Institution: University of Southampton		
Unit of Assessment: 12 Engineering		
Title of case study: 12-29 Cleaner, safer, smarter maritime		
Period when the underpinning research was undertaken: January 2000 – May 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
James Blake	Associate Professor	October 1998 – present
Stephen Boyd	Associate Professor	October 2001 – present
Barry Deakin	Research Engineer	February 1978 – October 2015
Gwyn Griffiths,	Professor	October 2000 – November 2012
Dominic Hudson	Professor	October 1994 – present
Anthony Molland	Professor	October 1970 – June 2008
William Price	Professor	October 1990 – September 2009
R Ajit Shenoi	Professor	October 1981 – present
Adam Sobey	Associate Professor	October 2009 – present
Pandeli Temarel	Professor	January 1993 – December 2018
Blair Thornton	Professor	September 2002 – June 2006; September 2016 – present
Stephen Turnock	Professor	March 1988 – present
Period when the claimed impact occurred: January 2014 – July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The maritime sector has directly benefited from University of Southampton (UoS) research into:

Cleaner ship design and operation methods that reduce greenhouse gas emissions and combustion products;

Safer ships through better understanding of hydroelasticity in large vessels; through-life reliability of composites in rescue lifeboats; fishing vessel stability;

Smarter seabed mapping through increased extent and intelligent processing of autonomous visual surveys.

Since 2014, this has generated local and global socio-economic impact by:

(1) Reducing CO_2 emissions by more than 200,000Mt and generating more than GBP120m of investment and saving by Shell Shipping and Maritime (SSM), Royal National Lifeboat Institution (RNLI) and local SMEs.

(2) Creating more than 400 high-skilled jobs in the Solent region and attracting more than GBP25m of investment in facilities by Lloyd's Register (LR) through their relocation to the UoS campus.

(3) Generating GBP5.3m overseas investment to adopt robotic methods for deep-sea mineral survey.

(4) Saving lives by improving regulations and policies that apply to more than 7000 ships through the Maritime and Coastguard Agency (MCA), LR and China Classification Society (CCS).

2. Underpinning research

UoS research into cleaner, safer and smarter maritime practices is underpinned by six bodies of work (**R1 to R6**). This has been funded by grants and contracts from the Lloyd's Register Foundation, European Commission, UK Ministry of Defence, Government and Research Councils totaling GBP7.4m between 2000 and 2020. The most representative papers are cited, with context and contributors highlighted respectively.

At least 90% of world trade travels by sea, with the International Council on Clean Transportation predicting that shipping's contribution to CO_2 emission will grow from 3.1% today to 7.8% by 2050. Our **hydrodynamic and ship performance research (R1, R2)** allows emissions of ships already in-service to be reduced without major refit or interruption to their operations. This is crucial to meet the International Maritime Organization's global target of 40% reduced sector emissions by 2030 with minimal disruption to trade. At the same time, safeguarding the lives of the 1.6 million seafarers is the sector's biggest priority. Our **structures, materials and stability research (R3, R4, R5)** underpins modern understanding of ship safety. As we look to the future, our ability to understand ocean resources, their relationship to their local ecosystem and the impact of designating Marine Protected Area (MPA) on ecosystem health is critical for sustainable development. Our **robotics and autonomy research (R6)** has improved ocean resource and ecosystem survey capability and has been incorporated into the UK's strategic technology development roadmap.

R1 Research by Molland, Turnock and Hudson from 2002 to 2016 identified the effect of operational factors such as loading, wind, wave and currents on ship energy consumption as critical for accurate assessment of energy efficient propulsion options [**3.1**]. Modelling research by Hudson and Sobey since 2014 demonstrated that these confounding effects can be decoupled and accurately modelled by combining physics based and data-driven models [**3.2**]. This allows optimisation of ship loading on a continuous basis, with improved modelling of environmental effects to reduce engine-sizing margins and design efficient hybrid propulsion systems.

R2 Full-scale Computational Fluid Dynamics (CFD) modelling of hull-propeller-rudder interactions by Turnock since 2008 demonstrated how significant efficiency gains can be achieved by modelling previously uncharacterised influences of the hull on flow into a ship's propulsion system [**3.3**]. This was shown to provide energy efficiency increases of up to 8% through propeller design optimisation with no need for significant refitting of existing ships.

R3 Modelling of wave-induced 3D bending loads by Price and Termarel showed that these loads accounted for 90% of the structural failures reported for large, in-service ships weighing >150,000 tonnes [**3.4**]. A breakthrough was achieved in 2003 with the development of a method that combines computationally efficient pressure models to simulate dynamic wave loads and applies these to full-scale finite element models of ship structural members. This allows 3D deflections to be modelled at sufficient resolution to accurately predict dynamic bending loads that remain computationally intractable for full field finite element and viscous flow solvers.

R4 Shenoi, Boyd and Blake characterised damage mechanisms of aged marine composites and modelled their impact on structural reliability between 2001 and 2010 under an EPSRC platform grant (Shenoi, GR/R07523/01), European EUCLID RTP 3.21, UK Ministry of Defence contracts and an RNLI Advanced Technology Partnership (RNLI-ATP). A decision tree to systematically assess joint failure and delamination in composite hulls [**3.5**] established guidelines to recognise and report damage, defining repair timelines based on UoS damage propagation models. The team developed a standardised database for ship operators to improve the management and safety of composite fleets through early, risk aware diagnosis.

R5 Deakin developed a method to assess small boat (<15m) capsize risk [**3.6**] in response to the Marine Accident Investigation Branch's (MAIB) mandate to reduce the number of fishing vessel accidents in the UK in 2002. The Maritime and Coastguard Agency (MCA) commissioned model scale experiments between 2004 and 2010 to the UoS Wolfson Enterprise Unit to fill gaps in sparse data from actual incident reports. A universal scaling law was developed to determine the minimum wave height that can cause any vessel to capsize. The results showed several classes of registered UK fishing vessel carried a high capsize risk in wave conditions previously considered safe and provided guidelines (later referred to as the Wolfson Stability Guidance) for boat owners to assess and reduce this risk.

R6 UoS robotics and autonomy research since 2006 has developed methods to increase the area over which 3D visual mapping data of the seafloor can be gathered and interpreted. The development of hover-capable Autonomous Underwater Vehicles (AUVs) and cameras systems improved near seafloor terrain following and visual survey capabilities [**3.7**]. The NEMO (Griffiths, Boyd and Blake EP/F066767/1) and BioCam (Thornton, NE/P020887/1) projects increased survey extent by developing novel imaging hardware and colour correction methods to allow high-resolution imaging from 10m instead of 2m altitude. Automated methods to interpret features larger than a single image's footprint (e.g. habitats, cables, pipelines, mineral deposits) in [**3.8**] achieved a 2~3 factor increase in classification accuracy by incorporating position information in deep-learning image analysis. This allows tens of thousands of images spanning multiple hectares to be grouped and ranked in order of similarity in near real-time for summarised representations and feedback to improve the planning of observations during survey expeditions.

3. References to the research

3.1 Dedes, E K., **Hudson, D.A.**, **Turnock, S.R.** (2012) Assessing the potential of hybrid energy technology to reduce exhaust emissions from global shipping. Energy Policy 40, 204-218. https://doi.org/10.1016/j.enpol.2011.09.046

3.2 Parkes, A.I., **Sobey, A.J.**, **Hudson, D.A.** (2018) Physics-based shaft power prediction for large merchant ships using neural networks. Ocean Engineering 166, 92-104. https://doi.org/10.1016/j.oceaneng.2018.07.060

3.3 Badoe, C.E., Phillips, A.B., **Turnock, S.R.** (2015) Influence of drift angle on the computation of hull–propeller–rudder interaction, Ocean engineering 103. 64-77. https://doi.org/10.1016/j.oceaneng.2015.04.059

3.4 Hirdaris, S.E., **Price, W.G.**, **Temarel, P.** (2003) Two- and three-dimensional hydroelastic modelling of a bulker in regular waves. Marine Structures 16(8), 627-658. https://doi.org/10.1016/j.marstruc.2004.01.005

3.5 Cripps, R.M., Dulieu-Barton, J.M., Jeong, H.K., Phillips, H.J., **Shenoi, R.A.** (2006) A generic methodology for post-damage decisions, Journal of Ship Production 22(1) 21-32. Available on request.

3.6 **Deakin, B.** (2010) Collating Evidence for a Universal Method of Stability Assessment or Guidance. Transactions of The Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering 152 (Part A2 2101), A-85. https://doi.org/10.3940/rina.ijme.2010.a2.175

3.7 Akhtman, J., Furlong, M., Palmer, A., Phillips, A.B., Sharkh, S.M., **Turnock, S.R.** (2008) SotonAUV: The design and development of a small manoeuvrable autonomous underwater vehicle, International Journal of the Society for Underwater Technology 28(1), 31–34. https://doi.org/10.3723/ut.28.031

3.8 Yamada, T., Prügel-Bennet, A., **Thornton B.** (2020) Learning Features from Georeferenced Seafloor Imagery with Location Guided Autoencoders, Journal of Field Robotics. https://doi.org/10.1002/rob.21961

4. Details of the impact

Cleaner - Reduced CO2 emissions

I1 Since 2014, Shell Shipping and Maritime (SSM), one of the largest liquified natural gas (LNG) carrier operators in the world, have made over GBP3,000,000 in internal investment to adopt methods developed in **R1** and **R2**, including sponsorship of a chair in Ship Safety and Efficiency at UoS. In 2014, SSM piloted the trim and draft optimisation measures based on the modelling in **R1** on their operational fleet, and have to date (up to 31 July 2020) deployed the method to more than 70 in-service vessels. This has achieved a cumulative fuel saving of GBP30,000,000 and 200,000Mt reduction in CO2 emission by SSM that would not have otherwise been possible [**5.1**]. The innovation manager at SSM states "*UoS … addresses fundamental research questions that are very relevant to Maritime. Their programme has a major impact on our company and the UK economy at large*" [**5.1**]. The modelling in **R1** has had impact beyond SSM in 2020 through an Innovate UK Knowledge Transfer Partnership led by Silverstream Technologies, who are leveraging the combined physics-based and data driven modelling to optimise ship efficiency gains using their proprietary air lubrication technology [**5.2**].

I2 In 2018, CJR propulsion Ltd., a Southampton propeller manufacturer, adopted CFD design methods of **R2** as part of a GBP4,000,000 investment in manufacturing facilities. This led to the launch of a rapid design and production service to deliver bespoke ISO 484/2-1981 Class S certified propellers in just 2 weeks, more than 6 weeks faster than the industry standard. The managing director (MD) states they can now offer "*an unrivalled solution to replace damaged propellers*" and can *"fix issues in a timeframe that the owner is likely to accept*". Delivering this unique service has secured "*hundreds of thousands of pounds in charter revenue*" for CJR customers. The MD concludes "*we would not be able to guarantee this two-week design and production service if it was not for the advanced, in house CFD capability developed at UOS*" [**5.3**].

Safer – Guidance, regulations and operating practices

I3 In 2014, Lloyd's Register (LR), a classification society regulating more than 21% of global ship construction (by tonnage), changed their Rules & Regulations for the Classification of Ships (Part

3 Ch. 16 Section 5 and Part 4, Ch. 8 Section 14) to account for wave-induced 3D bending, or whipping, loads based on the modelling results of **R3**. According to the Technical Director, Marine & Offshore at LR, the rule change has "*directly impact(ed) approximately 160 ships*". LR's adoption of the methods in **R3** led to the International Association of Classification Societies (IACS) modifying their Unified Requirement S11A in 2016, requiring their members to account for whipping in container ships. LR's Technical Director explains that the modelling work has now impacted the structural design and safety of *"more than 900 new container ship*s *(internationally)*" [**5.4**].

I4 The UoS developed codebase implementing the modelling method of **R3** was adopted by the China Ship Scientific Research Center (CSSRC) in 2011, who built on the code to create their own hydroelasticity programme. This led to the China Classification Society (CCS), the largest ship classification society in China accounting for approximately 8% of global tonnage transported by sea, making the first ever guidance note in China on the springing and whipping of ships in 2018, with the corresponding rule change (Section 7.2.6.3; Whipping) in 2019 [**5.5**].

I5 UoS maritime engineering expertise has had impact on the Solent region's local economy through LR's decision to invest in a new global technology centre on the UoS campus. LR's relocation in November 2014 was driven by the recognition that "*co-location with a research-intensive university would enable collaboration at a greater scale, essential in a rapidly changing world*", citing the unique influence and leadership of the UoS Southampton Marine & Maritime Institute in the sector. The decision led to LR investing more than GBP25,000,000 in offices and facilities between 2014 and 2020, bringing "*400 professional salaries into the local economy*" and generating GBP180,000,000 of gross value added income to the region [**5.4**].

I6 The composite modelling methods in **R4** have led to a life extension program across the Royal National Lifeboat Institution (RNLI) all-weather composite rescue lifeboat fleet that would not have otherwise been possible. The RNLI operates more than 80 composite rescue lifeboats that were originally developed in partnership with the UoS and introduced to the RNLI fleet in 1996. The exceptional safety track record of these lifeboats and development of principled methods for assessing, documenting and evidencing damage progression and structural impacts in aging marine composites (**R4**) led to a key decision by the RNLI in 2014 to inspect and where appropriate extend the life of their composite fleet by 25 years using the evidence generated using the methods developed in **R4**. The Principal Naval Architect at RNLI states "*The Severn life extension programme will allow the RNLI to retain existing vessels, avoiding in the region of an GBP80,000,000 spend when compared with building new tonnage*", going on to say they *"expect that the entire fleet will be life extended … the significant saving would (not be) possible had it not been for the rigorous, high quality, collaborative work with the University of Southampton*" [**5.6**].

I7 In November 2018 the Maritime and Coastguard Agency (MCA) adopted the Wolfson Stability Guidance method of **R5** in "Marine Guidance Note 526 (F)" as UK-wide capsize assessment policy regarding capsizing for all vessels under 15m in length [**5.7**]. The guidelines apply to more than 6000 UK vessels. According to MAIB reports, prior to its introduction there were an average of 3.7 fishing vessel capsize incidents per year between 2000 to 2018, but only 1 UK-registered fishing vessel capsize incident has been reported since the method's introduction. Corresponding MAIB reports since have instructed "*all existing vessels of under 15m to be marked using the Wolfson Method*" (2016/130 [**5.8**]), and that shipyards "*Amend … construction standards to include a requirement for new fishing vessels and vessels joining the UK fishing vessel register to be fitted with a Wolfson freeboard mark*." (2016/132 [**5.8**]), and "*encourage owners of fishing vessels of under 15m … engaged in trawling, scalloping and bulk fishing to affix a Wolfson Mark to their vessels and operate them in accordance with the stability guidance provided*" (2016/134 [**5.8**]).

Smarter – autonomy in extreme environments

I8 UoS visual mapping and data interpretation methods (**R6**) were adopted by [text removed for publication] who conducted three dedicated robotic seafloor mineral surveys in the high-seas, outside of national jurisdiction and exclusive economic zones. [text removed for publication]

I9 The methods in **R6** were applied during the Schmidt Ocean Institute's #Adaptive Robotics ocean survey expedition that took place off the coast of Oregon USA in July 2018. The philanthropic organisation (founder Eric Schmidt, former CEO Google LLC) dedicated a 17 day expedition on their Research Vessel Falkor to support the initiative. During the expedition, multiple AUVs were deployed to generate the largest ever continuous visual maps of the seafloor, which covered more than 17.8 hectares at sub-centimeter resolution [**5.10**]. **R6** technology was also used by Team KUROSHIO, Japan's 2018 entry to the USD7m International Shell Ocean Discovery Xprize competition, where visual data was used to progress to the final where the team placed second, receiving a USD1.1m prize and an award from Japan's Prime Minister Shinzo Abe in 2019 [**5.11**].

I10 In 2019, the BioCam mapping instrument developed in **R6** was used to survey the Darwin Mounds UK Marine Protected Area (MPA), together with UK government's Joint Nature Conservation Committee (JNCC). The data collected by BioCam led to the discovery of a whale carcass and plastic litter in the MPA and was covered by the BBC and Times [**5.12**, **5.13**]. The data obtained showed for the first time, the hectare-scale distribution of live cold-water coral, a UNESCO approved essential ocean variable, and their impact on the distribution of Xenophayaphorea, a large single cell organism recognised as a Vulnerable Marine Ecosystem indicator species, where understanding the distribution of these protected species is critical to monitoring the MPA's ecosystem health. The Marine Monitoring Evidence Manager at JNCC stated to the press that the methods developed at UoS, "the data BioCam collects could support marine conservation by providing vital evidence at a large scale about how effective measures like marine protected areas are at conserving our environment, especially in fragile, complex habitats that can't be physically sampled" [**5.13**]. In 2019, BioCam was integrated in the UK National Marine Technology Roadmap as a unique capability for UK marine science [**5.14**].

5. Sources to corroborate the impact

5.1 Letter from Technology, Innovation and Decarbonisation, Shell Shipping and Maritime
5.2 Clean Shipping International Silverstream https://www.csi-newsonline.com/news/article/silverstream-technologies-wins-machine-learning-grant.html
5.3 Letter from Managing director, CJR Propulsion
5.4 Letter from Technical Director, Marine & Offshore, Lloyd's Register
5.5 Letter from Research Professor, China Ship Scientific Research Center
5.6 Letter from Principal Naval Architect, RNLI
5.7 MCA MGN 526 Stability Guidance for Fishing Vessels – Using the Wolfson Method https://www.gov.uk/government/publications/mgn-526-stability-guidance-for-fishing-vessels-wolfson-method
5.8 MAIB 2018 Annual Report (see pages 50 and 51 for recommendations 2016/130, 132, 134) https://www.gov.uk/government/publications/maib-annual-report-2018
5.9 [text removed for publication]
5.10 Environment, Coastal and Offshore Magazine #Adaptive Robotics Article https://www.ecomagazine.com/news/oceans/artificial-intelligence-guides-rapid-data-driven-exploration-of-changing-underwater-habitats
5.11 Shell Ocean Discovery USD7m X-prize winners announced https://www.xprize.org/articles/ocean-discovery-winners-announced
5.12 BBC news: Whale carcass encountered on deep sea survey off Scotland https://www.bbc.co.uk/news/uk-scotland-highlands-islands-49753440
5.13 The Times: Protected coral reef is blighted by plastic waste https://www.thetimes.co.uk/article/protected-coral-reef-is-blighted-by-plastic-waste-03k85j63v
5.14 National Marine Facilities Technology Roadmap 2019/20 https://noc.ac.uk/files/documents/about/ispo/NMF_Technology_Roadmap___1920_V3.pdf