Institution: **Loughborough University**

Unit of Assessment: **B13: Electrical and Electronic Engineering, Metallurgy and Materials**

Title of case study: **Transformational Cost-Risk Reductions and Significantly Increased Safety Through Interdisciplinary Model Based Systems Engineering in Extremely Complex Operational Environments**

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

Loughborough University's (LU) interdisciplinary model based systems engineering (MBSE) research (2001–2010) has directly enabled life-saving operations by i) Developing synthetic vision systems to improve the safety of emergency services helicopter operations involving low level flight during day, night, all weather and conditions of zero visibility, and ii) Saving lives through a reduction in morbidity and mortality of babies born with congenital heart defects.

The impact translates directly into significant cost savings and safety risk reductions in expensive flight trials costing millions of pounds by BAE Systems **[5.1]**, and in supporting clinical practice/surgical interventions by University Hospital of Rennes **[5.2]** with a reduction in the morbidity and mortality of babies born with congenital heart defects in Brittany, France.

2. Underpinning research (indicative maximum 500 words)

The increasing inter-connectivity of today's complex systems has exceeded one individual's ability to comprehend the plethora of interactions/emergent behaviours. Over the past decade MBSE has slowly become the preferred technique for designing and understanding increasingly complex systems (in terms of performance, behaviour and their emergent properties). However, the overarching question has been "how to model and simulate complex systems across multi-disciplinary boundaries?" Research underpinning the impact here has given rise to novel simulation solutions across multi-disciplinary and multi-scale boundaries that successfully addressed this challenge by creating heterogeneous, coupled simulation environments. Research by Prof Kalawsky (Professor at LU since 1995 to present) was undertaken through a succession of projects and developed important innovative steps to create multi-disciplinary/multi-scale MBSE simulation environments. Their ability to solve complex systems problems has been validated against real-world applications. Key influencers underpinning the research included:

- EPSRC's e-Science RealityGrid funding enabled Kalawsky to extend heterogeneous modelling within a distributed simulation environment and its associated interactive visualization by exploiting visualization system architectures **[G3.1 and G3.2]** [Kalawsky, Nee (PhD 1996-2001), Dr O'Brien (Research Associate at LU 2008-2012) and Holmes PhD (2004-2011)]. This research **[3.1 and 3.2]** provided important new insights into novel simulation architectures (using grid technology) enabling creation of coupled heterogeneous computational/simulation/visualization environments. In particular, **[3.1]** solved the integration of real-time visualization with a distributed computational simulation environment by overcoming the effect of system latencies on real-time interactive visualization. Research **[3.2]** [Kalawsky and Holmes] and **[3.3]** [Kalawsky and Dr Al-Najdawi (Research Associate at LU 2006-2008)], overcame complex human perception issues associated with visually-coupled systems and optimal image compression for human perception respectively by overcoming critical performance requirements.
- e-Science Centre funding **[G3.3]** developed new human factors design guidelines [Kalawsky & O'Brien] to achieve real-time interactive visualization in visually coupled systems
- Comprehensive real-time modelling and simulation research **[G3.4]** [Kalawsky & Dr Atkins (Research Associate at LU 2005-2008)] provided the basis and subsequent establishment of innovative architectures for cross-domain coupled simulation systems.
- BAE Systems funded LU **[G3.5]** to support the UK DNAW (Day/Night All Weather) Demonstrator Programme to extend helicopter flight into both the night and adverse weather conditions by the safe use of synthetic vision (enabling operations in conditions currently outside of flying regulations). Kalawsky (2005 onwards) established the world's first

comprehensive coupled-simulator integrating real-time models of the atmosphere, sensor suite, avionic system performance, helicopter flight dynamics, synthetic vision system and models of human reaction time/behaviour. This research was subjected to a detailed integrity assessment (involving calibration against real-world flight trials and helicopter sensor/system performance), proving it comprehensively addressed perceptual issues of spatial awareness, and range to interference (collisions with pylons, terrain, telephone poles etc.) in obscured visibility conditions.

- EPSRC grant **[G3.6]** concerned with bridging the gap across interdisciplinary boundaries enabled Kalawsky to find solutions to the coupling of different domain models into a common simulation environment. The concept of multi-scale perspectives were developed [(Prof Summers, (Professor at LU 1998-current) & Tariq Abdulla (PhD 2009-2013], **[3.4]** and integrated as part of the modelling/simulation framework.
- New approaches for linking real systems with simulated components through model transformations were developed **[G3.7]** and used to provide the comprehensive MBSE environment for subsequent simulation trials.
- The multi-scale aspects of **[G3.5]** developed a novel approach for multi-cell models for modelling endocardial epithelial to mesenchymal transition and understanding of congenital heart disease **[R3.4]** with Paediatric Cardiologists at the University Hospital of Rennes. Summers exploited this approach, pioneering multi-scale systems modelling research and successfully applying it to biomedical systems applications, including founding investigations about causal mechanisms in congenital heart defects.

3. References to the research (indicative maximum of six references)
Academic Papers Supporting the Impact

The journals used for the dissemination of the research are an indicator of its quality and strength; these journals have the highest rating for reporting systems inspired research. Also, our more recently published papers have further confirmed and validated the research.

3.1 Kalawsky, R.S., O'Brien, J., and Coveney, P.V. (2005) “Improving scientists' interaction with complex computational-visualization environments based on a distributed grid infrastructure”, *Philosophical Transactions of the Royal Society A -Mathematical Physical and Engineering Sciences*, 363(1833), pp. 1867-1884. Doi: 10.1098/rsta.2005.1616.

3.2 Kalawsky, R.S., Nee, S.P., Holmes, I, Coveney, PV (2005) “A grid-enabled lightweight computational steering client: a .NET PDA implementation”, *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 363(1833) pp. 1885-1894. Doi: 10.1098/rsta.2005.1617

3.3 Al-Najdawi, A., Kalawsky, R.S. (2010) "Visual Quality Assessment of Video and Image Sequences-A Human-based Approach" *Journal of Signal Processing Systems for Signal Image and Video Technology*, vol. 59, pp. 223-231. DOI: 10.1007/s11265-008-0289-0

3.4 Summers, R., Abdulla, T., Houyel, L., Schleich, J-M. (2011) “Progress with a multi-scale systems engineering approach to cardiac development”, *Automatika*, 52(1), pp. 49-57. Available at request from Loughborough University.

A further indicator of the quality of the research was that the team was invited against significant competition to join the European Union’s largest funded project **[G3.8]** involving M&S FP7 ICT Project (Designing Adaptability in Systems of Systems Engineering) (€12m) as the only University group in the team.

Research Grants which provided the expertise and environment

G3.1 {Kalawsky}, EPSRC "The RealityGrid - a tool for investigating condensed matter & materials", EPSRC, GR/R67699/01, £3,441,471 and GR/R67699/02, £2,616,211 (LU £385,730) (2001-2005)
G3.2 {Kalawsky}, EPSRC "RealityGrid Platform Grant", EP/C536452/1, £424,909, (LU £50,000) (2005-2010)
G3.3 {Kalawsky}, DTI (TSB) "East Midlands e-Science Centre (EMeSC) for Collaborative Environments", £100,468, (LU £55,521) - (2003-2009)
G3.4 {Kalawsky}, DTI (TSB), "Technology Programme: Environmentally Friendly Airport ATM Systems, a SoS distributed coupled model based synthetic environment", £737,720, (LU £160,000) - (2005-2008)
G3.5 {Kalawsky}, BAES "UK DNAW Demonstration Programme – Synthetic Vision System Integrity", £75,000, (LU £75,000) - (2005-2010)
G3.6 {Kalawsky}, EPSRC "Bridging the Gap -Enabling a strategic and long lasting alliance between academic research staff", EP/E018521/1, £194,280, (LU £194,280) - (2006-2010)
G3.7 {Kalawsky}, ERDF J12358 "Transport iNet - Platform Independent Model Driven Architectures for Future Vehicle Systems, £140,000, (LU £140,000) - (2009-2010)
G3.8 {Kalawsky}, European Commission FP7-ICT-2011-7 "Designing for adaptability and evolution in systems of systems engineering" (DANSE), €12,000,000, (LU €848,863) – (2011-2014)

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

LU's interdisciplinary model based systems engineering (MBSE) research as cited in section 2 and 3 (2001–2010) has directly enabled life-saving operations by i) Developing synthetic vision systems to improve safety of emergency services helicopter operations involving low level flight during day, night, all weather and conditions of zero visibility, and ii) Saving lives through a reduction in morbidity and mortality of babies born with congenital heart defects.

The impact translates directly into significant cost savings and safety risk reductions in expensive flight trials costing millions of pounds by BAE Systems **[5.1]**, and in clinical practice/surgical interventions by University Hospital of Rennes **[5.2]** with a reduction in the morbidity and mortality of babies born with congenital heart defects.

LU's integrative cross-discipline MBSE research has solved previously intractable challenges by developing new techniques in multi-disciplinary/multi-scale modelling and simulation. The consequences of the impact are diverse and have wide reach across different domains and not confined to the two examples described below.

i) Synthetic vision systems to improve safety of helicopter operations involving low level flight during day, night and all weather to zero visibility

The goal was to enable the emergency services, military and other services to operate into day and night, under adverse weather conditions, through the safe use of synthetic vision (thus enabling operations in hazardous conditions), addressing the big challenge of presenting time-critical sensor information to the aircrew. In order to fly at low-level and high-speed in these extremely adverse conditions, a suite of active/passive sensors capable of detecting hazards must be integrated to present a synthetic display of the outside world to the pilot. However, combining sensory information from multiple sensors (operating in different wavelengths/modalities) with on-board databases has previously been an intractable problem due to the time critical nature of the information. Before a synthetic display system can be cleared for flight the system must be tested under complex and inherently expensive flight-trials in representative operational conditions. Such flight-trials involve testing in extreme conditions that are currently outside flying regulations with all hazards including terrain, building structures, telegraph wires, pylons, and aerial masts. Such tests expose the crew and helicopter to serious risks where the crew and helicopter could be lost. Consequently, each new system concept must be tested which leading to escalations in costs and risks.

Applying the research results **[3.1-3.3]** in conjunction with **[G3.1-G3.7]** enabled Loughborough to implement a comprehensive coupled-model systems simulator which integrated real-time models (atmosphere, on-board sensors, sensor performance, system performance, helicopter flight dynamics, synthetic vision display presentation and models of human reaction time/behaviour). The heterogeneous model based simulator directly enabled BAE Systems to rapidly evaluate simulations of candidate synthetic vision systems with time critical information symbology before commencement of flight trials. This simulator enabled the development of highly effective visually-coupled head-mounted augmented reality perceptual cue displays comprising synthetic information, including accommodating the implications and rationale of 2000m visibility (dictated by air regulations). The simulator took the place of early flight trials and reduced the number of flight tests that had to be undertaken by identifying conflicting sensory and perceptual cues so that they could be excluded from flight trials. Consequently, months of flight development time and significant costs (£millions) were saved along with the inherent reduction in crew risks and improved safety enhancement through use of the simulator. This research was subjected to a detailed integrity assessment (involving calibration against real-world flight trials and helicopter sensor/system performance), proving it comprehensively addressed perceptual issues of spatial awareness, and range to interference (collisions with pylons, terrain, telephone poles etc.) in obscured visibility conditions.

Loughborough also developed key augmented reality perceptual cues that were presented via the visually coupled (head-mounted) display ensuring appropriate pilot evasive action could be taken within human reaction times. The simulator was validated constantly against the flight test vehicle enabling a comprehensive safety integrity assessment to address the issue of perceptual spatial awareness and range to interference in obscured visibility conditions. Loughborough's mathematical model of spatial error in relation to the obstacle profiles formed a key part of the safety case. Comprehensive simulator trials provided significant development timesavings and reduced risks leading to effective perceptual display symbology through testing of concepts prior to flight-testing in the Lynx helicopter (Army Air Corps base - Middle Whallop). Benefits are significant for all helicopter operators by offering unprecedented increase in safety whilst extending current limited operational envelopes.

ii) Saving lives through a reduction in morbidity and mortality of babies born with congenital heart defects

Significant impact has accrued through a reduction in morbidity and mortality of babies born with congenital heart defects (the congenital heart defect known as the 'tetralogy of Fallot'). This is one of the most common cyanotic heart defects, affecting 20% of babies born with a congenital heart defect. LU's multi-scale systems models have advanced the theoretical knowledge and understanding of the multi-scale mechanisms that underpin the clinical condition. Since 2012, 591 babies in Brittany (i.e. population served by Rennes who were diagnosed with the condition) have had their treatment and surgical intervention significantly influenced by the research through its adoption by the only Paediatric Cardiologist (Prof J-M. Schleich) based in Brittany. LU's multi-scale systems models confirm the hypotheses of findings from the wet biologists (experimentalists) - and have for the first time allowed the paediatric cardiologists at the University Hospital of Rennes (CHU) to integrate findings from geneticists, cell biologists, and pathologists to gain a more complete understanding of this congenital heart defect. The use of multi-scale systems engineering, has allowed modelling of clinical findings and their patho-physiological underpinnings to take place. With the addition of CHU's work in medical imaging of heart specimens it has been possible to pin-point the anatomical landmarks important for the diagnosis of tetralogy of Fallot.

Our unifying cross-discipline MBSE research has solved previously intractable challenges confirming the wide diversity/applicability of the research. Both examples supporting the impact case studies involved extensive end-user stakeholders working alongside LU researchers to provide effective and timely bi-directional knowledge transfer. This method of working has been cited (in letters of support **[5.1 and 5.2]**) as an excellent mechanism for delivering rapid impact from low technology readiness level research.

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

5.1 Letter of corroboration from the Managing Director, Advanced Technology Centre, BAE Systems

5.2 Letter of corroboration from Paediatric Cardiologist, University Hospital of Rennes