion Sickness Assessment

The presented method suggests developing diagnostic motion sickness criteria using real-world sensor measurements and feedback from seafarers through human digital twins. Then, the results are to be integrated into seakeeping methods conventionally performed in ship design. The operational and design methods of computing the MSDV are associated with the knowledge that the MSDV in Equation 1 can equivalently be computed using Equation 10,

$$\mathrm{MSDV} = \sqrt{T} \cdot a_{wRMS} \quad [10]$$

and that the square root of the weighted fourth ship spectral moment equates to the root mean square value of the weighted time signal of vertical ship acceleration, $a_{wRMS}$, measured over duration $T$ in seconds (ISO 2631-1, 1997; Lloyd, 1998).

It is observed that the relationship between the MSI and MSDV is not strictly linear or necessarily proportional with a 3:1 ratio for all cases. Factors, such as age and sex, influence susceptibility to motion sickness (ISO 2631-1, 1997). A criterion of 30 $m/s^{1.5}$ for the MSDV is reported (ABS, 2021), considering Equation 6, however Taylor *et al.* (2023a) suggest that a cumulative distribution function, using a normal distribution of MSDV thresholds, provides a more relevant fit for relating the MSI and MSDV. This suggestion aligns with findings of the relationship between MSI and vertical ship acceleration in literature (O'Hanlon and McCauley, 1974; McCauley *et al.*, 1976). Linking the MSI and MSDV through a cumulative distribution function enables the development of diagnostic motion sickness criteria, as shown in Figure 4 with 95 % confidence intervals for an exposure duration of 6 hours.

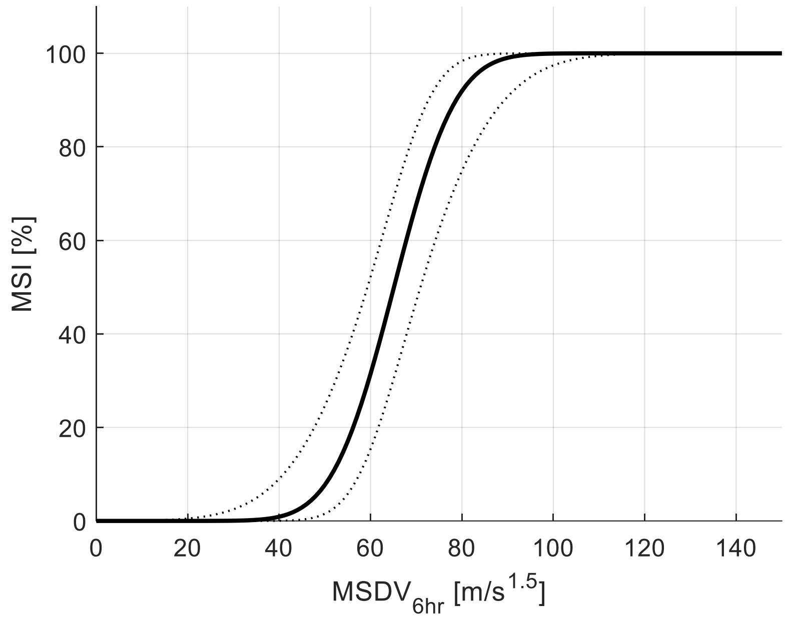


**Figure 4: Cumulative Distribution Function with 95 % Confidence Intervals Serving as Diagnostic Motion Sickness Criteria.**

Novel motion sickness criteria such as this can be used to estimate the MSI for a cohort of seafarers from ship motion predicted using seakeeping methods. The proposed method recommends computing the MSDV using Equation 8 and estimating the MSI from the generated diagnostic motion sickness criteria. The estimated MSI can then be assessed against the desired criterion for seakeeping performance. Alternatively, an MSI criterion could guide the selection of the associated MSDV threshold if there is a preference for working with the MSDV.

## Human Digital Twin Deployment During Ship Operation

Human digital twins were deployed on board the SA Agulhas II to monitor the motion sickness of participating passengers (Taylor *et al.*, 2023a). A mobile application deployed on participant cell phones collected subjective feedback from seafarers that indicated whether they experienced any motion sickness symptoms or not (MSI) and tracked their location as they moved throughout the ship using near field communication (NFC) technology. In parallel, ship motion was measured by a full-scale measurement system, which computed an MSDV at all NFC tag locations over consecutive 5-minute durations.

Each seafarer human digital twin integrated the seafarer's present location with MSDV's in real time, computing an equivalent MSDV over 6 hours every 5 minutes that represented their extended motion exposure on a 3-week long research voyage. The human digital twins additionally fused the subjective feedback with the equivalent MSDV's to analyse the measurements of motion exposure against subjective observations. Individual MSDV thresholds, which were unique to each participating passenger, were computed using receiver operating characteristic curve analysis.

The individualised thresholds were used by a human digital twin that represented the motion sickness state of the cohort to generate a cumulative distribution curve with a normal distribution, which linked the MSI and MSDV metrics. In this way, the Cohort Human Digital Twin enabled the determination of a cumulative distribution curve within a real-world contextual environment, managing the evolution of the curve throughout the voyage. The equivalent MSDV computation duration was extended to accommodate durations from 0.5 to 6 hours in 0.5 intervals. A unique final cumulative distribution curve was generated for each duration, as shown in Figure 5.

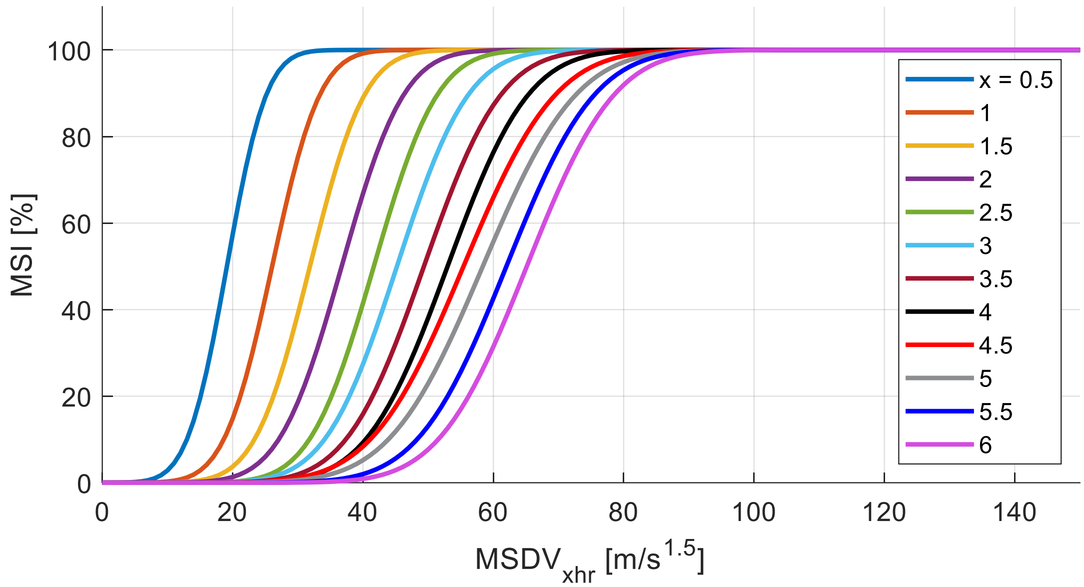


**Figure 5: Diagnostic Motion Sickness Criteria Over Various Durations of Motion Exposure (adapted from Taylor *et al.*, 2023a).**

The use of diagnostic motion sickness criteria managed through the Cohort Human Digital Twin was validated. The validation procedure included requesting the MSI from the Cohort Human Digital Twin each time a new mean equivalent $MSDV_{6hr}$ was computed based on the individually tracked locations of participating passengers. The procedure was run over the course of the 3-week research voyage to show that the latest cumulative distribution curve was accessible throughout the expedition.

Results of the estimated and observed MSI values are presented in Figure 6, of which the Spearman correlation was found to be 0.78 (Taylor, 2023). In Figure 6, MIZ is the marginal ice zone in the Southern Ocean. Ship motion in the MIZ was marginal compared to open water transits, hence the smaller values of observed MSI for participating passengers. Moreover, the MIZ separates the first and second open water voyage legs, such that adaptation to motion was observed by personnel having smaller MSI values (both estimated and observed) after the MIZ than at the start of the voyage.

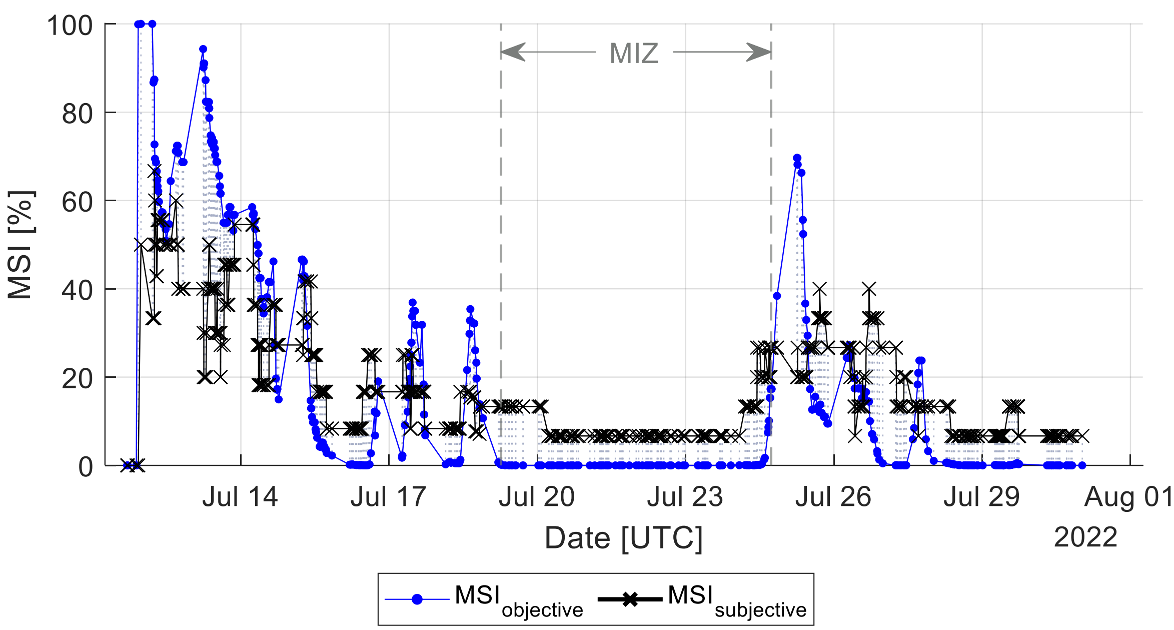


**Figure 6: MSI Estimated (Objective) versus Observed (Subjective).**

## DISCUSSION OF BENEFITS AND DRAWBACKS FROM THE INTEGRATION OF HUMAN DIGITAL TWINS TO INFORM SHIP DESIGN

Human digital twins for seafarers trialled in situ during a research voyage were seen to be effective systems for human-centred data acquisition and analysis on board a ship. The human digital twins enabled the development of diagnostic motion sickness criteria throughout the voyage, evolving with newly acquired data from both a full-scale ship measurement system and participating passengers.

The motion sickness criteria development was driven by data acquired from seafarers based on their actual experiences on board through a mobile application installed on participant cell phones. Therefore, the human digital twins tailored motion sickness criteria to a unique cohort based on individual responses. In this way, more detailed information is gathered about the MSI in relation to a human-centric ship motion dose metric (MSDV) than typical human response studies, which report using daily metrics acquired through paperbound questionnaires (Taylor, 2023). Moreover, the duration of motion sickness assessment can be tailored to specific voyage or vessel scenarios with periods ranging from 0.5 to 6 hours (see Figure 5). Motion sickness criteria identified in literature are applicable to a single duration only or do not provide related exposure times, which the MSDV computation is dependent on.

The diagnostic motion sickness criteria provided MSI estimates that were positively associated with the observed MSI, excluding the time in the MIZ. Here, a single participant stopped participating with their MSI showing a false positive while in the MIZ. The estimate of MSI is, therefore, more strongly associated with the observed MSI. The customised functionality of the human digital twins is considered beneficial for better understanding the real-world experiences of seafarers on board specific vessels, which could transpire motion sickness diagnoses. For example, the cruise industry could characterise customer satisfaction levels for their fleet.

It is envisaged that the best benefit of operational digital twins for informing design would be for fleets that operate with similar vessels, such as in the cruise and naval sectors. Human digital twins enabled production of data and results from analyses, which can provide access to results beyond a single operational voyage or the operational service of a vessel. Information flow could be facilitated from one voyage to the preparation phase of the next expedition, or from the service of one ship to the design of its or similar successors, as presented in Figure 7. The Cohort Human Digital Twin could make the cumulative distribution function accessible to Ship Digital Twin 2, which would need to define performance criteria for completing a seakeeping performance assessment. The motion sickness criteria provide an artefact of operation data acquisition and analysis that quantify the real-world experience of seafarers for informing ship design when defining performance criteria.

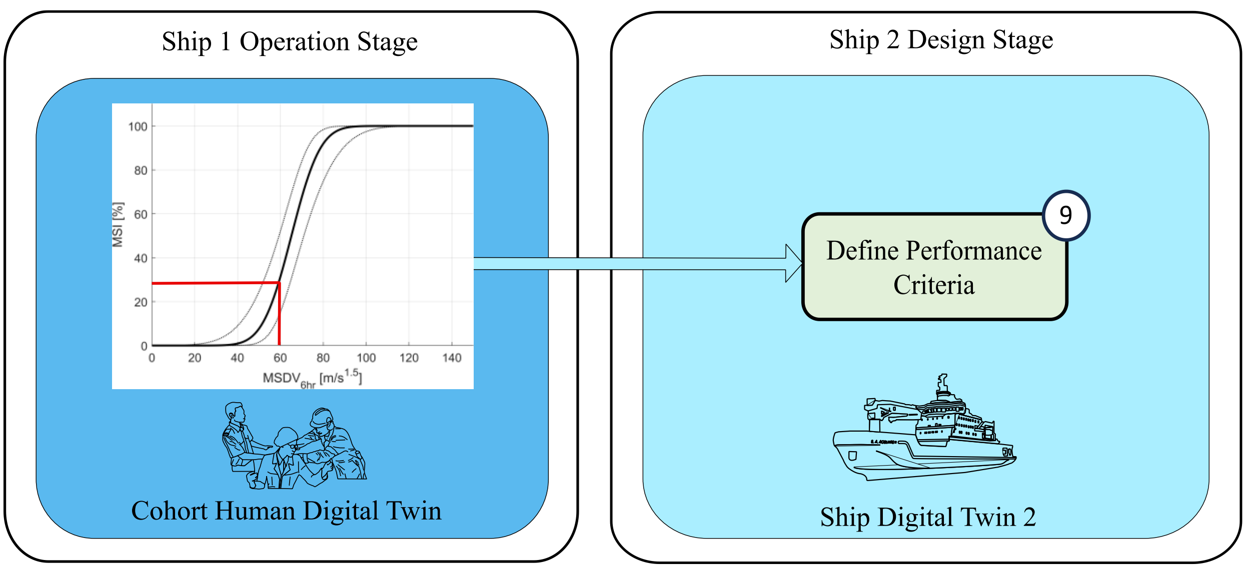


**Figure 7: Cohort Human Digital Twin in Ship 1 Operation Stage Informing Ship Digital Twin 2 in Ship 2 Design Stage.**

It is noted that the human digital twins require at least one deployment to incorporate real-world data. Results could be generated from simulations prior to a debut voyage, but would have to omit the inclusion of the actual experience of seafarers. The latter would provide the same results as seakeeping analyses performed previously. The human digital twins facilitated a quantitative, empirical means of generating human-centric diagnostic criteria, compared to qualitative results readily employed during conventional seakeeping performance assessments. Such a system can be regarded a form of real-world seakeeping trials, which capture invaluable data for rare operational occurrences in situations beyond that of controlled, systematic seakeeping trials (NATO, 2000). The implication for ship design is an increase in information about ship operability that is captured during operation, which can be made available and used to guide strategic decisions. Nonetheless, it is noted that ship design is inherently complex, and the work presented provides evidence of a proof of concept that requires further development to comprehensively construct an information pipeline from ship operation to design.

## CONCLUSIONS

Constructing information feedback from data acquired and analysed during ship operations to the design stage has been proposed through digital twins for people and a ship. Human digital twins captured feedback from participating passengers, which allowed the automated generation and use of diagnostic motion sickness criteria that link the MSI and MSDV. A ship digital twin that implements seakeeping performance assessment procedures acted as a client of a cohort human digital twin to integrate the diagnostic motion sickness criteria. A real-world validation of the use of diagnostic motion sickness criteria was offered, highlighting that data managed through human digital twins can be made accessible beyond the scope of an operational voyage. Human digital twins are regarded as beneficial for integration with ship digital twins during vessel operation aiming to inform decision making throughout the lifecycles of seafarers and ships, but particularly back into ship design. In this way, human digital twins refine the practical understanding of operational situations at the time of ship design through data-driven artefacts produced during ship operation.

Future work includes using the proposed seakeeping performance methods with weather forecasts to predict ship motion and human motion sickness responses for a voyage. Results could be compared with in-situ, full-scale ship motion measurements and observed human responses over the duration of the same voyage. Moreover, MSDV thresholds extracted from the diagnostic motion sickness criteria are to be used to generate novel MSDV operability envelopes for comparison with results of real-world ship operation measured through ship and human digital twins.

## DATA ACCESS STATEMENT

Research data used to generate the plotted results is publicly accessible in an institutional repository (Taylor *et al.*, 2023c).

## CONTRIBUTION STATEMENT

**NC Taylor**: Conceptualisation; data curation; methodology; writing – original draft. **A Bekker and K Kruger:** Conceptualization; supervision; writing – review and editing.

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