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A critical evaluation of systems engineering principles within the context of ESA's ExoMars 2016 mission

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Contents

I. Introduction

The purpose of this paper will be to critically evaluate UCLse's Principles of Systems Engineering[1] with regards to their applicability across a range of different system, enterprise, and industry contexts. This will be facilitated through an analysis of their application to the European Space Agency (ESA)'s ExoMars 2016 mission, with a particular focus on the Schiaparelli module's landing failure[2].

As stated in the original paper: "whilst derived from the space domain, it is felt that these principles have generic applicability and are fundamental to the management of systems engineering endeavours". The industry context for this system is composed of national and international agencies developing spacecraft for space science missions, with the enterprise context being driven by the long-term strategic objective of enabling space exploration towards Mars. The main players in this sector of the aerospace industry include ESA, NASA[3], Roscosmos[4], CNSA[5], JAXA[6], and ISRO[7].

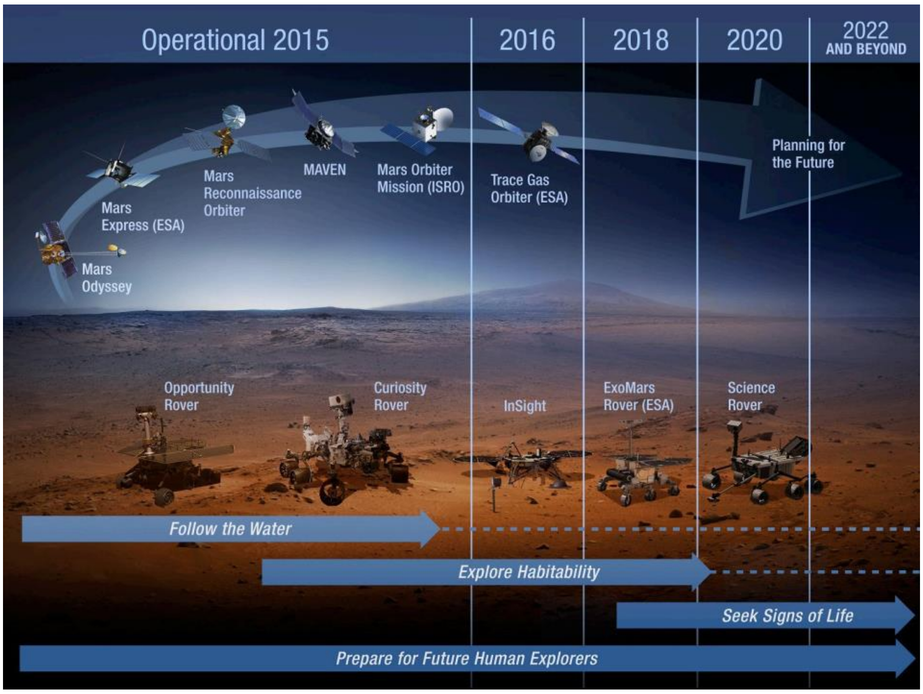

Fig. 1 - Timeline of Mars missions. Source: NASA[8]

[1] M R Emes et al. (2012)
[2] European Space Agency. "ExoMars 2016 Mission: Brief description of TGO and Schiaparelli" European Space Research and Technology Centre (2016). Web.
[3] National Aeronautics and Space Administration (US)
[4] Roscosmos State Space Corporation (Russia)
[5] China National Space Administration
[6] Japan Aerospace Exploration Agency
[7] Indian Space Research Organisation
[8] "Mars missions" National Aeronautics and Space Administration. Web. 10 Nov. 2018

II. System

Mission objectives

The ExoMars 2016 mission, which forms part of the wider ExoMars astrobiology programme, has two primary objectives: (1) “to search for evidence of methane and other trace atmospheric gases that could be signatures of active biological or geological processes”; and (2) “to test key technologies in preparation for ESA's contribution to subsequent missions to Mars”.[9] The second refers to laying the groundwork for ExoMars 2020, which will consist of a surface platform developed by Roscosmos and a Mars rover developed by ESA.[10] This system development context is likely to have had potential implications on the levels of acceptable risk (strategic importance), the project’s budget (limited resources), external time constraints (future missions), and technological compatibility requirements (international cooperation).

System structure

The super-system structure consists of a Trace Gas Orbiter (TGO); an Entry, descent, and landing Demonstrator Module (EDM); and a Proton launch vehicle provided by Roscosmos. The system of interest in this paper will be the EDM, also known as Schiaparelli, which is a system element of the ExoMars 2016 mission. The TGO includes the usual sub-systems found in spacecraft (solar arrays, propellant tank, antenna, electronics), as well as a scientific payload for atmospheric observations with spectrometers, infrared instruments, a high-resolution camera, and a neutron detector.[11] The EDM, which was attached to the TGO until ejection, includes a parachute system, a radar doppler altimeter, telemetry systems, tracking & command systems, a liquid propulsion braking system, and a crushable impact attenuator. It is also equipped with a small scientific payload which includes instruments to measure wind speed, humidity, atmospheric transparency, and electric fields on Mars.[12]

System properties

As a technological system, Schiaparelli’s emergent properties include structural integrity, thermal protection, aerodynamic shielding, guidance & navigation, attitude

[9] European Space Agency. "ExoMars 2016 Mission: Brief description of TGO and Schiaparelli" European Space Research and Technology Centre (2016). Web.
[10] "ExoMars Mission 2020" European Space Agency. Web. 10 Nov. 2018
[11] "ExoMars Trace Gas Orbiter Instruments" European Space Agency. Web. 10 Nov. 2018
[12] "Schiaparelli: The Exomars Entry, Descent and Landing Demonstrator" European Space Agency. Web. 10 Nov. 2018

control, landing capabilities, data collection, and data transmission. According to Perrow's model, it can be classified as a system with medium-high complexity (interaction) and tight coupling (time dependence).[13] Although the ExoMars 2016 mission's super-system would be characterised as highly complex, the EDM as a system element is relatively more linear. However, given its nature as a dynamic system which is open to its external environment, Schiaparelli should still be considered as "high-risk" from a systems engineering perspective.[14]

The mission was successfully launched in March 2016 with a Proton-M rocket. In October, three days before reaching Mars, the EDM separated itself from the TGO. Having coasted to the planet's orbit in a low-power hibernation mode, the system's intended behaviour was to: (1) enter the atmosphere; (2) decelerate with heatshield protection; (3) deploy parachute; (4) eject lower shield and activate radar; (5) eject parachute and upper shield; (6) ignite landing thrusters; (7) enter freefall at 2m altitude; and (8) land on crushable impact attenuator.[15] However, an unintended navigation sequence triggered by an anomaly in inertial measurements resulted in the premature execution of step 5, leading to system failure in the form of a crash landing.[16] This paper will analyse the reasons behind this anomaly by applying UCLse's Principles of Systems Engineering to Schiaparelli's development & testing process.

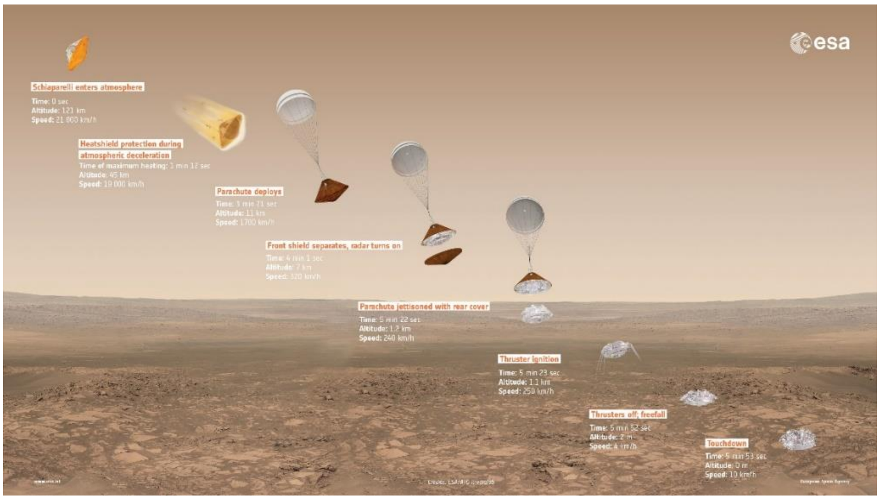

Fig. 2 - Schiaparelli EDM's landing sequence. Source: ESA[17]

[13] C Perrow (1999)
[14] Leal, Raul. "Systems Thinking & Engineering Management". University College London. 15 Oct. 2018. Lecture
[15] European Space Agency. "ExoMars 2016 Mission: Brief description of TGO and Schiaparelli" European Space Research and Technology Centre (2016). Web.
[16] "ExoMars 2016: Schiaparelli Anomaly Inquiry" European Space Agency. Web. 10 Nov. 2018
[17] European Space Agency. "ExoMars 2016 Mission: Brief description of TGO and Schiaparelli" European Space Research and Technology Centre (2016). Web.

III. Analysis

<u>Principles govern process</u>

UCLse's first principle is formulated as "principles govern process". This expresses the idea that processes should be "enabling rather than deterministic"[18], allowing for discretion when necessary, and continuously improving processes with reference to their underlying principles. As an international space agency with decades of heritage in systems engineering, ESA's design, implementation, and verification processes are expected to be highly robust. This appears to have been the case for most of the ExoMars 2016 mission, which resulted in the successful fulfilment of all its super-system requirements except for the final stages of Schiaparelli's landing sequence.

In its anomaly inquiry report, ESA highlighted some weaknesses in the EDM's testing process which are of relevance to this principle: (1) insufficient failure detection, isolation, and recovery (FDIR) analysis; (2) insufficient "what if" robustness analysis; and (3) insufficient worst case analysis.[19] In particular, it noted that the "phenomena of parachute area oscillations was not considered in the multi body model" used in end-to-end (E2E) simulations.[20] This was identified as a root cause of the system's failure, as parachute oscillations were responsible for the inertial measurement unit (IMU)'s saturation, which resulted in the unintended navigation sequence being triggered.

If UCLse's first principle had been applied to this verification process, the underlying principle would have been determined as the undertaking of a holistic and robust physics simulation which reflects the system's interaction with its operating environment as realistically as possible within the constraints of E2E software. In this case, although the anomaly inquiry acknowledged that parachute deployment is a "very complex dynamic unsteady phenomenon affected by several uncertainties and therefore very difficult to model and to predict", it also concluded that this was not a fundamental limitation of the simulation software and that parachute area oscillations could have and should have been included in the multi-body model. Therefore, a more careful application of "principles govern process" may have directed Schiaparelli's systems engineers to demand more accurate modelling and implement a greater degree of robustness analysis, worst case analysis, and uncertainty management.

It may equally be argued that the first principle would suggest greater flexibility and discretion in the testing process, which could be used to justify simplified modelling as

[18] M R Emes et al. (2012)
[19] "ExoMars 2016: Schiaparelli Anomaly Inquiry" European Space Agency. Web. 10 Nov. 2018
[20] "ExoMars 2016: Schiaparelli Anomaly Inquiry" European Space Agency. Web. 10 Nov. 2018

a compromise against unnecessary complexity, time constraints, or resource limitations. For example, as elaborated in UCLse's original paper with regards to vibration testing in space missions, "one should fall back on the principle underlying the testing process – namely that the activity is meant to reduce risk not increase it".[21] However, given the lack of technical risks such as stress damage in a software environment, and considering the mission-critical nature of E2E simulations, this would not have been a proper application of the first principle to Schiaparelli's development. As stated by UCLse: "in safety-critical systems and demanding environments such as space, very high levels of reliability and quality are essential".[22]

Finally, it must be noted that ESA's anomaly inquiry report is in itself an example of continuous process improvement. The report includes an anomaly tree to determine the system failure's cause-effect relationships, an examination of Schiaparelli's verification process, an identification of weaknesses in the systems engineering approach, and a set of observations & recommendations. This not only addresses improvements to ESA's general processes, but also emphasises the importance of integrating those recommendations into future missions through "Lessons Learned Implementation plans", with a specific focus on ExoMars 2020.[23]

Seek alternative systems perspectives

UCLse's second principle is to "seek alternative systems perspectives".[24] This expresses the idea that complexity can be better understood and managed by dividing a system into its interacting elements, identifying any overlapping hierarchies, and examining different time and performance dimensions.

One of the critical weaknesses in Schiaparelli's system design robustness was identified as the consideration of only radar doppler altimeter (RDA) anomalies. This approach excluded the possibility of issues arising from other components involved in altitude determination, which resulted in an over-reliance on one-way consistency checks.[25] If the second principle had been applied, the interaction between different instruments affecting attitude control would have been considered by testing for potential anomalies in the EDM from the perspective of both the RDA and the IMU. A more robust verification process would have included measurement data from various

[21] M R Emes et al. (2012)
[22] M R Emes et al. (2012)
[23] "ExoMars 2016: Schiaparelli Anomaly Inquiry" European Space Agency. Web. 10 Nov. 2018
[24] M R Emes et al. (2012)
[25] "ExoMars 2016: Schiaparelli Anomaly Inquiry" European Space Agency. Web. 10 Nov. 2018

instruments, which “could have been exploited for cross check purposes and to elaborate a parallel logic for degraded modes leading to a safe landing”.[26]

Some of the ways in which UCLse’s second principle was applied successfully to the ExoMars 2016 super-system include: (a) considering the time dimension with regards to the parallel processes of sub-system development and technological progress; (b) designing certain system elements to be re-usable in the ExoMars 2020 mission; and (c) engaging in multi-factor simulations of trade-offs between different performance indicators. For the purposes of this paper, these will not be explored in depth.

Understand the enterprise context

UCLse’s third principle is to “understand the enterprise context”. This expresses the idea that both the system development system and its external environment need to be examined in order to understand the different objectives, constraints, and dynamics which may affect the system’s development and operation. This can be related to the “Seven Samurai” framework of systems engineering, which similarly includes context systems (external environment), realisation systems (organisation & suppliers), collaborating systems, sustainment systems, and competing systems.[27]

At the organisation level, understanding ESA’s strategic objectives with regards to the ExoMars programme was an important factor in Schiaparelli’s development. The follow-up mission in 2020 was due to have a significant overlap in the design of its system elements, including the re-use of the EDM’s heatshield and attitude control systems for the Mars rover’s landing sequence.[28] This affected both the system’s design constraints and its validation requirements, placing it within the context of a preliminary mission to test key technologies for ExoMars 2020.

At the mission level, ESA’s collaboration with Roscosmos also had a considerable impact. Having agreed to use a Proton launch vehicle, the ExoMars 2016 mission’s super-system had to be designed in such a way that was compatible with the rocket’s payload fairing constraints. This was particularly notable due to the fact that the mission had been previously designed as a collaboration between ESA and NASA, with the intention of using an Ariane V or Atlas V launch vehicle.[29] This highlights the

[26] "ExoMars 2016: Schiaparelli Anomaly Inquiry" European Space Agency. Web. 10 Nov. 2018
[27] J Martin (2014)
[28] "Mars lander crash complicates follow-on rover in 2020" Science Mag. Web. 10 Nov. 2018.
[29] "ExoMars Project History" SpaceFlight101. Web. 10 Nov. 2018.

importance of understanding the enterprise context with regards to systems design and the systems integration process.

At the industry level, ESA's interaction with supplier Thales Alenia Space[30] proved to be a critical element in the mission's outcome. The anomaly inquiry report identified that a lack of effective specification, verification, and acceptance while receiving Schiaparelli from the manufacturer was one of the root causes for the system's failure. It concludes that the persistence of a saturation flag in the IMU's application software was "not identified, nor measured during acceptance of the unit", and that the anomalous behaviour was "never tested after delivery".[31] Effective communication of requirements and rigorous acceptance testing should therefore be regarded as some of the most important applications of this principle, especially for complex systems.

Systems engineering & project management

UCLse's fourth principle is to "integrate systems engineering and project management". This expresses the idea that there should be a symbiotic relationship between the two roles, avoiding the potential risks of either group adopting an "insular view of the project", and finding a balance between system performance (quality), resource limitations (budget), and time constraints (schedule).[32]

Within the context of a publicly-funded international space agency, project management plays a key role in the successful delivery of ESA's missions and financial accountability. Considering the ExoMars programme's budget limitations and the significant delays from original plans to launch its first two missions in 2007 and 2009, Schiaparelli's development was certain to require effective collaboration between its systems engineering and project management teams.[33]

Although it was not explicitly mentioned in the anomaly inquiry report, it is possible that such resource constraints played a role in the project's decisions to exclude parachute oscillation physics from E2E simulations and to neglect the importance of rigorous acceptance testing from suppliers. If that was the case, an application of the fourth principle would encourage more effective interface between engineering and management, resulting in the common understanding that certain mission-critical elements cannot be compromised due to project-related constraints. This principle

[30] "Exomars Mission" Thales Alenia Space. Web. 10 Nov. 2018
[31] "ExoMars 2016: Schiaparelli Anomaly Inquiry" European Space Agency. Web. 10 Nov. 2018
[32] M R Emes et al. (2012)
[33] "Aurora's Roadmap to Mars" European Space Agency. Web. 10 Nov. 2018

highlights the fact that project success is ultimately defined by the system's fulfilment of its requirements, which can be facilitated with such an integration.

Invest in the early stages of projects

UCLse's fifth principle is to "invest in the early stages of projects". This expresses the idea that a 'left-shift' in resources can result in the reduction of total effort required, reduce the risks of unforeseen difficulties, and increase the chances of project success. The application of this principle involves the identification of an "optimum ordering of activities" which depends on the circumstances of the system's project.[34]

Since its conception in 2001 as the "Aurora" programme, ESA's ExoMars initiative has been in development for almost two decades.[35] During that time, the mission concepts have gone through several different proposals, budget approvals, design reviews, timeline delays, budget cuts, partnership changes, and finally the initial mission's launch in 2016. All of this highlights the key benefits of left-shifting resources. Had ESA not invested in the early stages of the ExoMars programme, it would have likely faced much greater costs and technical difficulties due to the later timeframe of its changes.

The most significant example of this principle's application is the early planning phase during which ESA reached an agreement to collaborate with NASA, signing the "Mars Exploration Joint Initiative" in 2009.[36] Under this framework, the ExoMars rover was being designed to fit on board an Atlas V launch vehicle together with NASA's Mars orbiter.[37] However, this collaboration was cancelled in 2013 due to budgetary cuts from NASA, forcing ESA to completely overhaul its mission architecture and seek partnership with Roscosmos. Despite the importance of left-shift, this also highlights that maintaining some flexibility in system architecture was a key characteristic in ESA's ability to make this transition without complete mission failure.

As a result of this fundamental change, Proton was adopted as the new launch vehicle, which led to the decision to separate the programme into two missions. This would allow the first mission to have a test lander (Schiaparelli), which would offload some of the technical risk from the more expensive Mars rover.[38] In retrospect, with the knowledge that the EDM's landing failure has provided ESA with valuable lessons to

[34] M R Emes et al. (2012)
[35] "Aurora's Roadmap to Mars" European Space Agency. Web. 10 Nov. 2018
[36] "Mars Exploration Joint Initiative" National Aeronautics and Space Administration. Web. 10 Nov. 2018
[37] "NASA could take role in European ExoMars mission" Space News. Web. 10 Nov. 2018.
[38] "ExoMars Project History" SpaceFlight101. Web. 10 Nov. 2018.

improve ExoMars 2020's development process, the importance of having invested in the early stages of this project is clear. In that respect, Schiaparelli's nature as a demonstration module for ExoMars 2020 shows that this paper's entire system of interest is actually a direct manifestation of the fifth principle.

Other ways in which UCLse's fifth principle was applied to this mission's super-system include: (a) preparing design proposals for several different scientific payloads, some of which including the Humboldt (geophysics instruments) were cancelled during confirmation reviews due to budget limitations; (b) designing an initial setup with a dedicated carrier module which was later replaced by the TGO; and (c) running physics simulations during Schiaparelli's development process which resulted in the successful testing of most key technologies – despite the landing failure.[39]

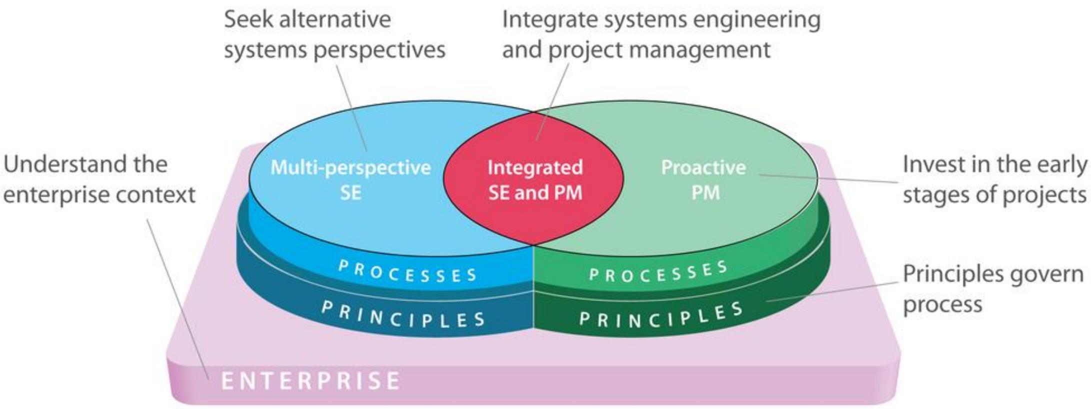

Fig. 3 – UCLse's Principles of Systems Engineering. Source: UCL[40]

[39] "Exomars Mission" Thales Alenia Space. Web. 10 Nov. 2018
[40] M R Emes et al. (2012)

IV. Evaluation

This paper will focus on evaluating the two principles of systems engineering which have been identified as the most interesting to discuss: (1) principles govern process; and (2) seek alternative systems perspectives.

Principles govern process

The first principle is a well-developed one which not only adds practical value to systems engineering management, but also addresses some of the most common criticisms of over-reliance on systems thinking: (a) lack of flexibility; (b) low creativity; and (c) inefficient cycles. The importance of establishing effective processes based on past experience cannot be understated. That is often what sets apart an industry-leading organisation from new entrants attempting to penetrate the market. When applied correctly, the existence and consistent utilisation of processes can lead to the emergence of resource efficiency, quality standards, and positive feedback loops.

Moreover, the idea of processes being governed by their underlying principles is a key philosophical wisdom which, although may seem obvious at times, has the potential to provide clarity in many situations where a process has entangled itself into its own construct, along with the people who have grown accustomed to it. Fundamental to this reasoning is the understanding that a process's architecting logic *is* its principles, which are often derived from past experience. Therefore, a process can only work as intended if it is constantly challenged and compared back to its original purpose.

A legitimate criticism of this approach is the notion that startups are able to develop their competitive advantage specifically due to a lack of established processes. This view of dynamic capabilities and efficient processes being on opposite ends of a spectrum is apparent in Teece, Peteraf, & Leigh[41], whereby "achieving organizational agility often involves sacrificing technical efficiencies". Within the context of this paper, it could certainly be argued that ESA and NASA have been eclipsed in innovation by 'New Space' companies such as SpaceX (launch vehicles), Spire Global (smallsat constellation), and NanoRacks (space logistics). However, UCLse's emphasis on the fact that individuals need to be "given a level of discretion in the application of high level processes" does address this issue to some extent.[42]

With regards to the second criticism, the concept of process innovation is an important element of the first principle. By acknowledging that engineers are fundamentally

[41] Teece, Peteraf, & Leigh (2016)
[42] M R Emes et al. (2012)

creative and that they should be "empowered to apply this creativity to processes as well as the products they design", the systems engineer should find a balance between following established principles and creating room for ideation. This also relates to project management in terms of employee satisfaction and therefore productivity.

Finally, the efficiency of improvement cycles within each process is also addressed by UCLse's original paper, whereby it is "essential to capture these lessons and continuously improve current processes". This is likely to depend on the project's interfaces and decision-making structures, but can and should be facilitated through the implementation of 'process improvement processes'. The issue of slow improvement cycles, which is sometimes described as 'bureaucracy', may simply be a reflection of the longer timescales that are essential to maintaining design robustness and adequate risk assessment in systems engineering projects.

To conclude, it is argued that "principles govern process" is an effective systems engineering principle which is formulated with enough dynamic characteristics to apply to a variety of scenarios. However, the effectiveness of its application between different industries should not be under-estimated. As per UCLse: "in safety-critical systems and demanding environments such as space, very high levels of reliability and quality are essential".[43] Industry or enterprise contexts with less safety-criticality and lower technological complexity may not benefit from the same level of reliance on processes governed by principles. Nevertheless, such situations can be effectively mitigated by considering the third principle, "understand the enterprise context", and applying (or excluding) other principles according to the insights derived from its analysis.

Seek alternative systems perspectives

The second principle is probably the one which most essentially captures the systems theory approach towards analysing technology projects. By using a "command and conquer" strategy, one can reduce complex systems into their interacting elements in order to facilitate multi-dimensional perspectives, which is particularly important when attempting to determine trade-offs between different parameters.

This is useful in industry contexts whereby the system of interest may have certain properties that are desirable to its primary users, but have alternative (and possibly negative) impacts on other stakeholders. It highlights the reality that sometimes the "apparent focus on one stakeholder is an illusion" which requires the systems engineer to establish a "set of value-adding system requirements" and determine their impact

[43] M R Emes et al. (2012)

on the system's environment. For example, an electric car may be designed to provide comfort and reduce air pollution in urban areas, but stakeholders involved in the metal extraction process for the production of its batteries may suffer from the release of toxic gases, which would eventually have an effect on the entire biosphere. This highlights the importance of lifecycle assessments and the potential of seeking alternative systems perspectives in order to facilitate the incorporation of reduction, re-usability, or recycling capabilities into a system's architectural design.

A potential criticism of this principle is that, depending on the system context, a reductionist approach to analysing its elements may not deliver useful insights, or may result in misleading conclusions about the dynamics involved in its emergent properties. In particular, 'soft systems' such as universities may not be amenable to structural or behavioural models. However, as per James, Smith, & Emes, a productive analysis can still be achieved by exploring "a range of systems perspectives, viewpoints, or abstractions".[44]

To conclude, seeking alternative systems perspectives will almost always be an insightful exercise to better understand and manage systems engineering projects. With regards to the ExoMars 2016 mission, considering the time dimension of Schiaparelli's development in parallel with initial designs for the Mars rover will have been an important part of the mission architecture's design. This principle can be used across a variety of sectors, including systems such as the management of environmental sustainability at University College London (UCL).[45]

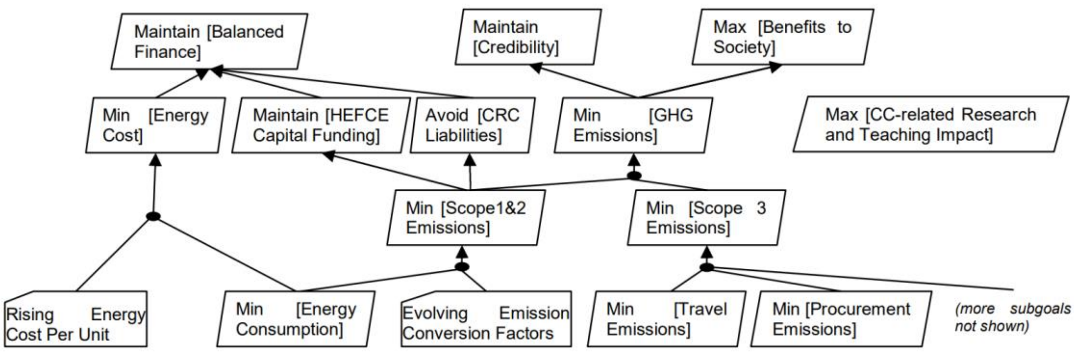

Fig. 4 – UCL's top-level sustainability goals. Source: Stefan et al.[46]

[44] James, Smith, & Emes (2012)
[45] Stefan et. al (2011)
[46] Stefan et. al (2011)

V. Conclusions

Based on this paper’s application of systems engineering principles to ESA’s ExoMars 2016 mission, the main conclusion is that a high level of insight and better understanding of Schiaparelli’s landing failure was gained from the analysis process.

This was especially true with regards to (1) the underlying principles which govern ESA’s verification process; (2) the time dimension’s impact on system architecture and acceptable risk levels; (3) the enterprise context’s effect on system constraints and validation requirements (at an organisation, mission, and industrial level); (4) a greater appreciation of the balance between systems engineering and project management within the context of an international space agency; and (5) the importance of left-shifting resources in a high uncertainty environment with significant potential for both organisational and technological changes. Despite the multitude of weaknesses in systems engineering which were identified as root causes in ESA’s anomaly inquiry report, this paper’s analysis found that those issues were addressed effectively and integrated as improvements into the ExoMars programme’s processes.

In terms of the critical evaluation of these principles, the main conclusion is that they are well-formulated for the purposes of systems engineering projects, but certainly have a bias towards high complexity technology systems. It may be useful to conduct further research in order to elaborate on the applicability of these principles for startups, soft systems, and others scenarios in which unpredictable factors may have a destabilising or disruptive effect which requires greater dynamic capabilities and less reliance on a systems thinking approach. However, the level of flexibility and contextual guidance in UCLse’s Principles of Systems Engineering is nevertheless adequate given its stated purpose and the MSSL’s background in space science.

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