Institution: University College London		
Unit of Assessment: 12- Engineering		
Title of case study: Research into new maritime structures and systems exploited in novel designs by commercial and naval designers and builders.		
Period when the underpinning research was undertaken: 2000- 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:**
Giles Thomas	Professor of Maritime Engineering	2014 – present
David Andrews	Professor of Engineering Design	1993 – present
Richard Bucknall	Professor of Marine Engineering	1995 – present
Jeom Paik	Professor of Maritime Technology	2014 – present
Paul Wrobel	Professor of Naval Architecture	2008 – present
Alistair Greig	Professor of Marine Engineering	1987 – present
Rachel Pawling	Researcher	2014 – present
John Calleya	Researcher	2013 – 2018
Period when the claimed impact occurred: 2013 - 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

This case study focuses on Marine Engineering, illustrating three complementary strands of research for improving ship design, and focusing on improved safety, comfort, stability and performance for ships and vessels. From the original UCL trimaran concept, the US Navy has built a fleet of thirteen Independence Class ships. World leading construction companies of offshore installations such as Hyundai Heavy Industries (HHI) and Daewoo Shipbuilding and Marine Engineering (DSME), implement UCL research outputs for their safety engineering of topside modules of floating production storage and offloading vessels (FPSOs). Shipbuilder, Incat, have incorporated UCL outcomes to guide the design of their vessels, introducing structural changes and saving EUR4,700,000 worth of alloy and fabrication costs. Novel design and analysis methods have been incorporated into the MAESTRO software to optimise ship structural design (used globally across 23 countries), and Paramarine® (SURFCON) software (with over 200 user organisations worldwide).

2. Underpinning research

UCL Marine Engineering research focuses on improved ship engineering for defence, commercial and complex ship designs. This is presented in three complementary strands of research; i) novel design concepts for trimarans, catamarans and complex ships (ii) shipping optimisation through nonlinear finite element models and (iii) reduced waste emission from the shipping industry.

UCL research on ship design has focussed on novel designs for trimarans and catamarans and new design approaches for complex ships. UCL developed the trimaran ship concept and led research activities in this field; from initial design concept, computational and experimental research and analyses of ship trials, along with contributions to a Classification Society's Ship Design Rules (**R1**). The concept was adopted by the UK Ministry of Defence (MoD) with a scaled 6m trimaran model of a 3,000-tonne destroyer, designed at UCL. When commencing an extensive series of trials for design and operational performance in 2000 (such as sea-keeping and helicopter operations), the results of this UCL-led research were sufficiently promising for the Defence Evaluation and Research Agency (DERA) to commission a two-thirds-scale Trimaran Technology Demonstrator built by Vosper Thornycroft, Southampton (UK).

UCL revolutionised the trimaran concept through predicted performance from hydrodynamic and structural perspectives, in turn publishing a comprehensive guide to the preliminary design of trimaran vessels (**R2**). UCL research into trimaran performance continued through

Office of Naval Research (ONR) funding with The Atlantic Center for the Innovative Design and Control of Ships (ACCeSS), with UCL as the only UK academic partner. Working with the Naval Surface Warfare Center (NSWC) Carderock on the design, testing and technology development for trimaran hullforms research addressed parametric resonance (the interaction of waves with hullform) and side-hull positioning, namely the relative location of the smaller sidehulls to the centre hullform (**R3**).

Catamaran hullforms are predominantly used as high-speed craft for both commercial and naval applications. They need to be lightweight, but strong enough to withstand loads imparted onto them from large waves. Research at UCL, in collaboration with Incat Tasmania, Revolution Designs and the University of Tasmania, has investigated the motions and loads characteristics of high-speed craft through a combination of numerical work, full-scale measurements and physical model experiments (**R4**). This work has been funded by a series of Australian Research Council Linkage grants, the most recent awarded in 2018; with additional partners being the National Research Council of Italy - Institute of Marine Engineering (CNR-INSEAN) and the University of New South Wales. Results from both towing tank and drop test experiments with a hydroelastic model provided a new understanding of the effect of hullform shape on the magnitude of wave loads and how changes to the form of the centrebow can reduce the loads experienced by the vessels (**R4**).

UCL research into a more architectural approach to complex ship design resulted in a highly novel approach, the Design Building Block (DBB) approach. This changes the basis of the initial ship synthesis and hence the resultant design process from the largely "outside-in" underwater hull form focus to an "inside-out" architectural approach, integrated with traditionally preferred sizing with a balance between weight, space and stability. By driving the size of a given design option from the internal and upper decks architectural demands this enables a more informative design exploration, bringing critical operational and human aspects to the fore in initial complex ship design decision making (**R5**) and with this a better basis for costing and efficient design for production.

From a safety perspective, accidents associated with ships and offshore structures continue to occur and can lead to environmental catastrophes with loss of lives and assets. Work at UCL identified that qualitative approaches with intuitive models and insights are not accurate enough to calculate frequency and consequence and assess risks. Therefore, to improve floating production storage and offloading vessels (FPSOs) safety against accidents, quantitative risk assessment methods have been developed using advanced computational models and physical model testing.

A new probabilistic method was developed to select a set of credible accident scenarios, where probability density distributions for individual random parameters affecting an accident were characterised based on a large database of historical evidence and a sampling technique was employed to select a limited number of realistic scenarios. Nonlinear finite element method models involving structural crashworthiness in accidents have been formulated for the consequence analysis. Ultimate Limit States (ULS) for ship structural design optimisation with multiple objectives, were implemented for ship optimisation process. ULS calculations (**R5**, **R6**) were incorporated in ship design software Paramarine® and MAESTRO, to perform fast ULS calculations at each iteration step for the optimisation process.

Full-scale or large-scale physical model tests on steel stiffened plate structures (which are the dominant feature of ship and offshore structures), have been conducted in association with direct measurements of welding-induced initial imperfections, ultimate compressive limit states at cryogenic condition triggered by brittle fracture, ultimate limit states under lateral patch loading in fires, blast pressure characteristics in hydrocarbon explosions, and collision impacts between ships and icebergs in Arctic operations (**R6, R7**).
Global shipping currently accounts for approximately 3% of the world's total greenhouse gas emissions. Two major EPSRC research projects were led by UCL to find solutions to reduce these emissions. UCL developed technical models of ship performance with the ability to

accurately predict the influence of alternative fuels, hydrodynamic devices and efficiency improvement techniques, such as sails and micro bubbles, on fuel consumption and emissions. A concept design tool, the Ship Impact Model (SIM), was developed to rapidly calculate the technical performance of a vessel with one or more Carbon dioxide Reducing Technologies (CRTs) at an early design stage. The SIM was used to assess which selection (individual or combination) of CRTs have the most potential, in terms of cost-effectiveness and under other technical, operational and regulatory influences (**R8**). These technical models were then integrated into a UCL-developed techno-economic model of the global shipping industry, GLOTRAM. The GLOTRAM model reflects changes in the shipping sector by simulating its growth over time.

UCL researchers identified that greater efficiency could be achieved through waste heat recovery and worked with a marine diesel-engine manufacturer (MTU), Lloyds Register and Bowman Power Ltd with funding from Innovate UK. In this work, the waste heat recovery process was modelled and practical testing carried out in conjunction with Cranfield University. The energy efficiency results were applied to typical operational profiles of small ships (such as ferries and coastal tankers) to determine overall efficiency savings; typically, savings of 5% were identified leading to a payback in approximately six years.

3. References to the research

R1. **Andrews DJ** (2003) ‘A creative approach to ship architecture’, RINA *Transations International Journal of Maritime Engineering*, 145. DOI Ref No. 10.3940/rina.ijme.2003.a3.9031

R2. **Andrews DJ**, Chapter 46 `Multihulls', Ship Design and Construction (Ed. T. Lamb) SNAME, New Jersey. 2004. Volume II: ISBN-13: 9780939773411

R3. McDonald TP, **Bucknall RWG**, **Greig AR**. (2013) Comparing Trimaran Small Waterplane Area Center Hull (TriSWACH), Monohull and Trimaran Hullforms: Some Initial Results. *Journal of Ship Production and Design*, 29 (4). https://doi.org/10.5957/jspd.2013.29.4.211

R4. Shabani B, Lavroff J, Davis M, Holloway DS, **Thomas G.** (2018) Slam loads and kinematics of wave-piercing catamarans during bow entry events in head seas. *Journal of Ship Research* 62(3), September 2018, pp. 134-155(22). doi: 10.5957/JOSR.180001.

R5. **Andrews DJ** (2006) Simulation and the Design Building Block approach to the design of ships and other complex systems. published in Proceedings of the Royal Society Series A (2006) 462. https://doi.org/10.1098/rspa.2006.1728

R6. **Paik JK** (2018) Ultimate limit state analysis and design of plated structures’, 2nd Ed, John Wiley & Sons, Chichester, UK, (ISBN 978-1-119-36779-6).

R7. **Paik JK** (2019) Advanced structural safety studies with extreme conditions and accidents’, Springer, Singapore. (ISBN 978-981-13-8244-4).

R8. **Calleya J, Pawling, R, Greig, A.** (2015) Ship impact model for technical assessment and selection of Carbon dioxide Reducing Technologies (CRTs). *Ocean Engineering*, 97, pp 82-89. DOI: 10.1016/j.oceaneng.2014.12.014

4. Details of the impact

UCL engineering continues to work on shipping optimisation for defence and commercial use, to improve ships’ design, performance, safety and stability. For example, through novel design shipping concepts, research outputs continue to generate shipping contracts and reduce manufacturing costs. UCL work has also implemented additional safety parameters through ship design software, in turn promoting environmental changes for shipping emissions pathways. As such, work on low carbon technology and waste recovery have reduced environmental impact in the naval industry.

UCL trimaran concept in shipping industry

UCL developed the new concept of a trimaran ship; the research demonstrated advantages of trimaran ships for ferries and naval vessels (**R1-R3**). These ships have high speed characteristics due to their slender hulls, large deck areas for carrying cargo and equipment, inherently good performance in waves (over 50% reduction in motion sickness compared to a catamaran), yet providing extended operational profiles compared to monohulls (up to 70% improvement) (**S1**). Large ship builders have used UCL research outputs (**R1-R3**) to build their vessels. For example, 13 Independence Class trimarans of Littoral Combat Ships (LCS) have been constructed for the US Navy between 2010-2020 (the latest USS Savannah was launched on 8th September 2020). Four LCS are currently under construction with a further three on order **(S2)**, with the contract for each vessel worth approximately USD584,000,000 (**S2**). UCL research also led Austal USA (a global defence and commercial ship builder) to construct four high speed trimaran ferries for Fred Olsen Cruise Lines, each costing approximately AUD95,000,000 **(S2)**.

Another large high-speed ferry builder, Incat, has used research outputs (**R4**) to guide the design of their vessels, to ensure that their vessels are structurally reliable. UCL research has led to changes in the bow shape of Incat vessels to reduce the wave loads and improve passenger comfort (by 25%), leading to structural weight savings of the order of "[TEXT REMOVED FOR PUBLICATION] *in large vessels, this reduction in alloy and fabrication costs is worth approximately* [TEXT REMOVED FOR PUBLICATION]" **(S3)**.

The DBB approach (**R5**) has be used to develop ship designs for organisations and companies such as the UK MoD, BMT, DSTL, UK Shipbuilders & Shiprepairers Association, Canadian Defence Dept, US Navy ONR and Columbian Navy. Many of these studies were in support of governments and industry decision-making on major warship programmes (e.g. UK Type 26 Frigate, Canadian Joint Support Ship programme, UK Offshore Patrol Vessels, new Colombian Frigate). The DBB approach has also provided insights to inform specific design policies (e,g, topside design (NDP), personnel movement beyond just escape (UK DNA), design for survivability (DSTL), AXV impact on ship design (Babcock, BAES, NDP) and distributed systems (USNavy-ONR).

Improved safety for naval architecture design

UCL research into safety approaches (**R6, R7**) has led to changes of practice in global industry leaders. The outcomes from UCL research associated with quantitative risk assessment and management against fires and explosions have been transferred to the world's leading construction companies of offshore installations, namely Hyundai Heavy Industries (HHI) and Daewoo Shipbuilding and Marine Engineering (DSME). They partnered in the Joint Industry Projects and are using research outputs (**R6, R7**) for their safety engineering of topside modules of FPSOs, for safer structures against extreme conditions and accidents. The outcomes have been used to achieve safer structures with improved tolerances against such extreme conditions and accidents. HHI state **(S4)** that using research outcomes has "*provided the impacts associated with not only economical benefits by lowering engineering costs but also safer structural designs by enhancing the safety and production quality. Depending on the complexity and size of structures, the benefits have been achieved up to 5 million USD per vessel*".

UCL research outputs on ULS (**R5, R6**) have been directly implemented into MAESTRO software, for design optimisation. Specifically, into ALPS/ULSAP and ALPS/HULL computation modules, to provide computational efficiency and greater accuracy for buckling and ultimate strength for plates and stiffened panels, and hull girder collapse for ships. These outputs have been successfully integrated into MAESTRO to improve ship structural design. MAESTRO Marine LLC state "*The combined capabilities of MAESTRO with ALPS/ULSAP has ensured that MAESTRO has an advanced capability for structural panel-level limit-state analysis. Together the ALPS computational tools enable large scale optimization of sophisticated warships and advanced commercial vessels…and in supporting effective in-service structural engineering for ships through their life cycles*." **(S5)**.

There are 90 active ALPS users are in 23 countries, including Navy (eg US, Japan, Australia, Spain, Brazil, Columbia, South Korea), Coast Guard (eg USCG) and engineering companies (eg Navantia, Ingles, BIW, DSTO, SeaxeMers, Serco). User SpaarnWater have used Maestro for structural evaluation of maritime objects for over a decade **(S6)**. In a testimonial

SpaarnWater state "*MAESTRO is an excellent tool to perform a structural analysis of a complete maritime structure already in an early stage of the design process supporting the naval architect in his design decisions. SpaarnWater will continue to use MAESTRO as its main tool in structural design and analysis of maritime objects*."

Qinetiq, another user of UCL computational models through Paramarine®, state the tool is "*an integrated naval architectural design and analysis tool set (enabling) seamless collaboration between global teams*", including *"over 200 organisations worldwide"* and used on "*designs from aircraft carriers and submarines to commercial ships and megayachts*" **(S7)**.

Reducing the environmental Impact of shipping

Through stakeholders' collaborations, UCL research outputs have also helped reduce the environmental impact of the shipping industry by providing tools that support development of low carbon technology and better waste recovery. The improved technical models for ship designs, technology developments, and low carbon technology (**R8**) were amalgamated into GLOTRAM, UCL Energy Institute's (UCL-EI) techno-social-economic model of the global shipping industry. GLOTRAM influenced the shipping industry through changes in transport demand, macroeconomics (such as fuel, carbon price and newbuild price inflation), and the availability of technology and regulation (such as regulations on greenhouse gases and other emissions to air).

As such, the success of UCL-EI collaboration led to the allocation of the 3rd IMO GHG study, commissioned by the UN agency International Maritime Organisation (IMO) estimating the total GHG emissions from shipping; and has become a key reference in industry and policy debates. This work was submitted in its entirety to the IMO by the governments of Belgium, Denmark, France, Germany, Marshall Islands, Netherlands, Solomon Islands, Tonga, Tuvalu in the 71st session UN IMO Marine Environment Protection Committee (MEPC), at a critical point in the negotiation leading up to the climate deal **(S8)**. Not only has the MEPC become the key reference for future shipping emissions pathways aligned with the Paris Agreement temperature goals **(S9)**, but also provides technical background for specifying key commitments in the UK government's breakthrough policy Clean Maritime Plan, as well as to achieve UK government objectives on reaching net-zero by 2050.

Through the UCL-Bowman Power collaboration on marine engines, UCL research outputs on waste recovery led to the development of a new marine waste heat recovery unit. Independent tests at Cranfield University showed that this new system "*recovers 30% of waste heat thereby improving efficiency in the region of 5%"* **(S10)**. It is now being readied for commercial and naval marine markets with ongoing discussions with shipping company Stena.

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Is this the world's best ship design? The Austal 102 trimaran: http://bit.ly/GCOYvA
S2. Austal News
S3. Testimonial email from INCAT designer
S4. Testimonial letter from managing director, HHI safety engineering
S5. Testimonial letter from Managing Partner MAESTRO Marine LLC
S6. Testimonial from SpaarnWater: https://www.maestromarine.com/testimonials/
S7. Case Study: Paramarine® for Commercial Vessels https://www.qinetiq.com/en/blogs/paramarine-case-study
S8. IMO (2018) Resolution MEPC.304(72) on Initial IMO Strategy on reduction of GHG emissions from ships.
S9. Testimonial letter from former Head of Air Pollution and Energy Efficiency at the International Maritime Organization (IMO). (*From Bartlett EI Impact Statement*)
S10. https://www.bowmanpower.com/blog/bowman-power-at-inec-2018/