Institution: Lancaster University		
Unit of Assessment: 10, Mathematical Sciences		
Title of case study: Novel extreme value methods used to optimise the structural integrity of over 8% of worldwide offshore oil and gas facilities		
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:**
Professor Jonathan Tawn	Distinguished Professor of Statistics	01/09/1992 - present
Dr Emma Eastoe	Lecturer in Statistics	12/03/2003 - present
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

The research of Professor Jonathan Tawn and his team has led to a demonstrable change in how offshore engineers design, build, maintain and refurbish billions of dollars of offshore oil and gas facilities to ensure safe and sustainable operations. The team's extreme value methods have been fundamental to optimising the assessment of the structural integrity of over 8% of global infrastructure, against a range of individual and joint natural hazards. Through improved statistical modelling and inference, a range of organisations within the offshore sector, from multinationals through consultancies to regulators, have been able to ensure substantial financial and societal benefits without jeopardising the level of accepted risk.

Between 2014 and 2020 Lancaster's methods have been the fundamental statistical driver in:

- Shell's new statistical software which they estimate to have saved them up to USD100million when applied globally, across over 50 of their offshore structures.
- Total's ground-breaking approach to refurbishment of facilities in the Danish sector of the North Sea.
- The regulation and design specification of hundreds of new and existing offshore structures world-wide, impacting across a wide range of large-scale offshore engineering industries, including BP, Conoco-Philips, and Petronas.

2. Underpinning research (indicative maximum 500 words)

Overview of Research Area: The offshore sector has approximately 1,500 oil and gas offshore platforms and mobile offshore drilling units sited around the world. These offshore systems are exposed to extreme environmental conditions, which affect the structural integrity of the infrastructure. Estimating the frequency of events that are more extreme than any previous observation is a key element in environmental risk assessment and prevention. Extreme value theory provides mathematically justified models as the basis for extrapolations from observed large events out to more extreme events.

Extreme value theory and its methods and applications, particularly in relation to environmental problems, has been a core research area at Lancaster for over 25 years. Professor Tawn and Dr Emma Eastoe lead on the underpinning research, and Dr Jennifer Wadsworth is also a key member of the Extreme Value Statistics group. Co-authors for the cited papers, below, were predominantly at Lancaster as PhDs or PDRAs when the work was undertaken. This work contributed to Professor Tawn being the inaugural winner of the RSS Barnett Award 2015 for outstanding contributions to environmental statistics.

The underpinning research falls into two distinct sub-areas of extreme value theory: **non-stationary extremes** and **conditional multivariate extremes**. Publications include two papers in Applied Statistics [3.2, 3.3] on the former and a landmark paper [3.4] in the prestigious RSS discussion paper series in JRSSB on the latter.

Non-stationary extremes: The need for non-stationary extremes research arises due to scenarios where the characteristics of the extreme values can vary either over time, for reasons including seasonality or climate change, or as a result of other drivers such as wave heights changing with wave direction. Critical to the methodology and inference is the incorporation of covariates and random effects to describe changes in extremal behaviour, which allows for the relationship with covariates to differ between extremal and non-extremal states (for example extreme temperatures increasing at a faster rate than average temperatures). It is also important to recognise the spatial contexts of problems, to ensure coherent application of the methods (for instance, the distribution of extreme waves changes smoothly over space and a statistical model should take this into account).

Lancaster's research addresses fundamental and generic problems for non-stationary extreme value scenarios. It provides novel methods for accounting for seasonality and developed the first Bayesian inference approach to parametric covariate modelling in the extreme values [3.1]. The first nonparametric smoothing methods for sharing spatial information about temporal trends in extremes are developed by [3.2] and the most efficient inference methods for covariate effects in univariate extremes are achieved in [3.3], by a mixture of pre-whitening for covariates in the body of the data and threshold methods for residual extreme specific changes.

Conditional multivariate extremes: Multivariate extremes involve the joint analysis of multiple hazards, such as winds and waves. Such hazards can cause different levels of failure to infrastructure dependent on which extreme combinations of hazard level occur simultaneously, and thus having estimates of the probabilities of these different occurrences is vital. Here, the development of flexible asymptotically justified dependence models and associated inference methods for the tail region of the joint distribution are of fundamental importance. In many cases these same methods can be applied for spatial modelling of a single hazard at multiple locations, for example wave heights at multiple offshore facilities.

Prior to research at Lancaster, multivariate extreme value methods were restricted to low dimensional cases and relied on the very strong and restrictive underlying asymptotic assumption of multivariate regular variation. Though convenient mathematically, this assumption was rarely found to be consistent with properties of environmental data and, if used, would typically result in an overestimation of the risk, leading to an over-conservative design. Research in 2004 by Heffernan and Tawn [3.4] addressed the problem through an entirely novel limit theory conditioning on a component of the vector variable being extreme. This limit result and associated models have produced a step-change in the methodology for multivariate extremes, enabling substantive application for high-dimensional analyses and a broad range of dependence structures. It has been applied widely in environmental and financial contexts, with over 500 citations.

Important additional parameter constraints on the model in [3.4] were developed in [3.5] and are now in the widely used software package TEXMEX, on CRAN, which is routinely used by statisticians undertaking multivariate extreme value analyses. The work was extended and tailored for application to spatial oceanography, in conjunction with Shell, including the first formulation into spatial offshore contexts [3.6].

Partnership with Shell: Key to this impact case study is that the Lancaster extreme value group works closely with Shell's statisticians to ensure that research developments address key industry problems and that their associated solutions can be directly implemented. This deep, broad and long-standing partnership includes Professor Phil Jonathan (20% FTE at Lancaster since 2018 and an honorary appointment from 2008) and a number of Shell's statisticians working at Lancaster monthly, 12 funded and co-supervised PhD students, 4 ex-Lancaster PhD students appointed by Shell and 6 PhD internships at Shell. The collaboration has resulted in 12 co-authored journal papers, including [3.6]. Many other papers which have been developed independently, by Lancaster and Shell statisticians, are also a direct consequence of this engagement (see papers that Shell has published in peer review journals listed in their letter of support [5.1, Appendix 2]). We have developed this partnership with Shell as they are world-leading in the strength of their statistics group, being able to both collaborate on leading-edge extreme value methodological research and majorly influence the adoption of statistical methods across the offshore industry sector.

3. References to the research (indicative maximum of six references)

Non-stationary Extremes

[3.1] Coles, S. G. and Tawn, J. A. (2005). Bayesian modelling extreme surges on the UK east coast. Phil. Trans. Roy. Soc. A: Mathematical, Physical and Engineering Sciences. 363, 1387-1406. https://doi.org/10.1098/rsta.2005.1574
[3.2] Butler, A., Heffernan, J. E., Tawn, J. A. and Flather, R. A. (2007). Trend estimation in extremes of North Sea surges. Applied Statistics (Series C), 56, 395-414. https://doi.org/10.1111/j.1467-9876.2007.00583.x
[3.3] Eastoe, E. F. and Tawn, J. A. (2009). Modelling non-stationary extremes with application to surface-level ozone. Applied Statistics (Series C), 58, 25-45. https://doi.org/10.1111/j.1467-9876.2008.00638.x

Conditional Multivariate Extremes

[3.4] Heffernan, J. E. and Tawn, J. A. (2004). A conditional approach to modelling multivariate extreme values (with discussion). J. Roy. Statist. Soc., B, 66, 497-547. https://doi.org/10.1111/j.1467-9868.2004.02050.x
[3.5] Keef, C., Papastathopoulos, I. and Tawn, J. A. (2013). Estimation of the conditional distribution of a vector variable given that one of its components is large: additional constraints for the Heffernan and Tawn model. J. Multivariate Analysis, 115, 396-404. https://doi.org/10.1016/j.jmva.2012.10.012
[3.6] Kereszturi, M., Tawn, J. A., Jonathan, P. (2016). Assessing extremal dependence of North Sea storm severity. Ocean Engineering, 118, 242-259. https://doi.org/10.1016/j.oceaneng.2016.04.013

4. Details of the impact (indicative maximum 750 words)

Lancaster's research in extreme value methods has been implemented by a wide range of industry sectors active in large scale off-shore engineering, including BP, Conoco-Philips, Petronas, Shell and Total. It has also been embraced by global industry regulators such as the UK Health and Safety Executive and the maritime registrar and classifier organisation Den Norske Veritas (DNV GL); uptake by these regulatory bodies has secured extensive and substantial impact across the offshore industry. The research has led to a demonstrable change in how offshore engineers design, build and refurbish billions of dollars of facilities globally to ensure safe operations. The benefits are not only massive cost savings to the industry, but also improved assessment of structural integrity and better design criteria.

Lancaster's partnership with Shell provides a direct pathway into impact, both in Shell and across the offshore industry. The partnership facilitates Shell's take up of the methods and helps them to create tailored approaches and software to assess the structural integrity of offshore oil and gas platforms world-wide. Evidence for our research being key to their methods comes through a detailed letter of support [5.1] from Shell UK's Senior Met-Ocean Engineer, and from their published research listed in [5.1, Appendix 2] that exploits, builds on, and heavily references, the underpinning research [3.1 - 3.6]. The reach of the impact comes from the wider adoption of the methods and the creation of associated impacts across both oil and gas companies and offshore engineering consultants, such as Offshore Consulting Group - see letter [5.2]. This reach has been enhanced by Shell's research publications and their engagement in large scale international multi-company projects (AWARE, LOADS and ECSADES). The current combined impact is to over 8% of worldwide offshore oil and gas facilities, with over 3% via Shell, and over 5% via Total, LOADS, and Offshore Consulting Group.

4.1 Impact on Shell: cost savings of USD 100 million through adoption of new methodologies

Shell used the underpinning research to develop internal software CEVA (Covariate Extreme Value Analysis) for the quantification of extreme ocean environments, used in offshore structural design [5.1]. This software has some similar functionality to TEXMEX (see Section 2) but incorporates non-stationary extremes modelling, the conditional multivariate extremes model and uncertainty quantification. CEVA has been used to re-assess the structural integrity of over 50 of Shell's operated offshore facilities globally over the period 2014-2020.

Quantification of the monetary value of improved methods for characterisation of extreme ocean environments in complex engineering operations is notoriously difficult, especially in light of different mitigation strategies, the economics of which vary in time. Nevertheless, Shell [5.1] estimate that the value of the improved statistical modelling of extreme ocean environments arising out of Lancaster's research is in the region of USD100million between 2014 and 2020. This figure is based on detailed calculations [5.1, Appendix 1] that take account the following:

a. North Sea 1: Re-analysis of offshore structures in shallow water, saving USD 25 million: Improvements in physical understanding of extreme waves suggested that historical estimates of wave and crest heights for Shell's ten structures in the southern North Sea had previously been underestimated. If this conclusion of under-design was correct, then there would have been an unacceptable risk of 'wave-in-deck' events. Such events require expensive mitigation measures, with the cheapest being de-manning and/or shut-off, costing in the order of USD1million per annum per structure. Improved characterisation of the extreme storm environment using CEVA demonstrated that wave-in-deck events would in fact occur at a much lower rate than anticipated, removing the necessity for such mitigation.

b. North Sea 2: Design of new platforms and seasonal deployments, saving USD55million: The CEVA methodology has been used for five new designs in the North Sea, reducing the risks associated with historical procedures which may have over- or under-estimated design criteria. CEVA also provides a consistent approach to estimating seasonal design criteria rapidly and accurately. It is used to estimate design criteria for seasonally deployed jack-up and floating structures with increased confidence. As a result, mobile offshore drilling units with lower design specifications can be utilised, thereby saving daily hire rates for the period of deployment.

c. Southern South China Sea/Gulf of Mexico: Revised met-ocean design criteria, saving USD20million: In conjunction with Malaysian oil and gas company Petronas, Shell has used the CEVA methodology to develop revised met-ocean design criteria for the whole southern South China Sea, establishing consistent met-ocean design criteria across the region. CEVA has been used for the design of new platforms, improving estimates of the air gap and design loads, directional pipeline design criteria, and reliable marine assurance (for example confirming the adequacy of moorings for drill vessels and work support barges in seasonal deployments). CEVA has similarly been used to estimate directional design criteria for the Gulf of Mexico. In total, at least 20 offshore facilities have been influenced.

4.2 Wider impact of methodologies through joint-industry initiatives

The requirement for (re-)assessment of structural integrity is driven by regulation, changing use, improved understanding of the ocean environment and structural loading from waves, winds and currents, and subsidence of the seabed. These drivers affect hundreds of structures worldwide. For example, recent years have seen considerable concern regarding waves impacting the decks or horizontal beams at the top of offshore structures, with increased risk of structural collapse. The offshore industry typically responds by way of joint-industry initiatives, often involving regulators such as the UK's HSE and Norway's DNV GL, to establish and maintain best practice. Lancaster's extreme value research has influenced a number of such projects, including those are outlined below.

a. Abnormal Wave Assessment and Risk (AWARE), 2015-20: This USD3billion project, executed by Total on behalf of the Danish Underwater Consortium, reassessed the reliability of structures in the Danish sector of the North Sea. Its main objective is the extension of the life of the Tyra gas field for 25 years, requiring modification, removal and decommissioning of existing facilities and construction of new infrastructure. Critical to the success of AWARE is reliable characterisation of extreme storm environments in the Danish sector of the North Sea. The project involved the development of software for estimation of extreme ocean sea states by the Danish Hydraulics Institute (DHI). This development, supported by Shell's statisticians, see [5.1, Appendix 2, paper by Hansen et al. (2020)], incorporated all of the elements of the underpinning research [3.1 - 3.6]. Total Danmark's Lead Structural Engineer states: "*The statistical methodology developed in AWARE to characterise the long-term behaviour of extreme ocean storm environments incorporates three important elements to which Lancaster University has contributed considerable research. These are (1) conditional multivariate extremes models, (2) non-stationary extremes models and (3) extreme value inference within Bayesian framework*" [5.3].

b. Loading and Reliability of Fixed Steel Structures in Extreme Seas (LOADS), 2016-2020: This GBP500,000 joint offshore industry funded project involving the Offshore Consulting Group

(OCG), HSE, BP, Conoco-Philips, Shell and Total, assesses structural reliability concerns globally. LOADS has exploited all of the elements of the underpinning research, particularly [3.1], [3.3] and [3.4], to estimate the environmental loads on offshore structures, including improved descriptions of the wave field kinematics, with implications for a significant proportion of the 1,500 oil and gas offshore facilities worldwide [5.2]. In particular, OCG states that "*the use of Heffernan and Tawn (2004) has allowed us to predict joint extremes of wave heights and wave periods. This is critical for predicting the occurrence of wave breaking, and hence extreme loading*." The Managing Director of OCG reports [5.2] that "*many of the statistical methods used by OCG owe their existence*" to Lancaster's research.

c. Environmental contours for safe design of ships and other marine structures (ECSADES), 2016-19: This is a GBP150,000 EU-funded project involving DNV GL, University of Oslo, Shell and HR Wallingford. Environmental design contours are a popular means of describing extreme ocean environments for offshore and coastal design. Ross et al. (2020), see [5.1, Appendix 2], reports that ESCADES establishes best practice recommendations for the use of design contours and informs DNV-GL design guidelines by incorporating Lancaster's non-stationary and conditional multivariate extremes methodology [3.1-3.6]

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

Letters of Support:

5.1. Shell (Senior Met-Ocean Engineer) - corroborating Shell's impacts, and their financial value, using Lancaster's statistical methods.

Appendix 1: Outline of procedure for estimation of approximate benefit based on Lancaster University research.

Appendix 2: Illustrative academic publications from staff at Shell, building on Lancaster University Research.

5.2. Offshore Consulting Group (Managing Director) - corroborating the value of Lancaster's statistical extreme value methods on LOADS and other projects.

5.3. Total Danmark (Lead Structural Engineer, Project Manager, AWARE Project) - corroborating Lancaster's statistical methods impact on the AWARE project.