Professional Statement of Olivier L. de Weck

July 15, 2012

Motivation[1]

My main research interest is to study why and how manufactured products and systems evolve over time and how we can ultimately design them to better accommodate future changes. Based on my 20 years of experience as a scholar and practicing systems engineer I find that man-made artifacts are not static but that they undergo constant modifications to assimilate innovative technologies, to respond to new regulations or to accommodate an expanding customer base [3.117]. My work on the re-design of the Swiss F/A-18 aircraft (1991-96) taught me that systems inevitably change. While the upgrading of avionics and software was relatively easy on this aircraft, modifications to the airframe turned out to be more difficult (see Fig.1).

To certify the aircraft for 5000 flight hours and loads up to 9g we made numerous changes to the baseline U.S. Navy design. Some of these changes were well behaved. Others, such as the substitution of titanium for aluminum in the three main wing carry-through bulkheads, ended up rippling through the system in surprising ways. Unanticipated and subtle change propagation [2.28] to structures, manufacturing processes and flight-control software added significant costs to the program. This industrial experience sparked my passion for systems engineering and inspired my research on complex engineering systems.

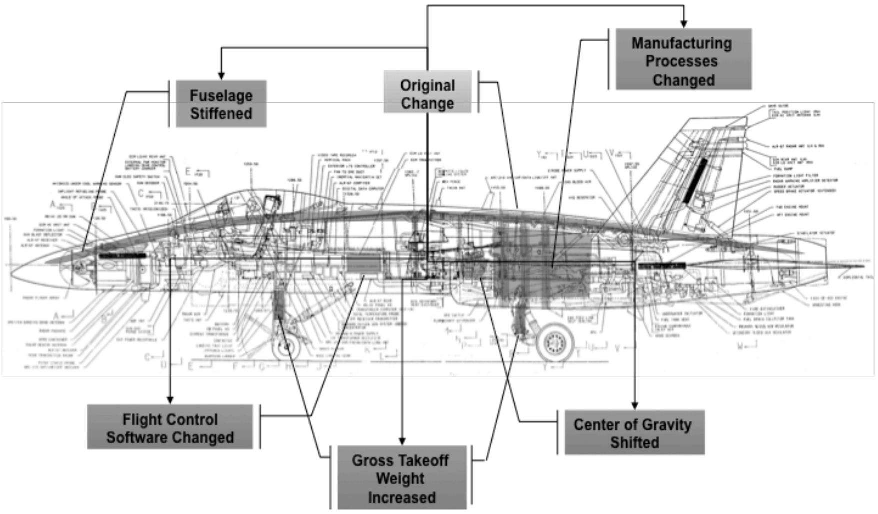

Fig. 1: F/A-18 Aircraft Design Change Propagation

My early focus as a researcher (ca.1997-2007) was on optimally solving multidisciplinary design problems – particularly those involving competing objectives [2.6, 2.11, 2.31] - within a range of industries such as aerospace, automotive, oil & gas exploration, digital printing systems and manufacturing. Since 2008 I have become increasingly interested in how we maximize value and design systems with a lifecycle perspective (often > 10 years) while exploiting synergies amongst sub-systems that are typically designed in isolation from each other. Resolving incompatibilities and problems at the interfaces of sub-systems and components is one of the most important sources of engineering change. Perhaps the ultimate “stress case” for lifecycle-driven design may be the International Space Station (ISS) that is currently orbiting Earth at an altitude of approximately 350 km. The hostile environment and extremely thin supply line to ISS [2.29] are changing the way we view the sustainability challenge here on Earth. Increasingly, we will repair and scavenge things

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[1] Numbers in square brackets, e.g. [2.34], refer to specific papers or reports in my list of publications.

rather than replace them [2.15], we will use "waste" heat instead of radiating it overboard, we will close water cycles at recovery rates of 92% and higher[2] and we will use a few reconfigurable artifacts [2.25] that can perform multiple functions rather than many special-purpose ones.

While this vision of a more sustainable future – on Earth and in Space – is attractive, it also significantly increases the size and complexity of the design problem [2.34]. How can we better design explicitly for lifecycle properties such as flexibility, reconfigurability and commonality during early engineering design of very large and complex products and processes? How do we model sources of uncertainty in system design and better anticipate future changes? Together with my strategic engineering research group and colleagues around the globe we are tackling some of these research questions.

Research

My doctoral research (1999-2001) developed an isoperformance method for finding designs that satisfy known performance targets [2.10][3]. However, since then I have found that optimizing complex systems and products for fixed objectives can be counterproductive, mainly because the context of these systems is often not fixed but dynamically evolving. Consequently, the core of my research is now focused on the development of general methods that allow the incorporation of lifecycle properties such as changeability during systems architecting and design.

Research Area A – Change Propagation Analysis

One of the key interests of my group has been to describe and formalize our understanding of change propagation. This is a phenomenon in the design of complex systems where one change leads to another leads to another etc…(see F/A-18 example). In the worst case an avalanche of changes can be kicked off that leads to significant cost and schedule overruns, missing of technical performance targets and eventually program cancellation. We published the most comprehensive empirical study of this phenomenon in [2.28] based on an industrial database of over 41,000 change requests and found (i) evidence of large networks of related changes (see Fig. 2), (ii) evidence that changes can but rarely do exceed 4 generations of propagated changes and (iii) an original way to classify subsystems as absorbers or propagators of engineering change based on their ratio of incoming and outgoing changes, which led to the definition of a Change Propagation Index (CPI) for each subsystem. We also collaborated with the University of Cambridge's Engineering Design Centre (EDC) and BP to analyze Management of Change across six major BP oil and gas projects [4.20, 3.38]. We found interesting patterns of engineering change activity before and after "first oil" in complex oil and gas projects and suggested an original framework for a-posteriori change analysis on large-scale engineering projects [3.38]. This is very relevant in the context of the recent Macondo well blowout and oil spill in the Gulf of Mexico. We believe – based on our research – that engineering change analysis can act as a "canary in the coal mine" for complex engineering projects.

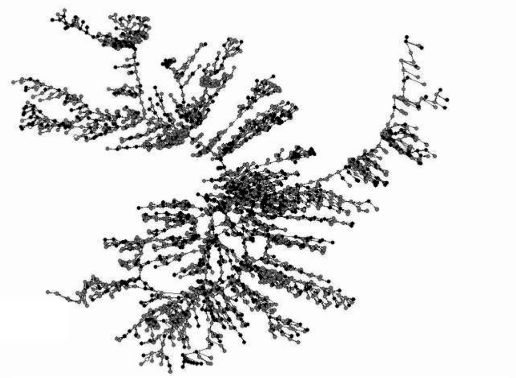

Fig.2: Network of changes in radar design

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[2] Scientific American, "New Menu Item on Space Station: Drinking Water Made from Recycled Urine", 2007, URL: http://tiny.cc/ISS-water

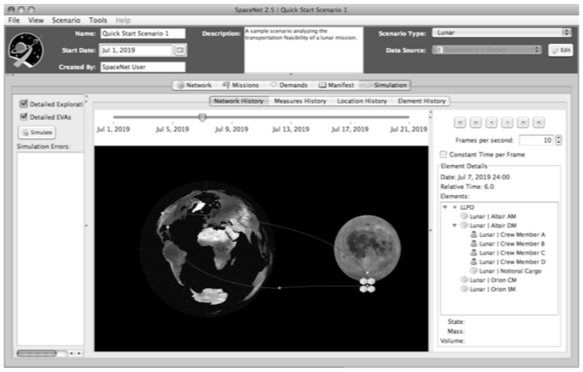
[3] Based on [3.35], which won a best paper award at the 2004 INCOSE Systems Engineering conference.

Research Area B – Technology Infusion Analysis

One of the major reasons for engineering change is the desire and need to evolve existing systems and products by incorporating new technologies and capabilities. However many organizations are asking: *How can we quantitatively weigh the risks and opportunities, both technical and financial, of new technologies before making a full commitment towards implementation?* In response we developed a new technology infusion methodology to assess the risks and opportunities of incorporating new technologies into products and systems [2.14, 2.32]. This approach makes use of a so-called Delta-Design Structure Matrix, or ΔDSM, to quantify the invasiveness of a new technology to the underlying host system and has been applied to a variety of products such as the iGen4 family of digital printing systems at Xerox and more recently the new Geared Turbofan (GTF) engine architecture at Pratt & Whitney. We received the 2008 and 2011 best paper of the year awards in the journal *Systems Engineering* for this research. Xerox has applied the technology infusion method to evaluate its patented image correction technology on its new generation of digital printing presses (iGen4) [2.32]. More recently, we are pursuing a similar approach to understanding how new technologies such as flexible parts fabrication techniques [2.18, 2.31] have the potential to transform advanced manufacturing. We expect to publish the role of these new technologies in the context of U.S. manufacturing as part of the 2013 report produced by the MIT Commission on Production in the Innovation Economy (PIE).

Research Area C – Maximizing Lifecycle Value of Engineering Systems

In a broader sense, my research is about maximizing the lifecycle value of engineering systems over extended periods of time, sometimes over several decades or more. This requires a deeper understanding and scientific approach to the so-called lifecycle properties or "Ilities". Scientific interest in system design for change and properties such as *reconfigurability* has risen sharply over the last 5-10 years [3.97]. We believe that our recent work on establishing rigorous principles and methods for modeling and designing *reconfigurable systems* using non-homogenous Markov Chains has the potential for long-term impact [2.25]. This extends to the design of systems that exhibit *performance robustness*, and can perform adequately in the face of partial failures. This is particularly relevant for systems such as long-endurance Unmanned Areal Vehicles (UAVs) that are likely to spend a significant portion of their life in partially failed states [2.42, 2.45].



Name: Quick Start Scenario 1
Start Date: Jul 1, 2019
Created By: SpaceNet User
Description: A sample scenario analyzing the transportation feasibility of a lunar mission.
Scenario Type: Lunar
☑ Detailed Explorati
☑ Detailed EVAs
Simulation Errors:
Frames per second: 10
☐ Constant Time per Frame
Date: Jul 7, 2019 24:00
Relative Time: 6.0
Elements:
LLPO
Lunar | Altair AM
Lunar | Altair DM
Lunar | Crew Member A
Lunar | Crew Member B
Lunar | Crew Member C
Lunar | Crew Member D
Lunar | Notional Cargo
Lunar | Orion CM
Lunar | Orion SM

Fig. 3: SpaceNet 2.5 Space Logistics Simulation

In the domain of space logistics, together with NASA and JPL, we developed a framework for modeling space exploration missions and campaigns as interplanetary supply chains [2.23, 2.29, 2.36, 4.18, 3.120][4]. The resulting software tool, *SpaceNet*, was adopted and officially accredited by NASA for use on the Constellation Program and has been released as version 2.5 under a GNU public license[5]. *SpaceNet* allows discrete-event simulation of the flow of vehicles, crew and cargo to and from the Moon and other destinations such as Mars (see Fig. 3 for a screen shot). *SpaceNet* has been able to reduce the typical evaluation time for lunar campaigns to the order of minutes rather than the weeks or months that were previously required. We have used these models to understand the optimal mix

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[4] See http://spacelogistics.mit.edu for additional details.

[5] *SpaceNet* 2.5 is available under a GNU public license at http://spacenet.mit.edu

of pre-positioning, carry-along and resupply flights for a lunar outpost, as well as to quantify the effects of system reliability, commonality, and reconfigurability on resupply needs and system availability [2.15]. A recent innovation is the development of a matrix manipulation method (the "M-Matrix") to analyze and visualize space logistics campaigns such as the assembly and resupply of ISS [2.29] and for optimal manifesting to multiple exploration destinations [2.36].

A synthesis of my views on the interactions and role of the lifecycle properties in complex Engineering Systems was recently published in Chapter 4 of a new book on Engineering Systems (see Fig.4). In this book my co-authors (D. Roos and C. Magee) and I argue that while there are "classical Ilities" of engineering such as quality, safety and reliability there is a new class of lifecycle properties that has only emerged in the last 20-30 years including concepts such as evolvability, sustainability, interoperability etc… that are not yet well understood but where a body of research is rapidly emerging. Turning the engineering for such properties from an art to a science has been my main mission in research in recent years. We believe that our work on descriptive and normative methods for system properties such as changeability, reconfigurability and sustainability for complex systems is an important step in this direction.


Engineering Systems
Meeting Human Needs in a Complex Technological World
Olivier L. de Weck, Daniel Roos, and Christopher L. Magee

Fig. 4: Engineering Systems: Meeting Human Needs in a Complex Technological World [1.1] MIT Press 2011

Teaching and Advising

My main focus in teaching has been to achieve excellence and innovation in graduate and undergraduate systems engineering education in both Aeronautics and Astronautics as well as in the Engineering Systems Division (ESD). My core course ESD.36 (System Project Management) and elective course ESD.77/16.888 (Multidisciplinary System Design Optimization)[6] have consistently earned me average instructor ratings of about ~6.4 out of 7.0. I achieve this by developing and applying active learning techniques [3.57], carefully balancing lectures, case studies and relevant homework, and by constantly refreshing my course materials with new research results. My industrial experience and personal energy allow me to work particularly well with the System Design and Management (SDM) students. With an average age of 34 and typically 10 years of work experience they represent some of the most rewarding, but also most challenging, students we have at MIT.

At the undergraduate level I embrace the Conceive-Design-Implement-Operate (CDIO) curriculum that has transformed engineering education in many universities around the world. I believe that systems engineering and engineering design education is most effective when it is not only theoretical, but when it is carefully combined with design-build projects. I have contributed to systems projects of this nature in Unified Engineering [3.21, 3.22] as well as through a new class, 16.810, on Engineering Design and Rapid Prototyping [3.34] for which I received the 2012 AIAA Teaching Award. Since 2008 I have created and taught the following new classes, in part because I saw an increasing need for unifying ways of teaching systems concepts to our engineering students:

- 16.842 Fundamentals of Systems Engineering (first offered in Fall 2009, evaluated 5.9/7)
- ESD.944 Engineering Systems Scholarship Seminar (first offered Fall 2009, evaluated 6.3/7)
- ESD.052 Project Engineering (first offered Spring 2010 for the Gordon Program[7], evaluated 6.3/7)

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[6] 16.888/ESD.77 is co-taught with my colleague in the Department of Aeronautics & Astronautics, Prof. Karen Willcox.

[7] The Gordon Engineering Leadership Program teaches engineering students leadership and career skills: http://web.mit.edu/gordonelp/

An issue I care deeply about is advising and mentoring. I spend a lot of time with my students to make sure that their MIT education is of a truly transformative nature. Perhaps the greatest honors I received in this respect were the Institute-wide 2006 Frank E. Perkins Award for Excellence in Graduate Advising and the 2010 Capers and Marion McDonald Award for Excellence in Mentoring and Advising. My alumni in academia and industry regularly stay in touch, which is one of my greatest joys.

Service

At MIT I served as Associate Director of the Engineering Systems Division (ESD) from 2008-2011. ESD is a crosscutting division in the School of Engineering and tackles problems associated with large systems that have significant intertwined technological and social complexity. ESD has grown four-fold since 1998 in terms of the number of credit-units taken by MIT students. It is quite challenging to create coherence and positive momentum in a unit that has about 60 dual and joint faculty appointments with all five schools at MIT and now over 440 graduate students. Related to this I also serve as secretary and treasurer of the Council of Engineering Systems Universities (CESUN) since 2010. CESUN is an organization of 51 universities with programs in Engineering Systems. In the Department of Aeronautics and Astronautics I served as chair of our graduate admissions committee from 2008-2010. We were able to completely change the way in which admissions is done by creating a graduate admissions committee, revising the business processes of the committee and by introducing the use of a new online system. As a result we received a record number of applications last year and are now one of the more competitive departments at MIT.

Following an invitation by President Susan Hockfield in late 2010, I serve as Executive Director of the *MIT Production in the Innovation Economy (PIE)* project that seeks to understand the nexus between innovation and manufacturing in the U.S. In this role I help to coordinate the research of 20 faculty members across MIT, worked to raise $3 million to support the study and lead research modules on the role of advanced manufacturing technologies (mentioned earlier) and scale-up of new enterprises from the laboratory to initial manufacturing. We expect to release a major report with national implications in September 2013.

The Future

It has been said that we have mastered the meso-scale $O(1\text{m})$ fairly well and that the frontiers of Engineering are in the very small (nanotechnology) and in the very large (macro systems). I agree and look forward to help broaden and deepen what we think Engineering is and should be, particularly on the macro side. In the area of designing large systems such as exploration vehicles, transportation networks, water supply chains, electrical energy grids and so forth I see enormous potential in co-designing and co-evolving such systems and infusing them with desired technologies and lifecycle properties such as flexibility and reconfigurability. This, however, requires the development of modeling, analysis, simulation, monitoring and prediction capabilities that are far beyond what we can do today. In many cases it is not computational or mathematical ability that is missing, but an understanding of how to account for human limitations, behaviors and preferences in dealing with exceedingly high levels of complexity. In a nutshell, Engineering in 2020 and beyond will be able to solve engineering systems problems that involve complex and coupled socio-technical systems over very long lifecycles. I look forward to contributing to this challenge.