Institution: University College London		
Unit of Assessment: 9 – Physics		
Title of case study: Systems engineering and project management training improving the effectiveness and efficiency of organisations		
Period when the underpinning research was undertaken: 2002 - 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:**
Michael Emes	Professor of Technology Management	2002 – 2020
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of Impact (indicative maximum 100 words)

The Technology Management Group (TMG) in the Department of Space and Climate Physics at UCL has developed a range of professional training courses for industry that promote a forward-looking approach to managing technology projects. These courses were delivered across Europe, North America and Asia to 16 customer organisations, including the European Space Agency (ESA), Jaguar Land Rover, PA Consulting, Leonardo and BAE Systems. Industrial customers have invested over GBP5,000,000 on the training since August 2013 and have received a total of 7148 trainee-days. The training has improved their capability to deliver complex, cutting-edge projects effectively, delivering significant value for stakeholders on a global scale. The TMG also took a leading role in developing the system engineering competency framework that is now used worldwide in the professional certification of systems engineers.

2. Underpinning research (indicative maximum 500 words)

Systems engineering is an interdisciplinary field of engineering and technology management that focuses on the successful design, integration and management of complex systems over their lifecycles. UCL's Department of Space and Climate Physics (also known as Mullard Space Science Lab or 'MSSL') research and expertise focuses on systems engineering in the most demanding environments with a low tolerance to project failure in any form.

Insights have been informed by a body of over 100 MSc Systems Engineering research projects supervised by MSSL's Technology Management Group (TMG) since 2000, and by MSSL's programme of instrument development for space science applications (running since 1959, but most developed in this area since 1993). Since the early 2000s, the TMG has conducted post-project interviews with project managers and systems engineers to review their experiences and in January 2010, the TMG undertook a project to formally consolidate their findings, to provide a coherent expression of good practice in project management and systems engineering. This project drew on the interviews and a three-day workshop in which TMG staff and programme managers identified the influences that made the greatest impact on the outcomes of projects. Five orthogonal 'principles' were found to be needed to cover the most important issues: 'principles govern process'; 'seek alternative systems perspectives'; 'understand the enterprise context'; 'integrate systems engineering and project management', and 'invest in the early stages of projects'. Behind these principles is a will to anticipate and respond to a changing environment with a focus on achieving long-term value for the enterprise. They were presented at the 2012 International

Systems Engineering Symposium and in a journal article (**R1**) and are now applied in both space projects and non-space projects at MSSL.

Further insights into systems engineering have arisen from MSSL's research as summarised in the table below.

Project	Key outcomes / findings
Impact of technology decisions in instrumentation supply chain with focus on pharmaceutical and agricultural sectors (2002-05). Research focused on understanding challenges of systems integration and technological change in the R&D process.	Led to the development of a methodology for mapping future project technology needs and capabilities. Paper won prize for most innovative application of Systems Engineering at INCOSE European conference (**R2**).
Costs and benefits of introducing new technology in transport (2008-11). Research improved the integration of systems engineering and economic aspects to enhance decision making for technological change.	Through-life value for money is often overlooked in technology development projects, with too great a focus on up-front cost and delivering functional requirements.
Improving the understanding across industry sectors of terminology used in systems engineering and systems architecting (2011). Research explored different interpretations of systems engineering and role of systems engineer.	Lack of standard systems engineering terminology is hampering understanding in UK industry (**R3, R4**); this research revealed for the first time key interfaces with overlapping disciplines.
Success factors in projects in a range of industries, including space and construction (2012-16). Research surveyed industry experts to gather statistical data on relative importance of various factors in determining project success.	Effective risk management was found to be a critical success factor for projects across multiple sectors (**R5**). Previous studies hadn't highlighted this.
How systems engineering ideas can be applied to improve processes in human-centric systems (2013-18). Research explored process of discharging patients with complex needs from a major acute hospital using soft systems methodology.	Three initiatives were implemented following the study. Taken together, these initiatives reduced total length of stay for patients with complex needs by 67% (**R6**). The research established that systems engineering can be a powerful lens when designing human-centric systems like healthcare.

Key UCL researchers were Alan Smith (Professor of Detector Physics, 1998-present), Michael Emes (Research Associate 2002-2005; Senior Research Associate 2005-2013; Principal Research Associate 2013-2016, Associate Professor 2016 - October 2020, Professor of Technology Management, October 2020-present).

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

R1. Emes M.R., Smith A., & Marjanovic-Halburd L. (2012). Systems for construction: lessons for the construction industry from experiences in spacecraft systems engineering. *Intelligent Buildings International*, *4*(2). https://doi.org/10.1080/17508975.2012.680428
R2. Emes M. (2007). Strategic Multi-Stakeholder Trade Studies. *INSIGHT*, *10*(1). https://doi.org/10.1002/inst.200710117
R3. Emes M.R., Bryant P.A., Wilkinson M.K., King P., James A.M., & Arnold S. (2012). Interpreting "systems architecting." *Systems Engineering*, *15*(4). https://doi.org/10.1002/sys.21202
R4. Emes M., Smith A., & Cowper D. (2005). Confronting an identity crisis?How to ?brand? systems engineering. *Systems Engineering*, *8*(2). https://doi.org/10.1002/sys.20028

R5. Tsiga Z.D., Emes M., Smith A. (2016). Critical success factors for the construction industry. *PM World Journal*, 5(8), 12 pages. Retrieved from http://pmworldlibrary.net/readers/pm-world-journal/
R6. Emes M., Smith S., Ward S., & Smith A. (2019). Improving the patient discharge process: implementing actions derived from a soft systems methodology study. *Health Systems*, *8*(2). https://doi.org/10.1080/20476965.2018.1524405

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

The drive to exploit the latest technology to tackle more and more ambitious problems means that successfully delivering complex engineering projects with limited time and resources is a major challenge. This is particularly true in the space sector due to the remote and hostile environment. Here, the complexity of systems and the nature of the development approach make projects susceptible to large cost and schedule overruns. Projects at NASA, for example, are consistently delivered with an average of 27.6% cost overrun and 13 months of schedule delay (**S1**), and the European Space Agency has long recognised the need for "implementation of measures to better control projects' costs and planning" (**S2**).

To address these challenges, the TMG has, since 2008, developed a portfolio of training courses in systems engineering and project management. The courses are underpinned by the principles derived from the TMG's experience in space instrument developments and their research into systems engineering practice across a range of sectors including space, transport, health and construction. There is a common focus on delivering value in the face of unpredictable or changing requirements, as today's complex projects demand. Integrating insights from the research described above reinforces the credibility of TMG staff as thought leaders, enabling them to bid for and win commercial contracts to train systems engineers and project managers. Extending their experience in delivering training for industry, TMG has also offered Master's apprenticeship programmes for PA Consulting in Systems Engineering (since 2019, 15 apprentices) and Transformation Leadership (since 2020, 30 apprentices).

These training courses ultimately improve performance and competitiveness of a range of companies, including some of the world's largest aerospace, defence and engineering companies. This know-how has received an even wider audience with TMG's contribution to the International Council on Systems Engineering (INCOSE) Systems Engineering Competency Framework, which is the only standard that has been adopted worldwide in the professional certification of systems engineers.

Impacts on practitioners and professional bodies

Three TMG members - Professor Alan Smith (at UCL since 1990), Professor Doug Cowper (Visiting Professor since 2017) and Dr Ady James (at UCL between 1988 – 2019, now at University of South Australia) – took part and led the INCOSE working group on the core competencies of systems engineering, with Professor Smith chairing the working group during its formative phase. Based on their knowledge and experience of systems engineering, underpinned by the research in references (**R1**) to (**R4**) above, they contributed significant insights to this group and development of the Systems Engineering competency framework to improve the practice of Systems Engineering. The framework was adopted worldwide by INCOSE in 2010 and continued being used to date (**S3**), including in the professional certification of systems engineers, and applied across 16 companies as a basis for career development and standardisation of systems engineering practice. Major organisations that have used the framework include Thales, General Dynamics, BAE Systems, Atego, Bombardier and the Ministry of Defence (**S3, S4).**

Improvement in the performance of organisations through the provision of training

The TMG has developed and delivers a range of tailored continuing professional development courses for industry in the areas of systems engineering, project management and technology management. Between 2014 and December 2020, 76 of these courses were

delivered across Europe**,** North America and Asia to 19 customer organisations, including the European Space Agency (ESA) (**S5**), Jaguar Land Rover PLC (JLR) (**S6**), National Physical Laboratory (**S6**), Marshall Aerospace and Defence Group (**S6**), PA Consulting (**S7**), Leonardo S.p.A (**S8**), BAE Systems PLC, Airbus SE, Ultra Electronics, Fusion for Energy, Shift2Rail, OFWAT and Transport for London. The number of trainee-days per year (number of courses x number of days x average number of trainees per course) increased from 360 in 2014 to 1964 in 2020 and totalled 7148 trainee-days in 2014-20.

One of indicators of impact is the overall cost of the training to the company, which includes direct costs (charged by UCL) and the staff-time of delegates (salary assumed to be GBP100,000 per year per delegate including overheads). The direct costs are GBP1,900,000 and the staff costs are GBP3,249,000 giving a total of GBP5,149,000 between 2014 and 2020. Companies have been prepared to invest this level of resource with an expectation that this will lead to an improved performance and greater profitability. The TMG has been successful with meeting this expectation as evidenced by a large amount of repeat business. Several of the customers, including the European Space Agency (ESA), have been using the courses provided by TMG throughout the five-year period covered (**S5**).

Training courses are developed to meet the client's needs and deliver maximum impact for participants and clients. A training programme developed in 2012 for the ESA focused on developing the capabilities of senior project managers (**S5**). The impact on professional development of managers was evidenced by evaluation conducted before and after the training. In addition to participants who rated their own competence against a range of 33 categories relevant to the project management tasks, line managers evaluated the competence of participants. Training participants reported improvement by 14.1% across the 33 dimensions while their managers' ratings increased by approximately 50% after training compared to pre-course evaluation. Subsequently, TMG secured a two-year contract in 2014 (EUR200,000) and three-year contract in 2016 (EUR160,000) to deliver the Systems Engineering training at the ESA. In total 54 project managers at ESA benefitted from professional development training provided by TMG (**S5**). In November 2020, ESA sent UCL a Contract Change Notice (EUR450,000) to extend the training programme again for a further 5 cycles over 10 years, so the contract overall now spans a period of 18 years from 2012 to 2030 (**S5**). This reflects **the high perceived value of the programme, which has become a focal point for the career progression of ESA project managers** and has led to changes in how project managers are trained, whereby, since 2016, all new and potential senior project managers (managing programmes worth over EUR50,000,000) are expected to complete the programme.

In 2015, PA Consulting contracted TMG to deliver PA's Systems Thinking & Engineering Academy, following a competitive procurement involving over 50 UK universities. PA's Systems Thinking and Engineering International Business Lead commented: "UCL was selected because of the applicability of their postgraduate programmes to real-world systems thinking and engineering, as well as their culture fit with PA and our clients. The academy completed with over 40 engineers (PA consultants and clients) finishing the programme. The programme has been a fantastic success for PA with delegates going on to lead some of our most significant engagements with major clients. The Systems Thinking & Engineering Academy played a key role in generating the Thought Leadership and showing PA's insights when bidding for Virgin Hyperloop One, where PA now runs the Systems Engineering function" (**S7**). This Academy was the inspiration for a Masters degree apprenticeship in Systems Engineering that took a first cohort of 14 PA apprentices in 2019. The successful relationship has since deepened through a second, larger, apprenticeship programme in Transformation Leadership introduced in 2020, as explained by PA's Senior Learning and Development Specialist: "Over the last two years we have been working with Professor Emes and UCL to develop the Transformation Leadership Master's Apprenticeship for senior leaders – another bespoke apprenticeship programme that will see over 100 PA people gain expertise, knowledge, skills and behaviours in a subject that will

help us transform and develop global business to meet immediate and future challenges. **UCL's insight in developing this programme has been invaluable**" (**S7**). They added: "Both of these [apprenticeship] programmes are core to enabling PA to deliver ingenuity to our clients, who face complex and wicked problems, such as our recent work at the centre of the UK's Ventilator Challenge in response to COVID" (**S7**).

Leonardo, an international electronics company, has also benefited from the training provided by the TMG. A range of courses in Engineering for Complex Systems have been developed and delivered at foundation, experienced and senior management levels. These were delivered to approximately 100 participants between 2014 and 2018. Leonardo's Chief Technical Specialist in Systems Engineering commented: "(…) the training is adding huge benefits to the company in many ways" (**S7**). The impacts on Leonardo that he identified are evident across the whole organisation on all levels: "The message of Systems Thinking and using the principles to add value to the wider company is gradually percolating to senior managers. Last year we used such principles to actually redesign part of our organisation and processes. (…) Engineers are becoming aware that the old way of thinking isn't enough today. Just that realisation is significant as they are asking questions or performing additional analysis that wouldn't normally be done'' (**S7**). **The training is changing attitudes and the way that engineers see their jobs.** As the result of the training, engineers at Leonardo understood that their role at the company is more than technical and included aspects such as leadership, time and cost management. Moreover, employees gained "a wider cross-discipline appreciation of Systems Engineering principles and of each other's discipline too" (**S7**).

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

S1. Government Accountability Office Report "Assessments of Major Projects" (May 2019) corroborates information on NASA projects.
S2. ESA Ministerial Council's "Resolution of the Evolution of the Agency" (2008) corroborates statement on requirements for improvements in project management.
S3. Supporting statement from Director of Cleave Systems Ltd (17/12/2019) corroborates the involvement of TMG members in the development of the Systems Engineering competency framework, its worldwide adoption by INCOSE.
S4. SEBoK Guide website, Press releases on General Dynamics (25/09/2018) and BAE Systems (date not provided) website and "Better Communication Through Standards" presentation (June 2013) by Chief Consulting Engineer at Atego corroborate adoption of INCOSE.
S5. Supporting statement from ISS Programme Manager at European Space Agency corroborates training delivered by TGM team to engineers at the agency, their results and benefits to participants and ESA.
S6. Supporting statement from Senior Manager Systems Engineering at JLR (02/01/2020), Head of Engineering at Military Aerospace Marshall ADG (20/12/2019) and Senior Research Engineer at NPL (02/01/2020) corroborate systems engineering training provided by TGM.
S7. Supporting statements from Director (25/11/2020), Senior Learning and Development Specialist (25/11/2020) and Leading PA's Adative Transformation Business (26/11/2020) at PA Consulting corroborate trainings delivered by TGM team to engineers at PA, apprentice programme and benefits of those activities to the company.
S8. Supporting statement from Chief Technical Specialist at Leonardo S.p.A. corroborates trainings delivered by TGM team to engineers at Leonardo and their benefits to participants and the company.