System Adaptability

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To *adapt* means "to make fit (as for a new use) often by modification" (Merriam-Webster, Inc. n.d.). The term adaptation is traditionally used in natural ecosystems as the "modification of an organism or its parts that makes it more fit for existence under the conditions of its environment" where the conditions can be either positive or negative (Andersen and Gronau 2005). Following from the dictionary definition, System Adaptability is a system's ability to satisfy mission and requirement changes, with or without modifications (Zhu 2015) (Jackson 2016). One common way to judge whether a system is more adaptable than another is if it is able to support mission and requirement changes at lower cost – an indication of how difficult a system is to adapt. Note that the term *cost* here may not necessarily be financial. It may include time, fuel, complexity as adopted in Zhu, et al. (2016) or any metric that designers, users, and other stakeholders value with regard to the difficulty of modifications.

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Contents

Adaptability in Systems Engineering

The adaptability concept is applicable to both real and conceptual systems as defined in Sillitto, Hillary, et al. (2017). Many concepts are related to system adaptability such as system resilience, flexible design, and design reuse.

- System resilience has traditionally focused on graceful degradation and recovery of a system's performance, triggered by adverse events and planned for in advance. (see System Resilience) System adaptability focuses on solutions for changes caused by either adversarial or beneficial events.
- Flexible design in industrial engineering (Saleh, et al. 2009) often requires up-front investment and justification of redundant design components or facilities, with more than 50 kinds of flexibilities defined and studied.
- System adaptability looks into future changes to inform current design choices for reduction of unnecessarily redundant design components. System adaptability encourages reuse, but generally does not promote it at the expense of higher cost.

Three Fundamental Factors

Comparing adaptability among different systems relies on three fundamental factors:

- Mission and Requirement Evaluation Space (MRES)
- Design Space

- Switching Cost

These factors are explained in the next three subsections.

Mission and Requirement Evaluation Space (MRES)

Common development practice assumes each requirement is for current needs and is often subject to budget constraint perceptions. MRES differs in that it uses systems thinking (see Systems Thinking) to project into the future and identifies requirements with high risk of change. These uncertain requirements come from stakeholder decisions, market changes, technology progression, engineering uncertainties, and other sources. They are potential needs that can optionally be considered. (Zhu, 2023) MRES is a collection of current needs (i.e. requirements and missions) and optional potential needs. These projections into the future offer valuable information when designing for adaptability. Of course, predicting possible future needs is an uncertain task and itself incurs costs. Important optional potential needs could be overlooked or poorly stated. Under cost and schedule pressure, developing optional potential needs could be shortchanged. Nevertheless, anticipating optional possible future needs and their potential impact on design is a valuable systems engineering (SE) activity.

Design Space

SE normally includes developing alternative possible designs and comparing them to pick the best one among the alternatives. A collection of different possible system designs is called the *design space* or *trade space* in which tradeoff studies or trade studies are performed to pick the one that will be implemented. (Cilli & Parnell 2014) (NASA 2016) In modern design approaches, design spaces can be enormous with automated and semi-automated means to conduct the trade study. (Raz, et al. 2018) The trade study is based on a set of decision factors, which can include system adaptability.

Switching Cost

If adapting the system requires modifying it, the ease of modification indicates the degree of adaptability. The cost of switching from one system design/state to another design/state is called the *switching cost* which is a good indicator of how difficult it is to adapt. As stated at the beginning of this article, the term *cost* here may not necessarily be financial.

Traditional financial cost estimation assumes a system is developed from scratch, which in reality is rarely done. Many products are developed by modifying designs from prior products, where the cost is actually a switching cost. Methods of estimating switching cost for a complete generic system, rather than individual components or systems of a specific kind, were initiated mainly by two research teams: a process-based method was developed and later reported in Zhu (2018) and a parametric approach was developed in COSYSMO (Alstad 2019).

Development History

Two major prior works on system adaptability were authored by Gu, Hashemian, and Nee (2004) and by Ross, Rhodes, and Hastings (2007). The first defines adaptability as a normalized savings in switching from one product to another, emphasizing the costs as the main consideration. In Ross, Rhodes, and Hastings (2007), for two designs *A* and *B*, if *A* can be modified to become *B*, then a link is created between them. They define the adaptability of a design as the outdegree or filtered outdegree from that design. A design's outdegree counts the links from this design to the other designs.

In a design space, some designs support the mission better than others. Without considering the support to missions or requirements, measuring the cost to switch to another design (Gu, Hashemian, & Nee 2004) or how many other designs one design can switch to (Ross, Rhodes, & Hastings 2007) can result in inverted measures, where an entity that would receive a higher value of the measurement result than another entity receives with a lower value result. A design that is able to switch with low cost to many other designs that are of no or low value for missions may receive a higher adaptability score than another design that actually supports the needed missions. Fundamentally, these two works capture only two of the three fundamental factors described in section *Mission and Requirements Evaluation Space* above - the MRES factor, which is needed to prevent inverted measures.

In an eco-system, a species adapts in order to survive and exist longer. In SE, being able to support future missions/requirement needs prolongs the service life of the system and extends its existence, which is well aligned with the eco-system definition of adaptability.

There are also domain-specific definitions of adaptability and switching costs in such domains as IT, control, and self-adaptive systems areas. (Zhu, et al. 2016).

Demonstrating Adaptability: An Aerospace Example

In the following example, a high-level abstraction of an aircraft engine is used to illustrate how to evaluate the adaptability of system designs (Zhu, et al., 2016) using the three critical factors: MRES, Design Space, and Switching Costs.

MRES

Capturing flight missions for the engine example is the first step. The following operations set the stage for key mission requirements:

1. One engine inoperative
2. Takeoff Gradient of Climb
3. Climb Rate
4. Cruise Range

Three typical types of aircraft are used in commercial airline operations:

- a city-to-city short range aircraft
- a regional jet
- a transatlantic jet

Support for one engine becoming inoperative is required by aviation regulations. In addition, Takeoff Gradient of Climb, Climb Rates, and Cruise Range are as indicated in Table 1.

Table 1. Mission Parameters. (SEBoK Original)

Aircraft Type	Takeoff Gradient	Climb Rate (Ft/Min)	Cruise Range (Nautical Miles)
City-to-City Aircraft	1.2% (low)	1000 (low)	700 (short-range)
Regional Jet	1.2% (low)	1500 (high)	2000 (mid-range)
Transatlantic Jet	1.2% (low)	1500 (high)	4000 (long-range)

Suppose a customer wants to build a customized aircraft that has different mission preferences beyond the three regular types of aircraft, and the engine supplier is asked to design an engine to support that customization. Enumerating all possible values for each mission parameter, where each parameter takes three values (low, median and high), would produce 27 missions. However, here the customer prefers to consider only the 6 missions described in Table 2. The remaining 21 missions are deemed not needed and omitted from the design space. In this table, “optional” preferences refer to possible future mission needs such as fuel economy.

Table 2. Mission and Requirement Evaluation Space. (SEBoK Original)

Missions	1	2	3	4	5	6
Takeoff Gradient	low	low	low	high	high	high
Climb Rate	low	low	low	low	low	low
Cruise Range	long-range	mid-range	short-range	long-range	mid-range	short-range
Preference	optional	required	required	optional	optional	optional

Design Space

In this top abstraction level, an exhaustive search for all possible engine designs is conducted, and 12 design architectures are found. Each engine architecture may support one or more of these 6 missions. To simplify the discussion, three representative architectures were selected and shown in Figures 1, 2, and 3 which will be used to illustrate how architecture optimization is performed.

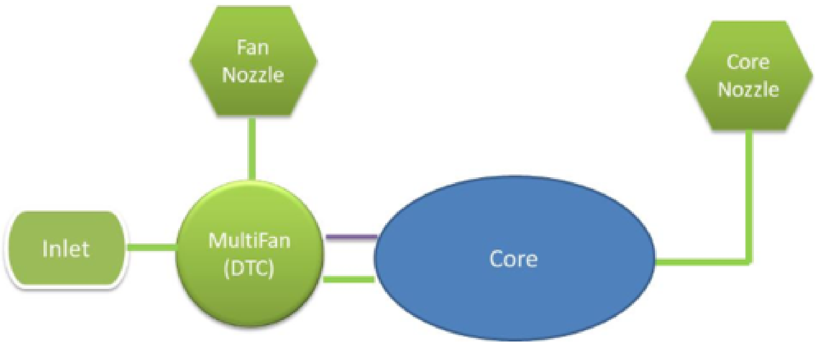

Figure 1. Selected Engine Architecture 3

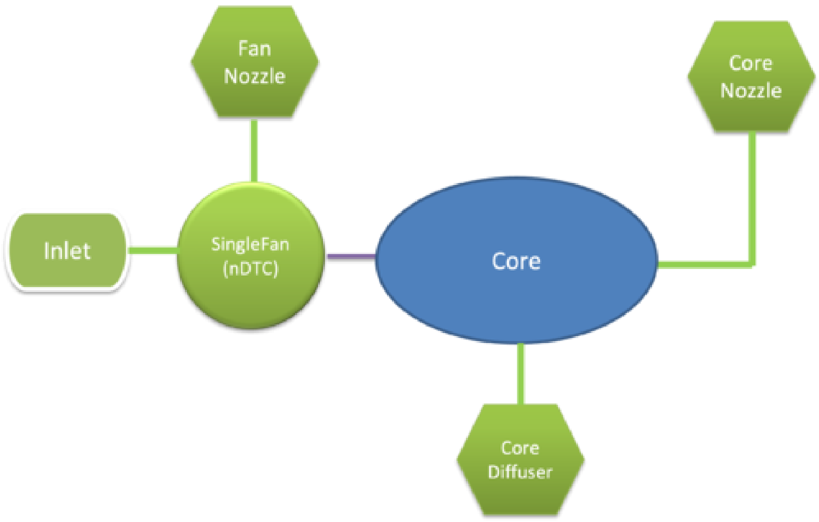

Figure 2. Selected Engine Architecture 6

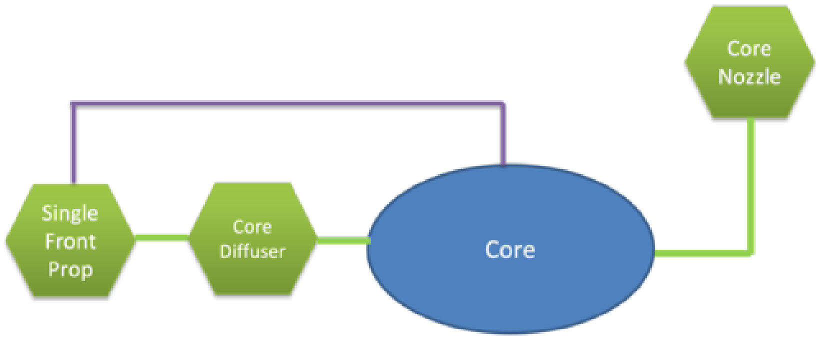

Figure 3. Selected Engine Architecture 9

Here, purple links represent the mechanical path and green links represent the gas path.

Switching Cost

In this aircraft engine example, the costs of switching from each architecture to each of the other 11 architectures would be estimated.

Architecture Optimization

When deciding which architecture to pick, a naïve approach would be picking the one that supports most of the missions in MRES. This often leads to a costly design that requires significant investment upfront that is undesirable. One of the advantages of developing a system with adaptability in mind is that it does not require significant upfront investment. For example, assume Architecture 3 and 6 can both meet the current needs, but there is a reasonable chance that changes may be needed such that only Architecture 9 is capable of supporting the future needs. If Architecture 3 and 6 are both acceptable in cost, but the switching cost from Architecture 6 to Architecture 9 is much higher than the switching from Architecture 3 to Architecture 9, one might want to choose Architecture 3. Note, however, that this discussion only considers system adaptability. It is likely other factors, such as schedule or company strategy, are also important and would be included in the trade study.

Quantification

System adaptability can be quantified. One such adaptability metric was developed by Zhu, et al. (2016), which can be conveniently used as a rule of thumb for engineers to judge how adaptable their system design is. This metric has a range of [0, 1] where a higher value indicates the system is more adaptable. The actual value is based on a function that considers both a weighting of the MRES missions/requirements as well as the switching costs to achieve the optional future missions/requirements. A design that can support all current and optional possible future missions/requirements within the cost threshold has an adaptability score of 1. A design that can support none of the optional missions/requirements within the cost threshold has an adaptability score of 0. All other designs have scores ranging between 0 and 1. Using the algorithm found in Zhu, et al. (2016), for the above aircraft engine example, Architecture 9 is *perfectly* adaptable with a score of 1, Architecture 3 is *mostly* adaptable with a score of 0.6, and architecture 6 is *partially* adaptable with a score of 0.25.

Other Applications

The same concept can be applied to any other system domain, such as Heating, Ventilation and Air Conditioning (HVAC) systems (Zhu, 2019), medical systems, transportation systems or social systems.

Technology and Engineering Management Phase

An adaptability metric is useful in system development and management whereby each design's adaptability metric is calculated and factored into trade studies for down-selections. (Zhu 2015) "Switching costs also significantly influence managerial decisions. They have been shown to influence the competitive strategies that managers adopt" as summarized by Whitten (2009) from Eliashberg and Robertson (1988). The adaptable design process in Figure 4 evolves with varying stakeholders, e.g. management, customers and technical teams. At the beginning of defining a system design, information such as requirements, financial budget information, management vision and a roadmap are generated. Current and optional possible missions and requirements are collected into MRES. The technical team then generates different designs within the design space and calculates the adaptability metric value for each design. That value can then influence design selection. This approach can be applied by both commercial and government organizations not only to internal development but also to acquisition from external organizations.

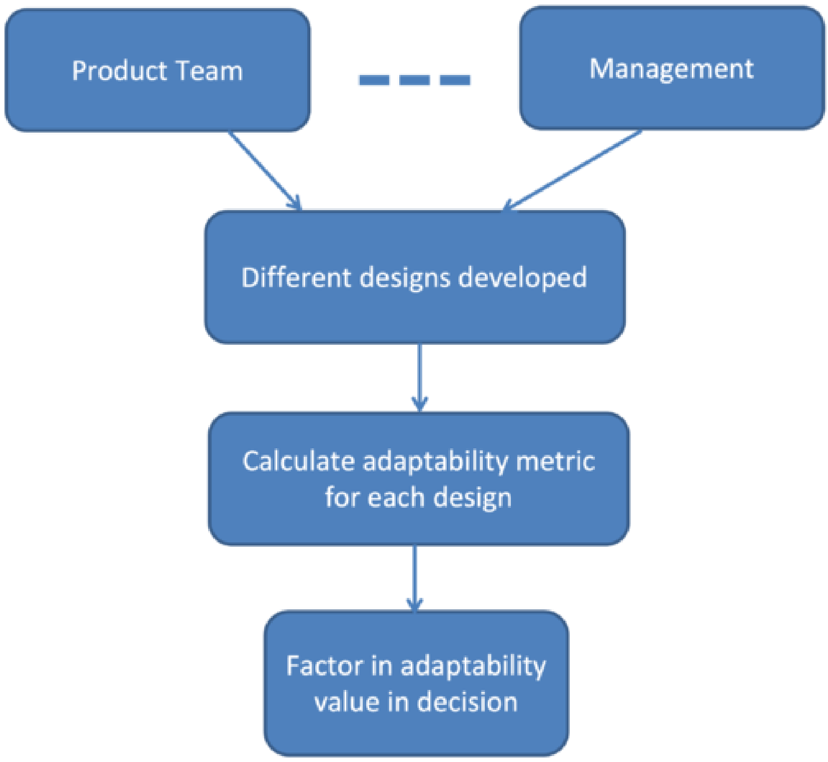

Figure 4. Adaptable Design Process

Also, agile, spiral, incremental and similar modern development lifecycles offer an opportunity to revisit both current and optional possible needs, allowing the then current architecture and design to be revisited in the context of system adaptability.

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