Successful Systems Engineering Effort: SpaceX

Genc, Ece Beren

Space Exploration Technologies Corporation (SpaceX) is an America based non-traditional spacecraft manufacturer which is founded in 2002 by Elon Musk. The aim of the company to make space transportation available for citizens and to provide sustainable life on Mars. They operate in spacecraft industry with Dragon and Starship spacecrafts and in satellite communication industry with Starlink, and in launch service provision with Falcon 9 and Falcon Heavy. They are also currently work on Starship, Rideshare, Starshield and human spaceflight projects. SpaceX is a pioneering private company in space exploration which achieves numerous milestones. They developed the first liquid-propellant rocket to reach orbit, launched, orbited, and recovered a spacecraft, sent missions to the International Space Station (ISS), and transported astronauts there. They accomplished the first vertical propulsive landing of an orbital rocket booster and pioneered its reuse. SpaceX has landed over 208 times has launched over 300 times with Falcon 9. It helps SpaceX to open a new era for space technologies.

Behind this success, there is a disciplinary system engineering effort with critical system thinking approach. This paper will evaluate SpaceX's system engineering effort with examples, and it will investigate the key success and failure points with their root causes. SpaceX has one main business goal that is provision of reliable and safe space transportation with the attainable price. They can be summarized as high-tech organization with flat organization structure, agile decisions, and traditional discipline.

Systems Engineering (SE) is an integrative approach aimed at helping teams collaborate to understand and manage systems and their complexity. The ultimate goal of system engineering is delivering successful systems. It is based on systems thinking, which emphasizes awareness of wholes and the interrelation of parts within those wholes. SE ensures that all pieces work together to achieve the objectives of the whole with a holistic view. Therefore, it brings balanced life cycle approach. It is a transdisciplinary and integrative approach which create basis for the successful realization, usage, and retirement of engineered systems. It considers both business and technical needs to manage risks effectively. SE's purpose is to conceive, develop, produce, utilize, support, and retire the right product or service at the right time within the defined budget and schedule constraints. Therefore, it requires a common understanding and vision of the system's current and future states.

SpaceX deals with large scale, complex and safety-critical projects. Therefore, their success related with team spirit and collaboration with different teams and disciplines to build the whole system. In this point, system engineering comes into play. System engineering is a discipline which anticipates and prevents emergent properties related problems and help to provide smooth and seamless integration of the large-scale complex systems. Therefore, it contributes to reduce the money, time and human resources waste. However, for early systems in the history, it was hard to forecast potential integration problems proactively and achieve successful integration right at the first time. However, SpaceX has changed it with model-based system engineering approach and has delivered high quality, reliable, safe and cheaper solutions. It makes traditional players to think the new dynamics and change the traditional methods. Especially for safety critical systems, technical excellence, integration of reliable systems and social content should be delivered at the first time. It requires a system-oriented company culture and applying the accountability and transability principles. Employees should take the responsibility of failure and provide solutions to recover the failure with minimum damage.

SpaceX applies spiral model effectively. Spiral model is suitable for large scale, more critical projects. Number of iterations which are required to complete the whole system is defined and planned by the project manager. It needs experts in the team for the risk assessment. It gives opportunity to combine different software development models. Therefore, by using these advantages and potential of different software models, high requirements' volatility can be handled, but it should not be preferred for contract-based projects. Because it takes time to complete. There is no partial implementation. Spiral continues infinitely. This model includes risk evaluation during each iteration. This system brings the advantage of prototyping and waterfall models together. Prototyping provides iterative nature with control and systematic advantages of the waterfall model. Therefore, increments are rapidly developed. It combines different software development approaches, so utilizing prototyping model can be useful for testing and understanding new or unknown technologies. Each iteration through the planning territory leads to new adjustments. Therefore, each one evolves the project. Therefore, SpaceX prefers spiral model rather than cleanroom model. Cleanroom model is also preferred for very important, critical and large sized projects like nuclear reactor cooling systems, aircraft avionics and medical devices. Main purpose of the system is defect prevention rather than defect removal. Requirements need to be specific and clear. It is a good choice for contract-based systems. It is obvious that SpaceX firstly decide the right model for their products. Spiral model is good for long lifetime projects, because the spiral model can be also continued after the development phase. It means throughout the software lifecycle this model can be adapted. It is also the only model which takes maintenance into consideration. Therefore, it is good for long lifetime projects. It is a risk driven model. The main goal of the model is identifying and resolving risks. It minimizes risk. However, risk assessments can be subjective, so on high-risk elements it can be problematic.

SpaceX uses each iteration for continuous and rapid prototyping to test the system and decrease the risk gradually by learning from mistakes. It helps to developing organizational agility and actions to failure. Root cause analysis and patching the mistakes in each iteration reduces the cost by iteratively solving problems and incrementally delivering better system. They also give importance to accountability and traceability. Ability of accountability is the result of the traceability of lower-level requirements by implementation of continuous design-build-quality-test cycles. It is help to validation and verification of every single requirement. By this way, the company can ensure that each and every requirement is addressed for both design and engineering element by tests, validations and verifications. It gives confidence to company to not miss anything. Especially for safety critical systems, it is crucial because traceability brings accountability. In large size complex projects, it is nearly impossible to integrate all possible system components successfully at the first time. To reduce this risk, it is critically to take small step and testing them in each increment. Their continuous testing approach brings the confidence in the real flight, because they reduce to cost of development, resources and time by detecting bugs in early stage. The flights are the same with what they test. Therefore, they detect problems in testing phase to prevent them in real flight. Continuous testing also helps them evaluate quality of each process, because they try to reduce number of bugs which are detected after delivery. They replicate the real environment during the test. Therefore, they reduced the risk of failure. Multiple layers of test and testing the multiple layers of integrated components meticulously increase the confidence of the product and brings quality organically. It helps to increase reliability and safety of the system which are very crucial for safety-critical systems.

As it is mentioned before, they deliver large scale complex systems. Therefore, each project requires to transdisciplinary and integrated approach. Distributed system level tasks make system engineering applications critical and they a required system thinking. Each product is developed the meet user needs and requirements. Therefore, understanding user requirements, project realities, policies and laws are fatal to deliver successful project. Each requirement should be understood well, be tracked, be validated, and be verified. It is important to traceability of each requirement and meeting them. According to Nasa's cost estimation, SpaceX can produce cheaper than NASA. It may be related with incremental steps, optimization of the system in each increment and their proactive approach. They provide how SpaceX differs from traditional Vee approach. It is the good example of tailoring. The tools are provided openly. However, they need to tailor according to problem type, problem size, how critical it is and organizational culture. SpaceX team gives importance to understanding top level requirement and accordingly realizing the key design parameters, their adjustment. After them, they build the system and test them to trace lower-level planning, failure point and measure the system performance. Integration and monitorization of the system is crucial. It brings specific, measurable, accepted, realistic, and timely (SMART) projects. They can validate the product. For the system level performance and cost optimization, it is important to decide using sub-contractors or built-in-house solutions. SpaceX company chose the second option to be sure about quality of them and reduce the cost. As it is mentioned before, they incrementally create the whole system. Therefore, they have chance to use iterative plan-design-build-test and measure cycle. It helps company to learn from mistakes by experience and reduce the cost of failure. As Elon Musk said “Failure is an option here. If things are not failing, you are not innovating.”. They use continuous test to determine the system capabilities, failure points and system weaknesses. Testing is a process, and the quality of the product highly relies on the quality of the process. Analysis of test result and improve them in the next cycle increase the system reliability, quick recovery of the system and quality.

To sum up, SpaceX aimed to develop reliable, cost-effective rockets to reduce space access and to provide accessible service. They identified reusable rocket technology as crucial for their goal, because it can help to reduce cost and contributes to the development of Falcon 9 with its business objectives and goals. Engineers designed Falcons with innovative technologies like Merlin engines and landing legs, by focusing on reliability and reusability. Extensive testing and iteration enhanced high performance and good quality products. SE ensures long-term sustainability and adaptability throughout the project lifecycle. SpaceX employs reliability measures, including certification for safety-critical materials and extensive testing, to prevent failures and ensure product quality. They would like to be obtain 100% reliability from suppliers to prevent raw material and supplier related failures. Even though one component can work successfully, it does not mean that it won't fail when whole system integration complete. Therefore, SpaceX requests certification for raw material for safety-critical systems, load testing and batch testing for acceptance of the product from the supplier. The company utilizes simulation software to digitally model rocket components and conduct virtual test which significantly contributes to reduce development time and costs. Data collection and analysis of data from various sources to identify design flaws and improve performance. SpaceX's iterative approach, like software development cycles, emphasizes learning from failures and continuous improvement. The company's philosophy of embracing failure as a steppingstone provides innovation driven progress. Collaboration, internal integration, and a culture of rapid iteration distinguish SpaceX's approach from traditional companies like NASA and make SpaceX faster and cheaper option. It also help SpaceX to become market leader, because spiral model enables faster development timelines and risk mitigation. SpaceX innovates by its ability to learn from failures. It emphasizes the importance of adaptability, collaboration, and continuous improvement in achieving sustainable success.

Resources:

https://www.spacex.com/vehicles/falcon-9/ (Last Access: 2024-04-29).
http://sewiki.ru/images/0/00/CASE2012_2-4_Muratore_presentation.pdf (Last Access: 2024-04-29).
https://journal.uptimeinstitute.com/examining-and-learning-from-complex-systems-failures/ (Last Access: 2024-04-29).
https://en.wikipedia.org/wiki/SpaceX (Last Access: 2024-04-29).
https://www.durolabs.co/blog/former-spacex-engineer-breaks-down-the-code-to-successful-hardware-engineering/ (Last Access: 2024-04-29).
https://www.linkedin.com/pulse/how-spacex-succeeded-because-use-data-engineers-luke-harrison/ (Last Access: 2024-04-29).
https://medium.com/the-systems-engineering-scholar/spacexs-starship-79cfc83abdba (Last Access: 2024-04-29).
https://www.usni.org/magazines/proceedings/2020/september/improve-systems-engineering-acquisition-process (Last Access: 2024-04-29).
https://www.youtube.com/watch?v=xCHuT7r38Es (Last Access: 2024-04-29).
https://www.youtube.com/watch?v=SMLDAgDNOhk (Last Access: 2024-04-29).
https://www.youtube.com/watch?v=I0qgBuIO6n4&t=15s (Last Access: 2024-04-29).
https://spaceref.com/uncategorized/nasa-study-why-spacex-can-build-a-rocket-cheaper-than-nasa/ (Last Access: 2024-04-29).
https://www.youtube.com/watch?v=TllA-WMdXy4 (Last Access: 2024-04-29).
https://www.linkedin.com/pulse/spacexs-journey-success-lessons-software-engineering-faith-warren-hkvte/ (Last Access: 2024-04-29).
https://www.valispace.com/why-spacex-and-tesla-move-faster-than-traditional-hardware-engineering-companies/ (Last Access: 2024-04-29).
https://aerospaceamerica.aiaa.org/departments/why-todays-systems-engineers-should-remember-their-pioneers/ (Last Access: 2024-04-29).
https://www.rocketstem.org/2023/04/27/first-launch-of-spacexs-starship-was-a-successful-failure/ (Last Access: 2024-04-29).
https://www.inc.com/alyssa-satara/in-2-sentences-elon-musk-explains-why-key-to-success-is-failure.html (Last Access: 2024-04-29).

Failed Systems Engineering Effort: Lockheed Martin F-35 Lightning II Program

The F-35 program was intended to support advanced technology and modular design principles to develop a fifth-generation multirole fighter aircraft. However, they have faced with significant delays, cost overruns, and technical issues due to failures in system engineering and project management approaches. The program's system engineering approach contributed to its failure which is stemmed from requirements complexity, concurrent development, complex software development process, lack of testing, validation, verification and evaluation.

F-35 has faced with reliability, maintainability, and availability problems. According to the report they provide annually, their availability of operations could not meet the goal and it could not meet the requirements of the project. Availability is indicating the accomplishing one of its missions. In 2023, availability of F-35 was also less than 2022. Pentagon has discussed the root causes and they have identified the complexity of the project and computer-intensive jet design. Poor system engineering efforts, ambitious goals and complex requirements, inefficient software developments, high volatility and lack of testing cause the missing the developmental exit criteria. Therefore, full rate production still doesn't operate. In addition, any of the development test has not been applied due to waiting the completion of awaiting completion of Tech Refresh-3 update testing. Report also focused on the supplier related quality and reliability problems. They could not deliver the fully functional F135 engines. Therefore, it contributes the lack of availability of the system. The F-35A could not meet all reliability requirements. In addition, none of the F-35 achieves the meeting the maintainability related requirements. They stated failure points as lack of troubleshooting, hardware reliability and software stability problems. Pentagon has faced with challenges of budget overrunning and delays in the timeline.

The main problems they have faced during this project can be summarized with one paragraph. The availability and full mission capability of the F-35 fleet were below the desired goals. Combat-coded aircraft performed better than the overall fleet but still fell short. Maintenance issues also contributed to these shortcomings. The program faced challenges in maintaining the aircraft. They had difficulty to stock critical spare parts and to address the reliability issues with key components. The F-35 fleet did not meet all the reliability and maintainability standards set in the Operational Requirements Document. The Mean Flight Hours Between Critical Failures fell short of the target for all variants which indicates the ongoing issues with reliability. During patrols along NATO's eastern flank, F-35s detected unusual radar emissions from Russian S-300 air defense systems. The jets' onboard computers were unable to identify these emissions due to potential changes in the radar's operating mode. Despite the above challenges, the F-35 demonstrated success on advanced electronic warfare capabilities and the ability to gather intelligence on enemy radar systems.

The F-35 program should accommodate diverse mission requirements across different military branches. Therefore, it resulted in a highly complex set of specifications. This complexity led to challenges in system integration, interoperability, and performance optimization. It is lack of experience to apply system engineering appropriately and they have been lacked of development of system thinking, because system engineering helps to manage complex system by reducing failure risk and maximizing team work, transdisciplinary and integrated approach. It prioritizes understanding of the needs of stakeholders, legal and political constraints and project requirements to develop the system accordingly. It encourages the verification and validation of each requirement, integration and continuous testing. SE helps to understand the project heuristically by considering the project from concept development to retirement of the product.

The decision of concurrent development of three distinct variants of the F-35 has caused coordination challenges among stakeholders. In addition, complex software development processes has contributed to software integration issues and performance problems, because depending on the change request frequency for requirement and design, Lockheed Martin team had challenges to manage them and delivered a working solutions on time. The F-35's advanced software systems has experienced significant delays and deficiencies. Lastly, The F-35 program faced delays and setbacks in testing and evaluation activities. It is a very critical point of failure of the project. Insufficient testing of critical systems and components prior to production contributed to reliability and performance issues in operational aircraft. They set a very ambitious mission requirements, a complex and challenging set of specifications. Therefore, it has caused the difficulties, delays, and cost overruns throughout the program's lifecycle. Technical risks and coordination challenges come together with high-frequency requirement and design changes, and they have resulted with the time and budget overruns. The F-35's advanced software systems has also caused the delays and deficiencies due to lack of integration, lack of alignment with the requirements and complicate development process. They affect the overall performance of the project because of lack of operational readiness and mission effectiveness. They also have had problems with sub-contractors. Quality and performance problems contributed to failure.

If we compare one successful system engineering effort and one failed example, we can detect the points which contribute the success. These are the points that SpaceX has successfully applied and has taken its award. On the other hand, these are the points F-35 points should apply to successfully deliver the project. However, it seems as it might be too late for F-35 project to apply them, because system engineering starts from concept development and goes through the retirement of the project. SpaceX team embedded them in their company culture and how they do business. Therefore, it may time for traditional companies to break the taboos and apply up-to-date methodologies. Key differences of SpaceX's and F-35's approaches are provided below.

1. Team spirit and individual accountability
2. Transparent and accountable company culture
3. Dedication to company's business goals and objectives
4. Applying requirement engineering, system thinking, verification and validation, integration and testing and lifecycle considerations from concept development to retirement of the product
5. SpaceX provides tailored solutions to stakeholders' needs and identified problem and related context.
6. SpaceX provides a holistic system view, and they are able to see the system as a whole while taking little details into considerations. They give importance to each system elements and their emergent properties. System should work seamlessly when whole system integrates.
7. Technical excellence is harmonized by real world, internal and external dynamics, political and social environment, and legal factors. They are also turn into constrains of system implementation.
8. SpaceX provides a solution which understands stakeholders' needs and expectations, its operational environment, interactions, and behaviors of system component.
9. Constraints like time, budget, technical requirements, are understood well by SpaceX.
10. SpaceX manages the risk under high uncertainty by applying spiral model and risk reduction in each iteration.

As a result, the Lockheed Martin F-35 Lightning II program is the example of a system engineering failure. Despite its ambitious goals and technological advancements, the program has been faced with delays, cost overruns, and technical deficiencies. This program emphasized the problems related with reliance on contractors for maintenance, lack of technical excellence, and integration problems of whole systems. It shows us that learning from mistakes during the test before deploying the system is very critical. Despite its advanced capabilities, the F-35 program has faced challenges in meeting performance metrics, maintaining aircraft availability, and addressing reliability issues. It is mainly stemmed from lack of system thinking and highly discipline system engineering applications.

Resources:
https://www.defenseone.com/technology/2016/02/f-35s-terrifying-bug-list/125638/ (Last Access: 2024-04-29).
https://en.wikipedia.org/wiki/Lockheed_Martin_F-35_Lightning_II (Last Access: 2024-04-29).
https://www.lockheedmartin.com/en-us/products/f-35.html (Last Access: 2024-04-29).
https://www.af.mil/About-Us/Fact-Sheets/Display/Article/478441/f-35a-lightning-ii/ (Last Access: 2024-04-29).
https://www.f35.com/f35/about/from-design-to-delivery.html (Last Access: 2024-04-29).
https://www.forbes.com/sites/davidaxe/2021/02/23/the-us-air-force-just-admitted-the-f-35-stealth-fighter-has-failed/?sh=7e94a8ab1b16 (Last Access: 2024-04-29).
https://www.theepochtimes.com/opinion/the-inside-story-of-the-f-35-lightning-ii-5484367?welcomeuser=1 (Last Access: 2024-04-29).
https://www.pogo.org/analysis/has-the-pentagon-learned-from-the-f-35-debacle (Last Access: 2024-04-29).
https://www.eurasiantimes.com/unusual-failure-f-35-jets-operating-in-stealth-mode-helping/ (Last Access: 2024-04-29).
https://www.airandspaceforces.com/f-35-reliability-maintainability-availability-2023/ (Last Access: 2024-04-29).