Institution: University of Bradford		
Unit of Assessment: B12 Engineering		
Title of case study: Enhanced Automotive Product Development through Model-Based Failure Mode Avoidance Methodologies		
Period when the underpinning research was undertaken: 2006 - 2017		
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:**
Felician Campean	Professor of Automotive Reliability	1998 –
Andrew Day	Professor of Automotive Engineering	1985 – 2013 (now Emeritus)
Steve Wright	Reader in Materials	1986 - 2017
Amad Uddin	Post-Doctoral Research Associate	2015 - 2017
Martyn Jupp	Senior Research Fellow	2013 - 2014
Edwin Henshall	RAEng VP Integrated Systems Design	2006 – 2010 (now Honorary)
Period when the claimed impact occurred: 1 August 2013 - 2020		
Is this case study continued from a case study submitted in 2014? N		

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

A “Failure Mode Avoidance” (FMA) methodology for complex automotive systems engineering, based on our research on model-based methods for function and function failure analysis, was adopted and deployed at scale within Ford Motor Company and Jaguar Land Rover. This led to product development (PD) productivity improvement evidenced by (i) **Business results** – enhanced creativity, cost effectiveness and quality; (ii) **Improved processes** based on the adoption of the new methods; (iii) Enhanced **PD team effectiveness** and **capability improvement**, facilitated by the adoption of the methods; (iv) **Enrichment of learning and motivation** for the individuals and teams of engineers directly and indirectly reached by the research.

2. Underpinning research (indicative maximum 500 words)

The Bradford Engineering Quality Improvement Centre (BEQIC) team, founded by Prof Day and Dr Wright in 1995, and led by Prof Campean since 2000, has engaged successfully in collaborative research with the automotive industry (specifically Ford and Jaguar Land Rover, JLR) over 25 years, to develop processes, methodologies, methods and tools for design assurance and quality improvement in automotive Product Development (PD). Dr Henshall was appointed RAEng Visiting Professor in Integrated Systems Design (2006 – 2010, thereafter continued as Honorary), having previously worked as European Manager for the Ford Design Institute; he has contributed greatly to the development of the Failure Mode Avoidance (FMA) framework for Product Development. Two postdoctoral researchers (Dr Uddin and Dr Jupp – both subsequently employed by JLR) and one doctoral researcher (Dr Yildirim, currently with Hubei University) have contributed significantly to the fundamental underpinning research. Two KTP Associates (J. Hartley – TMETC, and J. Goodland – BAE Systems) as well 21 MPhil and 4 PhD researchers based in industry (at Ford and JLR) have contributed to the preliminary industrial validation of the methods in the early stages of the research.

The close interaction with Ford and JLR provided insight and motivation for research to address the prevailing effectiveness challenges in automotive PD. The existing methods for design assurance that underpinned the FMA practice in industry did not adequately support the design and development of complex automotive systems, with the increasing emphasis on software-based control systems. While advanced virtual engineering capability supported an increase in PD productivity, the gap in applicability of design assurance methods *early* in technology and systems design, led to persistent inefficiencies in PD (costly late engineering changes, quality issues at launch, warranty expenditure), despite adopting a systems engineering (SE) framework for PD. The research team worked to address the methodological root causes for these inefficiencies and to improve the integration of the FMA methods with the SE framework. The main challenges identified were: (i) the lack of a rigorous functional framework to underpin both FMA and SE analysis; (ii) shortcomings in the integrity of the current methods (underpinning both FMA and SE) for capturing system integration requirements within a complex multidisciplinary system (hardware / software /

controls / human); and (iii) the lack of coherence and integration between methods in the FMA process flow, leading to poor integrity of analysis in many cases.

Accordingly, the key elements of the underpinning research contribution include the development and validation of:

1) New model-based methods for function analysis - the System State Flow Diagram (SSFD)[1,2,3] and the Enhanced Sequence Diagram (ESD)[4]. Both methods are based on a rigorous representation scheme and a taxonomy for function / functional requirement articulation. These methods facilitate more rigorous functional models that are easier to interpret and support deployment of function failure analysis in the early conceptual phase of a new system or feature.

2) An Interface Analysis Template (IAT)[5] to guide a structured and comprehensive analysis of systems integration requirements, based on the systematic characterisation of interface exchanges (using a rigorous scheme and taxonomy), and the derived functional and performance requirements. The IAT provides the fundamental core that links the functional model of the system, the system requirements database, and the design assurance through Function Failure Analysis (e.g. using FMEA).

3) The "BEQIC Failure Mode Avoidance Framework" as a methodology that integrates model-based methods to support function analysis, function failure analysis, robustness and design verification in a coherent information flow. This addressed the gap in both theory and practice for (i) the horizontal integration of methods to support the methodological chain linking requirements analysis with verification methods based on failure modes and robustness; and (ii) the vertical integration of design assurance analysis across the levels of the system. The coherent model-based approach across the methods chain provides assurance for the rigour of the analysis of the design, supporting the achievement of "right first time design".

The approach to research adopted by the BEQIC academic team was to develop new methods and processes to address the identified gaps, and then to work collaboratively with industry to adapt the methods for adoption and transfer to wider engineering PD practice. The development of effective approaches to transfer the research-driven design methods and methodologies to industrial practice played an important part as translational research. This included both adaption of methods through co-development research for best practice process, and the approach to knowledge transfer. The approach adopted (developed by RAEng VP Henshall) promoted the use of a common systems approach as a reference context for both the communication of complex technical knowledge and the development of effective teamwork skills required for the effective application of PD methods.

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

1. Campean, IF., Henshall, E., Brunson, D., Day, A.J., McLellan, R., Hartley, J. (2011) A Structured Approach for Function Analysis of Complex Automotive Systems, SAE Int. J. Mater. Manuf., 4(1):1255-1267, https://doi.org/10.4271/2011-01-1268.[*led to an invited Technical Keynote delivered by Prof Campean for the Product Development Stream at the SAE World Congress Detroit, April 2011*]
2. Campean, F., Henshall, E., Yildirim, U., Uddin, A., Williams, H. (2013) A Structured Approach for Function Based Decomposition of Complex Multi-disciplinary Systems, in Abramovici, M. and Stark, R. (Eds): Smart Product Engineering, Proc 23rd CIRP Design Conference, LNPE Springer-Verlag Berlin Heidelberg, pp 191-200 [*Best paper award at the CIRP Design Conference 2013, Bochum*] https://doi.org/10.1007/978-3-642-30817-8_12
3. Yildirim, U., Campean, F., Williams, H. (2017) Function Modelling Using the System State Flow Diagram, Artificial Intelligence in Engineering, Design and Manufacturing, 31(4):413-435. DOI: https://doi.org/10.1017/S0890060417000294
4. Yildirim, U., Campean, F. (2020) Functional modelling of complex multi-disciplinary systems using the enhanced sequence diagram, Res Eng Design, 31, 429–448. https://doi.org/10.1007/s00163-020-00343-8

5. Uddin, A., Campean, F., Khan, M. (2016) Application of the Interface Analysis Template for Deriving System Requirements, Proc. International Design Conference "Design 2016", 543-552. https://core.ac.uk/download/pdf/76945845.pdf
6. Campean, I., Henshall, E., and Rutter, B. (2013) Systems Engineering Excellence Through Design: An Integrated Approach Based on Failure Mode Avoidance, SAE Int. J. Mater. Manf. 6(3):389-401. https://doi.org/10.4271/2013-01-0595

Grants

G1 Campean - Contract research – Jaguar Land Rover - Systems Engineering Design Excellence through Failure Mode Avoidance - GBP220,000 – 2014 -2017.
G2 Campean – Contract research – Ford Motor Company - Right First Time Through Design - GBP241,000 – 2011 – 2013.
G3 Campean – TSB - KTP008646 – BAE Systems - Manufacturing Failure Mode Avoidance - GBP118,000 – 2011-2013
G4 Day, Campean – TSB - KTP007377 – TMETC - GBP119,000 - Advanced Braking System Design for Full Electric Vehicles, 2009-2011
G5 Wright, Campean – EPSRC - GR/N06021/01 – Customer Correlated Life Prediction Models for Improved Design Verification of Automotive Components - GBP156,000 – 09/00 – 02/04.
G6 Campean – Collaboration Contract – Jaguar Land Rover – TAS - GBP3,675,000 – 2011-2020.

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

Ford Motor Company and **Jaguar Land Rover** are automotive original equipment manufacturers (OEMs) with significant global presence and large product development operations, and with wide recognition for their leadership in technology and customer-led innovation. The increasing complexity of automotive systems, in particular the adoption of intelligent and interconnected features to enhance safety and environmental sustainability of vehicles, amplifies the challenges for the effective management of product design and development. The focus on the integrity of the early system analysis and design is essential as it is the most effective way to impact the quality of the systems developed and the overall PD cost effectiveness. Both **Ford** and **JLR** have engaged with the BEQIC research team to co-develop effective approaches to *adapt, enhance and adopt* the FMA systems analysis methods and methodologies developed by the BEQIC team, to improve the integrity and effectiveness of their PD processes.

Ford Motor Company approached the BEQIC research team in *2011* [*G2*] "*to engage in a major action to refresh the methods and skills within our Product Development organisation to improve our right first-time performance in product development and launch*" [***S3***]. The resulting programme, deployed within Ford as **SEED** (Systems Engineering Excellence by Design), was rolled out on a global basis (**UK/EU**, **Turkey** and the **US**) between 2013-2020. Globally, over **1,000** engineers and engineering managers participated in the SEED internal training programme developed as part of the research collaboration with BEQIC (SEED programme is still ongoing). Following the collaborative research [G2], Ford *internal investment* to support the adoption and transfer of the methodology to PD practice was significant. This included the technical specialists' input to the research and internal dissemination, SEED facilitators' development programme and the time of engineers participating in the SEED internal courses) conservatively estimated at **7,000** engineer days, or approximately **GBP3,500,000** [***S1/p7***], with significantly more investment in the SEED application projects.

Jaguar Land Rover (**JLR**) – following the initial adoption of the BEQIC FMA methodology in *2011* (through a research-led short-course as part of the JLR Technical Accreditation Scheme (TAS) [*G5*]; [***S5***]), JLR engaged in 2014 a 2-year research project on "Systems Engineering Design Excellence through FMA" (SEDE) [*G1*]. The SEDE project aimed to enhance and extend the methods in the BEQIC FMA framework to integrate with the Systems Engineering approach adopted by JLR for complex vehicle features development. The research project also delivered a knowledge transfer package (as an enhanced short course delivered through the JLR TAS scheme [***S5***]) to support the transfer of the methods to JLR PD practice. Additional to the direct research funding [*G1*], significant *internal investment* was made by JLR to support the validation and adoption of the methods by PD engineering teams, conservatively estimated at approximately GBP**5,000,000** [***S2/p4***]. This included the engineering input for the research project for the case studies to validate the methodology (evaluated at *1,200* hours of engineering subject matter experts time); the direct cost of the advanced training for PD engineers delivered by BEQIC through the JLR TAS programme (GBP*530,000* for **374** engineers [part of *G5*]); the cost of the engineers' time for the training and the completion workplace based projects that every participating engineer had to undertake within a team context [***S2/p4***].

This does not include the investment in rolling out the methodology through the JLR internal FMA training (levels 1-3 [**S2/p3**]) – *updated following the research project*, which included a much larger number of PD engineers.

In addition, JLR has embarked on a major software upgrade for the DFMEA, which incorporates both the methods and the FMA methodology flow established as best practice by BEQIC research [***S4***]. This is now *used across the JLR PD organisation,* across all areas of engineering competence, and on all technology development and new vehicle programmes as part of the design assurance sign off at PD gateways. The efficiency savings from the use of the new software tool implementing the BEQIC FMA methodology flow was estimated to "*amount to several hundreds of engineering hours per programme*".

Given the significant internal investment from both Ford and JLR in both the collaborative research and the implementation of the research outcomes through the transfer of the methods to PD engineering practice, both companies have initiated an evaluation of the impact as ROI, conducted jointly with the BEQIC Team. In both cases, quantitative methods have been employed for a longitudinal study, to identify and capture the impact, including both the direct and indirect benefits. The results of this impact assessment exercise are documented in two reports: [***S1***] "Impact of the SEED Programme within Ford Motor Company", and [***S2***] "Impact of the Systems Engineering Design Excellence research project within JLR". In addition to the quantitative analysis, both reports include sample statements of impact from individual engineers – see: [***S1 p11, 13, 14; p12/Tables 3 &4; Appendix C, and Appendix D – p 38-39***]. [***S2 p9***].

Based on the evidence collected across Ford [***S1 & S3***] and JLR [***S2, S4, S5, S6***], the main impacts of the research can be summarised as:

A. **Business results**:

- ***Increased cost effectiveness, quality enhancement and warranty costs avoidance*** in PD. Examples: **Ford** Global Manual Transmission Core Engineering [***S3, S1/Appendix D/p38-39***] were able to "*reduce physical testing by **59% within 12 months** to January 2019*"; achieved "*a **99% warranty reduction** compared to the outgoing system*"; "*A design change on a transmission component led to **ongoing savings of EUR4,000,000***". **JLR** [***S2 p9***] "*showing a **97% improvement** so far*" in the ppm (defective parts per million); [S5] "*The function and function failure analysis provided a level of analytical focus … and avoided further spend on engineering design, development, tooling, testing and ongoing piece-cost that might otherwise have resulted if a decision to proceed had been made instead*".
- ***Innovation*** [***S3, S1/Appendix D/p37***] the application of SEED methodology at Ford on two major projects "***generated 15 patents** (25 applications, 15 granted, some still in process) and one Ford Technical Award*".
- The quantitative analysis based on 100 projects at **JLR** [**S2**] showed that "***24%** of the projects have identified at least one directly quantifiable business result as costs avoided / saved, quality improvement, time saved or customer experience enhancement*" [**S2/p2**].

B. **Improved Processes**

- ***Sustained changes in engineering and process practice*** – there is clear evidence of the penetration of the BEQIC methods in engineering practice at both **Ford** [see ***S1/p10***] and **JLR** [see ***S2/p1&6-8***] – "*the quantitative assessment has shown engagement from across all areas of engineering competence and all phases of PD, and across all levels of systems*". The timescales reflected by the data for the evaluation (7 years for Ford, 3 years for JLR) provide clear evidence that these methods are firmly embedded in engineering practice.

- ***Adoption of methods and tools*** – **JLR** have adopted a new software tool for FMEA that embeds the BEQIC methods and methodology flow; this is now used as the Corporate FMEA tool (commercially implemented by Reliasoft as a JLR custom version of xFMEA), and its use in PD at JLR gives "*big benefits in terms of quality of event and time efficiencies … amounts to several hundreds of engineering hours per programme*" [***S4***]. At **Ford**, the SEED methods have impacted the development of the Ford Engineering Design Environment [***S1***].
- ***Enhanced process efficie*ncy** – the FMA methodology facilitated early identification of potential failure modes avoiding late engineering changes with significant cost of rework; specific examples – **Ford** [***S1/p11 & 12/Table 3***] e.g. "*during the project we identified 20 missing failure modes and 100 additional causes*". **JLR** [***S2/p9***] e.g. "…*more than 200 new causes were identified in the DFMEA, with new requirements and test cases generated to mitigate them*"; of the 100 projects reviewed at JLR [***S2/p10***] 55% have reported identification of previously unidentified failure modes. At both Ford [***S1***] and JLR [***S2***] the further outcome from the discovery of new functional requirements, failure modes, test cases and verification methods was the development of ***new design standards and design and process core knowledge updates***.

C **PD teams' effectiveness and capability improvement**

- ***Closing the FMA skill gap*** – the development knowledge transfer actions contributed to closing the identified skills gap for effective design assurance in PD within a systems engineering context (at **Ford** the SEED internal training has reached over **1,000** engineers ***globally***; at **JLR** the ESA-FMA TAS module delivered by BEQIC reached **374** engineers; the internal JLR FMA training was also updated in line with the SEDE methodology).
- ***Enhanced communication within teams*** and ***enhanced engineering practice*** – both the quantitative analysis [e.g. ***S1/p13/Figure 7***] and individual statements [***S1/p13 & p41-42***]; [***S2/p9-10***]; and [***S4***] - show the clear impact on enhanced communication and teamwork effectiveness within PD teams. This leads to increased rigour in the application of the design assurance methods and methodologies, leading to knowledge generation and improved quality **[*S6*]**. Example quotes: Ford [***S1/p13***] "*the diligence and thoroughness through which we described every interface in great detail was greatly appreciated by the wider team and drove a level of discussion above anything that had happened on prior projects*"; "*it made people think, ask different questions and capture things that could be missed, and led to solutions that gave a better chance of programme success*". JLR [***S1/p10***] 33% of the projects sampled have reported "*more effective team-working*" as a benefit of the methodology.

D. **Enhanced individual and team learning and motivation.**

Without exception, all engineers at both Ford and JLR recognised their personal learning and skills gains, with a clear perception of motivation for continuous improvement [***S1/p13-14; S2/p11; S6***]. Example quote: [***S2/p9***] "*thanks to the positive feeling after using these tools, many members of the team have started to apply them in other projects with good results*".

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

S1. Ford Report on the Impact Evaluation of the SEED Programme (co-authored with Ford Engineers)
S2. Jaguar ESA-FMA Impact Report (co-authored with two JLR Engineers)
S3. Statement from Ford of Europe Powertrain Applications Chief Engineer
S4. Statement from Senior Manager - Quality Engineering, Jaguar Land Rover
S5. Statement from Business Improvement Manager, Jaguar Land Rover
S6. Statement from Quality Engineering & Product Compliance Director, Jaguar Land Rover